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4 **Early Cretaceous vegetation and climate change at high latitude: palynological evidence from**
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6 **Isachsen Formation, Arctic Canada**
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4 **Abstract**
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6 Quantitative palynology of the marginal marine and deltaic-fluvial Isachsen Formation of the
7 Sverdrup Basin, Canadian Arctic, provides insight into high latitude climate during much of the
8 Early Cretaceous (Valanginian to early Aptian). Detrended correspondence analysis of main
9 pollen and spore taxa is used to derive three ecological groupings influenced by moisture and
10 disturbance based on the botanical affinities of palynomorphs: 1) a mixed coniferous assemblage
11 containing both lowland and upland components; 2) a conifer-filicopsid community that likely
12 grew in dynamic lowland habitats; and, 3) a mature dry lowland community composed of
13 Cheirolepidaceans. Stratigraphic changes in the relative abundance of pollen and spore taxa
14 reflect climate variability in this polar region during the ~20 Mya history of the Isachsen
15 Formation. The late Valanginian was relatively cool and moist and promoted lowland conifer-
16 filicopsid communities. Warming in the Hauterivian resulted in the expansion coniferous
17 communities in well-drained or arid hinterlands. A return to relatively cool and moist conditions
18 in the Barremian resulted in the expansion of mixed lowland communities. This work
19 demonstrates the utility of a multivariate statistical approach to palynology to provide insight
20 into the composition and dynamics of ecosystems and climate of high latitude regions during the
21 Early Cretaceous.
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48 **Keywords**
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50 Isachsen Formation; Sverdrup Basin; Cretaceous; Canada, Arctic; Palynology
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1.0 Introduction

Understanding the behaviour of global climate during relatively warm periods in Earth's history, such as the Cretaceous Period, advances our overall understanding of the climate system and provides insight on drivers of climate change over geologic time. It has been suggested that the Valanginian Age (~139 Ma to 134 Ma; Gradstein et al., 2012) represents the first episode of Cretaceous greenhouse climate conditions with high atmosphere pCO₂ levels and stable, relatively equable warm temperatures that persisted through the Hauterivian and beyond (Lini et al., 1992; Littler et al., 2011). Early Cretaceous greenhouse conditions have been related to Valanginian carbonate platform drowning (Föllmi et al., 1994) and the Paraná-Etendeka continental flood basalts that may have been a source of CO₂ (Channell et al., 1995; Courtillot et al., 1999; Erba et al., 2004). However, the greenhouse hypothesis for the Early Cretaceous (Lini et al., 1992) has been recently questioned (McArthur et al., 2004; Gröcke et al., 2005) and data to support cool climate conditions during the Valanginian have been revisited (Kemper, 1983, 1987; Frakes et al., 1994; Ditchfield, 1997; Podlaha et al., 1998) and are emerging (Price et al., 2000; Alley and Frakes, 2003; Erba et al., 2004; McArthur et al., 2004, 2007; Gröcke et al., 2005; Price and Mutterlose, 2004; Kessels et al., 2006; Price and Bassey, 2013;), with some exceptions (Littler et al., 2011). For example, nannofossil evidence from Europe suggest that the late Valanginian to early Hauterivian interval was cool (Mutterlose and Kessels, 2000; Mutterlose et al., 2003; Kessels et al., 2006). Ditchfield et al. (1997) analyzed belemnites from Spitsbergen and document high $\delta^{18}\text{O}_{\text{carb}}$ values (low paleotemperatures) for the lower to middle Valanginian and suggest the presence of high latitude ice. Price and Mutterlose (2004), Price and Nunn (2010), and Price and Bassey (2013) use oxygen and carbon isotope data from Valanginian

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4 glendonites and belemnites preserved in polar regions to reconstruct paleotemperatures
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6 consistent with transient glacial conditions. The abundance of ice-rafted debris decreases from
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8 the Berriasian/Valanginian into the Hauterivian (Kemper, 1987; Frakes, 1992) and glendonites,
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10 pseudomorphs after ikaite thought to form in cold sub-aqueous depositional conditions (Kemper,
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12 1987; Frakes and Francis, 1988; Price, 1999), are abundant and widespread in Valanginian strata
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14 from the Sverdrup Basin (Kemper and Jeletzky, 1979; Kemper 1983, 1987; Selmeier and
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16 Grosser, 2011), Spitsbergen (Kemper, 1983; Rogov and Zakharov, 2010; Price and Nunn, 2010),
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18 Siberia (Kaplan, 1978; Rogov and Zakharov, 2010), and northern Alaska (Tarduno et al., 2002),
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20 before becoming rare until the latest Aptian (Kemper, 1983, 1987; Schröder-Adams et al., 2014).
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McArthur et al. (2004) reconstructed changes in seawater temperature from isotopic and chemical signatures of belemnites preserved in Lower Cretaceous strata of East Yorkshire, Northern England, near the confluence of the Tethyan and Boreal realms. They document warming at the base of the Hauterivian to peak temperatures in the middle Hauterivan followed by a decline that persisted into the basal Barremian. This mounting body of evidence suggest that the Valanginian was cool and that a period of warming occurred during the Hauterivian.

Although recent advances in understanding of Early Cretaceous climate change have shed light on the nature and drivers of variability, paleoclimate is less understood in polar regions compared to mid- to low-latitudes (e.g., Pucéat et al., 2003; Price and Mutterlose, 2004; Price and Nunn, 2010) and this is particularly true for the Canadian Arctic (Hopkins, 1971, 1974; Embry, 1985a; Harland et al., 2007; Selmeier and Grosser, 2011; Galloway et al., 2012, 2013; Schröder-Adams et al., 2014). There is a paucity of data overall for the terrestrial realm as most paleoclimate studies have been based on marine material (Spicer and Parrish, 1986; Gröcke et al., 2005; Harland et al., 2007; Selmeier and Grosser, 2011; Galloway et al., 2012, 2013). These

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4 few studies suggest that a diversity of coniferous trees occurred in Early Cretaceous high
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6 northern latitude forest communities despite long dark winters and summers with continuous
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8 sunlight. Polar forests potentially promoted climate feedback effects at regional to global scales
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10 through albedo, land surface heat budget, hydrological and carbon cycles (Foley et al., 1994;
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12 DeConto et al., 2000; Beringer et al., 2005) and are therefore important to include in global
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14 climate modelling (Harland et al., 2007). Constraining the long-term vegetation and climate
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16 history of polar regions, especially during extreme warm but variable periods such as the Early
17
18 Cretaceous, offers a possible analogue for a much warmer future Earth.
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24 In this study we analyze fossil pollen and spores preserved in the Isachsen Formation
25
26 exposed on Ellef Ringnes Island, Sverdrup Basin (Figures 1, 2), to reconstruct high northern
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28 latitude climate and terrestrial ecosystem dynamics during the Early Cretaceous.
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33 **2.0 Geologic setting**

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38 Sverdrup Basin is a 1300 km by 350 km sedimentary basin that underlies the northern
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40 part of the Canadian Arctic Archipelago (Figure 1). The basin began its history with rifting in the
41
42 Carboniferous to Early Permian, followed by a period of thermal subsidence with episodic uplift
43
44 of basin margins that lasted into the Cretaceous (Embry and Beauchamp, 2008). Subsidence rate
45
46 greatly increased in the Early Cretaceous when basaltic volcanism and widespread emplacement
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48 of diabase dykes and sills occurred (Balkwill, 1978; Stephenson et al., 1987; Embry and
49
50 Beauchamp, 2008). The basin then underwent slow subsidence for much of the Late Cretaceous.
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52 Sverdrup Basin strata are deformed by structures that developed during episodic flow of
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54 Carboniferous evaporites during the Mesozoic (Figure 1; Balkwill, 1978; Boutelier et al., 2010;
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4 Galloway et al., 2013), by Hauterivian to Cenomanian magmatism and faulting (Embry and
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6 Osadetz, 1988; Embry, 1991), and by the Eurekan Orogeny (Eocene), which produced high
7
8 amplitude folds and thrust faults in the northeast basin and gentler folds to the west (Harrison et
9
10 al., 1999).

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14 The age of Mesozoic strata in Sverdrup Basin are based primarily on ammonites,
15
16 bivalves, dinoflagellate cysts and foraminifera (Table 1) but paleoclimate studies using pollen
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18 and other climate indicators in the Early Cretaceous of the Canadian Arctic are limited (Table 1;
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20 Hopkins, 1971, 1974; Wall, 1983; Embry, 1985a; Harland et al., 2007; Selmeier and Grosser,
21
22 2011; Galloway et al., 2012, 2013; Schröder-Adams et al., 2014).

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26 Ellef Ringnes Island is located near the axis of the Sverdrup Basin in the Canadian Arctic
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28 Archipelago and was situated between paleolatitudes $74 \pm 2^\circ$ (standard error) and $79 \pm 1^\circ$ in the
29
30 Early Cretaceous (Wynne et al. 1988; Figures 1,2).

31 32 33 34 35 36 2.1 Isachsen Formation

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41 The Isachsen Formation was first described by Heywood (1957) on Ellef Ringnes Island
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43 for a succession of arenaceous strata between two shale-siltstone units (Deer Bay and
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45 Christopher formations) (Figures 1, 2). The Isachsen Formation is widespread throughout
46
47 Sverdrup Basin, ranging in thickness from ~120 m at basin margins to 1370 m on western Axel
48
49 Heiberg Island (Hopkins, 1971).

