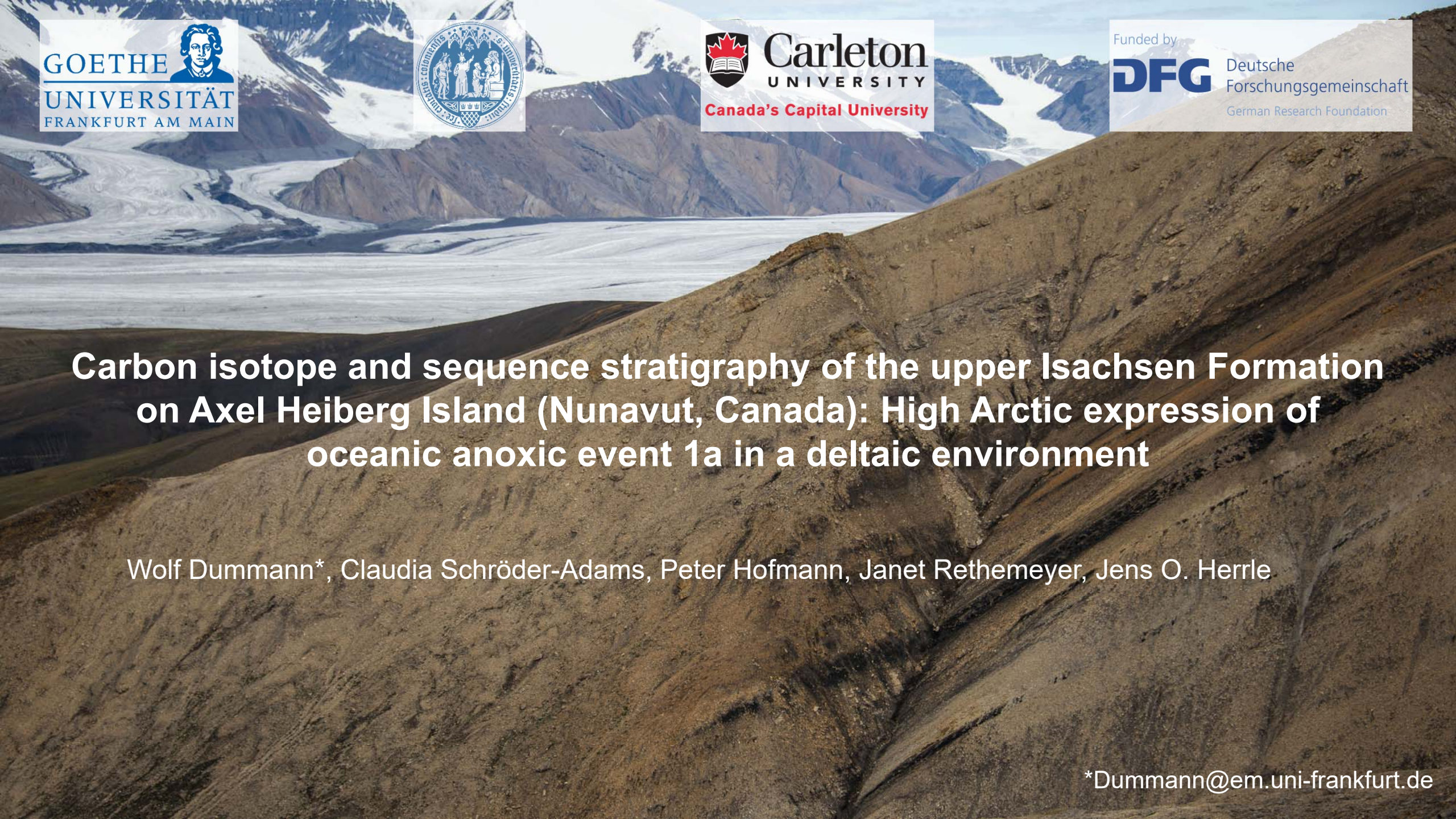

Carbon isotope and sequence stratigraphy of the upper Isachsen Formation on Axel Heiberg Island (Nunavut, Canada): High Arctic expression of oceanic anoxic event 1a in a deltaic environment

