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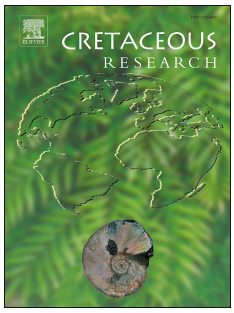

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Exploring the role of High Arctic Large Igneous Province volcanism on Early Cretaceous Arctic forests

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Abstract

The Hauterivian–Aptian aged Isachsen Formation at Glacier Fiord, Axel Heiberg Island, in the Sverdrup Basin of the Canadian Arctic Archipelago was deposited contemporaneous with

initiation of the High Arctic Large Igneous Province (HALIP). New palynological biostratigraphy and paleoenvironmental reconstruction, in coordination with the emerging geochronology of HALIP igneous rocks, permits exploration of the effects of volcanism on Arctic vegetation during the Early Cretaceous. Four informal terrestrial palynofloral zones are defined and used to reconstruct vegetation change over the Isachsen Formation's ca. 17 million year history and explore the role of the HALIP in these changes. Climate warming during the Hauterivian promoted expansion of a hinterland community dominated by members of the Pinaceae. By the middle Barremian, this community was replaced by mixed heathland and mire, represented by up to 70% fern spores in the uppermost Paterson Island Member,that may be, in part, in response to environmental disturbance associated with volcanic flows of the HALIP. Above the fern spore spike, dinoflagellate cyst assemblages suggest an early Aptian age and a marine setting for mudstones of the Rondon Member in which Ocean Anoxic Event 1a is recorded. An interval of floral instability is recorded in the overlying Walker Island Member, characterized by fluctuations in Pinaceae and Cupressaceae pollen and fern spores, possibly as a result of post-OAE 1a temperature variabilty and landscape disturbance associated with lava flows of the HALIP that were repeatedly extruded onto the subsiding delta plain during deposition of the member.

Keywords

Cretaceous; Arctic; Palynology; Paleoecology; High Arctic Large Igneous Province; OAE 1a

1.0 Introduction

The Cretaceous Period is generally considered to have been a time of warm and equable greenhouse climate (e.g., Föllmi, 2012). This is attributed mainly to high partial pressure of carbon dioxide (~700->4000 ppmv; Bice and Norris, 2002) as a result of elevated background rates of volcanic degassing (e.g., Larson, 1991). However, recent research shows that a number of cooling events punctuated otherwise warm climatic conditions of this interval in the planet's history (e.g., Kemper, 1975; Frakes and Francis, 1988; Price, 1999; McAnena et al., 2013; Galloway et al., 2015; Herrle et al., 2015; Jenkyns et al., 2017; Grasby et al., 2017; Rogov et al., 2017; Vickers et al., 2019). These cooling events may even have caused transient glacial conditions in high northern latitudes (Price and Nunn, 2010; Vickers et al., 2019). The forcing mechanisms of some Cretaceous climatic perturbations may have been related to carbon drawdown associated with the construction and destruction of one or more large igneous provinces (LIPs) (Erba and Tremolada, 2004; Jenkyns et al., 2017; Beil et al., 2020). For example, the High Arctic and Caribbean LIPs, Ontong Java Plateau, and Madagascar Flood Basalts are implicated in the genesis of Ocean Anoxic Event 2 and cooling associated with the Plenus Cold Event (Jenkyns et al., 2017). The release of CO_2 associated with emplacement of LIPs coupled with weathering of newly extruded basalt may have led to elevated nutrient levels and planktonic productivity in global oceans multiple times during the Cretaceous, periodically resulting in widespread ocean anoxia (e.g., Erba, 1994; Jarvis et al., 2011; Jenkyns et al., 2017; Jenkyns, 2018). The ensuing carbon burial associated with ocean anoxic events (OAEs) and silicate weathering of newly exposed LIPs are important mechanisms of drawdown of atmospheric carbon dioxide that, in the absence of replenishment, ultimately led to transient global cooling (Jarvis et al., 2011; Jenkyns et al., 2017). Thus, LIPs are important drivers for sequences of biogeochemical events that affect global climate.

The High Arctic Large Igneous Province (HALIP) was a protracted event lasting more than 40 myr but is probably the least studied of all known LIPs (Saumur et al., 2016). There were two dominant pulses (Maher, 2001; Ernst, 2014; Jowitt et al., 2014): a tholeiitic phase of magmatism that began as early as 127 Ma and peaked at 122 Ma, followed by an alkaline phase that started at ca. 94 Ma in Canada and later in Greenland at ca. 85 Ma in Greenland (Estrada and Henjes-Kunst, 2004, 2013; Tegner et al., 2011; Evenchick et al., 2015). Polteau et al. (2016) and Planke et al. (2017) speculated that carbon mobilization associated with the Barents Sea Sill Complex (part of the HALIP) could have triggered OAE 1a and its associated negative $\delta^{13}C$ excursion in the early Aptian. Schröder-Adams et al. (2019) considered that methane release associated with the HALIP contributed to the rapid global warming that led to OAE 2 at the end of the Cenomanian.

Polar regions are highly sensitive to changes in climate forcing (Holland and Bitz, 2003) and are important in global climate feedback mechanisms, at present and in the geological past (Poulson and Zhou, 2013). High northern latitudes were covered with dense coniferous forests during the Early Cretaceous despite extreme photic seasonality (Galloway et al., 2013, 2015). The composition and extent of terrestrial vegetation plays an important role in climate feedback (Woodward, 1998), but information on the role and response of high northern latitude terrestrial plant communities to Mesozoic climate variability is sparse relative to lower latitudes (Spicer and Parrish, 1986; Gröcke et al., 2005; Harland et al., 2007; Selmeier and Grosser, 2011; Galloway et al., 2012, 2013, 2015). Moreover, few studies have evaluated the effects of LIPs on terrestrial vegetation despite the importance of terrestrial ecosystems in the carbon cycle (e.g., Jolley, 1997; Jolley et al., 2008; Ebinghaus et al., 2015), and none have explored the effects of the HALIP on Arctic forests.

The Sverdrup Basin in the Canadian Arctic (Fig. 1) contains a nearly continuous succession of Lower Cretaceous strata (Fig. 2). During the Jurassic and Cretaceous, the Sverdrup Basin was extensional and separated from the developing Amerasia Basin by a paleohigh, possibly a horst-like rift shoulder, called the Sverdrup Rim (Meneley et al., 1975; Embry and Dixon, 1990; Hadlari et al., 2016). The upper Valanginian to lower Aptian Isachsen Formation of the Sverdrup Basin is a unit of particular interest from a tectonic and paleoclimatic perspective because it was deposited in marine, deltaic, and fluvial environments during the development of the adjacent Amerasia Basin (Embry and Dixon, 1990; Tullius et al., 2014) and contains a well-preserved mainly terrestrial fossil record (Galloway et al., 2015). During Jurassic to earliest Cretaceous rift-related subsidence in the Sverdrup Basin, space was created for the Jameson Bay Formation to the Deer Bay Formation succession, with maximum subsidence during deposition of the Deer Bay Formation. The Isachsen Formation was then deposited and represents the post-rift succession and contains the breakup unconformity associated with the formation of the Amerasia Basin (Hadlari et al., 2016; Fig. 2). Deposition of the Isachsen Formation is contemporaneous with initiation of the HALIP at ca. 127 Ma and its main pulse at ca. 122 ± 2 Ma (Dockman et al., 2018 and references therein). The HALIP likely played a role in environmental change during the Early Cretaceous (Polteau et al., 2016; Planke et al., 2017; Schröder-Adams et al., 2019). Study of the Isachsen Formation can thus provide insight into the role of tectonism and volcanism associated with the HALIP on the Cretaceous Arctic biome. However, a lack of biostratigraphic characterization of the Isachsen Formation poses a challenge for understanding Cretaceous geology of the Canadian Arctic in general (e.g., Evenchick et al., 2019) and limits understanding of the chronology and environmental effects of the HALIP in particular. Herein, the integration of a biostratigraphic and carbon isotopic (Herrle et al., 2015) framework in coordination with the emerging geochronology

of HALIP igneous rocks permits exploration of the consequences of Arctic volcanism on Early Cretaceous climate and terrestrial ecosystems.

2.0 Regional setting

2.1 Sverdrup Basin

The Sverdrup Basin is a 1300 km by 350 km paleo-depocentre in the Canadian Arctic Archipelago (Fig. 1). Developed through subsidence and rifting that began during the early Carboniferous (Thorsteinsson, 1974), the basin contains an up-to-13 km-thick succession of nearly continuous strata as young as Paleogene (Balkwill, 1978; Embry and Beauchamp, 2019; Figs. 1, 2). Rifting continued through the late Carboniferous, resulting in widespread flooding and increasingly open-marine connections with Panthalassa to the west and seas that covered northern Greenland and the present-day Barents Sea region to the east (Embry and Beauchamp, 2019). Another major episode of rifting began by the Early Jurassic, the later stages of which were associated with the opening of the Amerasia Basin. Rifting peaked during deposition of the Deer Bay Formation, and the lowermost Isachsen Formation represents deltaic progradation across the basin when rift-related subsidence had slowed, marking the early post-rift stage (Hadlari et al., 2016). In the adjacent Amerasia Basin, rifting during the Jurassic to earliest Cretaceous progressed to sea-floor spreading by the Early Cretaceous, as inferred from the breakup unconformity in the post-rift succession of the Sverdrup Basin (Hadlari et al., 2016; Embry and Beauchamp, 2019), most likely marking the onset of sea-floor spreading in the proto-Arctic Ocean. Sedimentation in the Sverdrup Basin was then dominated by terrigenous clastic material that recorded basin-wide

transgressive-regressive cycles driven by a combination of tectonism, sediment supply, and eustatic sea-level change (Embry, 1991). Deposition in the Sverdrup Basin ended during the Paleogene as a consequence of regional compression and widespread uplift during the Eurekan Orogeny (Embry and Beauchamp, 2019). Strata in the Sverdrup Basin are deformed due to several factors: episodic flow of Carboniferous evaporites during the Mesozoic (Balkwill, 1978; Boutelier et al., 2010; Galloway et al., 2013; Dewing et al., 2016), Barremian to Cenomanian magmatism and faulting (Embry and Osadetz, 1988; Embry, 1991), and compression during the Eurekan Orogeny in the Eocene. The Eurekan Orogeny produced high amplitude folds and thrust faults in northeastern parts of the basin and smaller folds to the west (Harrison et al., 1999).

The age of Mesozoic strata in the Sverdrup Basin is based primarily on ammonoids, bivalves, dinoflagellate cysts (dinocysts), radiolarians, and foraminifers (e.g., Frebold, 1960, 1975; Tozer and Throsteinsson, 1964; Jeletzky, 1973; Hopkins, 1971, 1973; Balkwill, 1983; Wall, 1983; Nøhr-Hansen and McIntyre, 1998; Schröder-Adams et al., 2014; Pugh et al., 2014; see Galloway et al., 2013, 2015, 2019 for more complete literature) and supplemented by carbon isotope stratigraphy (Herrle et al., 2015; Galloway et al., 2019; Dummann et al., 2021), as part of an emerging geochronological framework (Omma et al., 2011; Estrada and Henjes-Kunst, 2013; Schröder-Adams et al., 2014; Evenchick et al., 2015; Herrle et al., 2015; Midwinter et al., 2016; Anfinson et al., 2016; Davis et al., 2016; Hadlari et al., 2016; Dockman et al., 2018; Kingsbury et al., 2018; Evenchick et al., 2019; Fig. 2).

Axel Heiberg Island is located in the Canadian Arctic Archipelago, in the west-central part of Sverdrup Basin, near the basin's axis. It was situated between paleolatitudes 74 ± 2˚ (standard error) and 79 ± 1˚ during the Early Cretaceous (Wynne et al. 1988). Glacier Fiord on southern Axel Heiberg Island (Fig. 1) was targeted for detailed study due to preservation at this location of

an exceptionally well-exposed succession of the Isachsen Formation (Schröder-Adams et al., 2014; Dummann et al., 2021).

2.2 Isachsen Formation

2.2.1 Lithostratigraphy of the Isachsen Formation

The Isachsen Formation was first described, on Ellef Ringnes Island, by Heywood (1957) as a succession of arenaceous strata between the mudstones and siltstones of the underlying Deer Bay Formation and overlying Christopher Formation (Fig. 2). The Isachsen Formation is widespread throughout the Sverdrup Basin, ranging in thickness from ~120 m at the basin margins to 1370 m on western Axel Heiberg Island (Hopkins, 1971).

The Isachsen Formation is subdivided into three members based on gamma-log interpretation of wire-line data from the Skybattle Bay C-15 well (Lougheed Island; 77º14'N, 105º05'W; Embry, 1985; Fig. 2). The Paterson Island Member overlies the Deer Bay Formation unconformably at basin margins and conformably in the basin centre. The Paterson Island Member consists of fine- to very coarse-grained sandstone with interbeds of mudstone, siltstone, coal, and volcanic and volcaniclastic/tuffaceous rocks (Embry and Osadetz, 1988; Evenchick and Embry, 2012a,b) deposited in a delta plain setting with fluvial environments (Embry, 1985). The coarsening-upward cycles in the basal portion of the member in basinal sections (e.g., on Ellef Ringnes Island) are of delta front origin (Embry, 1985; Tullius et al., 2014). Sandstone units are up to 35 m thick, and argillaceous intervals 2–10 m thick occur in the 152 m-thick type section in Skybattle Bay C-15 well (Embry, 1985). The Paterson Island Member is conformably overlain by

interbedded medium- to dark-grey siltstone of the Rondon Member, which was deposited in a marine-shelf setting (Embry 1985; Nøhr-Hansen and McIntyre, 1998; Tullius et al., 2014). The type section in the Skybattle C-15 well is 47 m thick (Embry, 1985). The second largest accumulation of oil in the Sverdrup Basin was discovered in 1980 during drilling of the Panarctic Balaena D-58 well off Ellef Ringnes Island, where the Paterson Island Member is an oil and gas reservoir, with the Rondon Member acting as a seal (Waylett and Embry, 1992). The Rondon Member is conformably overlain by interbedded fine- to coarse-grained sandstone, siltstone, and minor coal of the Walker Island Member. The type section of the Walker Island Member in the Skybattle C-15 well is 140 m thick (Embry, 1985). The Walker Island Member is composed of marginal marine, bioturbated and fluvial sandstones with mud-drapes indicating tidal influence and was deposited in a delta front to delta plain environment (Embry 1985; Tullius et al., 2014). The Walker Island Member is conformably overlain by mudstones, siltstones, and fine-grained sandstones of the Christopher Formation.