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53 Sediments of the Isachsen Formation were deposited in marginal marine/deltaic and
54
55 fluvial environments during the development of the Amerasia Basin (Embry and Dixon, 1990;
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57 Tullius et al., 2014), synchronous with volcanism related to its opening (Embry and Osadetz,
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4 1988; Grantz et al., 2011). The Isachsen Formation is divided into three members (Embry,
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6 1985a). The Paterson Island Member overlies Deer Bay Formation or Mackenzie King
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8 Formation with unconformable contact at basin margins and conformable contact in basin centre.
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10 The Paterson Island member consists of fine to very coarse-grained sandstone with interbeds of
11
12 carbonaceous siltstone, mudstone, coal, and volcanic and volcanoclastic/tuffaceous rocks (Embry
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14 and Osadetz, 1988; Evenchick and Embry, 2012a, b). Sandstone units are up to 35 m thick and
15
16 argillaceous intervals between 2 and 10 m thick occur in the 152 m thick type section in the
17
18 Skybattle Bay C-15 oil and gas well (77°14'N, 105°05'W) (Embry, 1985a). Lowermost
19
20 sandstones of the Paterson Island Member exposed on Ellef Ringnes Island contain interbedded
21
22 mudstone and are bioturbated, reflecting deposition in a marginal marine setting (Embry 1985a;
23
24 Tullius et al., 2014). Shallowing and a northward progradation of paleoshoreline resulted in
25
26 deposition of cross-bedded, fluvial sandstones. These sandstones grade upward into finer-grained
27
28 non-marine deposits consisting of fining-upward sandstones interbedded with siltstone,
29
30 mudstone, and coal deposited in a delta plain setting with overbank and channel environments
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32 (Figure 3; Embry 1985a; Tullius et al., 2014). The Paterson Island Member is conformably
33
34 overlain by interbedded medium to dark-grey mudstone and siltstone of the Rondon Member that
35
36 were deposited in a marine shelf setting (Embry 1985a; Nøhr-Hansen and McIntyre, 1998;
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38 Tullius et al., 2014). The type section in the Skybattle C-15 well is 47 m thick (Embry, 1985a).
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40 The Rondon Member is conformably overlain by interbedded fine to coarse-grained sandstone,
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42 siltstone, and mudstone with minor coal of the Walker Island Member. The type section of the
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44 Walker Island Member in the Skybattle C-15 oil and gas well is 140 m thick (Embry, 1985a).
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46 The Walker Island Member on Ellef Ringnes Island is composed of marginal marine, bioturbated
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48 sandstones and fluvial sandstones with mud-drapes indicating tidal influence and inferred to have
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4 been deposited in a delta front to delta plain environment (Embry 1985a; Tullius et al., 2014).
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6 Walker Island Member is conformably overlain by mudstones and fine-grained sandstones of the
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8 Christopher Formation.
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10 11 12 13 14 2.1.1. Biostratigraphy and paleoclimate 15 16 17 18

19 Initial palynological research on Isachsen Formation by Hopkins (1971) qualitatively
20
21 describes palynoflora preserved in samples collected from the bottom of seismic shot hole
22
23 samples on northwest Melville Island. A stable temperate climate was inferred (Hopkins, 1971).
24
25 Galloway et al. (2013) quantitatively examined seven well-cuttings samples from Isachsen
26
27 Formation for pollen and spores as part of a longer stratigraphic succession preserved in the
28
29 Hoodoo Dome H-37 oil and gas well drilled on southern Ellef Ringnes Island. They suggest that
30
31 the development of humid and cool high-latitude paleoclimate conditions caused a vegetation
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33 shift in the late Valanginian or early Hauterivian. Sedimentological and preliminary
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35 palynological analyses of four samples from the Isachsen Formation exposed on Ellef Ringnes
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37 Island (and revisited here) are presented by Tullius et al. (2014). Flora (e.g., bisaccate and
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39 Cupressaceae-Taxaceae pollen) representative of the relatively cool and moist post-late
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41 Valanginian/early Hauterivian climate shift described by Galloway et al. (2013) are abundant.
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48 There is limited fossil evidence for age control from the Isachsen Formation (Table 1).
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50 The age of the underlying Deer Bay Formation ranges from Tithonian to Valanginian (Table 1).
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52 The age of overlying marine mudstones of the Christopher Formation ranges from Aptian to
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54 Albian based on marine macrofossils, foraminifera, and pollen and spores preserved in material
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56 from various localities (Table 1). The lower 30 m of the Isachsen Formation on Ellef Ringnes
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4 contains *Buchia* cf. *B. bulloides* (Lahusen) and “*Buchia* cf. *B. terebratuloides* (Lahusen)”
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6 (reported by Heywood, 1957; Stott, 1969, but probably *Buchia crassicolis* (Keyserling) as re-
7
8 interpreted by Jeletkzy (1973) that are dated as late Valanginian). Late Valanginian bivalves
9
10 have also been reported in the basal Isachsen Formation rocks on nearby Amund Ringnes Island
11
12 (Balkwill, 1983). Palynology of un-subdivided Isachsen Formation on Banks, Prince Patrick, and
13
14 Melville islands suggest a Valanginian to Aptian age for the formation (Hopkins, 1971; Plauchut
15
16 and Jutard, 1976; Dorenkmap et al., 1976). Pelecypods preserved in Paterson Island Member
17
18 from an unknown locality suggest a Valanginian to Barremian age for this lower unit of the
19
20 Isachsen Formation (Balkwill, 1983). Dinoflagellate cysts preserved in the Rondon Member of
21
22 Isachsen Formation exposed at Glacier Fiord and at Buchanan Lake, Axel Heiberg Island, and
23
24 from south Sabine Peninsula on Melville Island suggest a Barremian age for this marine unit
25
26 (Costa, 1984; McIntyre, 1984; McIntyre pers. comm. 1984 in Embry, 1985a, 1991; Nøhr-Hansen
27
28 and McIntyre, 1998). Based on the age of the Rondon Member and overlying Christopher
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30 Formation, the age of the Walker Island Member is inferred to be Barremian to Aptian in age
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32 (Embry, 1985a).
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43 **3.0 Material and methods**

44 45 46 47 48 **3.1 Samples**

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53 Eighteen organic-rich samples from three measured and described outcrop sections of
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55 Isachsen Formation were collected in 2010 and 2011 from Ellef Ringnes Island and analyzed for
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57 pollen and spores (Table 2; Figures 2, 4). All microscope slides are stored at the Geological
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4 Survey of Canada, Calgary, Alberta, on loan from the Geological Survey of Canada, Ottawa.
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6 Curation, preparation, and specimen numbers are shown in Table 2 and Figure 6.
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19 Palynological data from four samples reported in Tullius et al. (2014) are built upon here
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21 by further inspection of material to achieve minimum pollen and spore counts of 300. Detailed
22
23 sedimentological descriptions and interpretation of the three sections are presented in Tullius et
24
25 al. (2014). Geographical locations of samples analyzed for palynology are shown in Figures 2
26
27 and 4. Where coordinates were unavailable (samples IS-734, IS-761, IS-1107, DS2-638),
28
29 locations are estimated. Lithological logs and the stratigraphic positions of samples are shown in
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31 Figure 5.
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36 The IS-01 Section captures the Deer Bay to Isachsen formational contact as well as the
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38 Isachsen to Christopher contact and is cut by several dip-slip faults that offset strata (Figures 4,
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40 5; Evenchick and Embry, 2012a). Uncertainties in the magnitude of displacement and correlation
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42 of marker horizons across the faults result in uncertainties in the true stratigraphic positions of
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44 samples between 1000 m and 1500 m (from base of the section). The fault at ~1480 m cuts out at
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46 least 100 m of the upper Paterson Island Member, all of the Rondon Member, and base of the
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48 Walker Island Member (Figure 4). Eight samples of organic-rich material were examined
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50 palynologically from the Paterson Island Member exposed in section IS-01 (Table 2).
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56 Ten samples from Isachsen Formation were examined from the DS-02 Section (Figures
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58 4, 5). This section begins in the Paterson Island Member and extends to the Isachsen-Christopher
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60 formation boundary. This section is on the gently folded to monoclinial flank of an anticline and
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4 does not appear to be cut by faults (Evenchick and Embry, 2012a). Five samples from the
5
6 Paterson Island Member, including three samples from the laterally traceable floodplain-
7
8 meandering stream facies (Figures 3, 5), were analyzed for pollen and spores. One sample was
9
10 analyzed from the Rondon Member and four samples were analyzed from the Walker Island
11
12 Member (Table 2).
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16 Four samples from Isachsen Formation were analyzed from the DS-03 Section (Figures
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18 4, 5; Table 2). This section is in fault contact with diapiric evaporates (Evenchik and Embry,
19
20 2012a) and extends to the boundary with the Christopher Formation. The sample lowest in this
21
22 stratigraphic succession (DS3-23) is near the fault contact with the evaporites. This area is
23
24 structurally complex and the relationship of sample DS3-23 relative to the three overlying
25
26 samples is not known. The remainder of section Dumbbells West is structurally unremarkable
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28 but differentiation of member lithostratigraphy is not possible (Evenchick and Embry, 2012a).
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34 35 36 3.2 Palynological preparation, microscopy, and terminology 37 38 39

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41 Organic-rich samples collected from IS-02, DS-02, and DS-03 sections were prepared for
42
43 palynological analysis at the Geological Survey of Canada, Calgary, following standard
44
45 extraction techniques, including washing, acid digestion, oxidation with Schulze's solution, and
46
47 staining with Safranin O (Table 2). Slurries were mounted with polyvinyl and liquid bioplastic.
48
49 Observations were made using an Olympus BX61[®] transmitted light microscope with oil
50
51 immersion at 400x and 1000x magnification. Digital images were captured using an Olympus
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53 DP72 camera and Stream Motion[®] software. All microscope slides are stored in the registered
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55 collections of the Geological Survey of Canada. Statistical analyses of palynomorphs are based
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4 on counts of unsieved preparations with greater than 300 spores and pollen enumerated per
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6 sample (mean 339 ± 24 SD).
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9 Ancient monosulcate pollen are ascribed to a large variety of genera (Jansonius and Hills,
10 1976) even though modern pollen of the Ginkgoales, Cycadales, and Bennettitales are difficult to
11 differentiate using light microscopy (Samoilovich 1953 translation 1961, p. 36; Hill, 1990). We
12 assign ellipsoid monosulcate pollen where the single longitudinal furrow reaches almost to the
13 end of the pollen grain to the genus *Cycadopites* Wodehouse. This genus accommodates grains
14 with exines of various texture that have a single longitudinal furrow reaching almost to the end
15 where it gapes open, even when closed in the middle (Wodehouse, 1933; Jansonius et al., 1998).
16 The type species *C. follicularis* ranges in size from 39-42 μm long and 18-21 μm wide (Wilson
17 and Webster, 1946). We do not distinguish *Cycadopites* to the species level, as this is rarely
18 possible even with living material (Wodehouse, 1933). We distinguish larger monosulcate pollen
19 (~52 μm long x ~30 μm wide) as *Entylissa* Naumova 1939 ex Ishchenko 1952, an obligate senior
20 synonym of *Gingkocycadophytus* Samoilovich 1953. *Gingkocycadophytus*, and thus *Entylissa*,
21 accommodates pollen ranging in size from 33-85 μm long and 20-40 μm wide (with one
22 specimen (*Gingkocycadophytus* sp. Pl. 111, Fig. 4 Samoilovich 1953 translation 1961) with an
23 “extraordinary” dimension of 117 μm by 56 μm) with a single furrow extending the full length
24 of the grain. The furrow may be closed to fully open and occasionally edges overlap
25 (Samoilovich, 1953, translation 1961). Samoilovich (1953, translation 1961, p. 36)
26 acknowledges that the pollen *Gingkocycadophytus* does not have adequate morphologic
27 characteristics to assign the pollen type to the Ginkgoales or Cycadales and notes that this
28 generic name reflects the similarity of the described pollen to both classes. We differentiate the
29 genus *Perinopollenites* Couper 1958 from *Inaperturopollenites* and undifferentiated
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4 Cupressaceae-Taxaceae by the presence of a perinosaccus (Jansonius and Hills, 1976). We use
5
6 the genus name *Inaperturopollenites* Pflug & Thomson & Pflug 1953 to refer to pollen with a
7
8 spherical original shape and with a thin, infrapunctate exine with many secondary folds
9
10 (Jansonius and Hills, 1982). Spherical, infrapunctate pollen with an exine that tends to split along
11
12 a more or less radial line (e.g., *Taxodiaceapollenites* Kremp 1949 ex. Potonié 1958) are retained
13
14 in Cupressaceae-Taxaceae and not differentiated. Other pollen and spore types are also identified
15
16 to the lowest possible taxonomic level (Table 3).
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23 3.3 Multivariate statistics 24 25 26 27

