Carbon isotope and sequence stratigraphy of the upper Isachsen Formation on Axel Heiberg Island (Nunavut, Canada): High Arctic expression of oceanic anoxic event 1a in a deltaic environment

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Abstract

The Early Cretaceous oceanic anoxic event (OAE) 1a documents a major perturbation of the global carbon cycle with severe consequences for the ocean-climate-biosphere system. While numerous studies over the past decades have provided a relatively detailed picture of the environmental repercussions of OAE 1a at low and mid-latitudes, studies from high latitudes, in particular the High Arctic, are limited. In this study, we present a high-resolution carbon isotopic and sequence stratigraphic framework for the lower to lower Aptian interval of the Isachsen Formation of the High Arctic Sverdrup Basin (Canada). These data enable us to precisely locate the stratigraphic position of OAE 1a in a deltaic sedimentary environment. The carbon isotope record allows, for the first time, identification of the different carbon isotope segments (CISs) of OAE 1a in the Sverdrup Basin and thereby correlate of the High Arctic record with sections from lower latitudes. Based on this improved chronostratigraphy, we revise the age of upper Paterson Island, Rondon, and Walker Island Members, important regional lithostratigraphic marker units. Whole-rock geochemical data record two episodes of marine incursion into the Sverdrup Basin during OAE 1a (CISs Ap3 and Ap8), which are interpreted as regional maximum flooding surfaces. This information is used in conjunction with detailed sedimentological logs and geochemical grain-size proxies to refine the sequence stratigraphic framework for the upper Isachsen Formation. We propose that transgressive-regressive cycles in the Sverdrup Basin were controlled mainly by the combined effects of eustatic sea-level changes and regional tectonic uplift, potentially related to the emplacement of Alpha Ridge, which culminated at ca. 122 Ma during CIS Ap9.

Introduction

The Early Cretaceous carbon cycle was subject to recurrent perturbations, frequently accompanied by times of global ocean anoxia, which are referred to as oceanic anoxic events (OAEs; Schlanger and Jenkyns, 1976). These perturbations are reflected as pronounced negative and positive excursions (≥1‰) in the stable carbon isotope record of carbonate, marine, and terrestrial organic carbon (e.g., Scholle and Arthur, 1980; Jenkyns, 1995; Menegatti et al., 1998; Ando et al., 2002; Weissert and Erba, 2004; van Breugel et al., 2007). Characteristic δ13C patterns can be correlated across different sedimentary environments on a regional to global scale (e.g., Scholle and Arthur, 1980; Vahrenkamp, 1996; Weissert et al., 1998; Herrle et al., 2004, 2015), providing a powerful chronostratigraphic tool to date marine and, in particular, terrestrial sediment sequences with poor biostratigraphic age control (e.g., Heimhofer et al., 2003). One of the major Cretaceous OAEs, termed OAE 1a (Arthur et al., 1990), occurred during the Aptian and was accompanied by widespread deposition of organic carbon (OC)-rich black shales in (hermi)pelagic settings (e.g., Arthur et al., 1990; Bralower et al., 1993; Weissert et al., 1998), fluctuations in ocean chemistry (e.g., elevated nutrient concentrations and deoxygenation of large parts of the global ocean; e.g., Jenkyns, 2010, and references therein), high-amplitude climate change (i.e., rapid warming followed by OC burial–induced cooling; e.g., O’Brien et al., 2017, and references therein), eustatic sea-level rise (e.g., Jenkyns, 1980; Weissert et al., 1998), and ecological crises (e.g., Erba, 1994; Leckie et al., 2002; Herrle and Mutterlose, 2003; Erba and Tremolada, 2004; Erba et al., 2010). The global carbon isotope record of the early Aptian shows a marked negative δ13C excursion of as much as 3‰ in marine carbonates and ~4‰–5‰ in Oceanic carbonates, which followed by a stepwise increase of ~3‰–4‰ in the δ13C record of marine carbonate (δ13Corg) and ~5‰–6‰ in δ13C of bulk organic matter (δ13Corg). (e.g., Menegatti et al., 1998; Erba et al., 1999; Herrle et al., 2004, 2015; Heldt et al., 2012; Bottini et al., 2015, and references therein). The former is thought to reflect an influx of 13C-depleted carbon into the ocean-atmosphere reservoir from volcanic sources linked to the emplacement of the Ontong-Java Plateau (Menegatti et al., 1998; Méhay et al., 2008; Tejada et al., 2009) and/or dissociation of methane clathrates (Jahren et al., 2001; Beerling et al., 2002), while the latter has been linked to sequestration of 13C into marine sediments via globally enhanced burial of OC (e.g., Weissert et al., 1998). Menegatti et al. (1998) first introduced a nomenclature for these characteristic early Aptian–early late Aptian carbon isotope segments (CISs C1–C8), which were later renamed to Ap1–Ap8 by Herrle et al. (2004) and Bottini et al. (2015).
To date, most research on OAE 1a has focused on sedimentary archives from low and mid-latitudes, while studies from high-latitude environments are scarce due to their remoteness (Herrle et al., 2015; Midtkandal et al., 2016; Vickers et al., 2016, 2019). Recent studies of outcrops on Axel Heiberg Island (Nunavut, Canada; Fig. 1A) suggest that the High Arctic Sverdrup Basin may comprise a detailed sedimentary record of OAE 1a (Fig. 2A; Herrle et al., 2015), which is preserved in fluvial to marginal marine siliciclastic sediments of the Isachsen Formation (Fig. 1B; Embry, 1985). These outcrops were revisited during a field campaign in 2014, and densely spaced samples were collected from the upper part of the Isachsen Formation (the uppermost Paterson Island, Rondon, and Walker Island Members). In this study, we present new high-resolution δ¹³C profiles, which provide a robust chemostratigraphic framework for OAE 1a in the sedimentary record of the High Arctic Sverdrup Basin and allow us to precisely correlate its different CISs with biostratigraphically well-dated reference curves of lower latitudes (Herrle et al., 2015; Beil et al., 2020). To assess potential impacts of local environmental factors (e.g., changes in the source and preservation state of OC) on bulk δ¹³C composition, lipid biomarker data are presented. Based on this refined chemostratigraphy, we revise the age of the uppermost Paterson Island, Rondon, and Walker Island Members, which represent important lithostratigraphic marker units in the Sverdrup Basin (Embry, 1985; Tullius et al., 2014). In addition, we provide a detailed sequence stratigraphic framework for the upper Isachsen Formation based on sedimentological logs and new bulk geochemical data that reveal repetitive marine incursions into the Sverdrup Basin. These data allow us to link local transgressive-regressive cycles to global eustatic sea-level changes and regional tectonic events.
Figure 2. (A) Low-resolution carbon isotope stratigraphy of the entire Early–Early Late Cretaceous sediment section at Glacier Fiord, adapted from Herrle et al. (2015). Lithological key is given in the lower left corner. Cen. — Cenomanian; M. — Middle; U. — Upper; Tur.-Con. — Turonian to Coniacian; BR — Bastion Ridge; RM — Rondon Member; OAE — oceanic anoxic event; P.-s. — paleosol; Sh — shale; Si — siltstone; Vf — very fine sandstone; F — fine sandstone; M — medium sandstone; Foram. zone — Foraminifera biozone; V. borealis — Verneuilinoi des 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. — Dorothya smokyensis; E. bound. — Evolutinella boundaryensis. (B) Detailed sedimentological log of upper Isachsen Formation at Glacier Fiord, which was resampled in high-resolution in 2014. Congl. — Conglomerate; VF — very fine sandstone; F — fine sandstone; M — medium sandstone; C — coarse sandstone; VC — very coarse sandstone; Paterson I. — Paterson Island; Invincible P. — Invincible Point.
GEOLOGICAL BACKGROUND