2.2.2. Age of the Isachsen Formation

The age of the Isachsen Formation is summarized in Suppl. 1 and ranges from late Valanginian to early Aptian. This interpretation is based on the age of bounding strata and limited fossil evidence. The age of the underlying Deer Bay Formation ranges from Tithonian to Valanginian (Galloway et al., 2019 and references therein), while the age of overlying Christopher Formation ranges from Aptian to Albian (Schröder-Adams et al., 2014; Herrle et al., 2015). The base of the Paterson Island Member is diachronous; it may be as old as late Valanginian and extends into the early or middle Barremian (Embry, 1985), or early Aptian (Herrle et al., 2015;

Dummann et al., 2021). Dinocysts preserved in the Rondon Member exposed at Glacier Fiord and Buchanan Lake on Axel Heiberg Island, and from south Sabine Peninsula on Melville Island, have been used to interpret a Barremian age for this marine unit (Costa, 1984; McIntyre, 1984; McIntyre pers. comm. 1984 in Embry, 1985, 1991; Nøhr-Hansen and McIntyre, 1998; Suppl. 1). However, comparison of carbon isotope stratigraphy of the Isachsen Formation at the Glacier Fiord on Axel Heiberg Island with a composite Tethyan curve provides convincing evidence for an early Aptian age of the Rondon Member because of the distinctive negative shift in $\delta^{13}C_{org}$ associated with OAE 1a (Herrle et al., 2015), as well as individual carbon isotope segments (CIS) that can be related precisely to well-dated reference curves of lower latitudes (Dummann et al., 2021). Therefore, the dinocyst-based age determinations are herein revisited. Based on the age of the Rondon Member and overlying Christopher Formation, the age of the Walker Island Member is inferred to be either Barremian to Aptian (Embry, 1985) or entirely Aptian (Herrle et al., 2015; Dummann et al., 2021). The uncertainty in the age of the Isachsen Formation and its members poses a challenge for understanding Lower Cretaceous rocks of the Sverdrup Basin (Evenchick et al., 2019).

2.2.2 Sequence stratigraphy of the Isachsen Formation

Four sequences are recognized in the Isachsen Formation (Galloway et al., 2015). Sequence 1 represents Valanginian strata of the lower Paterson Island Member and is preserved in the central Sverdrup Basin on Ellef Ringnes Island, and has typically been eroded in the eastern parts of the basin (Galloway et al., 2015). This sequence represents progradation of a delta when tectonic subsidence had slowed, designated as early post-rift (Hadlari et al., 2016). This bioturbated succession is absent from outcrops of Isachsen Formation at Glacier Fiord due to uplift associated

with crustal breakup in the adjacent Amerasia Basin and possibly thermal doming associated with the first pulses of the HALIP (Vickers et al., 2016). The base of sequence 2 represents the widespread sub-Hauterivian unconformity associated with breakup in the adjacent Amerasia Basin, and it truncates early post-rift strata of the lowermost Paterson Island Member at many localities in the Sverdrup Basin (Galloway et al., 2015; Hadlari et al., 2016). Above the unconformity are cross-bedded fluvial sandstones of the middle part of the Paterson Island Member. These sandstones grade upward into finer-grained non-marine deposits consisting of fining-upward sandstones interbedded with siltstone, mudstone, and coal, herein informally termed the Paterson Island shale (Galloway et al., 2015), indicating deposition in a floodplain setting with overbank and channel environments (Embry, 1985; Tullius et al., 2014). Sequence 3 in the Isachsen Formation is represented by fining upward successions of sandstone deposited in a fluvial environment during the late Barremian and forming the uppermost strata of the Paterson Island Member. These fluvial sandstones correlate across the northern part of the Sverdrup Basin above the Paterson Island shale (Tullius et al., 2014; Galloway et al., 2015), and are interpreted here to be at the base of the sequence that grades upward to the Rondon Member. The Rondon Member was deposited in a marine environment and is interpreted by Herrle et al. (2015) and Dummann et al. (2021) to be of early Aptian age at the Glacier Fiord locality. The marine deposits of the Rondon Member grade upward into shoreface to local fluvial facies of the lower Walker Island Member. The transition from regression to transgression in the upper part of the Walker Island Member, which is Aptian in age (Suppl. 1), marks the boundary at the base of a fourth sequence. The marine sandstones forming the lower part of this sequence represents a shoreline to shallow-marine setting and reflect an overall transgressive succession that continues into the lower Christopher Formation.

2.2.3 Previous work on the Isachsen Formation

Initial terrestrial palynological research on the Isachsen Formation in the Sverdrup Basin by Hopkins (1971) qualitatively described palynoflora preserved in samples collected from the bottom of seismic shot-holes on northwestern Melville Island to provide age control for the unit. Galloway et al. (2013) quantitatively examined seven samples from the Isachsen Formation for pollen and spores as part of a study of a longer stratigraphic succession preserved in the Hoodoo Dome H-37 oil and gas well, southern Ellef Ringnes Island. Palynoflora show that an episode of relatively cool and moist conditions punctuated an otherwise warm climate during the late Valanginian to early Hauterivian. In a more detailed facies and palynological study of the formation based on three outcrop sections exposed on Ellef Ringnes Island in the central Sverdrup Basin, Tullius et al. (2014) and Galloway et al. (2015) interpreted the following three climatic phases: a relatively cool and moist Valanginian interval; a relatively warmer interval in the Hauterivian; and a return to cool and moist conditions in the Barremian. However, in these previous studies the marine strata of the Rondon Member were either lacking (Galloway et al. 2013) or samples from the Rondon Member were barren of palynomorphs (Tullius et al., 2014; Galloway et al., 2015). Moreover, the Ellef Ringnes Island sections of the Isachsen Formation were incomplete due to local uplift associated with salt diapirism (Galloway et al., 2015). The exceptionally well-exposed and well-constrained outcrop succession from Glacier Fiord, Axel Heiberg Island, in the central-eastern part of the Sverdrup Basin, is employed here as a reference section to refine the understanding of the biostratigraphy, paleoclimate, and terrestrial-vegetation response to environmental perturbations associated with the HALIP. Carbon isotope stratigraphy

from this section has indicated that the age of the marine Rondon Member is early Aptian rather than Barremian (Herrle et al., 2015; Dummann et al., 2021). This is a significant finding in the context of relative dating of the first extrusive components of the HALIP in the absence of geochronology on minerals within the basaltic flows. Age control of the Isachsen Formation is herein explored using dinocyst biostratigraphy and quantitatively-defined pollen and spore assemblage zones.

2.2.4 The High Arctic Large Igneous Province and the Isachsen Formation

Basalt flows within the Isachsen Formation represent the first pulses of extrusive volcanism associated with the HALIP. The age of these flows is based on limited geochronology (summarized in Dockman et al., 2018) and therefore interpretation of their age is usually based on their stratigraphic position relative to the Rondon Member, where dinocyst ranges can be compared with known regionally and globally established ranges of species that have been calibrated in various ways. The position of the flows are based on lithostratigraphic height relative to the Rondon Member (Embry and Osadetz, 1988), or occasionally only as “above” or “below” the member (Evenchick et al., 2012). In the absence of geochronology, paleontology, and/or chemostratigraphy, interpretations of the age of the flows can be problematic (Evenchick et al., 2015, 2019). In some cases, reports of HALIP “flows” have been re-interpreted as intrusive rocks (Bédard et al., 2016; Evenchick et al., 2019), which changes their age interpretations significantly.

The oldest U-Pb age for the initiation of HALIP is 126.6 ± 1.2 Ma from a gabbroic sill on Ellef Ringnes Island that intruded into an undetermined member of the Iscashen Formation (see Evenchick et al., 2012, fig. 12). The first main pulse of igneous activity associated with the HALIP,

however, was centred later, at 122 ± 2 Ma (Dockman et al., 2018). Collectively, the ages of the first pulse of the HALIP, that, with error, span from 127.8 Ma to 120 Ma, therefore bracket the Barremian-Aptian boundary of 121.4 (Gale et al., 2020). These ages thus accord with both the previous Barremian age attribution and the Aptian age attribution of the Rondon Member proposed by Herrle et al. (2015) and Dummann et al. (2021) at Glacier Fiord based on carbon isotope stratigraphy. The Rondon member overlies the Paterson Island Member and its associated volcanic rocks. Whereas the volcanic flows in the Paterson Island Member are not dated, they are likely broadly contemporaneous with the dated intrusions.

Volcanic flows that occur in the Paterson Island Member are known from two localities: the Geodetic Hills on east-central Axel Heiberg Island and Bjarnason Island (Tozer, 1963). In the Geodetic Hills, a single 10.5 m-thick basalt flow interbedded with coarse-grained fluvial sandstone of the Paterson Island Member occurs 125 m below the Rondon Member (Embry and Osadetz, 1988). We herein report from our own field observations at Geodetic Hills in 2015 (Thomas Hadlari) that these are pillowed flows and confirm the volcanic interpretation. The age of the flow was interpreted to be late Hauterivian to middle to late Barremian by Embry and Osadetz (1988) based on interpretation of the age of the Rondon Member as middle to late Barremian and the position of the flow below the Rondon Member. Two basalt flows, each about 10 m thick, are present in the Paterson Island Member at Bjarnason Island (Tozer, 1963). The stratigraphic position of these flows similarly suggested a late Hauterivian or early Barremian age to Embry and Osadetz (1988), but could be as young as early Aptian based on the revised age of the Rondon Member of Herrle et al. (2015).

A second episode of volcanism is preserved in the Walker Island Member of the Isachsen Formation. Volcanic rocks of this episode have been documented from the following areas, as

summarized by Embry and Osadetz (1988) and Evenchick et al. (2019): northwestern Axel Heiberg Island, between Middle Fiord and Bunde Fiord (McMillan, 1963; Tozer, 1963; Fischer, 1985); central Axel Heiberg Island, near the head of Strand Fiord, the Geodetic Hills, and the mouth of Mokka Fiord (Fricker, 1963; Tozer, 1963; Thorsteinsson, 1971; Ricketts, 1985); and northwestern Ellesmere Island, in the valley between the Blue and Backwelder mountains (Thorsteinsson, 1971; Moore, 1981). Embry and Osadetz (1988) described a 28 m-thick volcanic unit consisting of three flows at the mouth of Mokka Fiord; they tentatively assigned it to the Walker Island Member because they interpreted the host sandstones to be overlain by Christopher Formation shales, and because the flow had reversed polarity (Wynne et al., 1988). In the Blue Mountains region of northwestern Ellesmere Island, a basalt unit up to 20 m thick lies near the top of the Isachsen Formation, just a few metres below the Christopher Formation (Moore, 1981; Embry and Osadetz, 1988). The rocks at Mokka Fiord are reinterpreted by Evenchick et al. (2019) to be a sill rather than a flow and the rocks at Blue Mountains are now considered also to be sills (Bédard et al., 2016).

Embry and Osadetz (1988) measured a 300 m-thick section of the Walker Island Member in the Bunde Fiord region that consists of up to 220 m of basalt flows, with interbedded quartzose sandstone and pyroclastic and epiclastic volcanic sediments. Individual flows are 5 to 30 m thick, columnar-jointed, amygdaloidal, and commonly contain abundant petrified wood fragments and tree stumps up to 60 cm long. The sandstone units of the Walker Island Member are fluvial and thick-bedded, and are commonly trough or planar cross-bedded and have basal granule and cobble lags. Volcanic fragments and grains are absent from these thick sandstone beds, although they are present in some thin sandstone beds associated with siltstones, coals, and mudstone that occur at the top of the thick sandstone beds. Embry and Osadetz (1988) further described a persistent unit

that is approximately 20 m thick and composed of poorly stratified lahars, thin-bedded volcanic granulestone, and lithic sandstone. This unit occurs near the top of the Isachsen Formation and commonly below the uppermost volcanic flows. A thin-bedded, fine-grained quartz sandstone, approximately 1 m thick, occurs on top of the uppermost flow and thus constrains the volcanic rocks to be within the Walker Island Member of the Isachsen Formation rather than the lowermost beds of the overlying Christopher Formation. At Li Fiord, a similar section of the Walker Island Member was documented by Embry and Osadetz (1988) that is 125 m thick. At the Geodetic Hills, east-central Axel Heiberg Island, three basalt flows with a combined thickness of 11 m occur in the Walker Island Member. The most southerly location of volcanic strata in the Walker Island Member occurs at the head of Strand Fiord, where an 80 m-thick unit of basalt breccia occurs near the top of the member (Ricketts, 1985; Embry and Osadetz, 1988). All of the flows in the Walker Island Member are interbedded with clastic sediments of fluvial origin, and are thus interpreted as being extruded onto subsiding delta plains (Embry and Osadetz, 1988). Embry and Osadetz (1988) inferred all of the basaltic flows in the Walker Island Member as being of late Barremian to Aptian age on the basis of their stratigraphic position above the Rondon Member and below the Christopher Formation, the latter being of late Aptian to early Albian age (Schröder-Adams et al., 2014). Herein, the age of the Walker Island Member basaltic flows are re-interpreted to have a maximum early Aptian age based on the revised age of the underlying Rondon Member (Herrle et al., 2015).

3.0 Material and methods

Cretaceous strata exposed at Glacier Fiord are over 3 km thick and include the Isachsen Formation, which is approximately 0.5 km thick. In 2011 the lithology of the Isachsen Formation was logged, including its contacts with underlying Deer Bay Formation and overlying Christopher Formation, and sampled material for palynological analyses (Fig. 3).

3.1 Palynology

Fifty-six samples were collected from coal, mudstone, and siltstone of the Isachsen Formation for palynological analysis (Table 1, Fig. 3).

Samples were prepared for palynology following standard extraction techniques (Traverse, 2007) at the Geological Survey of Canada (Calgary). The process included washing, acid digestion, oxidation with Schulze's solution, and staining with Safranin O; residues were mounted with polyvinyl and liquid bioplastic. A quantitative approach was used for terrestrial palynomorphs to evaluate the paleoecological effects of the HALIP on land plants. Observations of terrestrial palynomorphs were made by Jennifer M. Galloway at the Geological Survey of Canada (Calgary) using an Olympus BX61® transmitted light microscope with oil immersion at 400x and 1000x magnification. Digital images were captured using an Olympus DP72 camera and Stream Motion® software. A qualitative approach was used for dinocyst evaluation for the purpose of biostratigraphic age determination. This work was carried out by Robert A. Fensome at the Geological Survey of Canada (Atlantic) using a Zeiss Axioplan 2® transmitted light microscope. Photographs were made using a Phase 2 Plan Neofluar 40 x 0.75 lens and Nikon D90 camera body custom-mounted onto the microscope. Thirty-two of the 57 samples yielded sufficiently well-preserved and abundant terrestrial palynomorphs for quantitative analyses (Fig. 3; Table 1).

Quantitative analyses of palynomorphs are based on counts of unsieved preparations with mostly greater than 300 spores and pollen enumerated per sample. The +45 µm size fraction of a selection of these 32 preparations plus additional samples were evaluated for age-diagnostic dinocysts (Table 1).