28 The relative abundance of each taxon is based on a pollen and spore sum that includes
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30 palynomorphs with affinities to terrestrial land plants. Non-terrestrial palynomorphs, including
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32 dinoflagellate cysts, other algae, and acritarchs, are excluded from the pollen and spore sum and
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34 omitted from multivariate statistical analyses.
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38 We use two-way cluster analysis (Q- and R-mode) resulting in a cluster matrix to identify
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40 samples that cluster together based on palynomorph content to explore if palynoassemblages are
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42 unique to a section or part of a section (Q-mode) and to observe which pollen and spore taxa
43
44 group together (R-mode). Q-mode-defined sample clusters (SC) are shown on the lithological
45
46 sections to note which facies they occur in. Combined Q-and R-mode cluster analysis was
47
48 carried out using Ward's minimum variance method and relative Euclidean distance on relative
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50 abundance data using the computer program PC-ORD (Fishbein and Patterson, 1993; McCune
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52 and Mefford, 2006).
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4 Ordination techniques are commonly used in ecology and paleoecology to determine
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6 major gradients in taxa composition. These may be linked to environmental and ecological
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8 factors that control assemblage composition. In paleoecological data, ordination is a particularly
9
10 useful method because fossil assemblages may represent discrete communities, segments of
11
12 gradients in which taxa are distributed individualistically according to environmental
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14 preferences, and/or an association of community signatures transported and preserved in a
15
16 geologic deposit (Springer and Bambach, 1985; Bambach and Bennington, 1996; Bennington
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18 and Bambach, 1996; Holland et al., 2001; Bush and Balme, 2010). Spatial migration of
19
20 communities can also produce gradients in species composition in time-averaged geologic
21
22 deposits (Miller, 1988). Detrended Correspondence Analysis (DCA) is a technique that is
23
24 commonly used in ecological ordination because this method corrects for the arch/horseshoe
25
26 effects of Correspondence Analysis (Hill and Gauch, 1980). We performed DCA on the relative
27
28 abundance of taxa having an overall assemblage value of 0.5% or greater to reduce statistical
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30 noise (Stukins et al., 2013). In contrast, combined Q and R-mode cluster analysis was performed
31
32 using all palynomorph data. DCA was done using the Vegan package (v. 2.0-5) in R (v. 2.15.1),
33
34 with 26 segments and rescaling of axes with 4 iterations (Oksanen et al., 2012). We interpret
35
36 clusters of taxa observed in the DCA biplot to represent groups of parent plants with similar
37
38 ecologies that formed an ecological community (Stukins et al., 2013). Sample clusters defined by
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40 combined Q-and R-mode cluster analysis are also shown on the DCA biplot.
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50 Taxa preserved in samples from each of the three sections were graphed stratigraphically
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52 using the Tilia and TGView computer programs (Grimm, 1993-2001) to view changes over time
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54 at an assemblage scale. The relative abundance of plant types (Table 3) and cumulative
55
56 abundances of members of each of the four ecological groups delineated by DCA are also plotted
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4 stratigraphically to observe changes in plant communities over time. Stratigraphically
5
6 constrained cluster analysis using incremental sum of squares (CONISS; Grimm, 1987) was
7
8 applied to the relative abundance of all pollen and spores from obligately terrestrial plants to
9
10 delineate major changes in palynoassemblages over time.
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15 16 **4.0 Results** 17 18 19 20

21 Palynological preparations of samples collected from the three sections of Isachsen
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23 Formation contain numerous pollen and spores assigned to 58 taxa (Table 3; Figure 6).
24
25 Preservation ranges from exceptional to poor, except for sample IS-1030 that was barren.
26
27 Thermal alteration of palynomorphs was consistently low (TAI 1+ to 2; Pearson, 1984). Our
28
29 quantitative analyses are based on an average sample count of 339 ± 24 SD (n=22 samples)
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31 pollen and spores with affinities to obligately terrestrial plants.
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38 4.1. Descriptive palynology 39 40 41 42

43 Palynoassemblages preserved in Isachsen Formation samples from sections IS-01, DS-
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45 02, and DS-03 are dominated by pollen from gymnosperms (Table 3; Figure 7). Pollen
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47 attributable to plants belonging to Class Pinopsida compose, on average, 74.34% (± 9.56 SD,
48
49 n=22) of the total pollen and spore sum of each sample. Cupressaceae-Taxaceae (mean 33.93% \pm
50
51 14.24 SD) and undifferentiated bisaccate (mean 31.63% ± 14.61 SD) pollen make up the
52
53 majority of Pinophytes the samples. Pollen attributable to Division Pteridospermopsida represent
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55 a minor component (mean <1%). Pollen attributable to plants belonging to Divisions
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4 Cycadophyta/Gingkoephyta represent a mean of $4.04\% \pm 1.83$ SD of the total pollen and spore
5
6 sum of the samples while *Eucommidites troedsonii* pollen, the only taxon identified attributable
7
8 to Division Gnetophyta (Tekleva et al., 2006), comprises a mean of $<1\%$ of the pollen and spore
9
10 population of the samples. Filicopsids are the next most common group (mean $17.79\% \pm 8.70$
11
12 SD). *Gleicheniidites senonicus* (mean 5.46 ± 4.40 SD), *Deltoidospora hallei* (mean $4.95\% \pm 3.19$
13
14 SD), and *Dictyophyllidites harrisii* (mean $2.37\% \pm 1.14$ SD) are the main filicopsid spore taxa
15
16 present in the samples. Lycopodiophytes occur with an average of $0.74\% \pm 0.56$ SD of the total
17
18 pollen and spore sum of the samples and Bryophytes are also a minor group (mean $1.84\% \pm 1.49$
19
20 SD) represented almost entirely by *Stereisporites antiquasporites* (mean $1.62\% \pm 1.21$ SD). Non-
21
22 terrestrial palynomorphs represent a minor component of the total assemblage (mean of samples
23
24 $<1\%$; although *Sigmopollis* was not enumerated in all samples). Non-terrestrial palynomorphs
25
26 include undifferentiated algae, dinoflagellate cysts, *Chomotriletes*, *Sigmopollis*,
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28 *Pterospermopsis*, and the acritarch genera *Veryhachium* and *Micrhystridium*.
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38 4.2. Multivariate statistical palynology 39 40 41 42

43 Combined Q (sample)-and R (variable)-mode cluster analysis demonstrates that four
44
45 sample clusters can be delineated, labelled Sample Cluster (SC)-1 through SC-4 (Figure 8). We
46
47 describe each sample cluster in terms of plant classes, except for Pinopsida, which we further
48
49 distinguish to family and in the case of Pinaceae, to the lowest taxonomic level possible, due to
50
51 the predominance of pinaceous pollen. Classes and families not labelled are grouped as “other”
52
53 when representation was less than 10% of the total pollen and spore sum (Table 2). Sample
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55 Cluster-1 is characterized by a high relative abundance of bisaccate pollen (mean $60.26\% \pm 3.04$
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4 SD, n=3 samples) and Cycadopsida/Gingkopsida pollen (mean 10.39%±12.00 SD, n=3 samples).
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6 Sample Cluster-2 (n=10 samples) is characterized by a mixture of Cupressaceae-Taxaceae and
7
8 bisaccate pollen with filicopsid spores. Sample Cluster-3 is characterized by a high relative
9
10 abundance of Cupressaceae-Taxaceae pollen (mean 44.01%±10.11 SD, n=7 samples). Sample
11
12 Cluster-4 is characterized by a high relative abundance of Classopollis classoides pollen (mean
13
14 20.09%±1.55 SD) in the two samples that make up this sample cluster. The stratigraphic
15
16 locations of samples that comprise each sample cluster are shown in Figure 5 to provide insight
17
18 into any influence of facies on assemblage composition. Sample Cluster-1 (Bisaccate-
19
20 Cycadopsida/Gingkopsida assemblage) occurs in the DS-3 and DS-2 sections in facies indicative
21
22 of floodplain and fluvial depositional environments (Tullius et al., 2014). Sample Cluster-2
23
24 (Cupressaceae-Taxaceae-Bisaccate-Filicopsid assemblage) occurs mainly in the DS-03 and DS-
25
26 02 sections; only one sample (IS-1063) in the IS-01 Section represents SC-2. Sample Cluster-2
27
28 includes samples from facies indicative of delta plain and fluvial environments. Sample Cluster-3
29
30 (Cupressaceae-Taxaceae assemblage) occurs in all three sections from facies indicative of
31
32 shoreline and fluvial environments. Sample Cluster-4 (Classopollis classoides assemblage)
33
34 occurs only in the lowermost two samples of IS-01 Section (IS-322 and IS-482) that were
35
36 deposited in a prodelta to delta front environment (Figures 5, 7). The three stratigraphic sections
37
38 examined contain broadly similar palynoflora; using combined Q and R-mode cluster analysis
39
40 we defined sample clusters that for the most part contain samples from each of three sections and
41
42 do not differentiate based on facies (exception is SC-4) (Figures 5, 7). Therefore, we combine
43
44 data from samples collected from the three sections for the purpose of the following discussion
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46 on age interpretation and paleoecological and paleoclimate reconstruction of Ellef Ringnes
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48 Island during deposition of the Isachsen Formation.
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4 Detrended correspondence analysis (DCA) is used to further delineate clusters of taxa to
5 assist in determination of underlying gradients of compositional change. We term these clusters
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9 ‘ecological groupings’ (Stukins et al., 2013). Three ecological groupings (A, B, and C) are
10 identified in the DCA biplot that we interpret as representing paleoecological communities
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12 (Figure 9). Ecological grouping A comprises four pollen taxa, three of which have gymnosperm
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4.3. Palynostratigraphy