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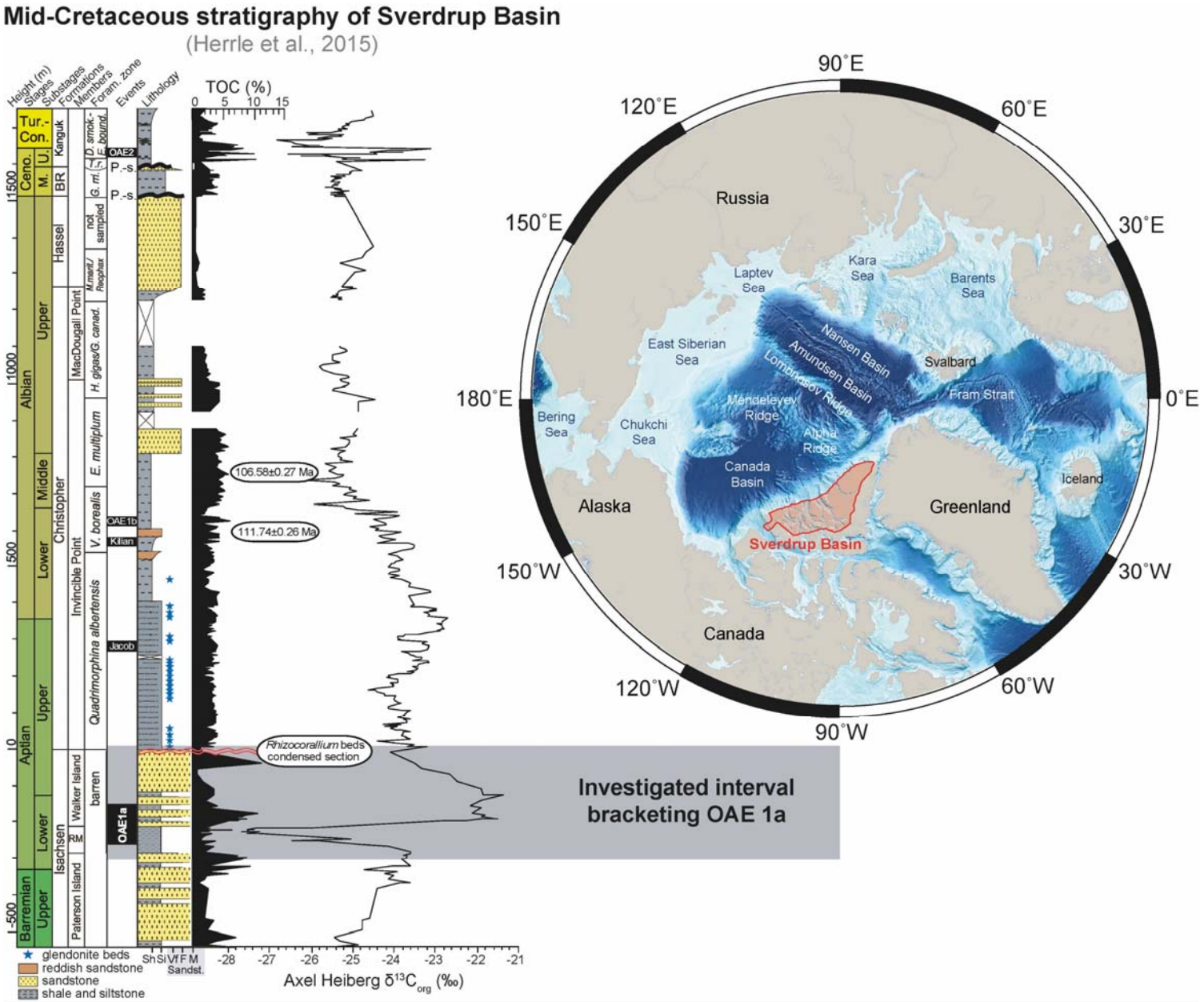
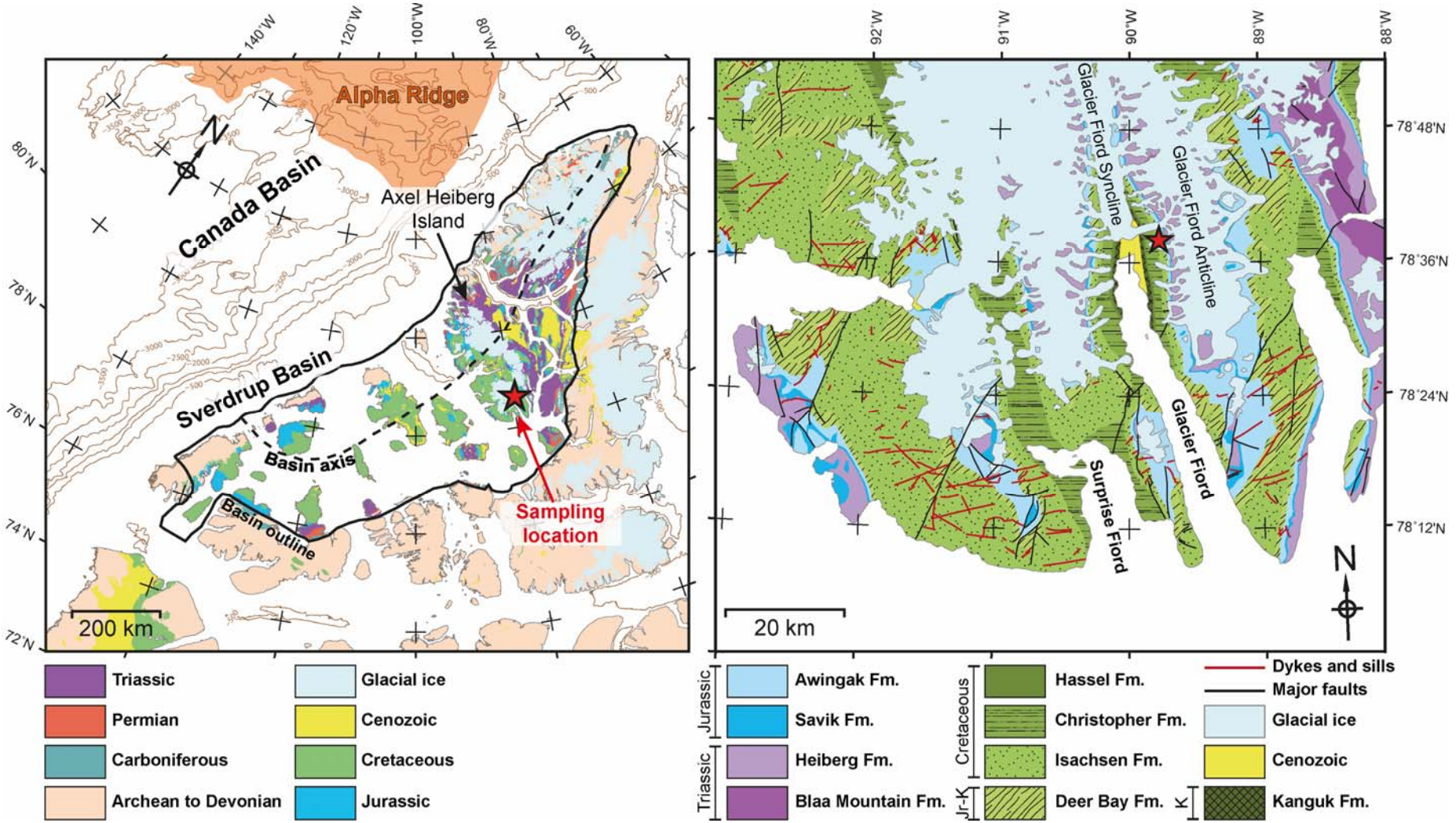


Introduction:

- The Sverdrup Basin in Arctic Canada contains a thick sequence of clastic sediments, which provide a record of the poorly studied climatic, tectonic, and magmatic evolution of the Cretaceous High Arctic. Of particular relevance, the sedimentary record offers insights into the response of the Arctic bio- and geosphere to Cretaceous carbon cycle-climate pertubations, such as oceanic anoxic event (OAE) 1a.