The Sverdrup Basin is a ~300,000 km² pericratonic basin underlying the Queen Elizabeth Islands in the Nunavut Territory of Arctic Canada (Fig. 1; Embry and Beauchamp, 2008). The geological record of the Sverdrup Basin spans the Carboniferous to Eocene (Fig. 1A) with sediment thicknesses of as much as 13–15 km (Balkwill, 1978), including extensive Mesozoic strata (Embry, 1991). Late Mesozoic sediments were deposited during a major rift phase of the Sverdrup Basin, which started in the Early Jurassic and has been linked to the opening of the oceanic Amerasia Basin (Embry, 1991; Embry and Beauchamp, 2008; Grantz et al., 2011; Hadlari et al., 2016) bounding the Sverdrup Basin to the north (Fig. 1A). During the early post-rift phase, fluvial and marginal marine sands propagated into the Sverdrup Basin from the southwest (Embry and Dixon, 1994; Hadlari et al., 2016); the resulting sandstones constitute the widespread Isachsen Formation (Embry, 1985, 1991; Tullius et al., 2014). The Isachsen Formation has a maximum thickness of ~1400 m in the basin center (Embry, 1991) and is commonly divided into three members (Embry, 1985). The lowermost Paterson Island Member consists mainly of fine to very coarse sandstones (Embry, 1985), which were deposited in a marginal marine to braided-fluvial and meandering-fluvial environment (Tullius et al., 2014). Sediments of the Paterson Island Member overlie Lower Cretaceous sediments of the Deer Bay Formation with unconformable contact at the basin margins and conformable contact near the basin center (Embry, 1985). On Amund Ringnes Island in the south-central part of the basin (Fig. 1A), bivalves indicate a late Valanginian age for the basal part of the Paterson Island Member (Balkwill, 1983). On Ellef Ringnes Island (Fig. 1A), a Valanginian age has been assigned to the basal Paterson Island Member based on benthic foraminifera (Tullius et al., 2014). The overlying Rondon Member is a variable ~5–30-m-thick mudstone-dominated interval, which occurs over most of the Sverdrup Basin and constitutes an important lithostratigraphic marker in the sandstone-dominated Isachsen Formation (Embry, 1985). The type section of the Rondon Member has been described by Embry (1985) from the Sun Skybattle Bay C-15 well, drilled on Lougheed Island in the western part of the Sverdrup Basin (Fig. 1A), and the member was named after Cape Rondon, located on the east coast of Lougheed Island. The age of the Rondon Member is debated. Biostratigraphic data are generally scarce and yield ambiguous age estimates. An Aptian age was initially inferred based on foraminiferal and palynomorph assemblages from Lougheed, Banks, and Melville Islands (Clowser et al., 1975; Wall, 1983). In contrast, dinoflagellate cysts preserved in the Rondon Member at Glacier Fiord (Axel Heiberg Island; McIntyre, 1984) and Melville Island indicate a late Barremian age (McIntyre, 1984; Nahr-Hansen and McIntyre, 1998). Recent carbon isotope stratigraphic evidence suggests an early Aptian age for the Rondon Member (Herrle et al., 2015). The Walker Island Member comprises marginal marine to fluvial sandstones and is thought to be of late Barremian–Aptian age based on stratigraphic relationships, although biostratigraphic age constraints are lacking (Emby, 1985). Carbon isotope stratigraphy indicates a late Aptian age for the Walker Island Member (Herrle et al., 2015). The Isachsen Formation is overlain by the late Aptian–Albian Christopher Formation (Fig. 2A), which was deposited in an outer shelf environment (Emby, 1985, 1991; Schröder-Adams et al., 2014). At Glacier Fiord, the transition from the Isachsen to the Christopher Formation is marked by a condensed interval with a hiatus of ~4 m.y. (Herrle et al., 2015).

The Isachsen Formation hosts abundant sill and dike complexes (Fig. 1B), which document widespread tholeiitic magmatism that has been linked to the plume-induced emplacement of Alpha Ridge in the Arctic Ocean (Fig. 1A; e.g., Embry and Osadetz, 1988; Grantz et al., 2011; Evenchick et al., 2015). This volcanic ridge is widely considered as a part of the High Arctic large igneous province (e.g., Grantz et al., 2011; Dissing et al., 2013). Available age constraints suggest that emplacement of Alpha Ridge and related magmatic complexes in the Sverdrup Basin occurred at ca. 122 ± 2 Ma (Dockman et al., 2018, and references therein).

Axel Heiberg Island is located in the eastern part of the Sverdrup Basin (Fig. 1A) and provides excellent exposures of Cretaceous strata that were uplifted and folded during the Paleogene Eurekan orogeny (Fig. 1B; Embry, 1991). In the study area at Glacier Fiord, located in the southern part of Axel Heiberg Island, nearly 3 km of Cretaceous strata, including the Isachsen Formation, are exposed in synclinal areas (Fig. 1B; Schröder-Adams et al., 2014; Herrle et al., 2015).

MATERIALS AND METHODS

Sampling of the Glacier Fiord Section on Axel Heiberg Island

Field work at Glacier Fiord (78°37.787′N, 89°52.123′W) was conducted in 2014 and included detailed sedimentological logging of a ~300-m-thick interval of the upper Isachsen Formation and lowermost Christopher Formation (Fig. 2B). This interval includes the uppermost 33.5 m of the Patterson Island Member as well as the entire Rondon and Walker Island Members and was chosen to bracket the OAE 1a interval (Fig. 2A; Herrle et al., 2015). Intercalated shale intervals were sampled for geochemical analyses. Geochemical data are provided in the Supplemental Material. Sample resolution varies greatly due to the varying abundance and thickness of sandstone beds (Fig. 2B). Where possible, shale samples were taken at a resolution of ~0.3 m.

Analysis of Foraminiferal Assemblages

A total of 38 samples were taken for benthic foraminiferal analysis covering the uppermost Patterson Island, Rondon, and Walker Island Members with emphasis on fine-grained beds. Samples of 200 g were processed with the method of Then and Dougherty (1983) and washed through a 63 µm sieve. Benthic foraminiferal specimens from the residues were picked into microslides and number of specimens and species (species richness) were counted.
**Geochanical Methods**

**Total Organic Carbon and Carbon Isotope Analysis**

Carbon isotope analyses were performed on bulk organic matter. Carbonate was removed by reacting aliquots of milled sediment with 10% HCl at 50 °C for >12 h and subsequently washing the sediment with deionized water and drying it at 50 °C. Carbon isotope analyses were conducted at the Goethe-University Frankfurt (Germany) using a Flash Elemental Analyzer 1112 (Thermoquest) coupled to a MAT 253 gas-source mass spectrometer via a continuous flow inlet. δ13C/δ12C ratios are reported relative to the Vienna Pee Dee belemnite standard (δ13CVPDB). The USGS24 standard was analyzed repeatedly during each measuring session to monitor accuracy and precision. Standards reproduced within ±0.2%. Total organic carbon (TOC) contents were determined using a Flash Elemental Analyzer 1112 (Thermoquest); standards reproduced within ±0.25%.