Appendix A shows that few and subtle changes occurred in the relative abundance of
palynomorphs throughout the Isachsen Formation. The most complete and intensely sampled
DS-02 Section shows a trend of increasing proportions of Cupressace-Taxaceae pollen up-
section (from ~20% to ~40-60%). Section IS-01 shows a similar trend where Cupressaceae-
Taxaceae pollen increases from ~20% to ~40% with associated increases in undifferentiated
bisaccate pollen. Palynomorph abundances in the DS-03 Section show changes in bisaccate
pollen composition and an increase in spores toward the top of the section, but these changes are
difficult to interpret based on the low sampling resolution and structural complexity of this
section. Stratigraphic changes in the relative proportion of the three ecological groupings
delineated using DCA are plotted in Appendix A. In Section IS-01 the proportion of taxa
composing Ecological grouping A cumulatively increases from ~20% to ~40% up-section in
depositional settings that include fluvial, floodplain, and shoreface environments (Figures 5, 10;

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4 Tullius et al., 2014). In Section DS-02 the proportion taxa composing Ecological grouping A
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6 increases between ~400 and 650 m in facies indicative of floodplain to fluvial depositional
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8 settings while the proportion of taxa that make up Ecological grouping B are abundant in the
9
10 basal and upper parts of the section. Ecological grouping C shows relatively low abundances in
11
12 all sections except in the basal two samples of Section IS-01.
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19 **5.0 Discussion**

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23 Our quantitative, statistical treatment of palynomorphs preserved in three sections of
24
25 Isachsen Formation exposed on Ellef Ringnes Island provides a palynological ‘fingerprint’ for
26
27 this formation that can be used for inter- and intra-basin correlation and insight on high latitude
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29 paleoclimate and terrestrial ecology during the Early Cretaceous (Galloway et al., 2012).
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36 **5.1 Age interpretation**

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40 Pollen and spores preserved in the Isachsen Formation are representative of the Early
41
42 Cretaceous Cerebropollenites Province of the northern hemisphere (Herngreen et al., 1996). The
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44 Cerebropollenites Province is characterized by relatively high abundances and diversities of
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46 filicopsid spores (e.g., Gleicheniidites, Cicatricosisporites, Pilosisporites) together with
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48 bisaccate and other gymnosperm pollen (e.g., Araucariacites, Inaperturopollenites,
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50 Perinopollenites, Classopollis). Cerebropollenites mesozoicus is a common and distinctive
51
52 element. Many taxa of this province are common to Late Jurassic floras (Herngreen et al., 1996)
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54 but the addition of certain taxa (e.g., Aequitriradites, Cicatricosisporites, Trilobosporites, and
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4 Foveosporites subtriangularis) indicate a Cretaceous age (Venkatachala and Kar, 1970; Hopkins,
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6 1971; Bose and Banerji, 1984; Taugourdeau-Lantz, 1988). Foveosporites subtriangularis has
7
8 been interpreted to be an index species for the Hauterivian to late Aptian interval in the eastern
9
10 North Atlantic (Taugourdeau-Lantz, 1988) and is present in the upper two samples of Section IS-
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12 01. Towards the pole, the Arctic sub-province of the Cerebropollenites Province is dominated by
13
14 bisaccate pollen and spores and contains palynoassemblages with restricted diversity and
15
16 abundance relative to more southern floras of the Cerebropollenites Province (Hengreen et al.,
17
18 1996). Other features of the palynostratigraphic record preserved in the Isachsen Formation may
19
20 refine our understanding of the depositional age of these rocks. On Ellef Ringnes Island,
21
22 Galloway et al. (2013) document an increase in Cupressaceae-Taxaceae pollen that begins in the
23
24 upper Deer Bay Formation. Peak abundances of these taxa are reached in lower Isachsen
25
26 Formation strata preserved in the Hoodoo Dome H-37 oil and gas well. The timing of onset of
27
28 this floristic event is interpreted as late Valanginian or early Hauterivian when climate became
29
30 cooler and more humid in high-latitude regions. Documentation of similarly high Cupressaceae-
31
32 Taxaceae pollen in outcrop samples of Isachsen Formation on Ellef Ringnes Island provides
33
34 local reproducibility of this signal. In Western Siberia, a broadly contemporaneous shift in
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36 Taxodiaceapollenites spp. occurs when this taxon increases in relative abundance (to ~17%) in
37
38 the middle Hauterivian (Pestchevitskaya, 2008). Shifts in the relative abundance of
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40 Cupressaceae-Taxaceae pollen may represent a time significant event for Arctic regions that can
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42 be useful in interpreting Early Cretaceous time systems. Further research is necessary to explore
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44 the provinciality of this signal.
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58 5.2 Paleocological interpretations

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7 Considerable uncertainty can exist regarding the botanical affinities of quantitatively
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9 important palynomorphs and/or of the ecological tolerances and optima of extinct parent plants.
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11 We base our inferences on actualistic principles and assume that certain paleoenvironments
12 supported taxa with broadly similar ecological preferences (Abbink et al., 2004).
13

14 15 16 5.2.1 Non-terrestrial palynomorphs 17

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19 Non-terrestrial palynomorphs collectively represent <1% of the pollen and spore sum,
20 reflecting the dominance of input of terrestrial material into the depositional environment (Figure
21 7). Dinoflagellate cysts are rare or absent in samples. In surface sediments of modern intertidal
22 marshes dinoflagellate and acritarch cysts are present in similarly low relative abundances as
23 observed in Isachsen Formation (~0.2-5.3%, 0.2-1.4%, respectively; Medeanic, 2006). The
24 occurrence of *Sigmopollis* spp. in some of the samples suggests that at times fresh and/or low
25 salinity environments existed (de Vernal et al. 1989; Matthiessen et al. 2000; Mudie et al., 2010).
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35 36 5.2.2 Bryophytes 37

38 Bryophytes (mosses, hornworts, and liverworts) are a minor group in Isachsen Formation
39 samples (Figure 7) and represented almost entirely by *Stereisporites antiquasporites*. Mosses
40 usually grow in moist soils typical of humid environments, but can also tolerate periods of
41 drought (Abbink et al., 2004). Bryophyte spores are likely derived from scattered parent plants
42 growing in humid, lowland environments, probably associated with riparian zones alongside
43 rivers and marshes.
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52 53 5.2.3 Lycopodiophytes 54

55 Lycopodiophytes are also a minor group in Isachsen Formation samples (Figure 7).
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57 Similar to bryophytes, lycopodiophyte spores can only be used tentatively in paleoecological
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4 interpretations due to broad ecological tolerances in modern plants. Most extant lycopsids occur
5
6 in humid tropical regions, but can also be found in temperate and even polar areas where they
7
8 often grow in moist settings, such as lowland, river, or tidally-influenced environments. Some
9
10 Triassic lycopods appear to have been facultative coastal halophytes and inhabited marine
11
12 shoreline environments in delta systems (Retallack, 1975). In the Mesozoic, lycopodiophytes
13
14 were components of early successional communities dominated by filicopsids established around
15
16 coastal or deltaic lowlands with poorly developed floodplains (Dejax et al., 2007; Stukins et al.,
17
18 2013).

23 24 5.2.4 Filicopsids

25
26 Filicopsids are a common and diverse group in Isachsen Formation samples (Figure 7).
27
28 Modern filicopsids flourish in humid and shady environments although a minority are tolerant of
29
30 full sunlight or grow in open habitats (e.g., Gleicheniaceae and Schizaeaceae (*Anemia*); Crane,
31
32 1987; Abbink et al., 2004). Ancient Schizaeaceae may have grown in heathland communities
33
34 (Dettmann and Clifford, 1992, and references therein) but most Early Cretaceous filicopsids are
35
36 inferred to have grown in moist riparian habitats and as understory components in forests (van
37
38 Konijnenburg-van Cittert, 2002; Abbink et al., 2004; Dejax et al., 2007; Schrank, 2010).
39
40 Filicopsids are considered to be the predominant, early colonizing, stress-tolerant floras in the
41
42 Mesozoic prior to the evolution of angiosperms and grasses (van Konijnenburg-van Cittert,
43
44 2002). Filicopsid spores range up to 70-75% in coal samples deposited in humid environments
45
46 during the Jurassic-Cretaceous in the mid-southern hemisphere (Schrank, 2010, and references
47
48 therein). Populations of ~20% in coaly mudstones of the Isachsen Formation are low relative to
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50 these more southern latitudes, reflecting the likely dryer and cooler conditions on Ellef Ringnes
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52 Island during the Early Cretaceous.
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5.2.5 Pteridosperms

Vitreisporites pallidus, and possibly some of the undifferentiated bisaccate pollen preserved in Isachsen Formation, may be attributable to pteridosperm parent plants.

Vitreisporites pallidus attains a mean relative abundance of <1% of the pollen and spore sum (Figure 7), indicating rare occurrences of parent plants that probably grew in deltaic flood plain to backswamp environments (van Konijnenburg-van Cittert, 1971; Abbink et al., 2004; Dejax et al., 2007; Stukins et al., 2013).