- The mid-Cretaceous (Aptian) OAE 1a, one of the major Cretaceous OAEs, is preserved in the upper part of the Isachsen Formation; a formation that mainly consists of fluvial and marginal marine sandstones, which were deposited in a large deltaic system.

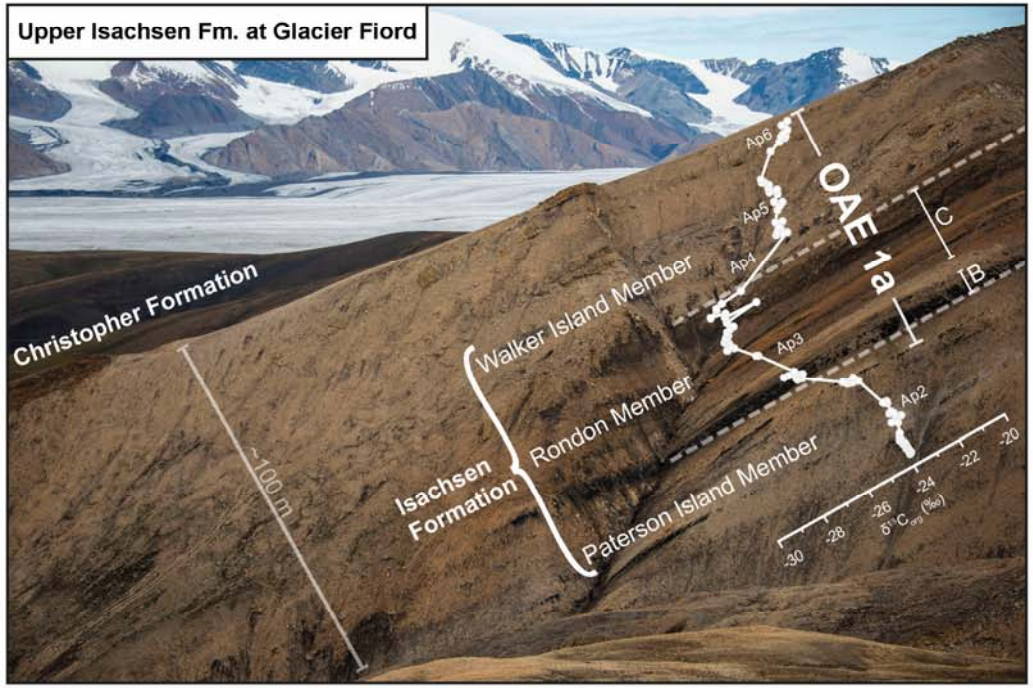
- This study presents new sedimentological, bulk $\delta^{13}C_{org}$, inorganic, and molecular geochemical data, which are used to refine the litho-, chemo-, and sequence stratigraphic framework for the upper Isachsen Formation to reconstruct depositional dynamics during OAE 1a.

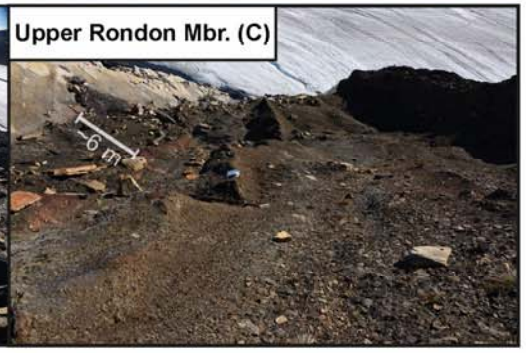


Geological setting:

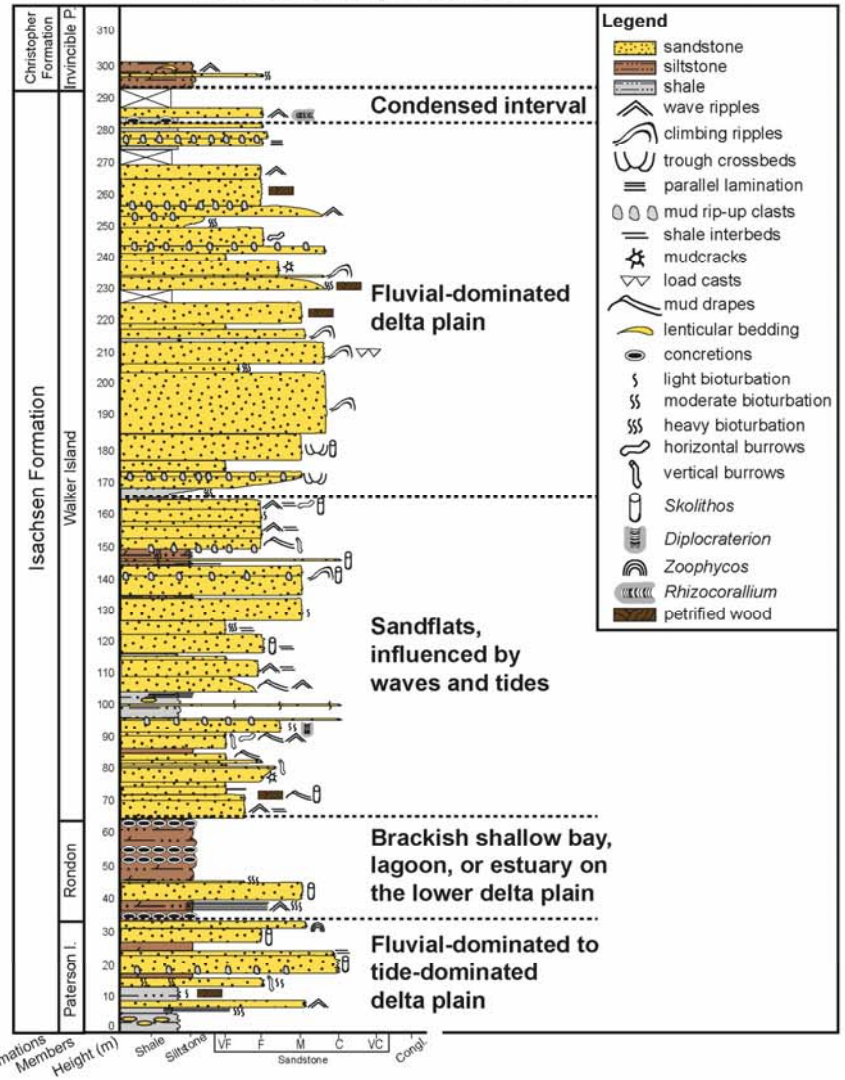
- The Sverdrup Basin is a ~300,000 km^2 pericratonic basin underlying the Queen Elizabeth Islands in the Nunavut Territory of Canada.
- The study site, Axel Heiberg Island, is located in the eastern part of the Sverdrup Basin and provides excellent exposures of Cretaceous strata that were uplifted and folded during the Paleogene Eurekan orogeny.
- Sampling was carried out in 2014 at Glacier Fiord, located in the southern part of Axel Heiberg Island. At this locality, nearly 3 km of Cretaceous strata, including the Isachsen Formation, are exposed in synclinal areas.

