Mid-Cretaceous High Arctic stratigraphy, climate, and Oceanic Anoxic Events

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ABSTRACT

Over the past decades, much research has focused on the mid-Cretaceous greenhouse climate, the formation of widespread organic-rich black shales, and cooling intervals from low- to mid-latitude sections. Data from the High Arctic, however, are limited. In this paper, we present high-resolution geochemical records for an ~1.8-km-thick sedimentary succession exposed on Axel Heiberg Island in the Canadian Arctic Archipelago at a paleolatitude of ~71°N. For the first time, we have data constraints for the timing and magnitude of most major Oceanic Anoxic Events (OAEs) in brackish-water (OAE1a) and shelf (OAE1b and OAE2) settings in the mid-Cretaceous High Arctic. These are consistent with carbon-climate perturbations reported from deep-water records of lower latitudes. Glendonite beds are observed in the upper Aptian to lower Albian, covering an interval of ~6 m.y. between 118 and 112 Ma. Although the formation of glendonites is still under discussion, these well-dated occurrences may support the existence of cool shelf waters in the High Arctic Sverdrup Basin at this time, coeval with recent geochemical data from the subtropical Atlantic indicating a drop in sea-surface temperature of nearly 4 °C.

INTRODUCTION

Although major progress in Cretaceous (145–66 Ma) paleoclimate and paleoceanography has been made during the past decade (e.g., Föllmi, 2012), high-latitudinal environmental change has been less studied relative to low- and mid-latitude marine and terrestrial environments (e.g., Herman and Spicer, 1996; Jenkyns et al., 2004). As an alternative to drilling the Arctic Ocean, which is challenging and expensive, the Canadian Arctic Sverdrup Basin provides excellent exposures on land (Embry and Beauchamp, 2008). Still, the exact timing of massive carbon perturbations such as Oceanic Anoxic Events (OAEs) in relation to global warming and cooling periods and their consequences for the evolution of the marine mid-Cretaceous Arctic realm are poorly constrained. Importantly, records of the OAEs are lacking in the High Arctic, except for OAE2. This event has been previously documented based on positive carbon isotope excursions from Ellef Ringnes Island (Pugh et al., 2014) and May Point on Axel Heiberg Island (Lenniger et al., 2014) in Nunavut, Canada. Here we present multi-proxy records from exceptional exposures of Cretaceous sediments on the southern part of Axel Heiberg Island (Fig. 1) at a Cretaceous paleolatitude of ~71°N. Our work provides a unique view into the mid-Cretaceous paleoenvironmental history of the Arctic in a fluvial-deltaic, brackish-water to outer-shelf setting. We present new sedimentological, whole-rock organic $\delta^{13}C$ geochemistry, and U-Pb zircon geochronology data, which we compare with a newly tuned low-latitude carbonate $\delta^{13}C_{carb}$ record compiled from the literature. Our detailed stratigraphic framework allows the correlation between High Arctic and low- to mid-latitudes. Therefore, major paleoceanographic events known from low latitudes can be compared with the Sverdrup Basin.

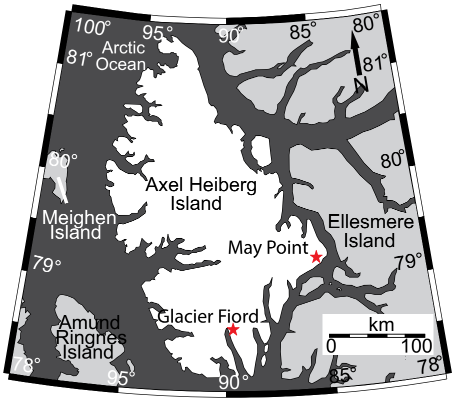

Figure 1. Location map of study area at Glacier Fiord, Axel Heiberg Island, Nunavut, Canada.