**Major and Trace Element Analyses**

Major and trace element concentrations were analyzed at the University of Cologne (Germany) using an Itrax X-ray fluorescence (XRF) core scanner (Cox Analytical Systems, Mölndal, Sweden) equipped with a Cr tube. Aliquots of milled samples were pressed into small plastic cubes, which were aligned under the core scanner. Individual measurements were performed for 60 s at 1 mm steps, yielding ~10 measurements per sample. Linear regression curves show excellent correlation coefficients (R² >0.85) for all reported elements.

**Biomarker Analyses**

Lipid biomarker analyses were conducted on dried and milled aliquots (~6–8 g) of a total of 10 samples at the University of Cologne. Biomarkers were extracted in an ultrasonic bath using methanol (Merck SupraSolv, Germany; 30 mL), methanol-dichloromethane (1:1 vol:vol; 30 mL), and dichloromethane (Merck SupraSolv; 30 mL) for 10 min each. The extracts were combined, reacted with acid-activated copper turnings to remove elemental sulfur, and dried using a rotary evaporator. The asphaltene fraction was precipitated in a 30-fold excess of n-hexane (Merck SupraSolv), and the maltene fraction was partitioned into three polarity fractions (aliphatic hydrocarbons, aromatic hydrocarbons, and heteroatomic nitrogen-sulfur-oxygen [NSO] compounds) over a self-packed silica column equipped with a Cr tube. Aliquots of milled samples were injected using a split and splitless injector operated in splitless mode at 290 °C.

**Sequence Stratigraphic Approach**

Definition of depositional sequences is based on a multi-proxy approach using sedimentological logs, XRF-derived proxies for grain-size variations in shale sample (i.e., Zr/Al), and S/TOC ratios. A recent review of the use of chemostratigraphic data to define depositional sequences can be found in LaGrange et al. (2020). These authors show that maximum flooding surfaces, maximum regressive surfaces, transgressive systems tracts, and regressive systems tracts are commonly associated with minima, maxima, increases, and decreases in XRF-derived grain-size proxies, respectively. We further use S/TOC ratios to discriminate marine from non-marine conditions based on a S/TOC threshold of 0.4, which is diagnostic for marine conditions (Berner, 1982; Berner and Raiswell, 1983; Leventhal, 1983). The rationale behind this approach is to infer the timing of marine incursions, which we link to maximum flooding surfaces.

**Framework for Carbon Isotope Stratigraphy**

A low-resolution carbon isotope stratigraphy for the entire Lower–lower Upper Cretaceous strata at Glacier Fiord has been presented by Herrle et al. (2015), indicating an Aptian age for the upper Isachsen Formation (Fig. 2A). This stratigraphic framework provides the base for correlating our new δ13Corg profile with other high-resolution Aptian reference sections from low latitudes. For correlation, we chose a δ13Corg record from the lower Aptian stratotype at Roquefort–La Bédoule, southern France (Flögel et al., 2010; Lorenzen et al., 2013; Moullade et al., 2015; Beil et al., 2020), and a δ13Corg composite curve compiled by Herrle et al. (2015). This composite curve consists of δ13Corg records from the Apticore drilled at Cismon, northern Italy (Erba et al., 1999), and the Serre Châtieu section in the Vocontian Basin, southern France (Herrle et al., 2004), which have been spliced based on common biotstratigraphic datums (Herrle et al., 2015). Correlation of our new δ13Corg record is carried out based on the identification of characteristic Aptian CISs introduced by Herrle et al. (2004) and Bottini et al. (2015).
Construction of Age Models

We develop floating chronologies for both δ13C_carbon reference curves (i.e., time relative to the onset of OAE 1a) based on available orbital chronologies (Huang et al., 2010; Malinverno et al., 2010; Ghirardi et al., 2014; Beil et al., 2020), which constrain the duration of individual Aptian CISs (Table 1). Assuming similar durations in the High Arctic, we calculate the depositional durations of the Rondon and Walker Island Members as well as sedimentation rates for the Glacier Fiord section. This information is used to construct three age models, which account for different age estimates for the Barremian-Aptian boundary. For age model I, the Barremian-Aptian boundary is placed at 126.3 Ma following Gradstein et al. (2012). Age models II and III are based on recently revised age estimates of 123.8 Ma and 121.8 Ma, respectively, as discussed in Olierook et al. (2019).

RESULTS

Sequence Stratigraphy

Lithostratigraphy and Paleoenvironmental Interpretation

The section analyzed here encompasses the uppermost Paterson Island (stratigraphic interval 0–33.5 m), Rondon (33.5–67 m), and Walker Island (67–278 m) Members (Fig. 2B). Lithostratigraphically, the Rondon Member is distinguished by the dominance of silty mudstone and shale in contrast to the underlying and overlying sandstone-dominated members (Fig. 3).

The uppermost Paterson Island interval is characterized by a gradually coarsening sequence with complex facies changes. Silty shale with rusty sandstone lenses changes to wave-ripped very fine to fine sandstone. A silty shale bed contains a channel with abundant wood. The member is topped by an 8-m-thick coarse sandstone bed with mud rip-up clasts at its base, followed by siltstone to medium-grained sandstone beds with flaser bedding. Marine influence is evidenced by Skolithos ichnofacies with light to heavy bioturbation in some horizons. Large petrified tree stem fragments and abundant plant debris point toward terrestrial influence in close vicinity. This interval is placed at the transition zone of a fluvial-dominated to tide-dominated delta plain with meandering distributary channels in alternation with interdistributary delta plain areas that include bioturbated tidal flats and organic-rich swamps.

The Rondon Member is characterized by two silty shale and mudstone intervals (Figs. 3B, 3C) that are separated by a 6-m-thick, fine- to medium-grained, bioturbated sandstone interval. The shales of the upper, thicker interval weather in a rusty orange color (Fig. 3C) and show traces of sulfur in the outcrop. Coarser beds within appear concretionized. A benthic foraminiferal assemblage of low species richness in the upper shale interval of the Rondon Member indicates sustained marine influence. The dominance of the genus Miliammina suggests intermittent brackish conditions (e.g., Tiber and Leckie, 2004). The paleoenvironment of the Rondon Member is interpreted as a brackish shallow bay, lagoon, or estuary on the lower delta plain with access to seawater. Low energy levels allowed for silts and clays to settle out, but floods or the diversion of distributary channels brought coarser clastics, particularly in the lower unit.

The overlying Walker Island Member is dominated by fine to medium and coarse sandstone with rare silty mudstone intervals. Sandstones are characterized by fine mudstone laminations, lenticular bedding, small wave ripples, and tidal indicators such as mud drapes. Bedding surfaces show interference ripples and in places heavy horizontal and vertical bioturbation. Water escape structures are also observed. Small channel structures and pebble lags are present. The interval up to ~165 m stratigraphic height is interpreted as sandflats, influenced by waves and tides. The interval above is again increasingly influenced by terrestrial processes such as fluvial activity leaving unidirectional ripples, rootlets indicating vegetated areas, mud cracks and dewatering structures, and increasing wood and finer plant debris. The top sandstone interval at ~285 m has abundant Rhizocorallium traces and wave ripples indicating a return to a shoreface environment. The Walker Island Member is for the most part barren of foraminifera.