Field photos



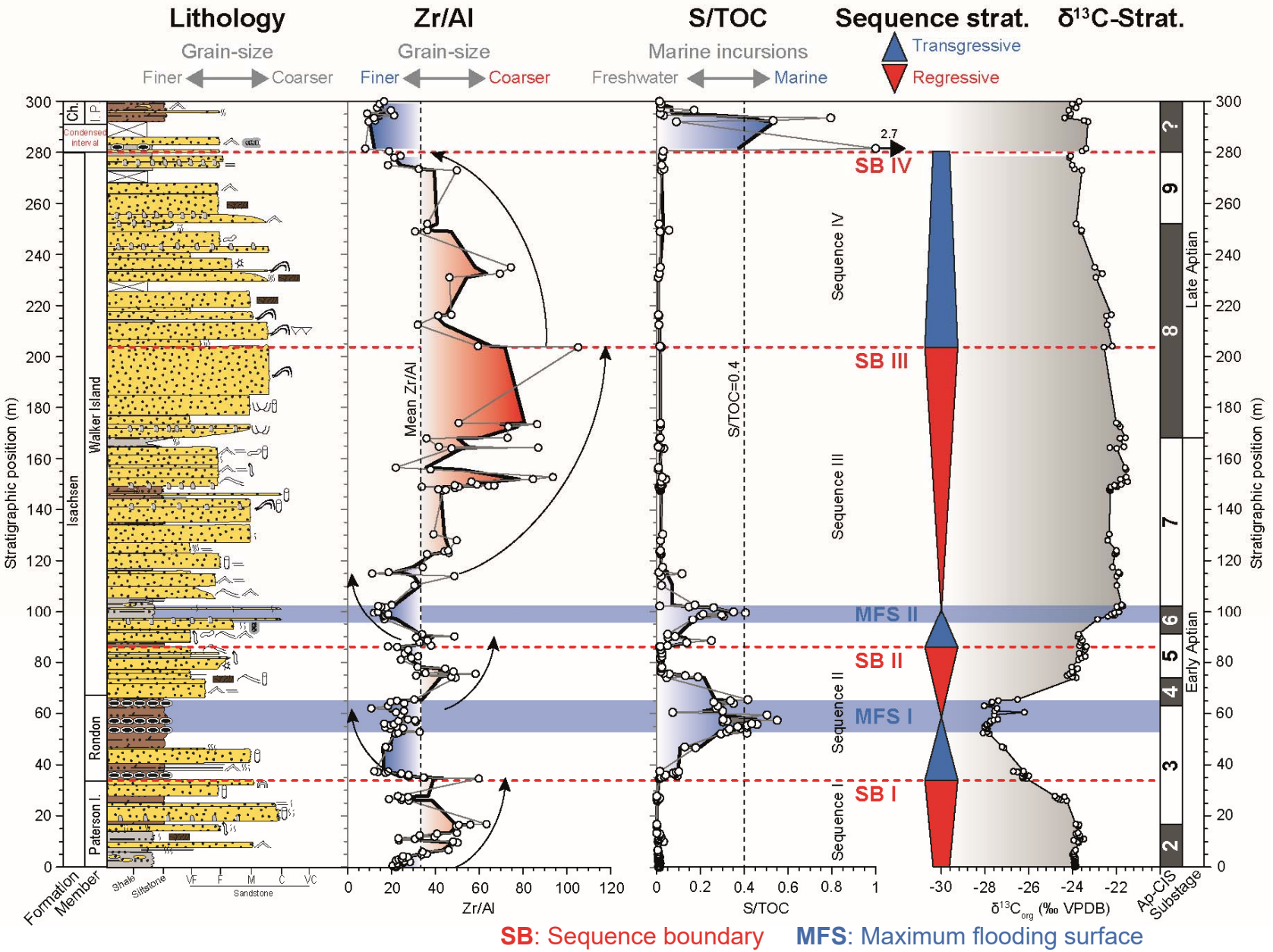


Sedimentological log and facies interpretation



Lithostratigraphy:

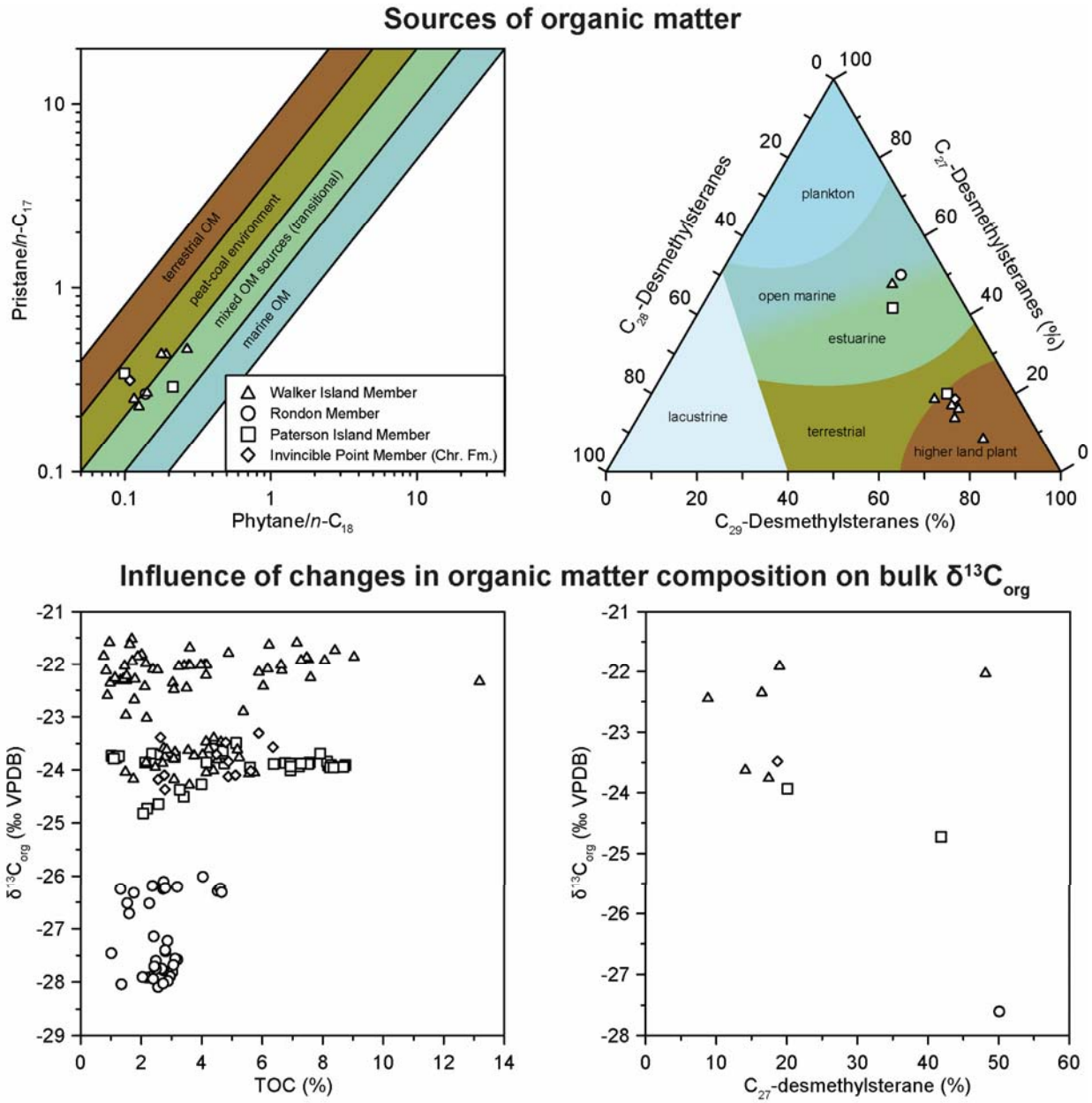
- The Isachsen Formation is divided into three members: Paterson Island Member, Rondon Member, and Walker Island Member.
- The Rondon Member is distinguished by the dominance of silty mudstone and shale in contrast to the underlying and overlying sandstone-dominated members.
- Facies analysis indicates deposition in a deltaic environment under varying marine influence.



SB: Sequence boundary **MFS**: Maximum flooding surface

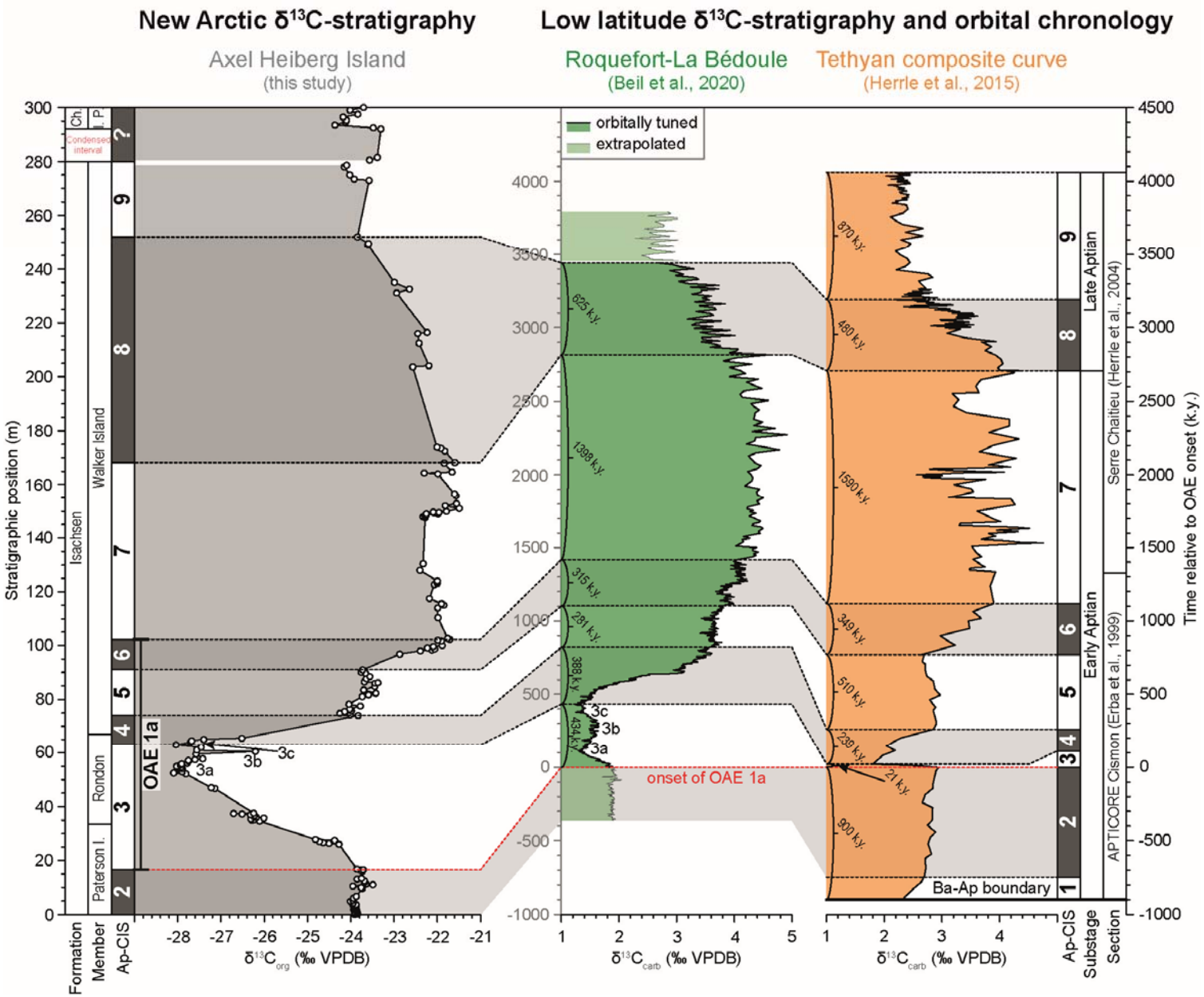
Sequence stratigraphy:

- Depositional sequences are defined based on a multi-proxy approach, which includes sedimentological logging, XRF-derived Zr/Al ratios, and S/TOC ratios. The latter two proxies reflect grain-size variations and changes between marine (S/TOC>0.4) and non-marine conditions, respectively.
- In total, four (two complete and two incomplete) transgressive-regressive cycles have been identified.
- A major transgression occurred during the early phase of OAE 1a (CIS Ap3), which led to the deposition of the Rondon Member under marginal marine conditions.
- The Walker Island Member marks a return to a fluvial environment (CIS Ap4–9), interrupted by a brief interval of renewed flooding during CIS Ap6.



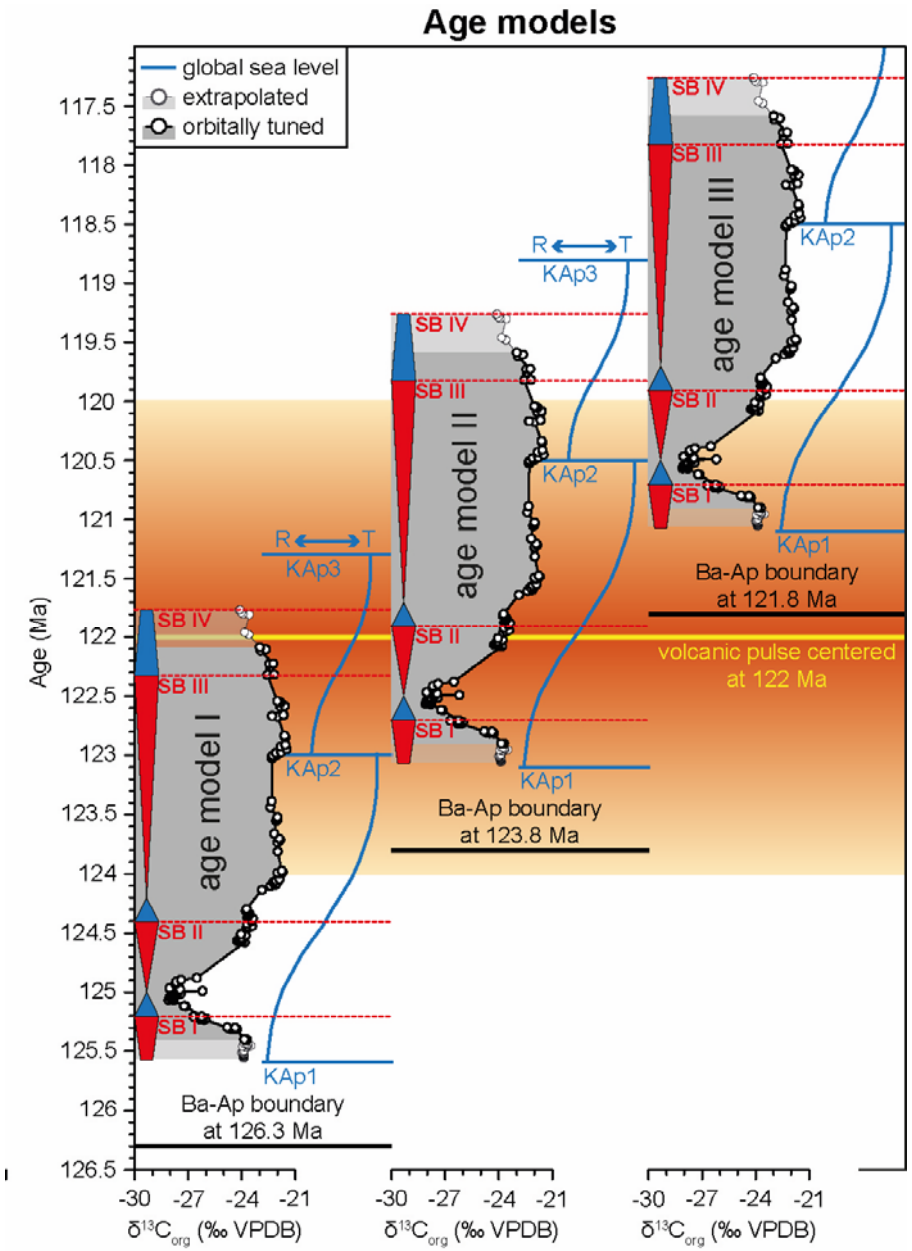
Composition of organic matter:

- Biomarker analyses are used to identify sources of organic matter and to assess potential impacts of local environmental factors (changes in the source and preservation state of organic matter) on bulk $\delta^{13}C_{org}$ composition.
- Biomarker data indicate a predominance of terrigenous organic matter throughout the Isachsen Formation. Some stratigraphic intervals, including the Rondon Member, show evidence for an enhanced contribution of marine organic matter.
- Changes in biomarker ratios and total organic carbon content are, however, unrelated to systematic trends in bulk $\delta^{13}C_{org}$, indicating that changes in organic facies had a negligible impact on $\delta^{13}C_{org}$ variations. We therefore interpret $\delta^{13}C_{org}$ trends at Glacier Fiord to reflect $\delta^{13}C$ fluctuations in the carbon reservoirs of the global ocean-atmosphere-biosphere system.