Rock samples, prepared residues, and microscope slides are stored at the Geological Survey of Canada, Calgary, Alberta, on loan from the Government of Nunavut.

3.2 Multivariate statistical analysis

Multivariate statistical analyses were used on quantitative assessment of the terrestrial pollen and spores (mean 277 ± 69 SD, *n*=32 samples; total 3634 terrestrial pollen and spores enumerated; Suppl. 2). The relative abundance of each taxon is based on a sum that includes palynomorphs with affinities to terrestrial land plants. Non-terrestrial palynomorphs, including dinocysts, algae, acritarchs, and reworked palynomorphs were also enumerated but excluded from the pollen and spore sum; their abundance is expressed as a proportion of the terrestrial pollen and spore sum. The relative abundance of these non-pollen palynomorphs (mean dinocysts 3% ± 9 SD, *n*=32; mean acritarchs 0.1% ± 0.5 SD; mean algae 0.2% ± 0.3 SD; mean undifferentiated non-pollen-palynomorphs 0.3% ± 0.9 SD) and reworked pollen and spores (mean 0.2% ± 0.7 SD) are included in the multivariate analyses but are unlikely to make a large impact on the results due to their low abundances.

Changes in the relative abundance of plant groups at the order level (Suppl. 3), where possible, were explored using multivariate statistical techniques. The order to which the extinct family Cheirolepidaceae was related to is unknown; family level classification is therefore used

for this gymnosperm taxon. We use the informal term bryophyte to encompass three divisions of non-vascular land pants, the liverworts (Marchantiophyta), hornworts (Anthocerotophyta), and mosses (Bryophyta), because the majority of spores encountered in the Isachsen Formation material have unknown or poorly known taxonomic affinities at the order level. Taxa with uncertain affinities up to and including the order level are grouped as *incertae sedis*. These taxa include: *Aequitriradites verrucosus*, *Foraminisporis dailyi*, *Triporoletes reticulatus* (putatively of the order Marchantiopsida), *Matthesisporites tumulosus,* and *Sestrosporites pseudoalveolatus* (Suppl. 3). Collectively taxa of uncertain affinity are a low proportion of the total palynomorph assemblage (mean 0.3 % ± 0.5 SD, *n*=32).

Ordination techniques are commonly used in ecology and paleoecology to determine major gradients in taxa composition that can be linked to environmental and ecological factors that control assemblage composition. Ordination techniques are operations on a community data matrix (e.g., taxa by sample matrix) whereby taxa and/or samples are arranged (ordinated) along gradients, and is used to represent species relationships in low-dimensional space whereby the most important and interpretable environmental gradients may be inferred. This is also a method whereby community level patterns may become evident (Gauch, 1982). Ordination is a particularly useful method to explore paleontological data because fossil assemblages may represent discrete communities, gradients in which taxa are distributed individualistically according to environmental preferences, and/or an association of community signatures transported and preserved in a geologic deposit (Springer and Bambach, 1985; Bambach and Bennington, 1996; Bennington and Bambach, 1996; Holland et al., 2001; Bush and Balme, 2010). Non-metric multi-dimensional scaling (NMDS) is used to compare potential dissimilarity of palynomorph content of stratigraphic levels in the Isachsen Formation at Glacier Fiord and to reduce the multivariate

data to two dimensions to facilitate ecological interpretation. NMDS was performed using the computer program R and the package 'vegan' (R Core Team, 2017; Oksanen et al. 2017). The Bray-Curtis dissimilarity calculation was used. Reworked and indeterminated palynomorphs (palynomorphs of uncertain affinity up to and including the order level), and non-pollen palynomorphs are also included in NMDS. Stress was <0.2 which was deemed "good". We integrate NMDS with Q- and R-mode cluster analysis using Ward's minimum variance method and relative Euclidean distance performed using the computer program SYSTAT to determine if a palynological signature for lithostratigraphic units of the Isachsen Formation could be determined.

Q-mode clusters, and the orders of taxa that compose them, were then graphed stratigraphically using the Tilia and TGView computer programs (Grimm, 1993-2001) to view changes over time at the assemblage scale. Stratigraphically constrained cluster analysis using incremental sum of squares (CONISS; Grimm, 1987) was applied to square-root transformed (to up-weigh rare types, partially reduce problems associated with closed sum percentage data, to improve normality, and because it is highly recommended when using count variables (Sokal and Rohlf, 1995) relative abundance of each order of obligately terrestrial plants to delineate major changes in palynoassemblages over time. Reworked and unidentified palynomorphs and non-pollen palynomorphs were not included in CONISS cluster analysis.

4.0 Results

Of the 57 horizons sampled for palynology, only 32 were sufficiently productive for quantitative analyses of palynomorphs. These samples contain pollen, spores, dinocysts, algae,

and acritarchs assigned to 96 taxa (Figs. 4, 5; Suppl. 4). Preservation ranges from exceptional to poor in the productive samples (Figs. 4, 5).

4.1 Dinocysts

In the quantitative analysis of unsieved preparations for terrestrial pollen and spores analysis, dinocysts are rare (<1%) in most samples except those of the Rondon Member, where dinocysts make up to 42% of the assemblage (sample B-36). In the uppermost Walker Island Member (B-56) dinocysts represent 4% of the assemblage. Samples qualitatively analyzed for dinocysts from the uppermost Paterson Island Member and Rondon Member yield a diverse assemblage (Suppl. 4).

Qualitative analysis of dinocysts was conducted in addition to quantitative analysis to improve the age control and determine if fully marine conditions prevailed during deposition of the Rondon Member. For all but one of the samples attributed to the Paterson Island Member, no dinocysts were found. The one exception is sample B-34, the sample immediately below the first sample tentatively considered to belong to the Rondon Member based on field observations. Rare dinocysts in this uppermost Paterson Island Member sample included *Oligosphaeridium pulcherrimum* and *Vesperopsis*? sp., neither of which are helpful biostratigraphically in the present context. The suite of samples that followed (B-35 to B-38) contain dinocysts that suggest neritic marine conditions from their diversity, possibly inner neritic because of the relatively common occurrence of *Vesperopsis* and other ceratiacean cysts (e.g., Nøhr-Hansen et al., 2016, table 1). Samples from the Walker Island Member proved mostly devoid of dinocysts, but a few (B-41, B-42, B-53, B-54) yielded rare to relatively common specimens of *Vesperopsis* and *Nyktericysta*,

which accords with a marginal marine/deltaic setting for the Walker Island Member. Occasional specimens of *Oligosphaeridium* in these samples may be reworked, but the genus is better represented in the top two samples of the member (B-55 and B-56), indicating more consistent marine conditions prior to the deposition of the overlying Christopher Formation.

The four samples tentatively identified as belonging to the Rondon Member yielded a total of 32 dinocyst taxa identified to species level (Fig. 4), including several unnamed species, and several other forms that could not be confidently identified. The assemblage is typical of the middle Early Cretaceous, dominated by gonyaulacaleans, including: common and diverse species of *Oligosphaeridium* (Fig. 4a, L–T); ceratioids such as *Pseudoceratium* (Fig. 4b, D–G) and *Vesperopsis* (Fig. 4b, R–T), although the rarity of specimens of *Odontochitina* is notable; and areoligeraceans represented by frequent *Tenua* (as defined by Fensome et al., 2019) (Fig. 4b, K–L, P). Peridinialeans are restricted to sparse specimens of *Palaeoperidinium* (Fig. 4b, A) and *Subtilisphaera* (Fig. 4b, I).

4.2. Pollen and spores

Numerous and diverse pollen and spores were recovered from the samples (Fig. 5; Suppl. 4). Quantitative analyses of pollen and spores are based on a mean count of 277 (± 69 SD, *n*=32) pollen and spores with affinities to obligately terrestrial plants.

4.2.1. Terrestrial palynoassemblages

Terrestrial palynoassemblages preserved in Isachsen Formation samples from Glacier Fiord are dominated by gymnosperm pollen. Pollen attributable to plants belonging to the class Pinopsida represent, on average, 48% (± 11 SD, *n*=32) of the total sporomorph sum. The majority of pollen attributable to the order Pinales are members of the family Pinaceae (bisaccate pollen, *Laricoidites magnus*, and *Cerebropollenites mesozoicus*), which make up 31% (± 13 SD). *Perinopollenites elatoides* and Cupressaceae-Taxaceae (Cupressales), *Classopollis classoides*, and minor abundances of *Araucariacites australis* and *Podocarpidites* represent the remaining 17% of total Pinopsida pollen. Pollen attributable to Pteridospermopsida represent a minor component (mean <1%) represented by *Vitreisporites pallidus*. Pollen attributable to plants belonging to Cycadales or Gingkoales (*Cycadopites*, *Monosulcites*, *Chasmatosporites*, and *Entylissa*) represent a mean of 11% ± 6 SD of the total pollen and spore sum of the samples. *Eucommiidites troedssonii* (Gnetopsida, unknown order) and *Ephedripites* (Ephedrales) pollen have a mean relative abundance of <1% of the pollen and spore population.

Important spore-producing plant groups represented in the palynological record of the Isachsen Formation include Filicopsida *incertae sedis* (mean 11% ± 4 SD, *n*=16 taxa), Osmundales (mean 9% ± 4 SD, *n*=5 taxa), Gleicheniales (mean 9% ± 6 SD, *n*=6 taxa), and Schizaeales (mean 3 ± 3 SD, *n*=17 taxa). Spores with affinities to the Marattiales, Polypodiales, Lycopodiales, Selaginellales, and Bryophyta are rare (mean <3%). Non-pollen and spore palynomorphs observed include undifferentiated dinocysts (mean 3% ± 9 SD), acritarchs (*Veryhachium*, *Micrhystridium*; mean 0.1% ± 0.5 SD), and chlorophytes (*Tasmanites*, *Pediastrum*, *Pterospermella*; mean 0.2% ± 0.3 SD). *Sigmopollis* and *Chomotriletes* are grouped as "other NPP" and represent <0.3% of the assemblage. While *Sigmopollis* is often grouped with acritarchs for the purpose of paleoecological analyses, it is a member of the Cyanophyta (cyanobacteria) according to Krutzsch and Pacltová

(1990). *Chomotriletes* is thought to have affinity to the Charophyceae. While collectively non-pollen and spore palynomorphs represent, on average, less than 4% of the assemblage, dinocysts are an important group in the marine Rondon Member where they increase to 42%.

R-mode cluster analysis is used to delineate six sample clusters that are broadly relatable to the lithostratigraphy of the Isachsen Formation (Fig. 6). Samples from the Rondon Member cluster distinctly due to their high relative proportion of dinocysts. Samples from the Paterson Island and Walker Island members do not appear to differ from each other based on palynomorph content (Fig. 6).

Q-mode cluster analysis was used to define four clusters of taxa (A-D; Fig. 6; Suppl. 3), and the botanical affinities and paleoecology of these taxa are discussed in detail in Suppl. 5. The Pinales form cluster A, Cycadales/Gingkoales, Gleichiniales, Osmundales, Filicopsida of uncertain affinity, and algae and protists (*Tasmanites, Pediastrum, Pterospermella* and undifferentiated dinocysts) form cluster B. Cluster C is composed of Schizaeales, Sphagnopsida, and indetermined pollen and spores. Cluster D is composed of reworked palynomorphs, Polypodiales, Lycopodiales, Selaginellales, Chierolepidaceae, Marrattiales, Caytoniales, Gnetopsida, bryophytes, and acritarchs (Suppl. 4).

4.3.3 Palynostratigraphy

Stratigraphically constrained cluster analysis of the relative abundance of palynomorphs resulted in delineation of four informal palynological zones (CONISS zones 1–4) and two sub-zones (CONISS subzones 4a, b; Fig. 7). The relative abundance of Q-mode clusters are plotted stratigraphically (Figs. 6, 7). The basal sample has a relatively high abundance of Pinales pollen

(~55%), followed up-section by an increase in the proportion of Cupressales pollen (35%), within the lower part of the Paterson Island Member at Glacier Fiord. Cluster D increases at this level as well, reflecting an increase in the proportion of other NPP. At the top of CONISS zone 1 (*n*=7 samples), an acme in Pinales pollen to near 60% occurs. CONISS zone 2 (*n*=2 samples) is characterized by an increase in cluster C, driven mainly by an increase in the proportion of spores with affinity to the Schizaeaceae. Samples of the Rondon Member cluster as distinct in CONISS zone 3 (*n*=5 samples) by an increase in the relative abundance of dinocysts (up to 42%) and acritarchs. The first occurrence of Marrattiales spores is at base of this zone. CONISS zone 4 comprises samples prepared from the Walker Island Member. CONISS sub-zone 4a (*n*=8 samples) is characterized by an increase in Pinales pollen (up to ~40%), followed by an increase in Cupressales pollen (up to ~30%) and Gleicheniales spores (~30%). The sub-zone is terminated by another increase in Pinales pollen. An acme in Cupressales pollen (~40%) and reworked Paleozoic palynomorphs (up to 3.6%) characterize the base of CONISS sub-zone 4b (*n*=10 samples). This signature is followed by an increase in Pinales pollen before a decline toward the top of the succession where Gleicheniales and then Filicopsida *incertae sedis* peak near the transition to a marginal marine depositional setting. These increases are concurrent with an increase in Marrattiales spores (up to 3%).

5.0 Discussion

5.1. Age interpretation

Table 2 indicates some of the more notable ranges (or last or first occurrences) among the dinocyst taxa identified in the Rondon Member of the Glacier Fiord section. Most accord with a Barremian to early Aptian age. The presence of *Muderongia crucis* (Fig. 4a, I–J), considered to have a last occurrence in the early Barremian (e.g. Costa and Davey, 1992; Stover et al. 1996), does not fit with a late Barremian or early Aptian age for the Rondon Member (see below). However, specimens of *Muderongia crucis* in the present material tend to be poorly preserved and thus may be reworked.

Dinocysts from the Isachsen Formation in general, and the Rondon Member in particular, have been interpreted previously as indicating a late Barremian age (Costa, 1984; McIntyre, 1984; McIntyre pers. comm. 1984 in Embry, 1985, 1991; Nøhr-Hansen and McIntyre, 1998; Suppl. 1), and based on dinocyst assemblages alone this conclusion remains reasonable. However, the study by Herrle et al. (2015) and Dummann et al. (2021) provided strong evidence that the Rondon Member is of early Aptian age, at least at the Glacier Fiord locality. Hence, it is useful to revisit the dinocyst evidence with the view that the Rondon Member could be younger than Barremian.