Bulk Inorganic Geochemistry

Figures 4B and 4D show Zr/Al and S/TOC ratios, used as proxies for grain-size variability
and changes between marine and freshwater sedimentation, respectively. Zr/Al ratios exhibit three (hemicycle) cycles of repetitive increase (hemicycles I–III; Fig. 4B) and decrease (hemicycles I′–III′; Fig. 4B) in the upper Isachsen Formation (0–278 m), which are paralleled by coarsening-upward and fining-upward trends in sandstones, respectively (Fig. 4A). Intervals of increasing Zr/Al ratios occur at ~0–34 m, ~62–90 m, and ~115–204 m, while decreasing Zr/Al ratios are present at ~34–62 m, ~90–115 m, and ~204–278 m (Fig. 4B). Superimposed on these hemicycles, several short-term fluctuations in Zr/Al ratios occur, which are commonly limited to individual beds. S/TOC ratios in the upper Isachsen Formation are generally <0.1, punctuated by two increases to values >0.4, which occur coeval with minima in Zr/Al ratios (i.e., hemicycles I′ and II′; Fig. 4D). Above 278 m, a sharp increase in S/TOC ratios to exceptionally high values of up to 2.7 is recorded (Fig. 4D), which coincides with the occurrence of *Rhizocorallium* ichnofossils.

**Trends in δ¹³Cₗ₀ at Glacier Fiord**

Bulk organic carbon isotope values of the uppermost Paterson Island, Rondon, and Walker Island Members at Glacier Fiord vary between −28.1‰ and −21.5‰. The δ¹³Cₗ₀ profile shows clear stratigraphic trends across the investigated sequence with minor variability (<1‰) within individual shale beds (Fig. 5A), indicating an overall low level of noise. The interval from ~0 to 30 m of the uppermost Paterson Island Member is characterized by invariant δ¹³Cₗ₀ fluctuating around −24‰, followed by a decrease of ~4‰ to −28‰ between ~30 and 63 m spanning most of the Rondon Member (Fig. 5A). Within this overall decreasing δ¹³Cₗ₀ trend, a brief return to more positive values of about −26‰ is recorded between 53 m and 60.5 m, followed by a second decrease back to about −28‰ at 63 m. Across the boundary between the Rondon and Walker Island Members (~67 m), δ¹³Cₗ₀ starts to increase to values of −22‰ in the lower part of the Walker Island Member (~102 m). This positive excursion of ~6‰ is punctuated by a plateau-like interval between ~74 and 91 m, which is characterized by stable δ¹³Cₗ₀ values fluctuating around −24‰. Above ~102 m, δ¹³Cₗ₀ remains high at values of around −22‰ (102–168 m) before gradually decreasing again to −24‰ between ~168 and ~252 m. The top of the Isachsen Formation (252–278 m) is characterized by a slight increase in δ¹³Cₗ₀ to values of about −23.5‰.

**Characterization of Sedimentary Organic Carbon**

We report selected biomarker ratios (Table 2) to assess relative contributions from different OC
Figure 4. Sequence stratigraphic framework of the upper Isachsen Formation at Glacier Fiord, which is based on sedimentological logging data (A), Zr/Al ratios of shale intervals reflecting changes in grain size (B), sulfur (S) and total organic carbon (TOC) content (C), and S/TOC ratios used to discriminate marine (S/TOC ≥ 0.4) from non-marine conditions (D). Sequence stratigraphic interpretation (E) is correlated to the δ13C record of bulk organic matter (δ13Corg) record (F). Red and blue triangles indicate highstand and transgressive systems tracts, respectively. Cut-off triangles indicate partial sequences. Key for sedimentological structures and abbreviations in A is given in Figure 2B. Thick black lines in B and D are three-point running averages. Red and blue background shadings indicate inferred phases of regression and transgression, respectively. SB—sequence boundary; MFS—maximum flooding surface; Ch.—Christopher; Paterson I.—Paterson Island; I.P.—Invincible Point; VPDB—Vienna Peedee belemnite; Ap-CIS—Aptian carbon isotope segment.
Figure 5. Carbon isotope stratigraphy of the upper Isachsen Formation based on correlation of the \( \delta^{13}C \) record of bulk organic matter \((\delta^{13}C_{\text{org}})\) at Glacier Fiord (A) to a high-resolution \( \delta^{13}C \) record of marine carbonate \((\delta^{13}C_{\text{carb}})\) from the lower Aptian stratotype at Roquefort–La Bédoule (southern France) (B) and a low-latitude composite \( \delta^{13}C_{\text{carb}} \) curve (C). Ages for the reference curves are calculated relative to the onset on oceanic anoxic event (OAE) 1a (base of carbon isotope segment [CIS] Ap3) using available orbital chronologies (Table 1; Huang et al., 2010; Malinverno et al., 2010; Ghirardi et al., 2014; Beil et al., 2020). \( \delta^{13}C_{\text{carb}} \) data in B were compiled from the literature (Lorenzen et al., 2013; Moullade et al., 2015; Beil et al., 2020). The composite curve in C comprises \( \delta^{13}C_{\text{carb}} \) data from the Apticore drilled at Cismon (Italy; Erba et al., 1999) and Serre Chaitieu section in the Vocontian Basin (southern France; Herrle et al., 2004) and has been compiled by Herrle et al. (2015). Ch.—Christopher; Paterson I.—Paterson Island; I.P.—Invincible Point; Ap-CIS—Aptian carbon isotope segment; VPDB—Vienna PeeDee belemnite; Ba-Ap boundary—Barremian-Aptian boundary.
sources and their potential impact on the bulk $\delta^{13}C_{org}$ record. All samples show pristane/$n$-C$_{17}$ ratios <0.5, low sterane/hopane ratios <0.6, and high fractional abundances of C$_{29}$-desmethylsteranes of >40% and up to ~80%. These characteristics are consistent with a predominance of terrigenous organic matter (Figs. 6A, 6B; Huang and Meinschein, 1979; Peters et al., 2007, and references therein). Biomarkers specific for planktonic inputs, including 24-n-propyl-cholestanate (Moldowan et al., 1990) and 4-methyl-steranes (Summons et al., 1987), are absent or occur in trace amounts only.

Although some samples, including from the Rondon Member, show evidence for an enhanced marine influence, as indicated by a higher abundance of C$_{29}$-desmethylsteranes (Fig. 6B; Huang and Meinschein, 1979), such changes in OC source are unrelated to systematic trends in $\delta^{13}C_{org}$ (note the spread of $\delta^{13}C_{org}$ values for samples with >40% C$_{29}$-desmethylsteranes in Fig. 6D). In order to test whether changes in OC source may have affected the bulk $\delta^{13}C_{org}$ composition, Spearman’s rank correlation of the $\delta^{13}C_{org}$ data and all reported biomarker ratios was performed (Table 2). Correlation coefficients $\rho$ are generally <0.4, indicating insignificant correlation between the $\delta^{13}C_{org}$ values and any of the reported biomarker parameters ($p \leq 0.05$).

### DISCUSSION

**Definition and Basin-Scale Correlation of Depositional Sequences**

Based on combined evidence from sedimentological logs, relative changes in grain size (approximated by Zr/Al ratios), and S/TOC ratios, we define a total of four (two partial and two complete) depositional sequences covering the uppermost Paterson Island, Rondon, and Walker Island Members at Glacier Fiord (Fig. 4). In this context, we note that there are additional short-term fluctuations in Zr/Al ratios superimposed on the hemicycles defined in Figure 4, which commonly occur on the scale of individual beds. These Zr/Al fluctuations may indicate the presence of additional higher-order sequences.