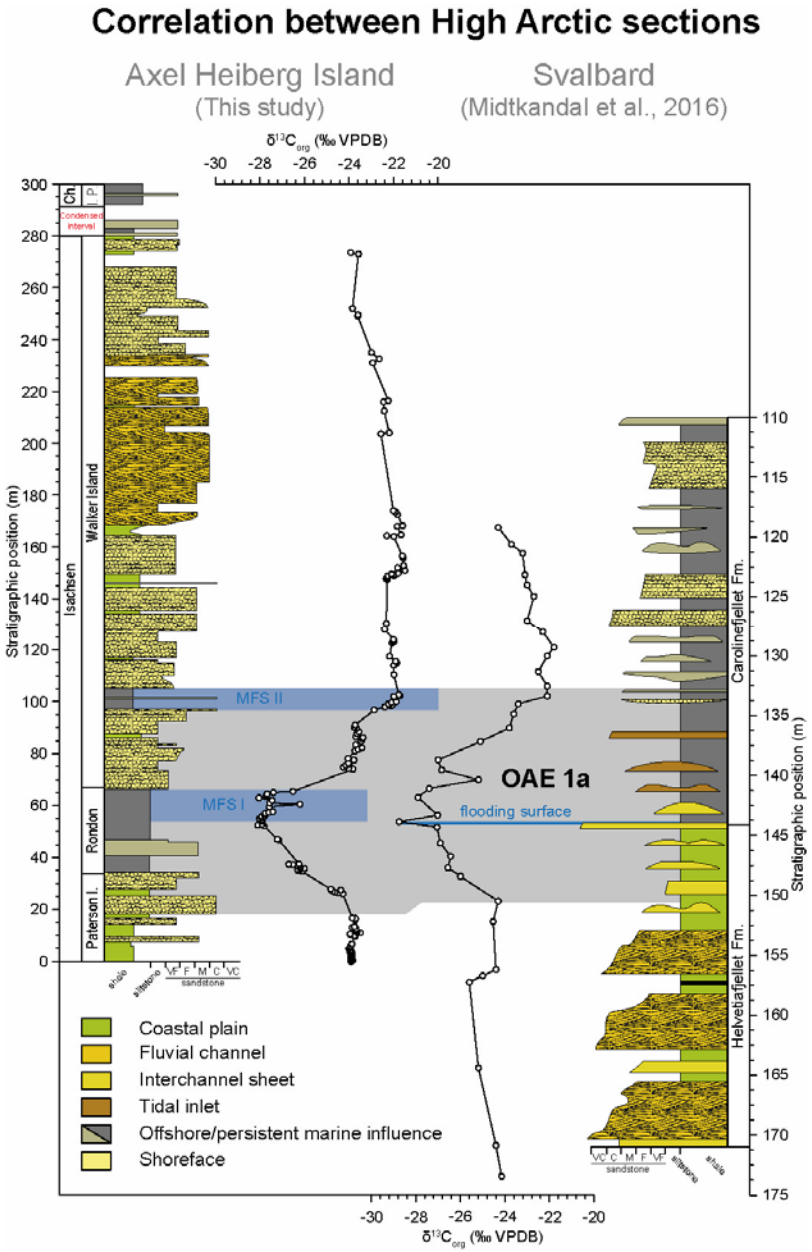
$\delta^{13}C$-Stratigraphy:

- Our new high-resolution $\delta^{13}C_{org}$ curve at Glacier Fiord is characterized by a very low level of noise and shows a series high-amplitude negative and positive $\delta^{13}C_{org}$ excursions, which are characteristic for OAE 1a. These excursions are unique in their shape and amplitude for the Cretaceous Period.
- The $\delta^{13}C_{org}$ record allows identification of characteristic Aptian carbon isotope segments (CISs) Ap2 – Ap9 and thereby correlation of the High Arctic record with biostratigraphically well-dated sections from lower latitudes.
- Available orbital chronologies for the reference curves, which constrain the duration of individual CISs, are used to calculate sedimentation rates for the Isachsen Formation, estimate depositional durations for the Rondon and Walker Island members, and construct age models.



Age models:

- Three age models are constructed, which account for different age estimates for the Barremian-Aptian (Ba-Ap) boundary. For age model I, the Ba-Ap boundary is placed at 126.3 Ma following Gradstein et al. (2012). Age models II and III are based on more recent age estimates of 123.8 Ma and 121.8 Ma, respectively.
- The age models constrain the depositional duration of the Rondon Member and Walker Island Member to ~100–420 k.y. and ~3.0–3.2 m.y., respectively. 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
- The age models further enable us to correlate sequence stratigraphic trends at Glacier Fiord with (radiometrically dated) thermo-tectonic events, including a major phase of magmatism in the Sverdrup Basin dated at ~122 Ma, which was potentially related to the emplacement of the Alpha Ridge in the Arctic Ocean.