5.2.6 Pinophyta

Class Pinopsida, which includes the families Pinaceae, Sciadopityaceae, Cupressaceae (includes Taxodiaceae; ITIS, 2014), Taxaceae, Araucariaceae, and Cheirolepidaceae represents one of the most important pollen producers in the ecosystems that existed during deposition of Isachsen Formation on Ellef Ringnes Island (Figure 7). Parent plants of bisaccate pollen were likely upland conifers growing in well-drained habitats (Stukins et al., 2013). *Cerebropollenites* may have affinities with modern *Tsuga* (Balme, 1995; Shang and Zavada, 2003), which grows in temperate regions where it is restricted to moist, poorly drained slopes (Tesky, 1992).

Cerebropollenites may also have affinities to Cupressaceae (Taxodiaceae) (van Konijnenburg-van Cittert and van der Burgh, 1989) or *Sciadopitys* (Dejax et al., 2007). Only one extant representative of the Family Sciadopityaceae exists (formerly assigned to the Family Taxodiaceae; ITIS, 2014). This species (*Sciadopitys verticillata* (Thunb.) Siebold & Zucc.) is endemic to Japan where it is common in mixed conifer (e.g., *Tsuga* and *Chamaecyparis*) and angiosperm forest communities that include filicopsids, lycopodiophytes, and bryophytes growing in cool and moist environments. *Sciadopitys* plant macrofossils are found in abundance in Middle to Upper Jurassic marine deposits from the northern hemisphere with remains of

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4 Ginkgo spp. and Pinus spp. (Manum, 1987; Vakhrameev, 1991), suggesting Sciadopitys co-
5
6 existed with other gymnosperms in the Mesozoic. Cupressaceae-Taxaceae and allies represent
7
8 the majority of the gymnosperm pollen in Isachsen Formation samples. Perinopollenites
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10 elatoides pollen is likely attributable to the Cupressaceae (Taxodiaceae) (van Konijnenburg-van
11
12 Cittert, 1971; Harris, 1979; van Konijnenburg-van Cittert and van der Burgh, 1989; Balme,
13
14 1995). Taxodiacean conifers are interpreted to have been hygrophilous plants that thrived in
15
16 warm to temperate wet lowland environments (Vakhrameev, 1991; Pelzer et al., 1992; Dejax et
17
18 al., 2007). Plant macrofossils with affinities to Cupressaceae (Cupressinoxylon) are reported
19
20 from Aptian-Albian strata of Axel Heiberg and Ellesmere islands in the Sverdrup Basin where
21
22 mean annual temperature is inferred to have been between 3 and 10 °C (Harland et al., 2007). In
23
24 modern environments Cupressaceae pollen is generally well dispersed and occurs with
25
26 frequencies of 10-40% in late Holocene lacustrine and marine sediments where parent plants are
27
28 dominant vegetation components (Gavin et al., 2005; Galloway et al., 2007, 2009, 2010).
29
30 Relative abundances of ~34% of Cupressaceae-Taxaceae pollen in Isachsen Formation samples
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32 therefore suggests that parent plants were important, even co-dominant, in forests surrounding
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34 the central Sverdrup Basin and that climate was cool-temperate and moist.
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43 Araucariacites pollen in Isachsen Formation is likely derived from parent plants
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45 belonging to Araucariaceae (van Konijnenburg-van Cittert, 1971; Boulter and Windle, 1993).
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47 Inaperturopollenites (also rare) pollen is also considered to have affinities to this family (Balme,
48
49 1995). Extant Araucariaceae are well adapted to drought and frequently grow in near shore
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51 environments (Abbink et al. 2004). In the Jurassic and Cretaceous, high proportions of
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53 Araucariacites pollen are indicative of warm climates with low seasonality (Reyre, 1980; Mohr,
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4 1989) and fossil trees are often associated with near-coastal depositional environments in the
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6 geologic record (Harris, 1979; Barale and Flamand, 1982; Vakhrameev, 1991).
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9 Classopollis pollen is thought to be derived from Cheirolepidiaceans, an extinct group of
10 xerophytic and thermophilous plants (Francis, 1983, 1984; Watson, 1988; Vakhrameev, 1987,
11 1991). Cheirolepidaceans likely preferred upland arid habitats (van Konijnenburg-van Cittert and
12 van der Burgh, 1996) but may have also thrived in coastal settings (Batten, 1975; Alvin, 1982;
13 Watson, 1988; Vakhrameev, 1987, 1991; Heimhofer et al., 2008) where they may have formed
14 mid to late successional communities (Stukins et al., 2013). Some Classopollis classoides pollen
15 grains in Isachsen Formation samples are preserved in tetrads, a rare phenomenon in the fossil
16 record (Figure 6; Stukins et al., 2013). This preservation suggests little transport of the grains by
17 the fluvial system prior to deposition (Carvalho et al., 2006; Traverse, 2007; Stukins et al.,
18 2013), suggesting that Cheirolepidaceans were components of coastal plain vegetation or,
19 alternatively, had a capacity for flotation that protected them from abrasion (Stukins et al., 2013).
20
21 Classopollis classoides pollen is common in samples from the lowermost Isachsen Formation in
22 Section IS-01 but are otherwise rare (Figures 7, 10). Abundances of Classopollis classoides
23 pollen near 10% in Deer Bay Formation marine mudstones preserved in the Hoodoo Dome H-37
24 oil and gas well are interpreted to represent seasonally arid conditions during the Late Jurassic to
25 Early Cretaceous in the Canadian high Arctic (Galloway et al., 2013). In this well, Classopollis
26 classoides pollen declines to ~2 to 5% in the uppermost Deer Bay Formation in the Valanginian
27 or Hauterivian and relative abundances remain low throughout the Isachsen Formation
28 (Galloway et al., 2013). Very low abundances (~0-2%; with the exception of ~20% in the
29 lowermost rocks of Section IS-01) of Classopollis classoides pollen in Isachsen Formation could
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31 be in response to increasing moisture in the Early Cretaceous that promoted expansion of mid to
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4 late successional conifers such as Cupressaceae at the expense of Cheirolepidaceans and other
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6 drought tolerant taxa and/or be an artefact of facies control on the distribution of this pollen.
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9 5.2.7 Cycadophyta

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11 Most fossil pollen grains of the Ginkgoales and Cycadales belong to the genera
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13 Monosulcites and/or Cycadopites. Some pollen grains of the extinct Bennettitales may also
14
15 belong to the Monosulcites/Cycadopites group (Abbink et al., 2004). *Ginkgo biloba*, the only
16
17 extant Ginkgoales, is a deciduous tree that grows in temperate regions. In the Mesozoic,
18
19 Ginkgoales also grew in temperate regions where they were a diverse group, although some
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21 representatives grew in subtropical regions (Abbink et al., 2004). Some Ginkgoales may have
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23 been components of lowland vegetation, occupying moist riparian zones (Stukins et al., 2013).
24
25 Extant Cycadales grow in tropical regions and are adapted for drought, suggesting tolerance of
26
27 dry summer seasons for Mesozoic ancestors. Similar to Ginkgoales, in the Mesozoic Cycadales
28
29 were a diverse group that included extinct taxa (e.g., Nilsoniaceae) that grew in lowland,
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31 subtropical areas (Abbink et al., 2004 and references therein), but in general Cycadales are
32
33 interpreted to have been mesoxerophilous plants and probably grew in well-drained upslope
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35 habitats (Dejax et al., 2007). Bennettitales may have been restricted to lowland deltaic habitats
36
37 (van Konijnenburg-van Cittert and van der Burgh, 1989; Dejax et al., 2007) while others grew in
38
39 drier climates in upland habitats (Watson and Sincock, 1992) or savannahs (Harris, 1973).
40
41 Regardless of botanical affinity, parent plants of Cycadopites pollen likely grew in drier lowland
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43 environments or on upslope, well-drained sites (Abbink et al., 2004; Dejax et al., 2007; Stukins
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45 et al., 2013).
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54 5.2.8 Magnoliopsida

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4 The pollen of angiosperm plants are absent from Isachsen Formation samples.
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6 Angiosperm pollen first appears in late Albian-aged strata of the central Sverdrup Basin: two
7 species of tricolpate pollen are reported from uppermost beds of Christopher Formation on Ellef
8 Ringnes and Amund Ringnes islands (Hopkins, 1974). Monocotyledenous pollen are reported
9 from the Cenomanian Bastion Ridge and Strand Fiord formations on Axel Heiberg Island in
10 eastern Sverdrup Basin (Núñez-Betelu et al., 1992), but are absent from underlying late Albian
11 Hassel Formation on Ellesmere Island (Núñez-Betelu et al., 1992) and from Hassel Formation on
12 Ellef Ringnes Island (Galloway et al., 2012). Albian and Cenomanian strata of the Sverdrup
13 Basin contain low abundance and diversity of angiosperm pollen relative to angiosperm pollen
14 occurrences in Alberta and the U.S.A. (Galloway et al., 2012). The late arrival of angiosperm
15 pollen to the Sverdrup Basin and subsequent low diversity relative to more southern latitudes
16 may be due to relatively cool northern continental climate experienced in the Canadian Arctic
17 and/or barriers to angiosperm plant migration. See Galloway et al. (2012) for a discussion.
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38 5.3. Paleoecological analysis 39 40 41 42