METHODS

Samples were collected at Glacier Fiord on Axel Heiberg Island (78°37.787′N, 89°52.123′ W). Total organic carbon (TOC, in %) and $\delta^{13}C_{org}$ measurements were performed on 454 samples. TOC measurements were conducted with a LECO RC-412 with reproducibility of 0.01%. $\delta^{13}C$ analysis of total organic carbon was performed using a Flash Elemental Analyzer 1112, connected to the continuous flow inlet system of a MAT 253 gas source mass spectrometer. Samples and standards both reproduced within ±0.2‰ and are reported relative to Vienna Peedee belemnite standard. The U-Pb geochronology used the chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) method. All zircon fractions were prepared using the annealing and chemical leaching technique (CA-TIMS) modified from that described by Mattinson (2005). Following the approach of Jarvis et al. (2006), who developed a calibrated carbonate-based $\delta^{13}C_{carb}$ reference curve for the Cenomanian–Campanian based on sections of the English Chalk, we extended this record to the Barremian (Fig. 2) by adding published high-resolution $\delta^{13}C_{carb}$ records from southeast France (Herrle et al., 2004; Gale et al., 2011) and Italy (Erba et al., 1999). The GSA Data Repository[1] provides more details on our methodologies and age interpretations used for U-Pb geochronology and the $\delta^{13}C_{carb}$ reference curve.

MID-CRETACEOUS HIGH ARCTIC CHEMO- AND CHRONOSTRATIGRAPHY

The age model for our studied section is based on lithostratigraphy and biostratigraphy including benthic foraminifera, dinoflagellates, and macrofossils (Schröder-Adams et al., 2014, and references therein). This is integrated with new U-Pb ages and refined with carbon isotope chemostratigraphy. The $\delta^{13}C_{org}$ record of Axel Heiberg Island plotted against stratigraphic depth is marked by several negative and positive excursions of >1‰ and distinctive intervals identified with letters *a* to *i* (Fig. 2). Based on correlation of the $\delta^{13}C_{org}$ records from Axel

[1]GSA Data Repository item 2015143, data used for compilation and methods, including Table DR1 (key biostratigraphic datum levels used to constrain the composite $\delta^{13}C$ values), Table DR2 (composite $\delta^{13}C$ values and important stratigraphic marker), Table DR3 ($\delta^{13}C$ and TOC results of Axel Heiberg Island), and Table DR4 (U-Pb analytical data), is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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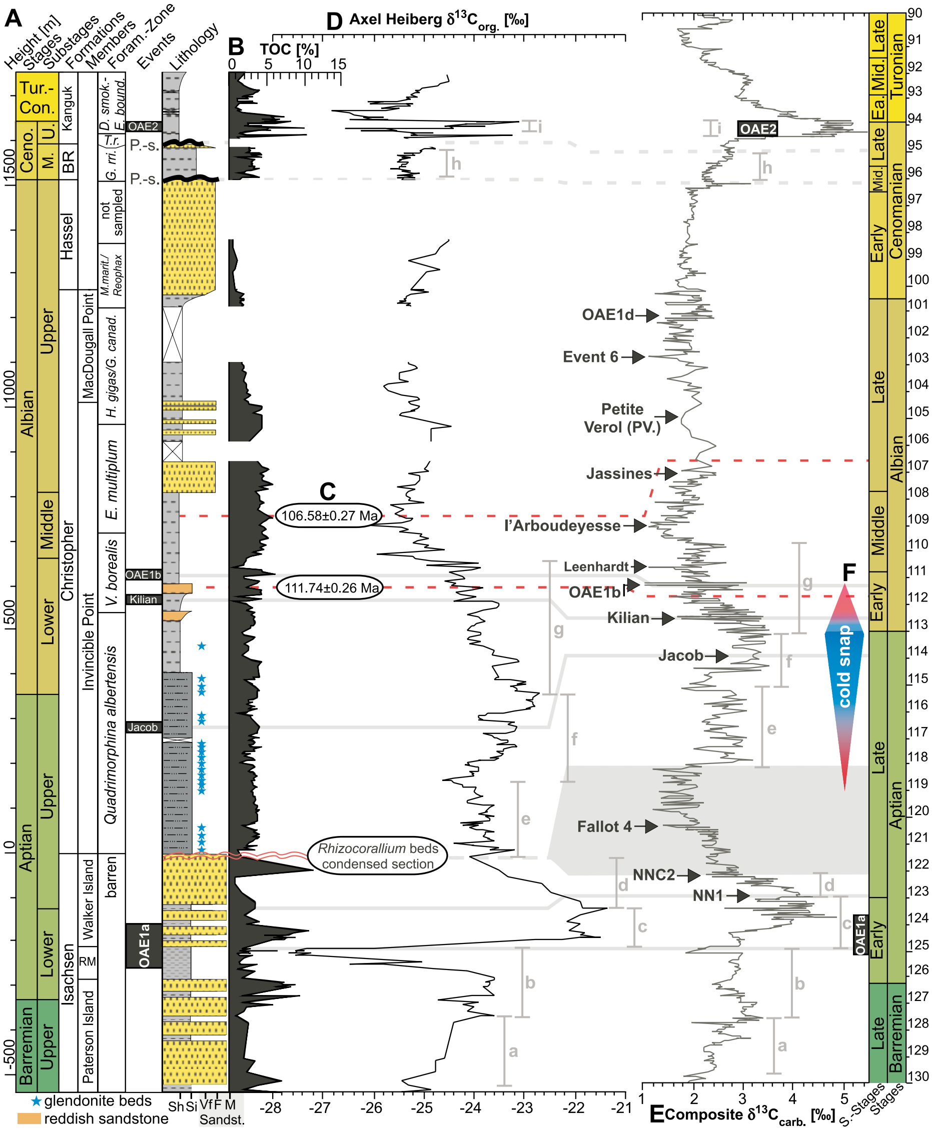