It can be noted initially that age control of the Lower Cretaceous of the Canadian Arctic based on dinocysts is not as consolidated as in some other regions, such as western Europe; and that ranges, although generally consistent within a region, can be variable from region to region. A key species in assessing the age of the Rondon Member is *Pseudoceratium pelliferum*, which is present in significant numbers in two of the samples (B-36 and B-37) examined in the present study. Both Costa and Davey (1992) and Brinkhuis et al. (2009) considered this species to have a last occurrence in the late Barremian; but according to Stover et al. (1996), the last occurrence of *Pseudoceratium pelliferum* is early Aptian. Another key species is *Pseudoceratium nudum* (also known as *Odontochitina nuda*): Nøhr-Hansen and McIntyre (1998) noted that "The last occurrence

of *Pseudoceratium nudum* has previously been recorded as Barremian by Brideaux (1977) but the species appears to range into the early Aptian in East Greenland (Nøhr-Hansen, 1993)." Many of the species encountered in the present study range from the Barremian or older into post-Barremian strata — for example *Chlamydophorella trabeculosa*, *Kiokansium unituberculatum*, *Oligosphaeridium albertense*, *Palaeoperidinium cretaceum*, *Subtilisphaera senegalense*, and *Tenua scabrosa* (which incorporates *Circulodinium asperum* of earlier authors — see Fensome et al., 2019). Although the full age ranges of *Nyktericysta vitrea* and *Vesperopsis mayii*, both found in the Rondon Member in the present study, span beyond the early Aptian, the protologues of both species indicate that their types are from the early Aptian. The first occurrence of *Kleithriasphaeridium cooksoniae* is given as early Aptian in Stover et al. (1996); although only a single specimen was found in the present study, it may add evidence to the possibility that the Rondon Member could be of Aptian age. However, Nøhr- Hansen (1993) recorded similar forms (as *Florentinia cooksoniae* / *Florentinia mantellii*) from the Barremian of North East Greenland.

In conclusion with regard to the age of the Rondon Member, dinocysts confirm a late Barremian to early Aptian age, and in conjunction with the carbon isotope data, reasonably conform to an early Aptian age.

Pollen and spores preserved in the Isachsen Formation provide less precise age control than the dinocysts and the previously published carbon isotope stratigraphy of Herrle et al. (2015). Pollen and spores are broadly representative of the Early Cretaceous *Cerebropollenites* Province of the northern hemisphere (Herngreen et al., 1996) and are generally similar to an assemblage described from the Isachsen Formation on Ellef Ringnes Island in the central Sverdrup Basin (Galloway et al., 2015). Long-ranging pollen and spore types that characterize the *Cerebropollenites* Province (e.g., *Gleicheniidites*, *Cicatricosisporites*, *Araucariacites*,

Inaperturopollenites, *Perinopollenites*, *Classopollis*, and *Cerebropollenites mesozoicus*) are unhelpful in providing a more precise age than Early Cretaceous. Many taxa found in the province are common to Late Jurassic floras (Herngreen et al., 1996), with the addition of certain taxa (e.g., *Aequitriradites*, *Cicatricosisporites*, *Ruffordiaspora*, *Trilobosporites*, and *Foveosporites subtriangularis*) that are indicative of a Cretaceous age (Venkatachala and Kar, 1970; Hopkins, 1971; Bose and Banerji, 1984; Taugourdeau-Lantz, 1988). *Foveosporites subtriangularis* has been interpreted as an index species for the Hauterivian to late Aptian interval in the eastern North Atlantic (Taugourdeau-Lantz, 1988), and the first occurrence of this spore is in sample B-44 of the Walker Island Member.

The preserved palynoassemblages of the Rondon Member cluster distinctly in the NMDS plot due to their high relative abundance of dinocysts (Fig. 6). The palynoassemblages of the Paterson Island Member and the Walker Island Member are similar to each other, with almost 50% of the pollen sum represented by pollen with affinities to the Pinales (Fig. 6). The only notable difference between the terrestrial palynoflora preserved in these two sandstone-dominated units is the occurrence of *Punctatosporites scabratus* (Marrattiales) in the Rondon and Walker Island members and its absence from the Paterson Island Member. This taxon first occurs in the Rondon Member (B-35), above which it remains present in low quantities (up to ~3%). *Punctatosporites scabratus* ranges from Late Triassic to late Albian in North America (Singh, 1971 and references therein) and so does not provide useful biostratigraphic information in the present context. This taxon was documented in Upper Triassic rocks in the Canadian Arctic Islands by McGregor (1965).

5.2 Vegetation and climate change: the influence of the HALIP

The Isachsen Formation at Glacier Fiord was deposited over approximately 17 million years, from the base of the Hauterivian to the late Aptian, contemporaneous with the onset of igneous activity associated with the HALIP and tectonism related to the opening of the Amerasia Basin (Figs. 2, 8). The HALIP in the Canadian Arctic was mostly intrusive but volcanic activity of the HALIP is represented by numerous flows in the Isachsen Formation. Vegetation and climate change are explored through analysis of stratigraphic changes in palynoassemblages defined by Q-mode cluster analysis and the potential impacts of the HALIP on climate and terrestrial ecosystems at Glacier Fiord are explored below, and summarized in Figure 8.

5.2.1 Hauterivian–early Barremian warming

The hinterland palynological assemblage (cluster A) is predominant in the lower part of the Paterson Island Member that was deposited during the Hauterivian and early Barremian at Glacier Fiord (CONISS zone 1; Fig. 7). Relatively arid and warm conditions at this time would have supported upland coniferous forests dominated by the Pinaceae (Suppl. 5). On Ellef Ringnes Island, in the underlying Valanginian part of the Paterson Island Member, the abundance of bisaccate pollen are relatively low (~30–40%; Galloway et al., 2015), reflecting the cool climatic conditions that prevailed in high northern latitudes at that time (Price and Nunn, 2010; Vickers et al., 2019). By the Hauterivian, bisaccate pollen had increased to 50–60% of the assemblage on Ellef Ringnes Island, similar to the median abundances of 45% (range 14–55%) of bisaccate pollen in CONISS zone 1 at Glacier Fiord. Galloway et al. (2015) interpreted the increase in bisaccate pollen in the Hauterivian on Ellef Ringnes Island as a response to the development of warmer

climatic conditions. Warming in the Hauterivian following the Valanginian cold interval is widely documented in the northern hemisphere. For example, Gröcke et al. (2005) examined the ^{13}C isotopic signature in fossil plant material from southern Ukraine and showed that the late Valanginian cold phase was short lived (<3 myr), and that the carbon isotope signature of terrestrial plant material had returned to pre-Valanginian levels by the late early Hauterivian. A stable isotope record from belemnites preserved in strata from the Speeton area, eastern England, documents a sea-water warming event from 11°C at the start of the Hauterivian to a maximum of 15°C by middle Hauterivian, before a long-term cooling to 11°C by the start of the Barremian (McArthur et al., 2004). Pucéat et al. (2003) used oxygen isotopes preserved in fish-tooth enamel to quantitatively reconstruct paleotemperatures of upper waters from the western Tethyan platform during the same interval. They show an increase from an early late Valanginian minimum of ~13–14°C to ~20°C during the middle Hauterivian to early Barremian; this was followed by a decline to ~16.5°C from the middle or late Barremian to the earliest Aptian. Podlaha et al. (1998) also showed a general warming trend from the Hauterivian into the Barremian. These data provide evidence of a widespread cooling phase in the northern hemisphere that culminated in the Valanginian, and possibly extended into the early Hauterivian. This cooling event was followed by warming throughout the middle and late Hauterivian and into the Barremian (e.g., Kessels et al., 2006; Price et al., 2018) (Fig. 8).

Valanginian cooling was associated with a widespread positive carbon isotope excursion (the Weissert Event; Erba et al., 2004) in marine sediments, and is dated as 135.22 ± 1 Ma based on U-Pb ages of tuff layers in the Neuquén Basin and an update of the astrochronological time scale of Martinez et al. (2015) (Aguirre-Urreta et al., 2015). The Valanginian "Weissert" event has now been also documented in the Canadian Arctic (Galloway et al., 2019) and North East

Greenland (Möller et al., 2015). This event was associated with a biogeochemical sequence that ultimately led to an increase in carbon burial (Price et al., 2018). An increase in atmospheric CO_2 and environmental changes at this time have been linked to volcanism associated with the Paraná-Etendeka igneous province (e.g., Lini et al., 1992; Gröcke et al. 2005; Erba et al., 2004; Charbonnier et al., 2017), which became active between 134.6 ± 0.6 Ma and 134.4 ± 0.8 Ma; Thiede and Vasconcelos, 2010; Janasi et al., 2001) or slightly earlier, during Chron 15, and remained active for at least 4 myr (Dodd et al., 2015). Rocha et al. (2020) present younger ages for siliciclastic rocks of the Paraná magmatic province (of 133.6 Ma and 132.9 Ma) and thus suggest that magmatism did not trigger the Valanginian event but may have extended its duration. Regardless of the proximal trigger, following the positive carbon isotope excursion of the Weissert Event, the enhanced carbon burial may have triggered a decline in pCO_2, ultimately leading to the cold conditions near the end of the Weissert Event. Price et al. (2018) argued that Paraná-Etendeka volcanism-related global warming did not stimulate the primary productivity that ultimately led to increased carbon burial. They considered instead that the increase in productivity was triggered by ocean fertilization associated with prolonged weathering of basalt. Additionally, they viewed the temperature increase that followed the Paraná–Etendeka episode and the Weissert Event in the Hauterivian as recovery to pre-Weissert event levels (Price et al., 2018) and not an interval of warming forced by volcanic outgassing and CO_2 production. In the Sverdrup Basin, the onset of the HALIP (the oldest age of 126.6 ± 1.2 Ma from a gabbroic intrustion on Ellef Ringnes Island; Evenchick et al., 2015) was initiated possibly as early as the latest Hauterivian or earliest Barremian, and thus post-dates the Hauterivian warming interval.

5.2.2 Volcanic flows and a “fern spike”

By the middle to late Barremian, the hinterland assemblage at Glacier Fiord had declined and was replaced by a mixed heathland and mire assemblage (Q-mode cluster C) marked by an increase in fern spores up to 70% of the assemblage in the uppermost Paterson Island Member. This brief vegetation change can be considered coeval with the first pulse of the HALIP, that, with error, spans from 127.8 Ma to 120 Ma (Figs. 7, 8). Schizaeales and Gleicheniales each represent ~20% of the total assemblage. The uppermost Paterson Island Member is a transgressive unit deposited during relative sea-level rise that culminated in the maximum flood that deposited the overlying marine Rondon Member. This eliminates sea-level fall that would have exposed delta plains to be colonized by early successional vegetation as the proximate driver of the spore spike. The increase of filicopsid spores in the floodplain deposits of the uppermost Paterson Island Member during the middle to late Barremian could reflect an increase in humidity and disturbance at this time that drove the expansion of mire and heathland plant communities. A small increase in other NPP (*Sigmopollis* and *Chomotriletes*; Fig. 8) indicate the presence of wet biotopes and standing water during this interval (Suppl. 5). Increased effective moisture at this time may have been related to the overall cooling climate conditions that began during the late Barremian and progressed into the Aptian (Pucéat et al., 2003). Relative sea-level rise at this time could have also decreased depth to water table in the broader environment, leading to wetter soils and more frequent and severe flooding. However, while filicopsid spores can range up to 70–75% in coal samples deposited in humid environments during the Jurassic and Cretaceous in the mid-latitudes of the southern hemisphere (Schrank, 2010, and references therein), values near 30–40% are typical for the Isachsen Formation (this work; Galloway et al., 2015).

Environmental change can also cause conversion of temperate forests into heaths due to disturbance-mediated increases in paludification, nutrient sequestration, release of allelochemicals and contaminants, and soil acidification that cause conifer regeneration failure (Mallik, 1995). The dominance of ferns following disturbance is the result of their tolerance of ecological stress, including the ability to grow on strongly leached and/or nutrient poor or metal-enriched soils, their tolerance of low-light conditions, and certain life-cycle traits such as gametophytic selfing and wind dispersal of spores; together these traits permit their rapid invasion of and growth in disturbed habitats (Page, 2002).

Fern spore spikes are commonly documented in the geological record associated with large-scale disturbance, including those related to LIP magmatism. Crises at the end-Permian (e.g., Hochuli et al., 2010), end-Triassic (e.g., van de Schootbrugge et al., 2009 and references therein), and end-Cretaceous (e.g., Vajda and Bercovici et al., 2014 and references therein) demonstrate similar successions of recovery phases of terrestrial vegetation, characterized by a bloom of opportunistic taxa followed by a pulse of pioneer communities and finally recovery of plant communities (Vajda and Bercovici, 2014). Ferns are the most common pioneer taxa, although bryophyte spores may also provide this signal (Brinkhuis and Schiøler, 1996). Geologically brief fern spikes are interpreted to represent the pioneering recovery stage by ferns and fern-allies following collapse of arboreal communities associated with widespread disturbance (e.g., van de Schootbrugge et al., 2009). For example, at the end-Cretaceous extinction event, a dramatic increase in the percentage of fern spores is documented in assemblages immediately overlying the iridium anomaly (e.g., Tschudy et al., 1984; Tschudy and Tschudy, 1986; Nichols et al., 1986). Berry (2019) noted that following the Cretaceous/Paleogene boundary, post-extinction recovery flora was dominated by *Cyathidites* and then *Laevigatosporites* fern spores. Schizaeaceae are also

notable early pioneers of disturbed habitats; for example, this group were the first plants to colonize a barren landscape following a volcanic eruption that preserved the Eocene Lagerstätte in Messel, Germany (Lenz et al., 2007). The magnitude of the fern-spore spike appears related to the severity of the crises; across the Cretaceous/Paleogene boundary, an increase in fern spores to ~70–100% (cf. 70% abundance in Isachsen Formation samples) of the total pollen and spore assemblage occurred (Vajda and Bercovici, 2014 and references therein). The Cretaceous/Paleogene fern spore spike was geologically brief, recorded in only a 1–2 cm-thick interval (Vajda and Bercovici, 2014).

Magmatism can be the agent of environmental disturbance provoking vegetation change, and basalt flows are abundant in the Paterson Island Member. Lava flows destroy vegetation in their immediate path and can cause widespread wildfire (e.g., van de Schootbrugge et al., 2009). For example, charcoal records from Greenland, Denmark, Sweden, and Poland show increased wildfire activity (leading to further CO_2 release) associated with emplacement of the Central Atlantic Magmatic Province (CAMP; Lindström et al., 2015). Grasby et al. (2011) documented fly-ash generated from coal combustion during the Siberian Trap LIP emplacement. In Triassic-Jurassic strata of the Newark Supergroup of eastern North America affected by CAMP volcanism, palynological assemblages change to a higher abundance of trilete spores occurs approximately 10 m below (and ~10 kyr prior) to the first exposed flood basalt flows of the Newark Supergroup (Fowell and Olsen, 1993). In northwestern Europe, an increase in Schizaeaceae spores (up to 35%) and Osmundaceae spores (up to 5–10%) occur in uppermost Triassic Triletes beds in response to magmatism associated with the CAMP (van de Schootbrugge et al., 2009). The dominance of pteridophyte vegetation across more than 2000 km^2 within Triassic/Jurassic boundary beds indicates that this floral change was unlikely to be due to a major sea-level fall that would have promoted growth of riparian habitats (van de Schootbrugge et al., 2009). Fern spikes are also well

documented in response to smaller scale disturbances. For example, ferns were early colonizers of denuded ground after landslides associated with 1980 Mount St. Helens eruption, and were dominant plants following the 1883 Krakatau eruption (Tschudy et al., 1984), and are the first colonizers of freshly deposited lava flows in Hawaii (Bercovici and Vellekoop, 2017 and references therein).