43 Palynomorph assemblages in Isachsen Formation are preserved in depositional settings,
44 ranging from near shore marine deposits to terrestrial sedimentary environments. Differential
45 transportation and sorting of pollen and spores types during transportation and deposition must
46 be considered, even though the effect is likely negligible in marginal marine to terrestrial
47 depositional settings where palynomorphs are less subject to hydrodynamic processes than in
48 open marine systems (Tyson, 1995; Traverse, 2007; Abbink et al., 2004; Heimhofer et al., 2012).
49 In marine deposits, palynomorph size, shape, density, and buoyancy can result in significant
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4 biases (Tyson, 1995; Traverse, 2007; Heimhofer et al., 2012). This is particularly evident for
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6 bisaccate pollen grains that can be transported long distances in air and water (Heusser and
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8 Balsam, 1977). However, in sections IS-01 and DS-02 increases in bisaccate pollen occur in
9
10 facies indicative of fluvial to floodplain settings of the Paterson Island Member (Appendix A).
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14 Robust-walled and ornamented spores can also be differentially sorted relative to thin-
15
16 walled, non-saccate palynomorphs; the former have been observed to be preferentially deposited
17
18 proximal to river mouths (Heusser and Balsam, 1977; Tyson, 1995). Similar to changes in the
19
20 proportion of bisaccate pollen, changes in the relative abundance of relatively robust walled
21
22 (Ruffordiaspora and Cicatricosisporites spp.) vs. thin walled spores (e.g., Deltoidospora ssp.) do
23
24 not seem to follow pattern associated with differential sorting. Classopollis pollen occurs mainly
25
26 in the delta front and prodelta environments of Paterson Island Member in Section IS-01. This
27
28 signature may be due to increased buoyancy and selective hydrodynamic transport of
29
30 Classopollis pollen in this marginal marine setting (Stukins et al., 2013) but in general we
31
32 consider the effects of hydrodynamic sorting to have had a minimal effect on palynomorph
33
34 abundances and patterns (Heimhofer et al., 2012).
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41 When palynological data are presented on a DCA biplot, taxa present in Isachsen
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43 Formation with a total relative abundance of greater than $\geq 0.5\%$ (n=17 taxa, n=22 samples)
44
45 exhibit groups that can be interpreted as ecological relationships with reference to their botanical
46
47 affinities (discussed above) (Figure 9). We interpret the main ecological gradients influencing
48
49 Isachsen Formation floristic communities to have been moisture availability and disturbance on
50
51 the basis of the botanical affinities of taxa (Stukins et al., 2013). We relate the horizontal (x-axis)
52
53 plane of the DCA biplot to moisture availability. Moisture availability is a major driver of
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55 terrestrial ecosystem dynamics. Large coniferous plants, such as the Cheirolepidaceae and
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4 members of the Pinaceae, can tolerate arid conditions, whereas other plants (e.g., many
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6 bryophytes and filicopsids) are limited to wet conditions. We infer the vertical (y-axis) of the
7
8 biplot to represent disturbance based on the botanical affinities of taxa and their position on the
9
10 plot. A disturbance, such as periodic flooding, can be discrete events or a change in a factor
11
12 influencing an ecosystem that eventually exceeds a critical threshold and results in a shift from
13
14 one persistent condition to another (Sparks et al., 1990). Moisture availability and disturbance
15
16 are main drivers of vegetation dynamics in modern coastal lowland settings (Bledsoe and Shear,
17
18 2000) and were also fundamental influences ecosystems during the Mesozoic (Abbink et al.,
19
20 2004; Stukins et al., 2013).

26 5.3.1. Ecological Grouping A—Mixed conifer assemblage

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28 This ecological grouping comprises four pollen taxa with coniferous affinities.
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30 Perinopollenites elatoides may have affinities to the Cupressaceae-Taxaceae and may be derived
31
32 from parent plants growing in poorly drained floodplains or moist habitats in upland areas.
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34 Inaperturopollenites pollen may have affinities to Araucariaceae and may be derived from
35
36 lowland vegetation growing in warm environments subjected to drought (Harris, 1979; Reyre,
37
38 1980; Barale and Flamand, 1982; Mohr, 1989; Vakhrameev, 1991; Abbink et al., 2004).
39
40 Assuming Entylissa pollen is derived from parent plants with affinities to Cycadophyta, this
41
42 pollen is likely derived vegetation growing in drier, upslope environments (Dejax et al., 2007).
43
44 Bisaccate pollen is the predominant pollen type in this ecological grouping. Bisaccate pollen is
45
46 commonly inferred to have originated from Pinaceae parent plants with a mesoxerophilous
47
48 ecology growing in upland and relatively arid or well-drained environments (Barrón et al., 2006;
49
50 Dejax et al., 2007). Macrofossil evidence from the Early Cretaceous of the Canadian Arctic
51
52 suggests that Pinaceae were common in high latitude forests, with constituents that may have
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4 been similar to modern *Pinus*, *Picea*, *Larix*, and *Pseudotsuga* (Harland et al., 2007). A
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6 component of the bisaccate pollen may therefore have been produced by parent plants with broad
7
8 ecologies similar to extant *Pinus* and *Picea*. Modern *Pinus* species can grow on soils of fluvial
9
10 origin and are early pioneers of disturbed habitats but can also form edaphic climax. Modern
11
12 members of *Picea* are tolerant of brackish water, can be a pioneer or a late successional tree, and
13
14 can grow on alluvial soils but prefer moist but well-drained substrates (Griffith, 1992; Carey,
15
16 1993). Pteridosperm parent plants that likely thrived in lowlands as a constituent in coastal or
17
18 deltaic climax communities during the Mesozoic also produce bisaccate pollen (e.g., *Alisporites*
19
20 Daugherty 1941) (Abbink et al., 2004; Stukins et al., 2013). Ecological grouping A therefore
21
22 likely contains pollen from mature upland coniferous communities that grew in well-drained
23
24 substrate with infrequent disturbance as well as pollen derived from lowland plants adapted to
25
26 more dynamic environments. Plotting in overlapping space as Ecological grouping A are
27
28 samples from from facies indicative of deltaplain, floodplain, fluvial, and shoreline settings and
29
30 cluster in three of the four Sample Clusters (SC) identified using combined Q- and R-mode
31
32 cluster analysis (Figures 5, 9). No clear facies control is observed. Pollen from upland plants
33
34 would have been transported to lowland environments as pollen rain and in rivers.
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43 5.3.2. Ecological Grouping B – Lowland conifer-filicopsid assemblage

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45 Ecological grouping B is characterized by spores from filicopsids and bryophytes,
46
47 namely *Deltoidospora hallei*, *Glecheniidites senonicus*, *Osmundacidites wellmannii*, and
48
49 *Stereisporites antiquasporites*, and pollen from conifers, including Cupressaceae-Taxaceae and
50
51 *Araucariacites australis*. Filicopsids were the predominant early colonizers of disturbed habitats
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53 in the Mesozoic prior to the addition of angiosperms and grasses to high latitude ecosystems (van
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55 Konijnenburg-van Cittert, 2002). *Stereisporites antiquasporites* spores may be derived from
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4 parent plants occupying lowland marsh habitats. Cupressaceae-Taxaceae pollen is likely derived
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6 from plants occupying poorly drained slope of upland forest environments and/or moist coastal
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8 forests (Stukins et al., 2013). Cycadopites pollen also occurs in this ecological grouping and may
9
10 represent plants growing in riparian zones (Stukins et al., 2013) while representatives of
11
12 Araucariaceae were likely derived from drier lowland habitats. Together, the pollen and spores
13
14 that compose Ecological grouping B suggest a parent community growing in a mosaic of wet and
15
16 more arid lowland environments subjected to varying degrees of disturbance.
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20 21 5.3.3. Ecological Grouping C – Lowland conifer assemblage 22

23 Ecological grouping C is composed solely of *Classopollis classoides* pollen. This
24
25 grouping may represent the distinct ecology of large xerophytic Cheirolepidaceans (Francis,
26
27 1983) and a mature community growing in a dry floodplain environment (Stukins et al., 2013).
28
29 Ecological grouping C is aligned with SC-4 in the DCA biplot, which includes only two samples
30
31 from facies indicative of delta front to prodelta settings of the Paterson Island Member of Section
32
33 IS-01 (Figure 5). This ecological grouping may therefore be a biogeochronological signature
34
35 whereby the high relative abundance of *Classopollis classoides* pollen in samples IS-322 and IS-
36
37 482 represents the last point in the stratigraphic succession of abundant Cheirolepidaceans prior
38
39 to their decline in the late Valanginian/early Hauterivian on Ellef Ringnes Island due to climate
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41 change (Galloway et al., 2013) and/or facies control, including increased buoyancy and selective
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43 hydrodynamic transport of *Classopollis* pollen in this marginal marine setting (Stukins et al.,
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45 2013).
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56 5.4. Stratigraphic palynology and paleoclimate 57 58 59 60 61 62 63 64 65