#### Sequence I (0–33.5 m)

The uppermost Paterson Island Member (0–33.5 m) comprises the highstand systems tract (HST; Fig. 4E) of sequence I, which is characterized by coarsening-upward medium- to coarse-grained sandstone beds (Fig. 4A), increasing Zr/Al ratios (i.e., hemicycle I; Fig. 4B), and S/TOC ratios consistently <0.1 (Fig. 4D). Sequence boundary (SB) I is placed at a medium-grained sandstone bed at ~33.5 m, which marks the top of the Paterson Island Member.

#### Sequence II (33.5–85 m)

The Rondon Member (~33.5–67 m) comprises the transgressive systems tract (TST) of sequence II (Fig. 4E), which is characterized by a marked change in lithology with a dominance of shale (Fig. 4A), a parallel decrease in Zr/Al ratios (hemicycle I; Fig. 4B), and a coeval increase in S/TOC ratios to values of ~0.4 (Fig. 4D). The maximum flooding surface (MFS) of sequence II is placed in the upper shale interval of the Rondon Member (~52–65 m), where S/TOC ratios are consistently >0.4, indicating persistent marine influence. Maximum flooding is also correlated with the highest abundance of benthic foraminifera.

The HST of sequence II in the lower part of the Walker Island Member (~67–85 m; Fig. 4E) is characterized by the recurrence of coarsening-upward sandstones containing mud-draped foresets and wave ripples, which we interpret as wave- and tide-influenced sandflats. In parallel, Zr/Al ratios start to increase again (hemicycle II; Fig. 4B). Across the HST interval, freshwater conditions reestablished, as indicated by a decrease in S/TOC ratios to <0.1 (Fig. 4D). SB II is placed at the bottom of a shale interval at ~85 m (Fig. 4E), above which S/TOC ratios start to increase again (Fig. 4D), indicating a return to marine conditions.

#### Sequence III (85–204 m)

The TST of sequence III (~85–105 m; Fig. 4E) is characterized by a decreasing abundance of sandstone beds (Fig. 4A), decreasing Zr/Al ratios (hemicycle II; Fig. 4B), and increasing S/TOC ratios (Fig. 4D). Transgression culminated in the deposition of a ~10-m-thick succession of shale (~85–105 m; Fig. 4A) under marine conditions (i.e., S/TOC >0.4; Fig. 4D), which represents the MFS II of sequence III.

### Table 2. Selected Biomarker Ratios Used to Infer Organic Carbon Sources

| Stratigraphic position (m) | Pri/$n$-C$_{17}$ (%) | Phy/$n$-C$_{18}$ (%) | Sterane/hopane | C$_{27}$-sterane (%) | C$_{28}$-sterane (%) | C$_{29}$-sterane (%) |
|---------------------------|---------------------|---------------------|----------------|---------------------|---------------------|---------------------|
| 6                         | 0.34                | 0.10                | 0.54           | 20.0                | 15.0                | 65.0                |
| 27                        | 0.29                | 0.21                | 0.58           | 41.8                | 16.1                | 42.1                |
| 57.4                      | 0.27                | 0.14                | 0.29           | 50.1                | 10.1                | 39.8                |
| 81                        | 0.25                | 0.12                | 0.28           | 17.3                | 15.3                | 67.3                |
| 100                       | 0.23                | 0.13                | 0.16           | 18.9                | 18.4                | 62.8                |
| 130.4                     | 0.27                | 0.14                | 0.37           | 16.4                | 14.3                | 69.3                |
| 174                       | 0.47                | 0.27                | 0.31           | 48.0                | 13.1                | 38.9                |
| 212.5                     | 0.44                | 0.19                | 0.34           | 8.7                  | 12.7                | 78.5                |
| 249                       | 0.41                | 0.18                | 0.33           | 14.0                | 16.3                | 69.6                |
| 292.5                     | 0.31                | 0.11                | 0.26           | 18.6                | 14.0                | 67.4                |

$\rho^*$ = 0.10

Note: Pri—pristane; Phy—phytane.

*Spearman’s rank correlation coefficient for correlation between respective biomarker ratio and $\delta^{13}C$ of bulk organic matter ($\delta^{13}C_{org}$).
Only rare, partly questionable, and poorly preserved fine- to medium-grained tidally influenced sandstone beds reappear, which develop into trough-bed coarse sandstone beds containing climbing ripple structures (Fig. 4A), marking a gradual return to a fluvial environment. Zr/Al ratios increase in parallel up to ~204 m (hemicycle III; Fig. 4B). S/TOC ratios decrease to <0.1 in the lower part of the HST (~105 m; Fig. 4B), suggesting a change to freshwater conditions. We place SB III at ~204 m (Fig. 4E), atop a prominent 20-m-thick coarse-grained fluvial sandstone bed with unidirectional flow ripples (Fig. 4A) and a coeval maximum in Zr/Al ratios (Fig. 4B).

**Sequence IV (204–278 m)**

The TST of sequence IV (~204–278 m; Fig. 4E) comprises fine- to medium-grained sandstones of the uppermost Walker Island Member, which gradually overlie thick and coarse-grained fluvial sandstones of sequence III below and are mostly organized in meter-scale beds containing wave ripples (Fig. 4A). Grain size of sandstones and Zr/Al ratios decrease upsection (hemicycle III; Fig. 4B), indicating finer upward. S/TOC ratios <0.1 suggest that the uppermost Walker Island Member was deposited predominantly in a freshwater environment (Fig. 4B). The TST sequence IV is truncated by a sudden return of marine conditions, as indicated by a sharp increase in S/TOC ratios (Fig. 4D) and the occurrence of *Rhizocorallium* at ~285 m. Consistent with previous studies (Herrle et al., 2015), we interpret this interval as a condensed section, which marks the contact between the Isachsen Formation and the overlying marine shales of the Christopher Formation (Fig. 4A). This interval represents a major break in sedimentation at Glacier Fiord that lasted for ~4 m.y. (Herrle et al., 2015).

**Basin-Scale Correlation of Sequences**

Previous sequence stratigraphic studies from different parts of the Sverdrup Basin identified two (partial) transgressive-regressive (TR) cycles in the upper Isachsen Formation (Embry, 1991; Embry and Beauchamp, 2008; Tullius et al., 2014). According to these studies, the lithological change from sandstone, dominating the Paterson Island Member, to shale, which makes up the Rondon Member, was related to base-level rise and transgression. On Ellef Ringnes Island in the basin center (Fig. 1A), marine conditions established during the deposition of the Rondon Member (Tullius et al., 2014). Regression occurred during the deposition of the lower Walker Island Member, followed by a second transgression recorded in the upper Walker Island Member, which culminated in the deposition of the marine Christopher Formation. The stacking patterns of T-R cycles and lithological changes observed at Glacier Fiord are overall consistent with the existing
Significance and Correlation of the $\delta^{13}C_{\text{org}}$ Record to Low-Latitude Reference Sections