In the Glacier Fiord assemblage, the increase in spore abundance from 30–40% to ~70% of the total palynoassemblage in the uppermost 20 m of the Paterson Island Member may reflect a response to landscape disturbance associated with the first volcanic flows of the HALIP in the Sverdrup Basin, or their geologically brief occurrence may be a coincidence or due to other factors such as disturbance or rising sea-level (Fig. 8). The basalts preserved in the Isachsen Formation indicate widespread volcanism that was likely to have impacted polar vegetation through, for example: i) release of sulfur aerosols and resulting short-term cooling and inhibition of photosynthesis triggered by darkening; ii) decrease in stratospheric ozone as a result of release of brominated and chlorinated halocarbons from heated evaporites and resulting increase in lethal radiation (but insufficient to cause aberrant spores); iii) acid rain; and/or iv) direct toxic effects from the release of polycyclic aromatic hydrocarbons and mercury (e.g., Svensen et al., 2009; Lindström et al., 2019). The direct impact of these effects are not evaluated here, although we note that no aberrant pollen or spores were documented (cf. Lindström et al., 2019). However, because ferns are common early colonizers following localized landscape disturbances associated with scoured riverbanks, dunes, and floodplains (Walker and Sharpe, 2010 and references therein), multiple studies across a wide geographical area are needed to test the hypothesis that the spore spike was caused by HALIP-related landscape disturbance, atmospheric toxicity (e.g., van de Schootbrugge et al., 2009), sea-level change, or is a coincidence.

5.3.3 Ocean Anoxic Event 1a

Palynoassemblages preserved in the marine Rondon Member are dominated by dinocysts (up to ~40%; Figs. 7, 8). Ocean Anoxic Event 1a (~121–122 Ma; Midtkandal et al., 2016; Olierook et al., 2019) is recorded as a major negative carbon isotope excursion in the marine mudstones of this unit at Glacier Fiord (Herrle et al., 2015).

In the Tethys, warmer temperatures are inferred to have developed and culminated in a maximum sea-surface temperature during the early onset of the negative carbon isotope excursion associated with OAE 1a (Hu et al., 2012; Bottini et al., 2015; Naafs and Pancost, 2016; Jenkyns, 2018). This warming is thought to be the result of intense volcanic activity of the Ontong-Java Plateau (Wang et al., 2014; Bottini et al., 2015; Adloff et al., 2020) In the Boreal Realm, sea-surface temperature rose prior to OAE 1a and reached a maximum of 4–9 ^{o} C higher than temperatures recorded for Hauterivian–lowermost Aptian sediments from the same basin, showing that "supergreenhouse" conditions existed even at paleolatitudes of up to 39 ^{o} N (northwestern Germany; Mutterlose et al., 2014). This magnitude of warming is comparable to that experienced during the end-Triassic event (~3–4°C; McElwain et al., 1999) that was associated with emplacement of ~700,000 km^3 of sills during the Central Atlantic Magmatic Event (Svensen et al., 2017) that could have produced up to 88,000 Gt CO_2 through contact metamorphism of organic-rich shales and hydrocarbon reservoirs (Svensen et al., 2017). The end of the Aptian OAE 1a coincided with cessation of Ontong-Java Plateau volcanics and pronounced cooling in the Vocontian Basin (Herrle et al., 2010; Kuhnt et al., 2011), Boreal Realm (Rückheim et al., 2006; Malkoč et al., 2010; Bottini and Mutterlose, 2012; Pauly et al., 2013; Mutterlose and Bottini, 2013;

Mutterlose et al., 2014) and Pacific Ocean (Jenkyns, 1995; Jenkyns and Wilson, 1999; Price, 2003; Dumitrescu et al., 2006; Ando et al., 2008).

Because of the broad temporal coincidence of the onset of OAE 1a with the emplacement of Ontong-Java Plateau, the negative carbon isotope excursion has been interpreted as resulting from a stepwise accumulation of volcanogenic CO_2 and release of isotopically light carbon from partial methane hydrate dissociation, and initiating OAE 1a by warming of the climate and nutrification of the ocean (e.g., Weissert, 1989; Jahren et al., 2001). Using a similar argument, the temporal coincidence of the HALIP with OAE 1a also suggests that this high latitude LIP could have played a role in carbon cycle and climate perturbations at this time (Polteau et al., 2016; Planke et al., 2017; Adloff et al., 2020). For example, the volume of igneous rocks associated with the Barents Sea Sill Complex of the northern and eastern Barents Sea (a conservative volume estimate of 100,000 to 200,000 km^2 of intrusions in an area of an area of ~900,000 km^2), that intruded mostly into Triassic and Permian sedimentary rocks resulted in thermogenic gas formation and mobilization of up to 20,000 Gt of carbon and may have triggered OAE 1a and the associated carbon isotope excursion in the early Aptian (Polteau et al., 2016; Planke et al., 2017; Adloff et al., 2020). The age of magma emplacement is interpreted as ~125–122 Ma (Barremian; Tarduno et al., 1998; Corfu et al., 2013; Polteau et al., 2016). Although ages of sills in the Sverdrup Basin are poorly constrained, abundant sills of probably the same age as the Barents sills, intrude into uppermost Permian and Triassic source rocks of the Blind Fiord, Murray Harbour, Hoyle, and Barrow formations (e.g., Hadlari et al., 2018). The earliest well-dated intrusive components of the HALIP were emplaced into the Upper Jurassic Deer Bay Formation and the Isachsen Formation on Ellef Ringnes Island at 127 Ma and 121 Ma (Evenchick et al., 2015; Fig. 2). The HALIP is by volume at least 3–5 times more intrusive than extrusive in character in its Canadian part, and

possibly 50–60% of the HALIP rock mass occurs as sills (Saumur et al., 2016). The total volume of magma in Canada alone is estimated as exceeding 100,000 km^3 (Saumur et al., 2016). The magmatic rocks associated with the HALIP exposed on Svalbard also occur mostly as sills (Maher, 2001; Senger et al., 2014 and references therein). It is primarily the intrusive magmatism associated with LIPs that generates volatiles and releases CO_2 through interaction with host rocks rich in organic matter and/or evaporites (e.g., Jones et al., 2016; Heimdal et al., 2018). Interaction of the early igneous events associated with the HALIP with organic-rich rocks of the Sverdrup Basin and other intruded northern basins would have released greenhouse gases into the atmosphere during the early Aptian.

The low sampling resolution of the Rondon Member for palynology at the Glacier Fiord section does not permit comparison of sequence of OAE 1a initiation and vegetation change. In better studied and expanded sections in lower latitudes, palynological and $\delta^{18}O$ records of a contemporaneous section in the Lombardian and Belluno basins, Italy (Keller et al., 2011), and the shelf section at La Bédoule, SE France (Lorenzen et al., 2013) show a time lag between the start of the negative carbon isotope excursion associated with OAE 1a and the main interval of warming. This lag is consistent with reconstructions by Adloff et al. (2020) that show that *p*CO2 increased, the driver of the climate warming and subsequent activation of the hydrological cycle causing increased nutrient flux to global oceans due to higher weathering rates (Jenkyns, 2010), after the onset of the carbon isotope excursion caused by release of a ^{13}C-depleted carbon source. Keller et al. (2011) show that during the C3 interval (onset of the CIE; *sensu* Menegatti et al., 1998) in the Lombardian and Belluno basins, an increase in *Classopollis* pollen occurred, with peak values in the lower C4 segment. The upper part of C4 and the C5 and C6 segments are marked by high but fluctuating *Classopollis* pollen abundance, followed by a decline subsequent to the termination of

the black shale episode. In the Belluno Basin, the decline in *Classopollis* pollen is paralleled by an increase in post-OAE bisaccate pollen abundance, interpreted to reflect cooling and an increase in humidity that followed OAE 1a (Hochuli et al., 1999). In the Maestrat Basin of eastern Spain, Cors et al. (2015) showed the climate cooling that appears to punctuate OAE 1a (e.g., Jenkyns, 2018) is also manifested as changes in terrestrial vegetation after the end of carbon drawdown. The climatic cooling triggered initially by carbon drawdown and deposition and preservation of marine black shales may have resulted in the equator-wards expansion of temperate humid belts, and resulting in the expansion of peat-forming environments that persisted after OAE 1a (McCabe and Parrish, 1992; Cors et al., 2015); thus OAE 1a left a legacy of prolonged change from predominantly marine to terrestrial carbon burial on a large scale. This protracted phase of terrestrial carbon burial in the aftermath of OAE 1a may partially explain the interval characterized by positive carbon isotope values during late early Aptian time (Cors et al., 2015), and possibly partially the floral instability that ensued in the early Aptian at Glacier Fiord.

5.3.4 Early Aptian floral instability

The early Aptian at Glacier Fiord is characterized by fluctuations in Pinaceae pollen and Cupressales pollen and fern spores (Figs. 7, 8). Two declines in the abundance of Pinaceae pollen in fluvial to shoreface deposits of the lower Walker Island Member and shoreline to shallow marine deposits of the upper Walker Island Member are notable. These declines are associated with increases in Cupressales pollen and fern spores. Floral changes between dominance of Pinaceae vs. Cupressales and ferns at Glacier Fiord likely reflect a combination of climate change associated with long-term instability following OAE 1a, landscape disturbance associated with relative sea-

level rise that would have destabilized lowland coastal environments, and/or lava flows associated with the HALIP that were repeatedly extruded onto the subsiding delta plain on Axel Heiberg Island during deposition of the Walker Island Member (Emby and Osadetz, 1988). Volcanic activity in the early Aptian is likely to have affected the landscapes of southern Glacier Fiord, resulting in repeated perturbation of gymnosperm-dominated forests and replacement by earlier successional communities dominated by Cupressales and ferns.

5.0 Conclusions

Large Igneous Provinces are increasingly accepted to have caused major global shifts in environmental conditions, and to be implicated in mass extinctions and smaller scale biotic crises (e.g., Ernst and Youbi, 2017, and references therein). The proximal causal mechanisms of environmental change associated with LIPs are global warming and cooling, ocean anoxic events, ocean acidification, introduction of toxic metals and gases, removal of bio-essential elements, and sea-level change (summarized in Ernst and Youbi, 2017). The absence of a relationship between LIP size and magnitude of extinction demonstrates complexities. The duration of short-term pulses of activity, extending down to the scale of individual flows, is probably more important than the overall volume of the event. LIPs are associated with some of the largest volcanic episodes in Earth's history, including areally extensive basaltic lava-flow fields. Lava flows destroy vegetation in their immediate path and cause widespread wildfire (e.g., van de Schootbrugge et al., 2009). Other environmental effects related to LIPs may be the rapid thermal maturation of organic-rich sediments that igneous bodies contact, and the associated volitolization of gases contained in those sediments. The gas thus released is composed dominantly of H_2O, but also of CO_2, SO_2 and

halogens (e.g., Self et al., 2014). The release of SO_2 can lead to warming and then cooling (when converted to sulphuric acid and then to sulphate aerosols). Ozone-destroying halogens may also be released via the intrusive component of LIPs interaction with volatile-rich sediments (Svensen et al., 2009). Mercury can also be released, with deleterious environmental effects (Sanei et al., 2012), including on vegetation (Lindström et al., 2019). A myriad of these effects commonly associated with LIPs, coupled with landscape disturbance that may have been associated with the fluvial and deltaic depositional setting of the Isachsen Formation and influenced Arctic vegetation during the Hauterivian to Aptian interval in the Sverdrup Basin. The interval of Hauterivian to early Barremian warming preserved in floral assemblage change from Glacier Fiord in Arctic Canada may be related to recovery from the Valanginian cold snap and/or CO_2 forced warming associated with LIP activity in mid and low latitudes (Paraná-Etendeka Province). An increase in fern spores up to 70%, comparable in abundance to spore spikes associated with mass extinctions (e.g., latest Permian, latest Triassic), in the uppermost Paterson Island is herein interpreted as a possible floral response to the initial flood basalt activity of the HALIP that disturbed landscapes in the proximity of Glacier Fiord. OAE 1a, documented at Glacier Fiord by a carbon isotope excursion in the marine Rondon Member, was probably at least partially triggered by CO_2 outgassing associated with contact metamorphism of intrusive components of the HALIP with carbon-rich rocks. Lastly, floral instability preserved as fluctuations in the proportion of pollen from trees in the hinterland during deposition of the Walker Island Member in the early Aptian is interpreted as a possible response to temperature instability following OAE 1a and repeated lava flows of the HALIP onto the subsiding delta plain on southern Axel Heiberg Island that disturbed vegetation and habitats. This analysis of the palynological signature of the Isachsen Formation exposed in the eastern Sverdrup Basin at Glacier Fiord refines the understanding of drivers of

Arctic climate change during Hauterivian to Aptian time by illustrating the effects of the HALIP on at least regional climate and habitat that, in turn, affected Arctic forest composition.

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Figure 1. (colour online) Geologic map of the Sverdrup Basin (after Dewing et al. 2007) showing the location of studied Glacier Fiord succession on Axel Heiberg Island

Figure 2. (colour online) Mesozoic lithostratigraphy of the Sverdrup Basin (after Hadlari et al. 2016). The Geological Time Scale v 2020 for Jurassic and Cretaceous systems (Hesselbo et al. 2020; Gale et al., 2020) is used. Note that ages of intrusive rocks should be younger than the strata that they intrude, and that detrital zircon ages can be older than the rocks in which they occur. For detailed summaries and discussions of age determinations of Lower Cretaceous strata, see Galloway et al. (2013, 2015, 2019), Schröder-Adams et al. (2014), and Herrle et al. (2015)

Figure 3. (colour online) Lithostratigraphic section of the Isachsen Formation measured at Glacier Fiord, Axel Heiberg Island, showing stratigraphic positions of samples collected and analyzed for palynology (Table 1), sequence stratigraphy (after Galloway et al., 2015), facies associations (after Tullius et al., 2014), and informal palynozones based on stratigraphically constrained cluster analysis of pollen of obligately terrestrial pollen and spores

Figure 4a. (colour online) Photographs of dinocysts identified in Isachsen Formation preparations from samples collected from Glacier Fiord. Photographs of the dinocysts have been cleaned of extraneous material, but the images of the specimens have not been altered beyond brightness and contrast adjustments. Sample number, GSC curation number (C-number), GSC Calgary Palynology Laboratory preparation number (P-number),

Government of Nunavut specimen number (pending), microscope and England Finder coordinates, and magnification:

A. *Callaiosphaeridium* sp. A, B-36, C-548345, P-5231-39H, 087 x 0815, EF H24-3, x40P. This is a form of *Callaiosphaeridium* with cingular processes significantly wider that those of *Callaiosphaeridium assymmetricum*.