Figure 2. Sedimentary succession and geochemical records of Axel Heiberg Island, Nunavut, Canada. A: Stratigraphy and bio- and lithostratigraphy, paleoceanographic events, and lithology. B: Total organic carbon (TOC, %). C: U-Pb geochronology ages (red dashed lines indicate absolute age tie points). D: Organic carbon isotopes. E: Carbonate carbon isotope composite age-calibrated curve (Gradstein et al., 2012) and major mid-Cretaceous paleoceanographic events. F: Position of the late Aptian to early Albian cold snap based on TEX_{86} sea-surface temperatures from the Mazagan Plateau (McAnena et al., 2013). Correlative intervals based on $\delta^{13}C$ fluctuations are indicated by segments (*a* to *i*). Gray areas and red wavy lines represent condensed intervals (*Rhizocorallium* beds). Black wavy lines represent disconformities (paleosols) of middle and upper Cenomanian. Benthic foraminifera stratigraphy after Schröder-Adams et al. (2014). Blue stars show glendonite beds; gray lines represent correlative paleoceanographic events. Time scale on left is in Ma. RM—Rondon Member; BR—Bastion Ridge; OAE—Oceanic Anoxic Event; P.-s. —paleosol; Sh—shale; Si—siltstone; Vf—very fine sandstone; F—fine sandstone; M—medium sandstone; *V. borealis—Verneuilinoides borealis; E. multiplum—Evolutinella multiplum; H. gigas— Haplophragmoides gigas; G. canad.—Gaudryina canadensis; M. mant.—Miliammina manitobensis; G. iri.—Gaudryina irinensis; T. r.—Trochammina rutherfordi; D. smok.—Dorothia smokyensis; E. bound.—Evolutinella boundaryensis.*

Heiberg Island with the low-latitude composite $\delta^{13}C_{carb}$ record, most major paleoceanographic and paleoclimatic events (e.g., OAEs and late Aptian–earliest Albian cooling) previously described from low- to mid-latitude sedimentary successions (e.g., Leckie et al., 2002) can be precisely identified in a single sedimentary succession of the Canadian High Arctic at Glacier Fiord (Fig. 2). Using our composite $\delta^{13}C$ stratigraphic approach, we are able to define the Barremian-Aptian, Aptian-Albian, and Cenomanian-Turonian boundaries and substages on Axel Heiberg Island, following the Gradstein et al. (2012; GTS2012) age assignments (Fig. 2). Furthermore, we are able to refine the ages of the Canadian High Arctic lithostratigraphic formations and members as well as recognize disconformities on Axel Heiberg Island.