Bulk $\delta^{13}C$ records of marine and terrestrial OC are known to reliably record global $\delta^{13}C$ fluctuations, though local effects, including changing proportions of marine and terrestrial OC, fluctuations in preservation conditions, and ecological and taphonomic effects, may partly obscure global $\delta^{13}C$ trends (e.g., Gröcke et al., 1999; Ando et al., 2002; Heimhofer et al., 2003; Vickers et al., 2016). Concurrent with previous studies (Embry, 1985, 1991; Tullius et al., 2014), our facies interpretation indicates that sediments of the Isachsen Formation were predominantly deposited in a fluvial to marginal marine environment, which received primarily terrigenous OC inputs, as indicated by biomarker data (Figs. 6A, 6B). Minor changes in organic facies marked by an enhanced contribution of marine OC may have occurred, as indicated by changes in the C$_{27}$–C$_{29}$-desmethylsterane distribution (Fig. 6B). These changes, however, had an insignificant effect on bulk $\delta^{13}C_{\text{org}}$ compositions, as indicated by the lack of correlation between $\delta^{13}C_{\text{org}}$ and any of the reported biomarker ratios (Table 2). Furthermore, $\delta^{13}C_{\text{org}}$ values do not covary with TOC content (Fig. 6C), suggesting that changes in OC preservation did not affect the bulk $\delta^{13}C_{\text{org}}$ signal. The shape of the $\delta^{13}C_{\text{org}}$ curve at Glacier Fiord shows a close similarity to those of biostratigraphically well-dated early Aptian–early Late Aptian reference sections from low latitudes, which record isotopic changes in the reduced carbon reservoir (Figs. 5B, 5C; Herrle et al., 2015; Beil et al., 2020). Given this precise reproducibility of $\delta^{13}C$ patterns between hemipelagic records from low latitudes and the Isachsen Formation, and the exceptionally low level of noise in the $\delta^{13}C_{\text{org}}$ record at Glacier Fiord, we consider ecological and taphonomic effects on the bulk $\delta^{13}C_{\text{org}}$ composition to be negligible, as discussed by Herrle et al. (2015), Jarvis et al. (2015), and Wagner et al. (2018). Hence, we conclude that $\delta^{13}C_{\text{org}}$ trends at Glacier Fiord largely track $\delta^{13}C$ fluctuations in the carbon reservoirs of the global ocean-atmosphere-biosphere system, which allows us to assign CISs Ap2–Ap9 to the different segments of our $\delta^{13}C_{\text{org}}$ curve (Fig. 5A). Beyond these globally recognizable segments, the Glacier Fiord record exhibits some distinct short-term trends within individual CISs, including three sub-segments (3a–3c) within the Ap3 segment (Fig. 5A). Similar patterns can also be seen in the high-resolution $\delta^{13}C_{\text{org}}$ record at Roquefort–La Bédoule (Fig. 5B) and other low-latitude records (Najarro et al., 2011), lending further support to the proposed correlation.

It is noteworthy that the magnitude of negative and positive $\delta^{13}C_{\text{org}}$ shifts during CISs Ap3 (~4‰) and Ap4–Ap6 (~6‰) at Glacier Fiord is comparable to those of other marine $\delta^{13}C_{\text{org}}$ records from different ocean basins, e.g., the Tethys (Menegatti et al., 1998; Naafs et al., 2016), Lower Saxony Basin (northern Germany; Bottini and Mutterlose, 2012; Heldt et al., 2012), and North Atlantic (Li et al., 2008), suggesting that early Aptian changes in the global marine and terrestrial carbon reservoirs occurred simultaneously and at the same amplitude, as hypothesized in previous studies (Ando et al., 2002; van Breugel et al., 2007; Herrle et al., 2015).

Age and Duration of the Rondon and Walker Island Members

**Comparison of Bio- and Chemostratigraphy**

Since the mid-1980s, the age of the Rondon Member as part of the Isachsen Formation has been under discussion because of rare occurrences of biostratigraphic indicator species, a generalized lithostratigraphy that did not distinguish the different lithostratigraphic members of the Isachsen (Paterson Island, Rondon, and Walker Island Members; e.g., Embry, 1991; Nøhr-Hansen and McIntyre, 1998), and unspecified personal communications regarding the basis and investigated sections for age assignment. Nevertheless, Clowser et al. (1975) and Wall (1983) dated the upper Isachsen Formation as Barremian to Aptian in age based on benthic foraminifera and palynomorphs from the western part of the Sverdrup Basin (Lougeheid, Banks, and Melville Islands). In contrast, dinoflagellate cyst–based age assignments indicate a late Barremian age for the Isachsen Formation at Glacier Fiord and on Melville Island (McIntyre, 1984; Nøhr-Hansen and McIntyre, 1998). More recently, Herrle et al. (2015) applied carbon isotope stratigraphy to date the Rondon and Walker Island Members at Glacier Fiord (Fig. 2A). These authors provided independent evidence for an early Aptian age of the Rondon Member based on the identification and correlation of characteristic negative and positive $\delta^{13}C_{\text{org}}$ excursions related to OAE 1a, which are unique in their shape and amplitude for the Cretaceous Period. The $\delta^{13}C_{\text{org}}$ data presented in this study refine the carbon isotope stratigraphy of Herrle et al. (2015) and further support an early–early late Aptian age of the upper Isachsen Formation at Glacier Fiord.

We consider that inconsistent age assignments between different dating techniques (i.e., foraminifera and carbon isotope stratigraphy versus dinoflagellate cyst) may partly be related to the rare occurrence of marker species, the low sample resolution, and/or different preservation in the High Arctic sedimentary records (e.g., Galloway et al., 2015), which limit their application and interpretation, particular in nearshore environments. In addition, benthic foraminifera tend to have long biostratigraphic ranges that do not allow differentiation between Barremian and Aptian. Conflicting age assignments may further reflect on different age ranges of dinoflagellate cyst biozones at high latitudes and/or a poor correlation of High Arctic dinoflagellate cyst biozonation schemes with low latitudes. If so, the Glacier Fiord section represents a primary target for future attempts to revise dinoflagellate cyst biostratigraphy, because available $\delta^{13}C_{\text{org}}$ profiles and absolute U-Pb ages allow for an independent age control (this study; Herrle et al.,...
2015). Alternatively, inconsistencies in age assignments from different parts of the basin may imply diachronocity of the transgressive Rondon Member over the large expanse of the Isachsen delta. This hypothesis can be tested once a greater number of high-resolution sequence stratigraphic studies with good age control become available from other sections within the Sverdrup Basin.

**Depositional Durations and Absolute Age Constraints**

Our data allow us to further constrain the depositional duration of the upper Isachsen Formation and to calculate sedimentation rates for different parts of the Glacier Fiord record (Fig. 7A) using available orbital chronologies for OAE 1a (Table 1; Figs. 5B, 5C). According to our correlation, the Rondon and Walker Island Members straddle (parts of) CISs Ap3 and Ap4–Ap9, respectively (Fig. 5A), corresponding to durations of ~100–420 k.y. and ~3.0–3.2 m.y., respectively (Malinverno et al., 2010; Beil et al., 2020). Estimated durations of CISs Ap4–Ap9 agree well among the different orbital chronologies (Table 1), resulting in overall consistent duration and sedimentation rate estimates for the Walker Island Member (Fig. 7A). In contrast, larger differences exist for CIS Ap3, the duration of which has been estimated at ~21 and ~434 k.y. in the Cismon Apticore (Malinverno et al., 2010) and at Roquefort–La Bédoule (Beil et al., 2020), respectively (Table 1). This leads to considerable differences (i.e., deviation by a factor of ~20) in the sedimentation rate estimates for the Rondon Member (Fig. 7A). Beil et al. (2020) attributed the substantially shorter duration estimate for CIS Ap3 at Cismon to hiatuses in the Apticore record. Similar conclusions were drawn by previous studies that consistently indicate a duration of >100 k.y. for CIS Ap3 (e.g., Kuhnt et al., 2011; Najarro et al., 2011; Hu et al., 2012). Additional support for the presence of hiatuses in the Apticore record comes from the lack of sub-segments 3a–3c (Fig. 5C), which, by contrast, are clearly discernable at Glacier Fiord, Roquefort–La Bédoule (Figs. 5A, 5B), and other high-resolution δ¹³C records (Najarro et al., 2011). Hence, we deem the orbital chronology of Beil et al. (2020) to provide more reliable sedimentation rate estimates for the Glacier Fiord section (Fig. 7A), especially the Rondon Member, which we therefore use to construct age models I–III (Fig. 7B).