High Arctic correlation of sequence stratigraphy:

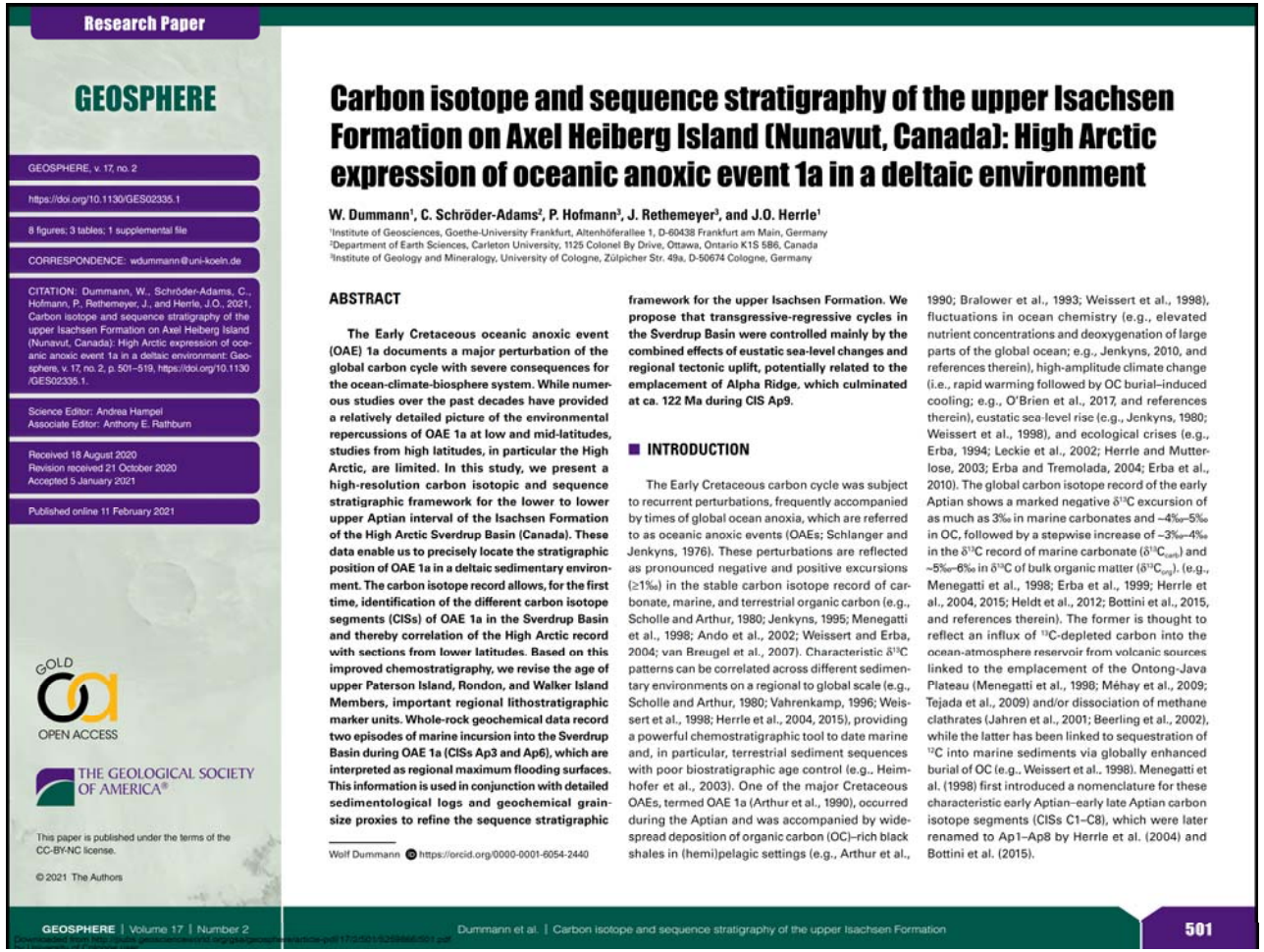
- Correlation of sequence stratigraphic trends in the Sverdrup Basin with other High Arctic (and low-latitude) sections may serve to identify allogenic and autogenic drivers of local base-level changes.

- The transgression recorded in the Rondon Member appears to be time-equivalent with a major flooding event that has been reported from Svalbard (i.e. change from fluvial and marginal marine sandstones to shelf deposits), potentially indicating synchronous and widespread flooding of peri-Arctic basins during the early stages (CIS Ap3) of OAE 1a. One underlying cause may have been rising eustatic sea levels at that time (transgression following KAp1; see previous slide).

- During later stages of OAE 1a (Ap4 – Ap9), sequence stratigraphic trends recorded in the Walker Island Member (i.e., a return to fluvial conditions) contrast with those on Svalbard (i.e., continuous shelf sedimentation), which may indicate uplift in the Sverdrup Basin at that time. Assuming that age model 1 is correct (see previous slide), this uplift may have been related to thermal doming in response to peak magmatic activity in the Sverdrup Basin.

Conclusions

- This study presents a refined carbon isotope and sequence stratigraphic framework for the upper Isachsen Formation, which provides a detailed sedimentary record of OAE 1a and its different CISs in the High Arctic.
- 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 $\delta^{13}C$ stratigraphy in the predominantly terrestrial sedimentary environment of the Isachsen Formation.
- The applicability of $\delta^{13}C$ stratigraphy opens up multiple avenues for future studies, including (1) correlation of temporal trends of transgressive-regressive cycles from different parts of the basin, which may serve to further constrain drivers of base-level change and (2) calibration and revision of high-latitude dinoflagellate cyst and foraminiferal biostratigraphy
- Correlating the Glacier Fiord record with currently available High Arctic (and low-latitude) sections suggests that eustatic sea level may have exerted an important control over local base-level changes during the early stages of OAE 1a (CIS Ap3), while base-level changes during the later stages of OAE 1a (CISs Ap4–Ap9) seem to have been primarily controlled by regional tectonic processes.



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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 upper 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 correlation of the High Arctic record with sections from lower latitudes. Based on this improved chemostratigraphy, 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 Ap6), 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 $\delta^{13}C$ 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 chemostratigraphic 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 (hemi)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 $\delta^{13}C$ excursion of as much as 3‰ in marine carbonates and ~4‰–5‰ in OC, followed by a stepwise increase of ~3‰–4‰ in the $\delta^{13}C$ record of marine carbonate ($\delta^{13}C_{carb}$) and ~5‰–6‰ in $\delta^{13}C$ of bulk organic matter ($\delta^{13}C_{org}$). (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 ^{12}C-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., 2009; 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 ^{12}C 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).

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