The U-Pb age dating of the Invincible Point Member of the Christopher Formation using bentonite zircons allows the assignment of 111.74 ± 0.26 Ma to the middle part of the section that correlates well with the $\delta^{13}C_{org}$ curve using the GTS2012 age-calibrated composite $\delta^{13}C_{carb}$ curve (Fig. 2). Therefore, the U-Pb age confirms the GTS2012 definition of the Aptian-Albian boundary at ca. 113 Ma based on the first occurrence of the calcareous subcircular nannofossil taxon *Praediscosphaera columnata* in southeast France (Herrle et al., 2004). The first appearance datum (FAD) of *P. columnata* is located in the range of the break point between the end of the uppermost Aptian positive $\delta^{13}C$ excursion and the onset of the long-term negative shift of $\delta^{13}C$ values in southeast France below the widespread black shale of the Niveau Kilian (Herrle et al., 2004; Fig. 2). It is also consistent with the U-Pb age assignment of 113.1 ± 0.3 Ma in the Lower Saxony Basin (Selby et al., 2009). Thus, our High Arctic U-Pb age assignment and $\delta^{13}C$ stratigraphy indicate a chronostratigraphic age of ca. 111.2 Ma and 112.5 Ma for the OAE1b and Kilian events, respectively. Both black shale intervals are potential marker beds for defining the Aptian-Albian boundary (Kennedy et al., 2014). In contrast, our age assignment of 106.58 ± 0.27 Ma in the upper part of the Invincible Point Member does not support the observed $\delta^{13}C$ fluctuation of the Axel Heiberg Island record and the GTS2012 composite $\delta^{13}C$ record. We speculate that the transition of the shale to a sandstone interval in the upper Invincible Point Member is probably marked by undefined hiatuses and/or that the GTS2012 needs to be improved for the middle to late Albian.

The Rondon Member of the Isachsen Formation has been previously assigned to the Barremian based on dinoflagellate assemblages (e.g., Nøhr-Hansen and McIntyre, 1998). However, the observed major negative (>4‰) and positive (>6‰) $\delta^{13}C_{org}$ changes in the Rondon and lower Walker Island Members is unique within the Cretaceous Period, likely reflecting a major perturbation of the global carbon cycle and the onset of the globally observed early Aptian OAE1a period. Our Arctic record shows the same character and amplitudes known from low-latitude $\delta^{13}C_{org}$ records at Cismon, Italy (Menegatti et al., 1998). Thus, our $\delta^{13}C$ stratigraphic age assignment indicates an early Aptian age for the Rondon and lower Walker Island Members (upper part of interval *b* to lower part of interval *c*, Fig. 2). Based on our $\delta^{13}C$ stratigraphy we propose a Barremian age for the fluvial-deltaic sandstone-dominated interval of the upper Paterson Island Member of the Isachsen Formation (interval *a*). The transition from the uppermost deltaic Isachsen Formation into the silty, muddy

Christopher Formation is marked by two major omission horizons indicated by *Rhizocorallium* sandstone beds (Cotillon, 2010) interbedded with reddish mudrock (base of interval *e*). These two horizons are interpreted to represent a condensed section on Axel Heiberg Island covering an interval of ~4 m.y. (Fig. 2), likely correlative with the global sequence boundary SB Ap5 (Al-Husseini and Matthews, 2010). Thus, the major long-term negative $\delta^{13}C$ shift between 122 Ma and 118 Ma of >3‰ as shown in the composite $\delta^{13}C_{carb}$ record is probably not recorded in the sedimentary succession on Axel Heiberg Island (Fig. 2). The Bastion Ridge Formation has been previously assigned to the late Albian, based on terrestrial and marine palynomorphs (Núñez-Betelu and Hills, 1994). In contrast, our $\delta^{13}C$ stratigraphy indicates a middle to late Cenomanian age, supported by the occurrence of the *Gaudryina irinensis* Zone at the base of this formation (Fig. 2).

MID-CRETACEOUS HIGH ARCTIC OAEs AND ENVIRONMENTAL AND CLIMATE EVENTS

Based on the unique $\delta^{13}C_{org}$ shifts, we interpret the Rondon Member to be the sedimentary expression of OAE1a on Axel Heiberg Island, which is characterized by a TOC-rich (average of 2.8%), mudrock-dominated transgressive unit with large iron concretions (>0.5 m) and coalified wood sandwiched within deltaic sandstones. The foraminiferal assemblage of OAE1a is dominated by the agglutinated benthic genus *Miliammina,* a brackish-water indicator (e.g., Tibert and Leckie, 2004). Thus, the High Arctic OAE1a expression occurs within a transgressive unit marked by a restricted brackish marine, shallow-water environment.