B. *Catastomocystis* sp. A, B-36, C-548345, P-5231-39H, 198 x 0773, EF T19-4, x40P. A form of *Catastomocystis* similar to *Catastomocystis spinosa* but with a smooth outline, without spines.

C. *Chlamydophorella nyei*, B-34, C-548343, P-5231-37H, 104 x 0884, EF K31-0/1, x40P.

D. Dinocyst gen et sp. Indet, B-35, C-548344, P-5231-38H, 158 x 0729, EF P15-0/3, x40P.

E. *Chlamydophorella trabeculosa*, B-35, C-548344, P-5231-38I, 181 x 0942, EF S37-0/1, x40P.

F. *Kiokansium unituberculatum*, B-34, C-548343, P-5231-37H, 195 x 0941, EF T37-0, x40P.

G. *Kiokansium unituberculatum*, B-36, C-548345, P-5231-39H, 052 x 0719, EF D14-0/3, x40P.

H. *Kleithriasphaeridium cooksoniae*, B-34, C-548343, P-5231-37H, 100 x 0751, EF J17-2, x40P.

I. ?*Muderongia crucis*, B-36, C-548345, P-5231-39H, 056 x 0724, EF E14-2, x40P.

J. ?*Muderongia crucis*, B-37, C-548346, P-5231-40H, 135 x 0725, EF N14-0/2, x40P

K. *Nyktericysta* sp. A, B-38, C-548347, P-5231-41H, 187 x 0917, EF S34-4, x40P. A *Nyktericysta* with a coarsely reticulate periphragm.

L. *Oligosphaeridium albertense*, B-34, C-548343, P-5231-37H, 187 x 0739, EF S16-0/1, x40P.

M. *Oligosphaeridium anthophorum*, B-35, C-548344, P-5231-38H, 066 x 0801, EF F22-0/2, x40P.

N. *Oligosphaeridium asterigerum*, B-34, C-548343, P-5231-37H, 117 x 0899, EF L32-4, x40P.

O. *Oligosphaeridium diluculum*, B-36, C548345, P5231-39H, 087 x 0848, EF H27-0, x40P.

P. *Oligosphaeridium diluculum*, B-36, C-548345, P-5231-39H, 197 x 0868, EF T29-3/4, x40P.

Q. *Oligosphaeridium porosum*, B-35, C-548344, P-5231-38H, 092 x 0966, EF J39-2, x40P.

R. *Oligosphaeridium porosum*, B-35, C-548344, P-5231-38H, 197 x 0827, EF T25-0, x40P.

S. *Oligosphaeridium pulcherrimum*, B-36, C-548345, P-5231-39H, 135 x 0679, EF N10-3, x40P, high focus.

T. *Oligosphaeridium pulcherrimum*, B-36, C-548345, P-5231-39H, 135 x 0679, EF N10-3, x40P, low focus.

Figure 4b. (colour online) Photographs of dinocysts identified in Isachsen Formation preparations from samples collected from Glacier Fiord. Photographs of the dinocysts have been cleaned of extraneous material, but the images of the specimens have not been altered beyond brightness and contrast adjustments. Sample number, GSC curation number (C-number), GSC Calgary Palynology Laboratory preparation number (P-number), Government of Nunavut specimen number (pending), microscope and England Finder coordinates, and magnification:

A. *Palaeoperidinium cretaceum*, B-36, C-548345, P-5231-39H, 118 x 0895, EF L32-0, x40P.

B. *Psaligonyaulax* sp., B-35, C-548344, P-5231-38H, 108 x 0767, EF K19-3, x40P.

C. *Pseudoceratium pelliferum*, B-36, C-548345, P-5231-39H, 160 x 1010, EF Q44-1, x40P.

D. *Pseudoceratium pelliferum*, B-37, C-548346, P-5231-40H, 079 x 0951, EF G38-0, x40P.

E. *Pseudoceratium nudum*, B-36, C-548345, P-5231-39H, 201 x 0910, EF U33-2, x40P. (Species here retained in *Pseudoceratium*.)

F. *Pseudoceratium nudum*, B-37, C-548346, P-5231-40H, 146 x 0825, EF O25-0/1, x40P.

G. *Pseudoceratium nudum*, B-37, C-548346, P-5231-40H, 137 x 0870, EF N29-4, x40P.

H. *Sirmiodinium grossii*, B-34, C-548343, P-5231-37H, 137 x 0940, EF N37-3, x40P.

I. *Subtilisphaera senegalensis*, B-38, C-548347, P-5231-41H, 124 x 0884, EF M31-0/1, x40P.

J. *Tanyosphaeridium xanthiopyxides*, B-35, C-548344, P-5231-38I, 144 x 0980, EF O41-0, x40P.

K. *Tenua hystrix*, B-36, C-548345, P-5231-39H, GSC 141134, 084 x 0818, EF G24-3/4, x40P.

L *Tenua scabrosa*, B-35, C-548344, P-5231-38H, GSC 141135, 108 x 0979, EF K41-3, x40P.

M. *Nyktericysta vitrea*, B-35, C-548344, P-5231-38H, GSC 141136, 102 x 0901, EF K31-0/1, x40P.

N. *Trichodinium* sp., B-35, C-548344, P-5231-38H, GSC 141137, 065 x 0811, EF F23-2, x40P.

O. *Trichodinium* sp., B-38, C-548347, P-5231-41H, GSC 141138, 196 x 0971, EF T40-0/3, x40P.

P. *Tenua scabrosa*, B-35, C-548344, P-5231-38H, GSC 141139, 137 x 0916, EF N34-0, x40P.

Q. *Nyktericysta*? *vitrea*, B-35, C-548344, P-5231-38H, GSC 141140, 119 x 0772, EF L19-2/4, x40P.

R. *Vesperopsis longicornis*, B-37, C-548346, P-5231-40H, GSC 141141, 189 x 0922, EF T35-1, x40P.

S. *Vesperopsis longicornis*, B-38, C-548347, P-5231-41H, GSC 141142, 198 x 0770, EF T19-3/4, x40P.

T. *Vesperopsis* sp. A, B-36, C-548345, P-5231-39H, GSC 141143, 168 x 0804, EF Q23-3, x40P.

Figure 5. (colour online) Pollen and spores photographed using differential interference contrast and oil immersion preserved in Isachsen Formation preparations from samples collected from Glacier Fiord. Sample number, GSC-C curation number (C-number), GSC-Calgary Palynology Laboratory preparation number (P-number), Government of Nunavut Specimen Number (pending), and England Finder coordinates where available:

A. *Classopollis classoides*, B-33b, C-548342, P5231-36B, W24/2.

B. *Cycadopites follicularis*, B-3, C-548317, P5231-11B, V13/4.

C. *Eucommiidites troedssonii*, B-38, C-548347, P5231-41E, M12/2.

D. *Perinopollenites elatoides*, B-3, C-54317, P5231-11B, U15/3.

E. *Aequitriradites verrucosus*, B-24, C-548332, P5231-26B, R38/3 (proximal surface in focus).

F. *Aequitriradites verrucosus*, B-24, C-548332, P5231-26B, R38/3 (distal surface in focus).

G. *Stereisporites antiquasporites*, B-31, C-548339, P5231-33b, M36/4.

H. *Antulisporites distaverrucosus*, B-3, C-548342, P5231-36B, GTA-B33b, J28/3.

I. *Baculatisporites comaumensis*, B-3, C-548317, P5231-11B, V12/2.

J. *Cicatricosisporites hughesii*, B-48, C-548357, P5231-51B.

K. *Ruffordiaspora australiensis*, B-41, C-548350, P5231-44B (proximal surface in focus).

L. *Ruffordiaspora australiensis*, B-41, C-548350, P5231-44B (distal surface in focus).

M. *Dictyophyllidites harrisii*, B-33b, C-548342, P5231-36B, N21/4.

N. *Gleicheniidites senonicus*, B-3, C-548317, P5231-11B, R12/2.

O. *Cicatricosisporites pseudotripartitus*, B-36, C-548345, P5231-39B, no England finder coordinates.

P. *Ruffordiaspora australiensis*, B-11, C-548219, P5231-13B, no England finder coordinates.

Q. *Trilobosporites*, B-9, C-548317, P5231-11B, no England Finder coordinates.

R. *Ischyosporites disjuncta*, B-3, C-548317, P5231-11B, V9/3.

S. *Punctatisporites scabratus*, B-33b, C-548342, P5231-36B, no England Finder coordinates.

T. *Punctatisporites scabratus*, B-19, C-548327, P5231-21B, no England Finder coordinates.

Figure 6. (colour online) Q- and R-mode cluster analysis of relative abundance data and Non-Metric Multidimensional Scaling (NMDS) bi-plot of square root transformed relative

abundance data of palynomorphs with affinities to plant order (with exceptions explained in the text), algae and protists (*Tasmanites*, *Pediastrum*, *Pterospermella* and undifferentiated dinocysts), acritarchs (*Veryhachium*, *Micrhystridium*), and other NPP (*Sigmopollis* and *Chomotriletes*) preserved in preparations of Isachsen Formation samples collected from Glacier Fiord. Pie charts are colour coded to show the proportion of Q-mode clusters A-D in the samples of the Paterson Island, Rondon, and Walker Island members of the Isachsen Formation. Taxa in each order are shown in Suppl. 3

Figure 7. (colour online) Stratigraphic diagram of the relative abundance of taxa at the order level composing each cluster determined from Q-mode cluster analysis (Fig. 6; Suppl. 3). Stratigraphically constrained incremental sum of squares cluster analysis (CONISS; Grimm, 1987) of square root transformed relative abundance of palynomorphs at the order level is used in conjunction with visual inspection to delineate informal palynomorph stratigraphic zones for each section (zones 1–4) (2 column formatting). Dinocysts and NPP are not included in the CONISS

Figure 8. (colour online). Summary diagram showing the relative abundance of spores, pollen, and non-pollen palynomorphs (NPP), stratigraphic palynological zones delineated using CONISS (see Fig. 7), palynological events, HALIP events, and inferred paleoclimate during deposition of the Isachsen Formation. References for HALIP ages are (1) Evenchick et al. (2015); (2) Dockman et al. (2018). References for volcanic flows in text

Table 1. Samples analyzed for quantitative and qualitative palynology from Isachsen Formation, Glacier Fiord, Axel Heiberg Island

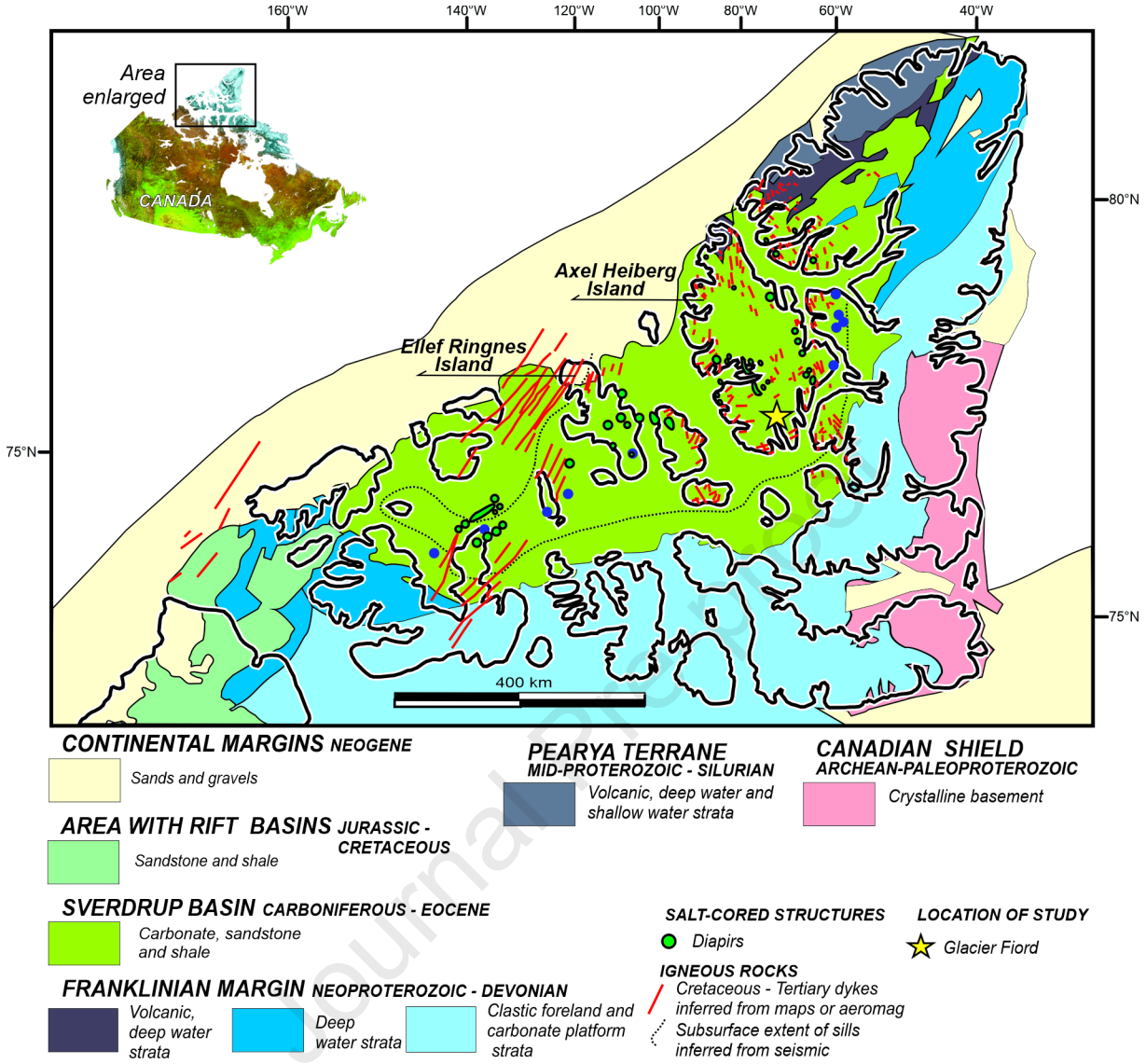
Lithostratigraphy	Sample name[a]	Meters above base of Isachsen Formation[b]	C-number[c]	P-number[d]	NUPB loan number[e]
Walker Island Member	2011-GTA-B-56	484	C-548365	P-523159[g]	NUPB 831
	2011-GTA-B-55	478	C-548364	P-523158[g]	NUPB 832
	2011-GTA-B-54	473	C-548363	P-523157[g]	NUPB 833
	2011-GTA-B-53	464	C-548362	P-523156[g]	NUPB 834
	2011-GTA-B-52	441.5	C-548361	P-523155[g]	NUPB 835
	2011-GTA-B-51	418.5	C-548360	P-523154[g]	NUPB 836
	2011-GTA-B-50	416	C-548359	P-523153[g]	NUPB 837
	2011-GTA-B-57	410	C-495034	P-523160[g]	NUPB 838
	2011-GTA-B-49	402	C-548358	P-523152[g]	NUPB 839
	2011-GTA-B-48	384	C-548357	P-523151[g]	NUPB 840
	2011-GTA-B-47	375.5	C-548356	P-523150[g]	NUPB 841
	2011-GTA-B-46	373	C-548355	P-523149[g]	NUPB 842
	2011-GTA-B-45	363	C-548354	P-523148[g]	NUPB 843
	2011-GTA-B-44	351	C-548353	P-523147[g]	NUPB 844
	2011-GTA-B-43	345	C-548352	P-523146[f]	NUPB 845
	2011-GTA-B-42	344	C-548351	P-523145[g]	NUPB 846
	2011-GTA-B-41	331.5	C-548350	P-523144[g]	NUPB 847
	2011-GTA-B-40	329	C-548349	P-523143[g]	NUPB 848
	2011-GTA-B-39	324.5	C-548348	P-523142[g]	NUPB 849
Rondon Member	2011-GTA-B-38	303.5	C-548347	P-523141[g]	NUPB 850
	2011-GTA-B-37	299.5	C-548346	P-523140[g]	NUPB 851
	2011-GTA-B-36	298	C-548345	P-523139[g]	NUPB 852
	2011-GTA-B-35	291	C-548344	P-523138[g]	NUPB 853
Paterson Island Member	2011-GTA-B-34	278.5	C-548343	P-523137[g]	NUPB 854
	2011-GTA-B-33b	275.5	C-548346	P-523136[f]	NUPB 855
	2011-GTA-B-33a	268.7	C-548341	P-523135[g]	NUPB 856
	2011-GTA-B-32	266.5	C-548340	P-523134[f]	NUPB 857
	2011-GTA-B-31	255.5	C-548339	P-523133[g]	NUPB 858
	2011-GTA-B-30	222	C-548338	P-523132[f]	NUPB 859
	2011-BTA-B-29	221	C-548337	P-523131[f]	NUPB 860
	2011-GTA-B-28	212.7	C-548336	P-523130[f]	NUPB 861
	2011-GTA-B-27	244.5	C-548335	P-523129[g]	NUPB 862
	2011-GTA-B-26	243	C-548334	P-523128[g]	NUPB 863
	2011-GTA-B-25	241.5	C-548333	P-523127[g]	NUPB 864
	2011-GTA-B-24	240	C-548332	P-523126[g]	NUPB 865
	2011-GTA-B-11	112	C-548319	P-523113	NUPB 866
	2011-GTA-B-9	74.5	C-548317	P-523111	NUPB 867
	2011-GTA-B-1	5	C-548309	P-523103	NUPB 868