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4 Northward movement of Sverdrup Basin from about 45-60 °N during the Late Triassic-
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6 Early Jurassic to 60 to >70 °N in the Middle Jurassic and Early Cretaceous led to progressively
7
8 cooler conditions in the Canadian High Arctic (Wynne et al., 1988; Embry, 1991) although Early
9
10 Cretaceous climate in the northern hemisphere was still warmer than today (Vakhrameev, 1991;
11
12 Herman and Spicer, 1996; Littler et al., 2011). Nearest living relative analysis of coniferous
13
14 wood from the Canadian Arctic suggests that by the Aptian to Albian, climate was cool-
15
16 temperate (between 3 and 10 °C mean annual temperature; Harland et al., 2007). The
17
18 consistently strong signal of pollen attributed to Pinaceae, indicative of temperate conditions, and
19
20 the subordinate amount of pollen attributed to parent plants indicative of relatively warm and dry
21
22 environments (e.g., Classopollis, Cycadopites, Araucariacites, and possibly also
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24 Inaperturopollenites, collectively comprising <10% of the pollen sum) suggest that overall cool
25
26 and humid conditions prevailed during deposition of the Isachsen Formation on Ellef Ringnes
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28 Island.
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36 Small but important stratigraphic changes in the proportions of pollen and spore types
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38 composing the three ecological groupings defined by DCA suggest that minor shifts in climate
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40 punctuated the overall cool and humid conditions of the late Valanginian-early Aptian of the
41
42 Canadian Arctic (Appendix A). In the upper Paterson Island Member in Section DS-02 the
43
44 relative abundance of the conifer-filicopsid assemblage (Ecological grouping B) declines while
45
46 the proportion of the mixed conifer assemblage (Ecological grouping A) increases (Zone DS-02-
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48 B; Figure 10). We interpret the age of these rocks to be Hauterivian based on ages of bounding
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50 strata. In Section DS-02 (Zone DS-020B) this change is represented by two samples but the
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52 proportion of pollen comprising Ecological grouping A also increases in abundance throughout
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4 the more intensely sampled Paterson Island Member in Section IS-01 (Zone IS-01-B; Appendix
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7 A), suggesting that this is a real and sustained palynological change.
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9 Drier and possibly warmer climate conditions could have promoted the development and
10 expansion of mature coniferous forests during the Hauterivian in the Sverdrup Basin. More arid
11 climate conditions would be expected to develop under warmer conditions that increased
12 evaporation and evapotranspiration and promoted plants that remained competitive, or thrived, in
13 well-drained or water-limited environments, such as bisaccate pollen producers (*Pinus*, *Picea*), at
14 the expense of plants with higher moisture requirements, such as members of lowland conifer-
15 filicopsid bryophyte communities. Harland et al. (2007) report a comparative study of coniferous
16 plant megafossils of the Canadian Arctic and Spitsbergen. They found that morphogenera with
17 affinities to *Taxodiaceae* (*Taxodium?*) and *Araucariaceae* were present only in the Spitsbergen
18 material and infer the greater diversity to reflect warmer conditions in Spitsbergen relative to the
19 Canadian Arctic. In Isachsen Fm samples *Araucariacites australis* pollen is associated with
20 Ecological group B, the lowland conifer-filicopsid assemblage although this pollen also increases
21 in upper strata of the Paterson Island Member in sections DS-02 (zone DS-02B) and IS-01 (zone
22 IS-01-B), concomitant with the increase in the relative proportion of Ecological grouping A, the
23 mixed conifer assemblage (Appendix A).
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45 The presence of pollen with affinities to *Cupressaceae* (*Taxodiaceae*) in Ecological grouping
46 B, along with a diversity of filicopsid spores, suggest that cool-temperate and moist lowland
47 environments were more expansive during the late Valanginian and Barremian to early Aptian
48 than during the more arid and/or warmer conditions we infer to have promoted coniferous
49 communities (Ecological grouping A) during the Hauterivian. Disturbance is also an important
50 influence on vegetation communities and large-scale fluvial systems that deposited the Isachsen
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4 Formation would have been an important mechanism of landscape change (Tullius et al., 2014).
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6 More vigorous fluvial systems and associated more frequent and intense substrate disturbances
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8 would be expected to develop under the wetter and cooler climate conditions we infer for the late
9
10 Valanginian and Barremian to Aptian intervals. This disturbance would have promoted the
11
12 expansion of parent plants in the lowland conifer-filicopsid community that were well adapted to
13
14 environmental disturbance. On Ellef Ringnes Island, a decline in Cupressaceae-Taxaceae pollen
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16 and increase in bisaccate pollen represented by two samples in the middle of the Paterson Island
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18 Member preserved in the Hoodoo Dome H-37 oil and gas well may be a manifestation of the
19
20 Hauterivian arid and warm event proposed here.
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26 Significant perturbations to global climate occurred during Valanginian to Aptian time when
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28 numerous “cool” excursions punctuated otherwise warm Early Cretaceous conditions in the
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30 northern hemisphere (McArthur et al., 2004; Gröcke et al., 2005; Kessels et al., 2006). These
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32 temperature excursions may have been expressed as glacial episodes in high northern latitudes
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34 during the Valanginian (Kemper, 1987; Price and Mutterlose, 2004; Kessels et al., 2006; Price
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36 and Nunn, 2010). A subsequent period of warming in the northern hemisphere during the
37
38 Hauterivian terminated late Valanginian-early Hauterivian icehouse conditions (Pucéat et al.,
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40 2003; McArthur et al., 2004; Gröcke et al., 2005; Kessels et al., 2006; Price and Nunn, 2010). A
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42 return to cool temperatures occurred in the mid-Barremian (Pucéat et al., 2003; McArthur et al.,
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44 2004) and persisted through the Aptian-early Albian interval in high-latitude regions (Harland et
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46 al., 2007). These Early Cretaceous climate events are manifested in the Canadian Arctic as
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48 changes in terrestrial vegetation whereby the Hauterivian warm episode promoted expansion of
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50 upland coniferous communities.
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4 **6.0 Conclusions**
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9 We use a multivariate statistical approach to palynology to provide insight on vegetation
10 dynamics and paleoclimate of the Early Cretaceous. Relatively cool and moist conditions during
11 the late Valanginian and early Aptian promoted disturbance-adapted plants that formed a conifer-
12 filicopsid community in lowland environments. More arid, warm, and stable environmental
13 conditions during the Hauterivian may have promoted expansion of mature coniferous
14 communities. Our paleoclimate inferences for this Canadian high latitude region are consistent
15 with reconstructions from lower latitudes, suggesting at least hemispherical expression of
16 Valanginian cooling and a subsequent warming event in the Hauterivian that influenced polar
17 vegetation.
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28 29 **Figure captions**

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34 **Figure 1: A) Geologic map showing location of Sverdrup Basin and Ellef Ringnes Island**
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36 **(after Dewing et al., 2007); B) Jurassic-Cretaceous stratigraphy of Sverdrup Basin (after**
37
38 **Embry 1991; Dewing and Embry 2007; Obermajer et al. 2007; Embry and Beauchamp,**
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40 **2008)**
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46 **Figure 2: Simplified geologic map of Ellef Ringnes Island (geologic contacts after**
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48 **Evenchick and Embry, 2012a, b). Middle and Early Jurassic units are undivided and no**
49
50 **divisions are shown for the Upper Cretaceous Kanguk Fm. Black lines represent locations**
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52 **of measured sections (see Figure 4 for detail). Location of wells with gamma logs shown in**
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54 **Figure 3 also shown and location of Hoodoo Dome well H-37 shown in red (Galloway et al.,**
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56 **2013)**
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7 **Figure 3: Lithostratigraphic cross-section of well and gamma ray logs showing Lower**
8 **Cretaceous strata of Deer Bay Formation to Upper Cretaceous strata of Christopher**
9 **Formation from northwest to southeast across Sverdrup Basin. Datum is the top of the**
10 **Rondon Member within the Isachsen Formation. Most of the Isachsen Formation is**
11 **laterally continuous across the basin, including over paleotopographic highs such as salt**
12 **diapirs. Horizontal dimension is not to scale; distances are indicated. Location of wells**
13 **shown in Figure 2**
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26 **Figure 4: Map showing locations of samples analyzed for palynology overlain on the map**
27 **of Evenchick and Embry (2012a). A- Isachsen Central (IS-01) section; B-Dumbbells West**
28 **(DS-03) Section and Dumbbells East (DS-02) Section. A location for the Rondon member**
29 **was tentatively identified by Evenchick and Embry (2012a). Based on analysis of well logs**
30 **and stratigraphy we interpret the Rondon Member to be at DB680 (denoted with *)**
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41 **Figure 5: Lithostratigraphic sections measured from Ellef Ringnes Island (locations shown**
42 **in Figures 2, 4) (After Tullius et al. (2014)). Sample clusters defined by combined Q- and R-**
43 **mode cluster analysis (Figure 8) and discussed in text are shown on measured sections**
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50 **Figure 6: Photomicrographs of pollen and spores captured using differential interference**
51 **contrast and oil immersion preserved in Isachsen Formation samples from exposures on**
52 **Ellef Ringnes Island. Sample number, GSC curation number (C-number), GSC Calgary**
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4 **Palynology Laboratory preparation number (P-number), GSC specimen number**
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7 **(pending), microscope (Olympus BX61) coordinate (µm), and England Finder coordinates**
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9 1 – Cupressaceae-Taxaceae, IS-946, C-549939, P5244-23B, GSC specimen number 136516,
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11 43872.3x76346.9, M26/1
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13
14 2 – Perinopollenites elatoides, IS-02, C-549937, P5244-20D, GSC Specimen Number 136517,
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16 39735.9x76346.9, M21/2
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18
19 3 – Cerebropollenites mesozoicus, DS3-701, C-549932, P-5244-15B, GSC specimen number
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21 136518, 34124.8x73814.3, J16/1
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23
24 4 – Undifferentiated bisaccate pollen, DS3-701 C-549932, P5244-15B, GSC specimen number
25
26 136519, 47739.3x76346.9, M30/1
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29 5 – Classopollis classoides tetrad, IS-02, C-549937, P5244-20D, GSC specimen number 136520,
30
31 45079.1x76346.9, M27/2
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34 6 – Classopollis classoides, IS-02, C-549937, P5244-20D, GSC specimen number 136521,
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36 43040.8x72335.1, G25/3
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39 7 – Entylissa, DS3-389.5, C-549930, P5244-13A, GSC specimen number 136522,
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41 60148.9x76346.9, M43/1
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44 8 – Entylissa, DS3-389.5, C-549930, P5244-13A, GSC specimen number 136523,
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46 60595.2x76346.9, M43/2
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49 9 – Cycadopites, DS3-389.5, C-549930, P5244-13A, GSC specimen number 136524,
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51 60646.8x76346.9, M43/2
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54 10 – Cycadopites, DS3-389.5, C-549930, P5244 13A, GSC specimen number 136525,
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56 54661.5x76346.9, M37/1
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4 11 – *Microreticulatisporites uniformis*, DS3-701, C-549932, P5244-15B, GSC specimen number
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6 136526, 44179.3x76346.9, M26/2
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9 12 – *Sigmopollis*, DS3-389.5, C-549930, P5244 13A, GSC specimen number 136527,
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11 47201.6x73764, J29/2
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14 13 – *Cyathidites australis*, IS-322, C-549937, P-5244-20D, GSC specimen number 136528,
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16 28021.5x76346.9, M9/2
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19 14 – *Ruffordiaspora australiensis*, IS-02, C-549937, P5244-20D, GSC specimen number
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21 136529, 41637.3x74802.6, K24/1
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23
24 15 – *Cyathidites minor*, DS3-389.5, C-549940, P-5244-23B, GSC specimen number 136530,
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26 37956.9x75638.3, L20/1
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29 16 – *Gleicheniidites senonicus*, IS-946, C-549939, P-5244-23B, GSC specimen number 136531,
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31 45625.8x75862.5, L28/4
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36 **Figure 7: A- Pie chart showing the relative abundances of pollen and spores from obligately**
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38 **terrestrial plants in each Class identified in samples collected from the Isachsen Formation**
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40 **(all sections), Ellef Ringnes Island. The relative abundance of non-pollen palynomorphs is**
41
42 **calculated based on the terrestrial pollen and spore sum. B - Pie chart showing the relative**
43
44 **abundance of taxa identified to the lowest possible taxonomic classification of members of**
45
46 **the Class Pinopsida, the most abundantly represented plant group**
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53 **Figure 8A: Combined Q- and R-mode cluster analysis of the relative abundance of pollen**
54
55 **and spores from obligately terrestrial plants identified in Isachsen Formation, Ellef**
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57 **Ringnes Island. Four Sample Clusters (1, 2, 3, and 4) are defined based on palynomorph**
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4 content and delineated by dashed line. Colour coding of Sample Clusters used to show
5 stratigraphic position and facies of samples belonging to each cluster in Figure 5
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11 **Figure 8B: Pie charts showing the relative proportion of palynomorph types in each**
12 **Sample Cluster. Other - <10% sum of means; C-T - Cupressaceae-Taxaceae**
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19 **Figure 9: Detrended correspondence analysis biplot of pollen and spores occurring with a**
20 **mean relative abundance of $\geq 0.5\%$ (n=17) in Isachsen Formation samples from all sections**
21 **(n=22) (Eigenvalue DCA1=0.209, DCA2=0.068). Three ecological groupings (A, B, and C)**
22 **of taxa are delineated by solid lines. Sample Clusters 1 through 4 defined by Combined Q-**
23 **and R-mode cluster analysis are delineated on the biplot and colour coded to be consistent**
24 **with Figures 5 and 8. SC-1 Bisaccate-Cycadopsida/Gingkopsida assemblage; SC-2**
25 **Cupressaceae-Taxaceae-Bisaccate-Filicopsida assemblage; SC-3 Cupressaceae-Taxaceae**
26 **assemblage; SC-4 Classopollis classoides assemblage**
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41 **Appendix A**