Based on the Aptian orbital chronology presented by Huang et al. (2010) (Fig. 1; Fig. 5C), we assume a duration of 900 k.y. for the time interval between the Barremian-Aptian boundary and the onset of OAE 1a (i.e., the base of CIS Ap3). Absolute age estimates for the Barremian-Aptian boundary, however, vary by as much as 5 m.y., mainly due to the lack of a Global Boundary Stratotype Section and Point (GSSP; Olierook et al., 2019). We therefore present three different age models for the upper Isachsen Formation, placing the Barremian-Aptian boundary at 126.3 Ma (age model I), 123.8 Ma (age model II), and 121.8 Ma (age model III) (Fig. 7B; Gradstein et al., 2012; Olierook et al., 2019). According to these age models, deposition of the Rondon Member commenced between 125.2 Ma and 120.7 Ma, while deposition of the Walker Island Member started between 124.8 Ma and 120.3 Ma and lasted to between 121.8 and 117.3 Ma (Table 3).

**Potential Drivers of Sea-Level Change in the Sverdrup Basin**

Our data indicate recurrent episodes of base-level rise—partly accompanied by marine ingression—and base-level fall in the eastern Sverdrup Basin (Fig. 4), which probably resulted from a complex interplay of allogenic and autogenic processes (for a recent review, see Catuneanu [2019]), including eustatic sea-level changes, tectonic uplift and subsidence, and delta-internal processes (e.g., channel avulsion, delta lobe switching, migration of alluvial channel belts). Moreover, previous studies indicate that Axel Heiberg Island was a site of active salt diapirism during the Early Cretaceous, which is documented by exposed salt diapirs and fold trends with irregular wavelengths of <10 km, in particular in the central and western parts of the island (Jackson and Harrison, 2006; Harrison and Jackson, 2014). In the vicinity of Glacier Fiord, however, no diapirs have been reported, and (Eurekan) anticlines trend north with a regular wavelength of ~20 km (Fig. 1B), suggesting that salt diapirism had little, if any, impact on the base-level changes in the study area.

Differing the relative importance of allogenic (e.g., eustasy, tectonism, and climate) and autogenic (i.e., delta–internal) processes is challenging based on the available data, in particular because additional carbon isotope records from the Sverdrup Basin are currently lacking, which renders it difficult to identify temporal trends of base-level change across different parts of the basin. Uncertainties in absolute age assignments (reflected in age models I–III; Fig. 7B; Table 3) further complicate the correlation of sequence stratigraphic trends at Glacier Fiord with (radiometrically dated) local thermo-tectonic events. However, the timing of some of the base-level changes at Glacier Fiord can be correlated to other Arctic records (Fig. 8) and globally recognizable sequence stratigraphic trends (Figure 7B), suggesting that they may partly be controlled by supraregional or global processes.

**TABLE 3. NUMERICAL AGE ESTIMATES FOR THE RONDON AND WALKER ISLAND MEMBERS**

| Lithostratigraphic horizon | Age according to age model I* (Ma) | Age according to age model II† (Ma) | Age according to age model III‡ (Ma) |
|---------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Base of Rondon Member     | 125.2                             | 122.7                             | 120.7                             |
| Base of Walker Island Member | 124.8                             | 122.3                             | 120.3                             |
| Top of Walker Island Member | 121.8                             | 119.3                             | 117.3                             |

*Barremian-Aptian boundary placed at 126.3 Ma.
†Barremian-Aptian boundary placed at 123.8 Ma.
‡Barremian-Aptian boundary placed at 121.8 Ma.
Figure 7. Construction of age models for the Glacier Fiord section. (A) Sedimentation rates calculated based on the duration estimates for individual carbon isotope segments at Roquefort–La Bédoule (southern France; Beil et al., 2020) and Cismon–Serre Chaitieu (northern Italy and southern France; Malinverno et al., 2010; Ghirardi et al., 2014). Please note the break in the sedimentation rate axis. (B) Three age models for the Glacier Fiord section using the orbital chronology of Beil et al. (2020) with the Barremian-Aptian (Ba-Ap) boundary being placed at 126.3 Ma (Gradstein et al., 2012), 123.8 Ma, and 121.8 Ma (Olierook et al., 2019). Global sequences were taken from Haq (2014). KAp1–3 are major eustatic events identified by Haq (2014). R and T refer to globally recognizable regressive and transgressive trends, respectively. Background shading in B represents peak magmatic activity in the Sverdrup Basin, which has been dated at 122 ± 2 Ma (Dockman et al., 2018). Sequence stratigraphy at Glacier Fiord is plotted for reference in A and B. Red and blue triangles indicate highstand and transgressive systems tracts. Cut-off triangles indicate partial sequences. δ13Corg—δ13C of bulk organic matter; SB—sequence boundary; Ch.—Christopher; Paterson I.—Paterson Island; I.P.—Invincible Point; Ap-CIS—Aptian carbon isotope segment; VPDB—Vienna Peedee belemnite.
At Glacier Fiord, the TST of sequence II records a first rise in base level, which lasted for ~420 k.y. (Fig. 7B). It is documented as a major facies change at the base of the Rondon Member, reflecting the formation of a shallow bay, lagoon, or estuary under sustained marine influence at this locality (Fig. 4). A similar shift from terrestrial to marine conditions has been reported from early Aptian strata on High Arctic Svalbard, where inner shelf deposits of the Carolinefjellet Formation replaced fluvial and marginal marine sandstone of the Helvetiafjellet Formation (Fig. 8B; Midtkandal et al., 2016; Vickers et al., 2016, 2019). Chemostratigraphy places this transition into the negative carbon isotope excursion at the onset of OAE 1a (Midtkandal et al., 2016; Vickers et al., 2016, 2019), indicating a similar age for the basinal Carolinefjellet Formation and the Rondon Member at Glacier Fiord (Fig. 8B). Time-equivalent transgressions across CIS Ap3 have also been reported from various low-latitude carbonate platform settings, including the Arabian Platform (e.g., Vahrenkamp, 1996; Vahrenkamp, 2010; van Buchem et al., 2010), the northern (e.g., Föllmi et al., 2006; Embry et al., 2010; Pictet et al., 2015) and southern Tethys margins (e.g., Huck et al., 2010; Graziano, 2013; Amodio and Weisert, 2017), the North Atlantic margin (e.g., Millán et al., 2011), the Russian Platform (Sahagian et al., 1996), and mid-Pacific guyots (Röhl and Ogg, 1996). We therefore hypothesize that the transgression recorded at Glacier Fiord (i.e., TST of sequence II; Fig. 4) resulted from eustatic sea-level rise during the early stages of OAE 1a (transgression following eustatic event KAp1 of Haq [2014]; Fig. 7B), which culminated in marine flooding of the Sverdrup Basin recorded in the upper part of the Rondon Member (MFS I; Fig. 4).