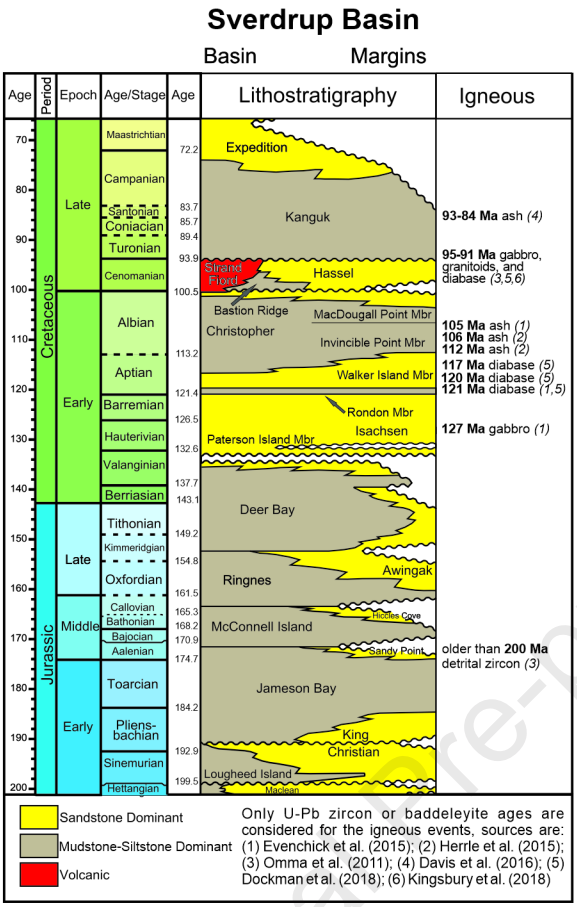
[a]GSC code for Jennifer Galloway is GTA; [b]0 m is base formational contact with underlying Deer Bay Formation; [c]GSC Palynology Laboratory Preparation Number; [d]GSC Curation Number; [e]Nunavut Curation Number, Canadian Museum of Nature Registration Number NL2020-001 on loan from 05/03/2020 to 31/03/2021;[f]qualitatively analyzed for dinocysts (+45 µm size fraction) but not included in quantitative analyses of terrestrial pollen and spores; [g]qualitatively analyzed for dinocyst identification and included in quantitative analyses of terrestrial pollen and spores

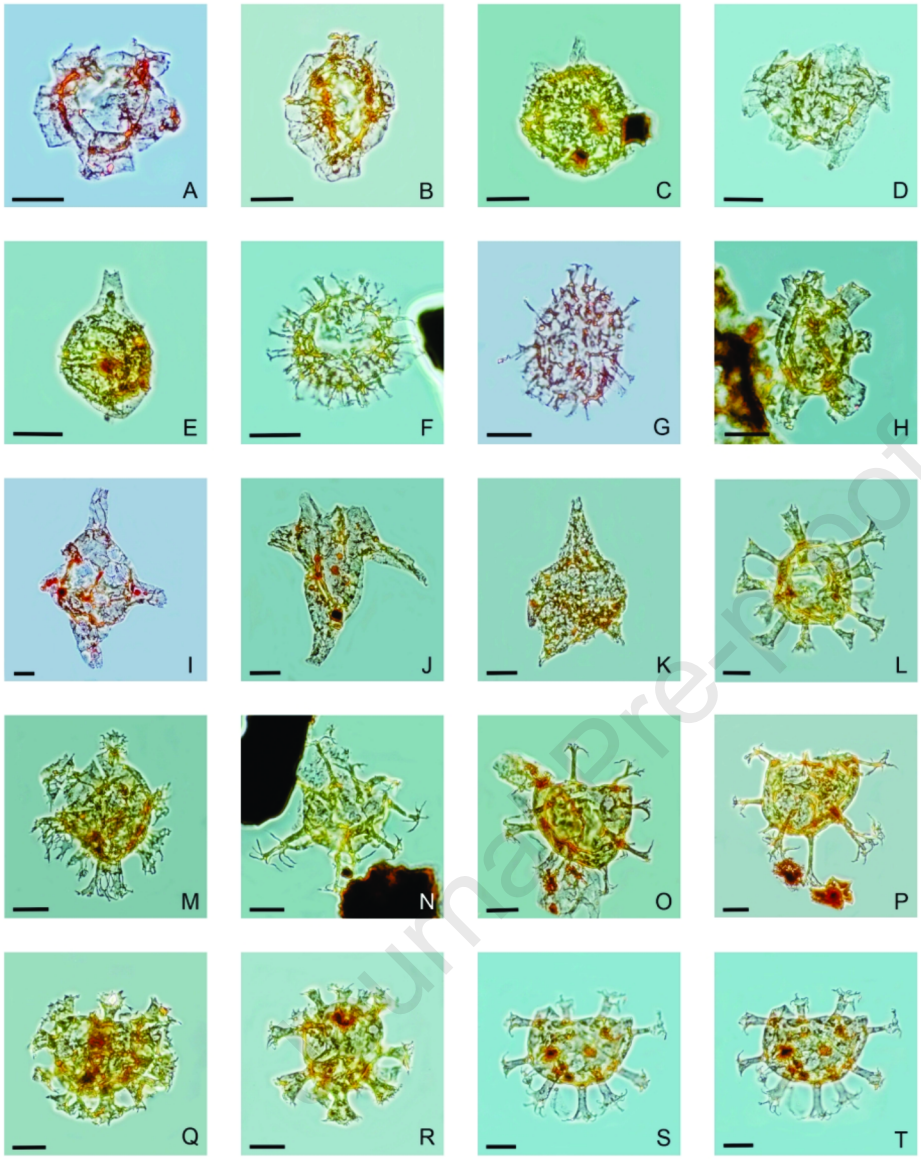
Table 2: Age information of the dinocyst taxa identified in the Rondon Member of the Isachsen Formation at Glacier Fiord

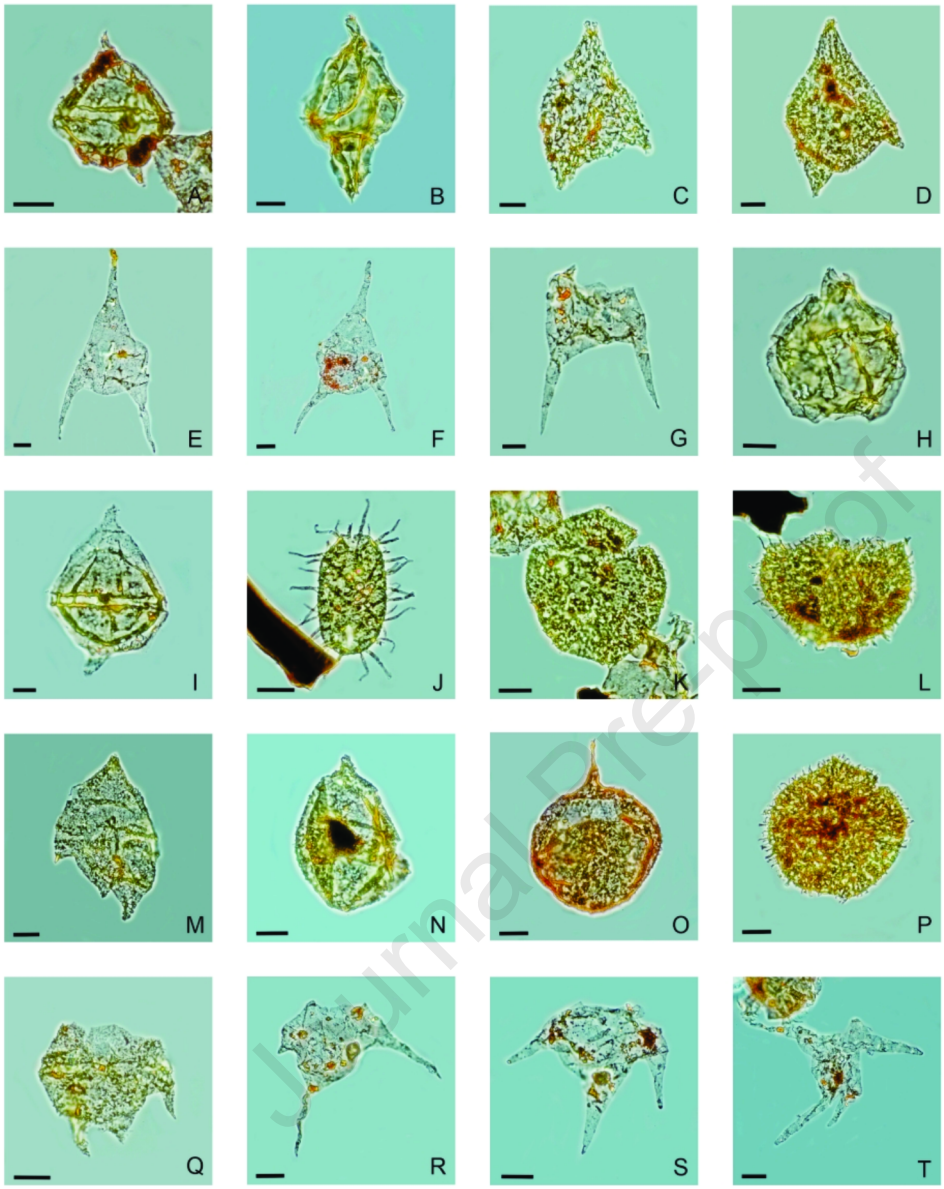
Taxon[a]	Age
Batioladinium daviesii	Type is late Valanginian
Callaiosphaeridium	*Callaiosphaeridium asymmetricum* ranges from early Hauterivian to early Campanian according to Costa and Davey (1992); and early Hauterivian to late Campanian according to Stover et al. (1996).
Catastomocystis	The type *Catastomocystis spinosa* is early Cenomanian.
Chlamydophorella trabeculosa	Early Hauterivian to late Aptian according to Costa and Davey (1992) and Stover et al (1996).
Kiokansium unituberculatum	LO[b] is late Cenomanian according to Costa and Davey (1992).
Kleithriasphaeridium cooksoniae	Type is late Albian. Range is early Aptian to top Cenomanian according to Stover et al. (1996).
Muderongia crucis	*Muderongia crucis*/*tetracantha* LO plotted as early Barremian by Costa and Davey (1992). Range of *Muderongia tetracantha* is early Valanginian to early Barremian according to Stover et al. (1996).
Nyktericysta and *Vesperopsis*	The range of *Vesperopsis* spp. is recorded as late Barremian to early Cenomanian by Stover et al. (1996). LO of *Nyktericysta tripenta* recorded as late Albian by Fensome et al. (2008).
Oligosphaeridium albertense	LO is early Cenomanian according to Costa and Davey (1992).
Oligosphaeridium diluculum	FO[c] is plotted as Ryazanian in Costa and Davey (1992) and questionable from early Valanginian upwards.
Pseudoceratium pelliferum	Range is late Ryazanian to top Barremian according to Costa and Davey (1992); and late Ryazanian to early Aptian in Stover et al. (1996).
Sirmiodinium grossii	Tentatively goes into early Aptian according to Costa and Davey (1992). LO plotted as early Aptian in Stover et al (1996).
Tanyosphaeridium xanthiopyxides	The possibly synonymous species *Tanyosphaeridium variecalamum* was plotted as Valanginian to Maastrichtian in Stover et al. (1996).
Tenua hystrix	Based on discussion in Fensome et al (2019a), this species ranges from Berriasian to Maastrichtian.
Tenua scabrosa	According to Fensome et al. (2019a), the provisional range of this species is late Hauterivian to Cenomanian.