Using the $\delta^{13}C$ stratigraphy, the Kilian and OAE1b climate events can be identified within the middle part of the Invincible Point Member by intercalated reddish siltstone to sandstone beds within a lower shoreface to offshore transition with TOC values of up to 6%. Thus, in the Sverdrup Basin, the Kilian and OAE1b events occur in a transgressive unit with restricted bottom-water conditions (Schröder-Adams et al., 2014), comparable with findings from the subtropical Vocontian Basin in France (Herrle et al., 2003).

The lowermost Kanguk Formation contains finely laminated organic-rich black shales (paper shales) marked by a significant positive $\delta^{13}C_{org}$ excursion of >2‰ that corresponds to the latest Cenomanian OAE2 (interval *i*, Fig. 2). This excursion is used to place the Cenomanian-Turonian boundary in the lower part of the Kanguk Formation at the top of the paper shale. The OAE2 event spans an interval of ~20 m, with TOC values of up to 10% (Fig. 2). Dynamic paleoenvironmental conditions during this interval are marked by fluctuations between dysoxic and anoxic bottom waters, indicated by the presence and absence of benthic foraminifera, and fluctuating surface-water productivity as indicated by varying hydrogen indices (Schröder-Adams et al., 2014). Thus, our $\delta^{13}C$ record supports previous findings on OAE2 in terms of structure and thickness of the same event recently described at May Point on Axel Heiberg Island by Lenniger et al. (2014). Their absolute $\delta^{13}C$ values are ~0.4‰ lighter compared to our locality, which might reflect a slightly more terrestrial influence. However, benthic foraminiferal assemblages indicate that OAE2 is marked by varying dysoxic to anoxic conditions at Glacier Fiord, in contrast to the prevailing anoxic conditions at May Point. This suggests a complex biotic response to OAE2 within the Polar Sea.

The Invincible Point Member of the Christopher Formation is marked by up to 20 glendonite beds, including the level of the Jacob black shale within the second late Aptian positive $\delta^{13}C$ excursion (interval *e* to middle of interval *g*, Fig. 2). The Jacob event was originally described from the Vocontian Basin as a response to enhanced delivery of terrestrial-derived organic matter during a sea-level lowstand, causing bottom-water anoxia (e.g., Bréhéret, 1994). Glendonites represent calcite pseudomorphs that favor marine settings of elevated alkalinity and dissolved phosphate with near-freezing bottom-water temperatures (~0–7 °C) and methane seeps (e.g., Selleck et al., 2007). The now-confirmed age of the glendonite-rich interval based on our $\delta^{13}C$ stratigraphy in our section corresponds well with the late Aptian to early Albian surface-water cooling of ~4 °C observed in the subtropical Atlantic Ocean, as well as the occurrence of the Boreal calcareous nannofossil species *Repagulum parvidentatum* in the low latitudes (McAnena et al., 2013). If the glendonite occurrences on Axel Heiberg Island are the Arctic representation of the late Aptian to early Albian cold snap (Kemper, 1987), the mid-Cretaceous cooling would have lasted for at least 6 m.y. based on our composite $\delta^{13}C_{carb}$ stratigraphy. In the Glacier Fiord section, the youngest glendonite bed occurs at ca. 112.8 Ma (lowermost Albian) corresponding to a return to warm temperatures as recorded in the subtropical Atlantic Ocean (McAnena et al., 2013) and black shale formation of the Niveau Kilian event (Herrle et al., 2003).

CONCLUSION

By using a chemostratigraphic approach, we demonstrate that the major mid-Cretaceous OAEs and paleoclimatic events previously described from the mid- to low latitudes are recorded in a single TOC-rich marine sedimentary succession at Glacier Fiord on Axel Heiberg Island in the High Arctic Sverdrup Basin. Depositional environments range from fluvial-deltaic to shallow, brackish to offshore distal shelf settings. We demonstrate that the occurrence of upper Aptian to lowermost Albian glendonite beds within the Polar Sea are coeval with a subtropical Atlantic drop in sea-surface temperatures of ~4 °C. Thus, our data support the presence of cool shelf waters in the High Arctic at this time.

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