The overlying Walker Island Member records a gradual shift from a marine to a fluvial environment (HST of sequence II to SB III; Fig. 4), indicating a long-term (i.e., ~1.6 m.y.; Fig. 7B) base-level fall at Glacier Fiord during the later stages of OAE 1a (CISs Ap4–Ap8). This base-level fall was punctuated by a brief (i.e., ~470 k.y.) interval of transgression (TST of sequence III; Fig. 4), which culminated in renewed marine flooding (MFS II; Fig. 4). The sequence stratigraphic trends recorded in the Walker Island
Member contrast with those recorded in time-equivalent strata on Svalbard, where marine conditions continued to prevail (Fig. 8). Similarly, continued transgression during the later stages of OAE 1a (i.e., CISs Ap4–Ap7) has also been reported from carbonate platforms at low latitudes (Vahrenkamp, 1996; Embry et al., 2010; Huck et al., 2010; Vahrenkamp, 2010; Millán et al., 2011; Amodio and Weissert, 2017), which has been linked to a rising eustatic sea level (Fig. 7B; Haq, 2014). Hence, we propose that contrasting sequence stratigraphic trends at Glacier Fiord and other Arctic and low-latitude sections resulted from changes in local to regional topography within the Sverdrup Basin. The duration of ~1.6 m.y. may suggest that this base-level fall in the Sverdrup Basin was related to long-term tectonic driving mechanisms. If we assume age model I (Barremian-Aptian boundary at ca. 126.3 Ma) to be correct, the time interval straddling the HST of sequence II to SB III lasted from 124.8 to 122.3 Ma (Fig. 7B). This time interval corresponds to a major magmatic phase in the Sverdrup Basin centered at ca. 122 ± 2 Ma (Fig. 7B; Dockman et al., 2018), which is documented in voluminous tholeiitic magmatism (Fig. 1B) and commonly attributed to mantle upwelling beneath Alpha Ridge (Fig. 1A; Dissing et al., 2013; Evenchick et al., 2015; Dockman et al., 2018). Accordingly, we tentatively hypothesize that the long-term base-level fall recorded in the Walker Island Member was induced by regional uplift, potentially related to plume-generated crustal doming beneath the Sverdrup Basin.

The driving mechanisms of intermittent base-level rise during CISs Ap5–Ap6 (i.e., TST of sequence III; Fig. 4) are difficult to assess and might be limited to the eastern Sverdrup Basin, given that previous sequence stratigraphic studies on Ellesf Ringnes Island, located in the western part of the basin (Fig. 1A), did not report a similar transgression interval in the lower Walker Island Member (Tullius et al., 2014). However, we note that this may be due partly to the limited resolution of the sequence stratigraphic framework presented by Tullius et al. (2014). One mechanism that may have induced intermittent transgression and marine incursion (i.e., MFS II; Fig. 4) into the Sverdrup Basin, or parts of it, could be related to an accelerated eustatic sea-level rise during CISs Ap5–Ap6, which may have temporarily outpaced regional uplift. This interpretation is based on studies from carbonate platforms along the southern Tethys and North Atlantic margins, which indicate that maximum flooding occurred during the positive δ13C excursion associated with OAE 1a (CISs Ap4–Ap6; Vahrenkamp, 1996; Embry et al., 2010; Huck et al., 2010; Millán et al., 2011; Amodio and Weissert, 2017). More precise temporal constraints are provided by high-resolution δ13C data from the Arabian Platform, which suggest that maximum flooding occurred during CIS Ap6 (Vahrenkamp, 2010), contemporaneous with MFS II at Glacier Fiord (Fig. 4). Along similar lines, we invoke global sea-level rise, which commenced at ca. 123 Ma (transgression following eustatic event KAp2 of Haq [2014] in Fig. 7B) as a potential mechanism to explain renewed base-level rise recorded in the uppermost Walker Island Member (TST of sequence IV; Fig. 4). This hypothesis will also need to be tested as soon as additional carbon isotope data become available.

Sequence IV is truncated by a condensed interval (Fig. 4), which represents a major hiatus in sedimentation at Glacier Fiord that lasted for ~4 m.y. (Herrle et al., 2015). Age model I dates SB IV, which marks the base of the condensed section, at 121.8 Ma (Fig. 7B). SB IV thus seems to correspond in time with peak magmatic activity in the Sverdrup Basin at ca. 122 Ma (Fig. 7B; Dockman et al., 2018). We tentatively hypothesize that intense magmatic activity was accompanied by enhanced thermal upwelling at that time, inducing particularly high rates of uplift and causing a break in sedimentation at Glacier Fiord.

Following condensed sedimentation, deposition of the Christopher Formation commenced in the early late Aptian in an outer shelf environment (Fig. 2A; Schröder-Adams et al., 2014; Herrle et al., 2015). This transgressive episode was one of the largest in the history of the Sverdrup Basin (Emby and Beauchamp, 2008) and records the establishment of a broad marine shelf that extended beyond the Sverdrup Basin (Hadlari et al., 2016). This long-term transition to marine deposition has been attributed to thermal subsidence (Hadlari et al., 2016). One underlying mechanism for increased subsidence in the late Aptian may have been reduced thermal upwelling due to the cessation of plume-related magmatism (Fig. 7B). Again, this scenario is overall consistent with age model I (Fig. 7B).

CONCLUSIONS

In this study, we present a detailed carbon isotope stratigraphic and sequence stratigraphic framework for the upper Isachsen Formation (the Paterson Island, Rondon, and Walker Island Members) at Glacier Fiord, based on sedimentological and geochemical data, that refines a previous study by Herrle et al. (2015). Our improved chronostratigraphy identifies OAE 1a and its different CISs in the High Arctic sedimentary record, providing additional support for an early Aptian–early late Aptian age for the upper part of the Isachsen Formation. The precise reproducibility of global carbon isotope trends at Glacier Fiord, an exceptionally low level of noise, as well as lipid biomarker data confirm the applicability of δ13C stratigraphy in the predominantly terrestrial sedimentary environment of the Isachsen Formation, opening up multiple avenues for future studies, for which our record may serve as a reference curve. These include: (1) comparing temporal trends of transgressive-regressive cycles from different parts of the basin to reconstruct depositional dynamics in the deltaic system of the Sverdrup Basin, which may serve to further constrain drivers of base-level change across OAE 1a; and (2) calibrating and revising high-latitude dinoflagellate cyst and foraminiferal biostratigraphy.

Correlating the Glacier Fiord record with currently available High Arctic (and low-latitude) records suggests that eustatic sea level may have exerted an important control over local base-level changes during the early stages of OAE 1a (i.e., CIS Ap3) and led to widespread flooding of peri-Arctic continental basins (as recorded in the Sverdrup Basin and on Svalbard). In contrast, local base-level changes during the later stages of OAE 1a (i.e., CISs Ap4–Ap9) seem to have been primarily controlled by regional tectonic processes, potentially related to the emplacement of a mantle plume beneath Alpha Ridge in the Arctic Ocean at ca. 122 ± 2 Ma.
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