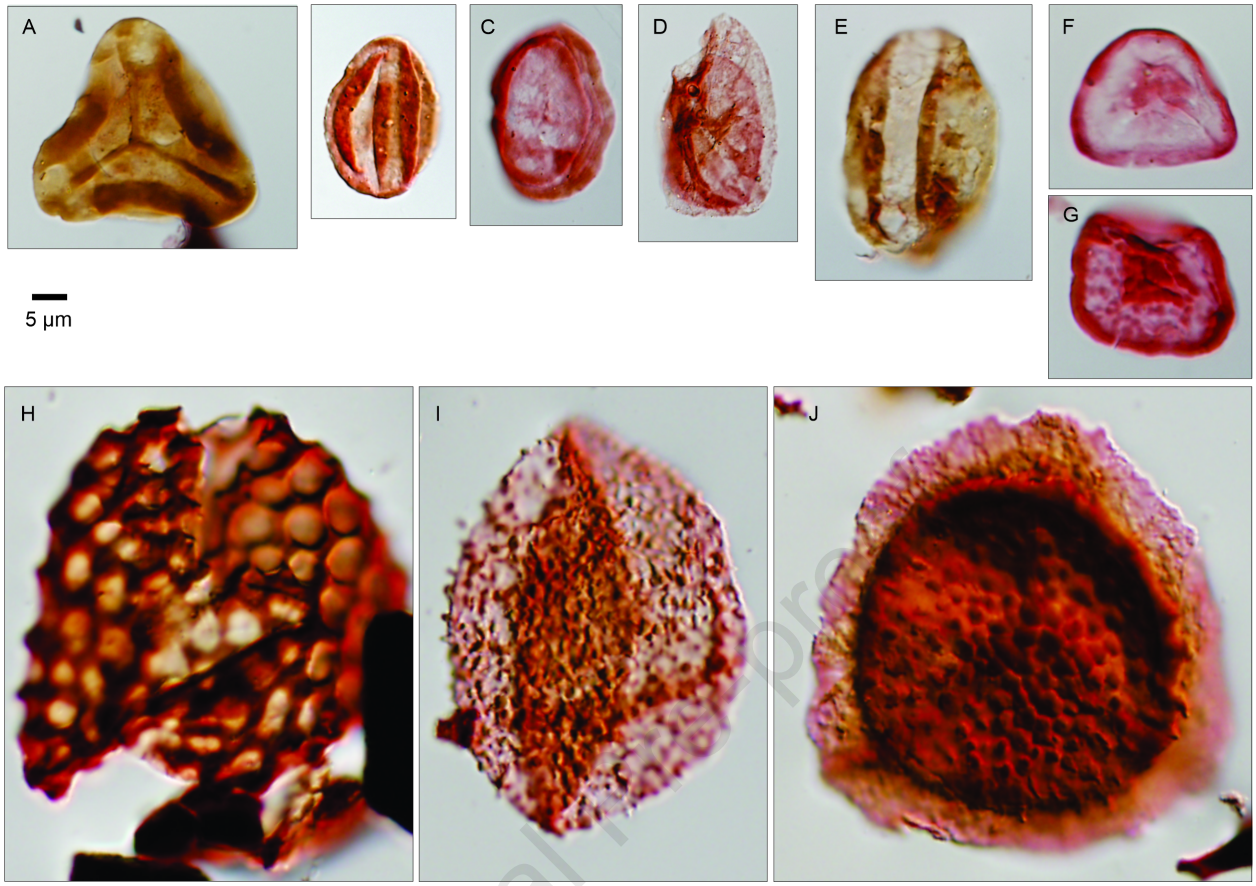
[a]see Appendix A for taxonomic authority; [b]LO-last occurrence; [c]FO-first occurrence

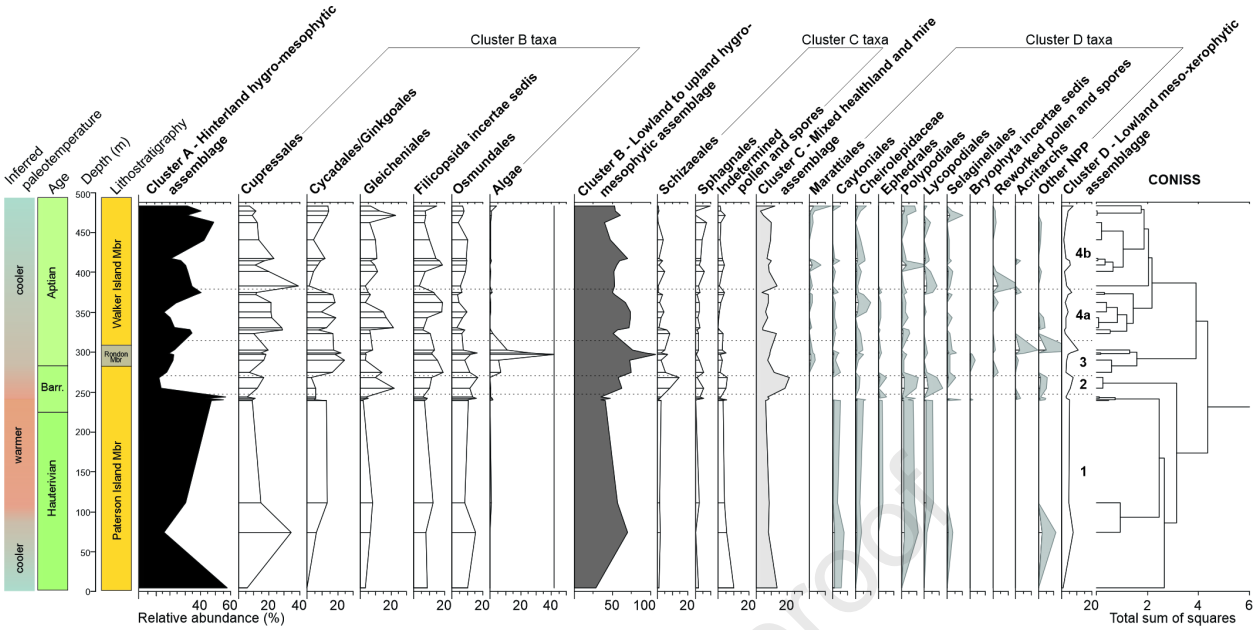


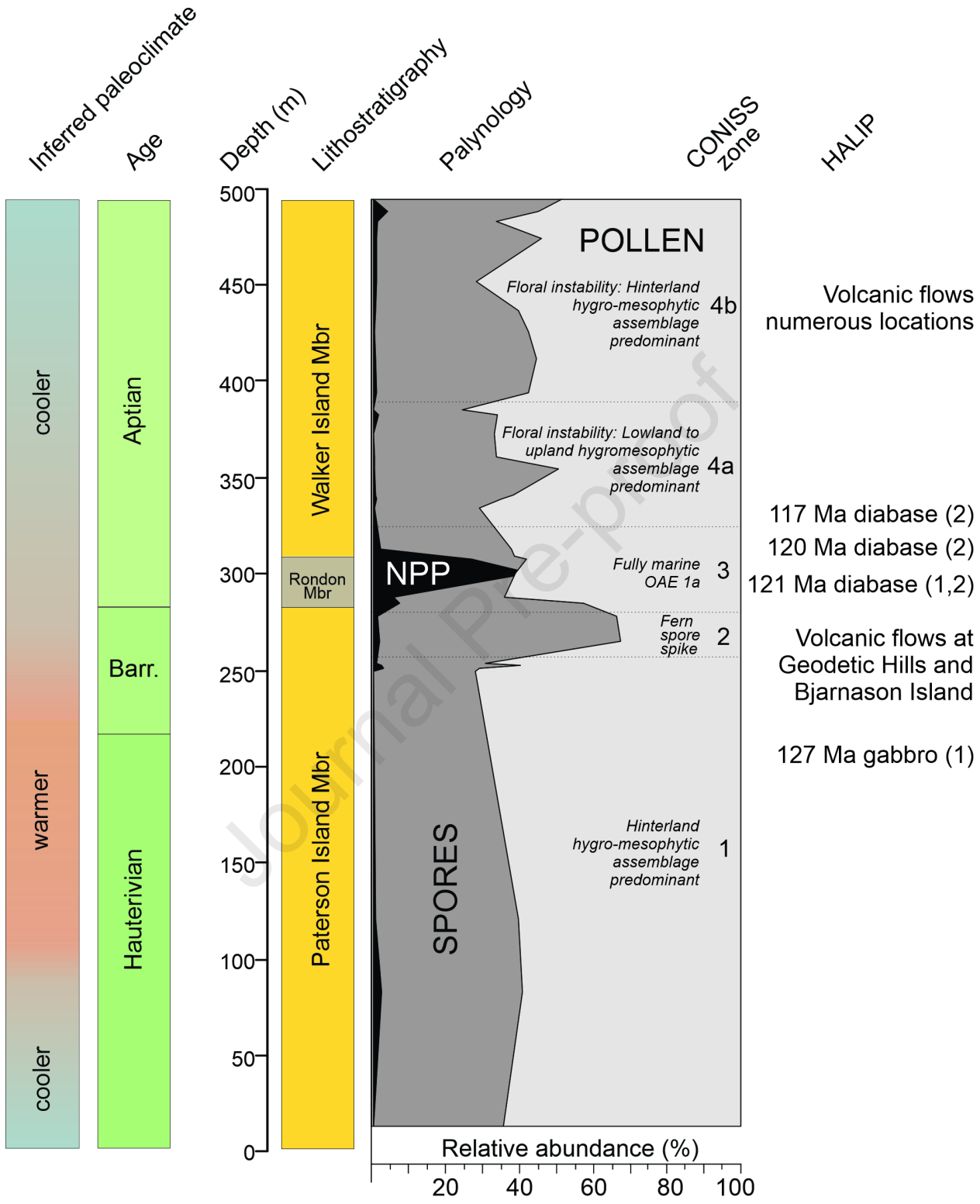


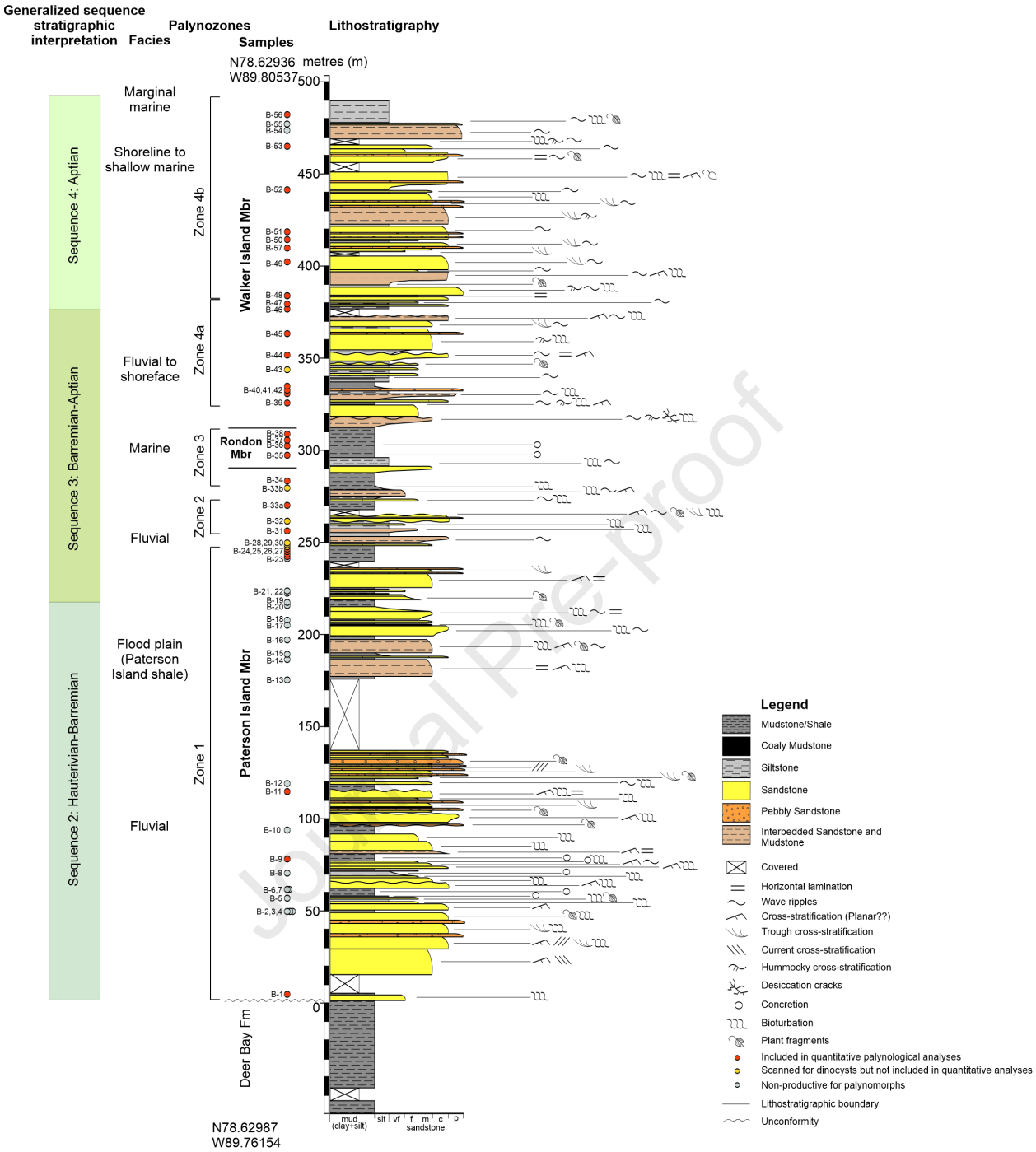












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June 07, 2020

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Dear Editor,

Please find enclosed a manuscript submitted for consideration of publication in *Cretaceous Research* by Galloway et al. entitled:

High Arctic Large Igneous Province Impacts on Arctic forests during the Hauterivian to early Aptian

All work in this manuscript represents original contributions that are not being considered for publication elsewhere. All previously published work cited in this manuscript is acknowledged. Each co-author of this manuscript has contributed substantially to this work and approve of its final submission to *Cretaceous Research*.

We declare no conflict of interest.

Our CRediT author statement is as follows **Galloway:** conceptualization, methodology, formal analysis, investigation, resources, data curation, writing-original draft preparation, project administration, visualization, project administration, funding acquisition **Fensome:** methodology, formal analysis, investigation, data curation, writing-original draft preparation, visualization **Swindles:** methodology, formal analysis, writing-review and editing **Hadlari:** methodology, investigation, formal analysis, writing-original draft preparation **Fath:** investigation, data curation, writing-review and editing **Schröder-Adams:** conceptualization, methodology, investigation, funding acquisition, writing-review and editing **Herrle:** conceptualization methodology, investigation, funding acquisition, writing-review and editing **Pugh:** investigation, writing-review and editing

Sincerely,

Jennifer Galloway