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43 **Stratigraphic diagrams of the relative abundances of palynomorphs preserved in three**
44 **measured sections of Isachsen Formation (A – Section IS-01; B – Section DS-02; C –**
45 **Section DS-03). Changes in cumulative relative abundance of pollen and spores of**
46 **Ecological groupings A, B, and C as defined by DCA (Figure 9) also shown. DCA axis 1**
47 **(moisture availability) and axis 2 (disturbance) sample scores plotted stratigraphically.**
48 **Diagrams produced using TILIA (Grimm, 1993-2001). Stratigraphically constrained**
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4 **incremental sum of squares cluster analysis (CONISS; Grimm, 1987) used with visual**
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6 **inspection to delineate informal palynomorph stratigraphic zones for each section**
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11 **Tables**
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14 **Table 1: Background information on age determination of Isachsen Formation and**
15 **bounding strata and summary of paleontological data for the Lower Cretaceous of the**
16 **Sverdrup Basin**
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Unit	Age determination	Based on	Reference(s)
Christopher Formation	Aptian (126-113 Ma ¹) to Albian (113-100 Ma)	Macrofossils, foraminifera, and palynology from various localities	Jeletzky, 1970a, b, 1973, 1974a, b; Hopkins, 1974; Wall, 1983; Nøhr-Hansen and McIntyre, 1998; Wall in Harrison and Brent, 2005; Davies and Wall in Harrison and Brent, 2005; Embry and Beauchamp, 2008; Haggart, 2007; Poulton, 2010; Schröder-Adams et al., 2014
Isachsen Formation, Walker Island Member	Barremian (131-126 Ma) to Aptian (126-113 Ma)	No age-diagnostic fossils identified but bracketed by a Barremian age below (Rondon Member) and an Aptian age above (Christopher Formation)	Embry, 1985a
Isachsen	Barremian	Dinoflagellate cysts, Axel	Costa, 1984; McIntyre, 1984;

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Formation, Rondon Member	(131-126 Ma)	Heiberg and Melville islands	McIntyre pers comm. 1984 in Embry, 1985a, 1991; Nøhr- Hansen and McIntyre, 1998
Isachsen Formation, Paterson Island Member,	Valanginian (139-134 Ma) to Barremian (131-126 Ma)	Pelecypods, Amund Ringnes Island	Balkwill, 1983
Unsubdivided Isachsen Formation	Valanginian (139-134 Ma) to Aptian (126- 113 Ma)	Palynology, Banks, Prince Patrick, Melville islands; Macrofossils, various localities; Pelecypods, Mould Bay Formation that underlies Isachsen Formation on Mackenzie King Island;	Jeletzky, 1970a, b, 1973, 1975, 1976, 1984; Hopkins, 1971; Jeletzky in Dorenkamp et al., 1976; Plauchut and Jutard, 1976; Dorenkamp et al., 1976;
Deer Bay Formation	Tithonian (152-145 Ma) to late Valanginian (139-134 Ma)	Dinoflagellate cysts 1359- 2012 m, 4460-6600 ft in Hoodoo Dome H-37; Palynology and foraminifera, interfingering Awingak sandstones, Prince Patrick Island; Macrofossils, Ellef Ringnes and Amund Ringnes islands; Foraminifera, eastern Axel Heiberg Island	Jeletzky, 1953a, b, 1970a, b, 1974a, b, 1977; Brideaux and Fisher, 1976; Wall, 1983; Davies, 1983; Embry, 1985b; Davies and Wall in Harrison and Brent, 2005; Poulton, 2009

Table 2: Samples analyzed for palynology from Isachsen Central Section, Ellef Ringnes

Island^a

Section^a	Lithostratigraphy	Sample name	Location in section (m)	C-number^b	P-number^c
Isachsen Central (IS-01)	Paterson Island Mbr	IS-322 ^e	322	C-549937	P-5244-20B
		IS-482	482	C-549938	P-5244-22B
		IS-946	946	C-549939	P-5244-23B
		IS-1015	1015	C-549940	P-5244-24B
		IS-1030	1030	C-549941	P-5244-24B
		IS-1063	1063	C-549943	P-5244-26B
		IS-1071	1071	C-549944	P-5244-27B
		IS-1430 ^e	1430	C-549946	P-5244-28B
IS-1450 ^e	1450	C-549945	P-5244-29B		
Dumbbells East (DS-02)	Paterson Island Mbr	DB-175	175	C-549918	P-5244-1B
		DB-347	346	C-549919	P-5244-2B
		DB-382	382	C-549920	P-5244-3B
		DB-409	409	C-549921	P-5244-4B
	Rondon Mbr	DB-638	638	C-549922	P-5244-5B
		DB-680	680	C-549923	P-5244-6B
		DB-801	801	C-549926	P-5244-9B
		DB-818	818	C-549924	P-5244-7A
Walker Island Mbr	DB-985	985	C-549928	P-5244-11B	
	DS3-23	23	C-549929	P-5244-12B	
	DS3-389.5	389.5	C-549930	P-5244-13A	
	DS3-517	517	C-549931	P-5244-14B	
Dumbbells West (DS-03)	Undifferentiated	DS3-701 ^e	701	C-549932	P-5244-15B

^aDetailed stratigraphic sections shown in Figure 4 and in Tullius et al. (2014); ^bC-Number – GSC Calgary Curation Number;

^eP-Number – GSC Calgary Palynology Laboratory Preparation Number; ^epreliminary palynology of sample presented in Tullius et al. (2014)

Table 3: Biological nomenclature of spore and pollen taxa identified in Isachsen Formation

Division	Class	Order	Family	Genus and species	Authority ^a
			Pinaceae	Undifferentiated bisaccate pollen	
			Pinaceae	<i>Laricoidites magnus</i>	(Potonié 1931) Potonié, Thomson and Thiergart 1950
			Pinaceae	<i>Cerebropollenites mesozoicus</i>	(Couper 1958) Nilsson 1958
		Pinales	Taxodiaceae, Sciadopityaceae	<i>Sciadopityspollenites</i>	Raatz 1937 resp. Thiergart 1938 ex Potonie 1958
	Pinopsida		incertae sedis	<i>Inaperturopollenites</i>	Pflug and Thomson in Thomson and Pflug 1953
			Araucariaceae	<i>Araucariacites australis</i>	Cookson 1947
		Cupressales	Cupressaceae/Taxaceae	Undifferentiated	
			Cupressaceae (Taxodiaceae)	<i>Perinopollenites elatoides</i>	Couper 1958
		incertae sedis	Cheirolepidaceae	<i>Classopollis classoides</i>	(Pflug 1953) Pocock and Jansonius 1961
	Pteridospermopsida	Caytoniales	Caytoniaceae	<i>Vitreisporites pallidus</i>	(Reissinger 1950) Nilsson 1958
	Cycadopsida/Gingkopsida	Cycadales/Ginkgoales	incertae sedis	<i>Entyliassa</i>	Naumova 1939 ex Ishchenko 1952
			Cycadales	<i>Cycadopites</i>	Wodehouse 1933
	Gnetopsida	incertae sedis		<i>Eucommidites troedsonii</i>	(Erdtman 1948) Potonié 1958
		Polypodiales	Cyatheaceae/Dicksoniaceae	<i>Cyathidites australis</i>	Couper 1953
				<i>Cyathidites minor</i>	Couper 1953
				<i>Concavissimisporites parkinii</i>	Pocock 1963
	Tracheophyta		Matoniaceae/Dicksoniaceae	<i>Matonisporites</i>	R.A. Couper 1958
		Gleicheniales	Gleicheniaceae	<i>Gleicheniidites senonicus</i>	Ross 1949
				<i>Gleicheniidites apilobatus</i>	Brenner 1963
			Dipteridaceae	<i>Converrucosisporites</i>	Potonié and Kremp 1954
				<i>Ruffordiaspora australiensis</i>	(Cookson 1953) Dettmann & Clifford 1992
				<i>Ruffordiaspora ludbrookiae</i>	(Dettmann 1963) Dettmann & Clifford 1992
				<i>Cicatricosisporites</i> cf. <i>C. pseudotripartitus</i>	(Bolikhovitina) Dettmann 1963
				<i>Cicatricosisporites</i> indetermined	Potonié and Gelletich 1933
		Schizaeales	Schizaeaceae	<i>Plicatella</i>	Maljalkina 1949
	Filicopsida			<i>Klukisporites</i>	Couper 1958
				<i>Klukisporites pseudoreticulatus</i>	Couper 1958
				<i>Distaltriangulisporites perplexus</i>	Singh 1971
				<i>Trilobosporites</i> sp.	
				<i>Concavissimisporites</i> sp.	
				<i>Baculatisporites comaumensis</i>	(Cookson 1953) Potonié 1956
				<i>Osmundacidites wellmannii</i>	Couper 1953
		Osmundales	Osmundaceae	<i>Todisporites major</i>	Couper 1958
				<i>Todisporites minor</i>	Couper 1958
				<i>Biretisporites potoniaei</i>	Delcourt and Sprumont 1955
		Polypodiales	Polypodiaceae/Blechnaceae	<i>Laevigatosporites ovatus</i>	Wilson & Webster 1946
		incertae sedis		<i>Deltoideospora hallei</i>	Miner 1935
				<i>Deltoideospora psilostoma</i>	Rouse 1959

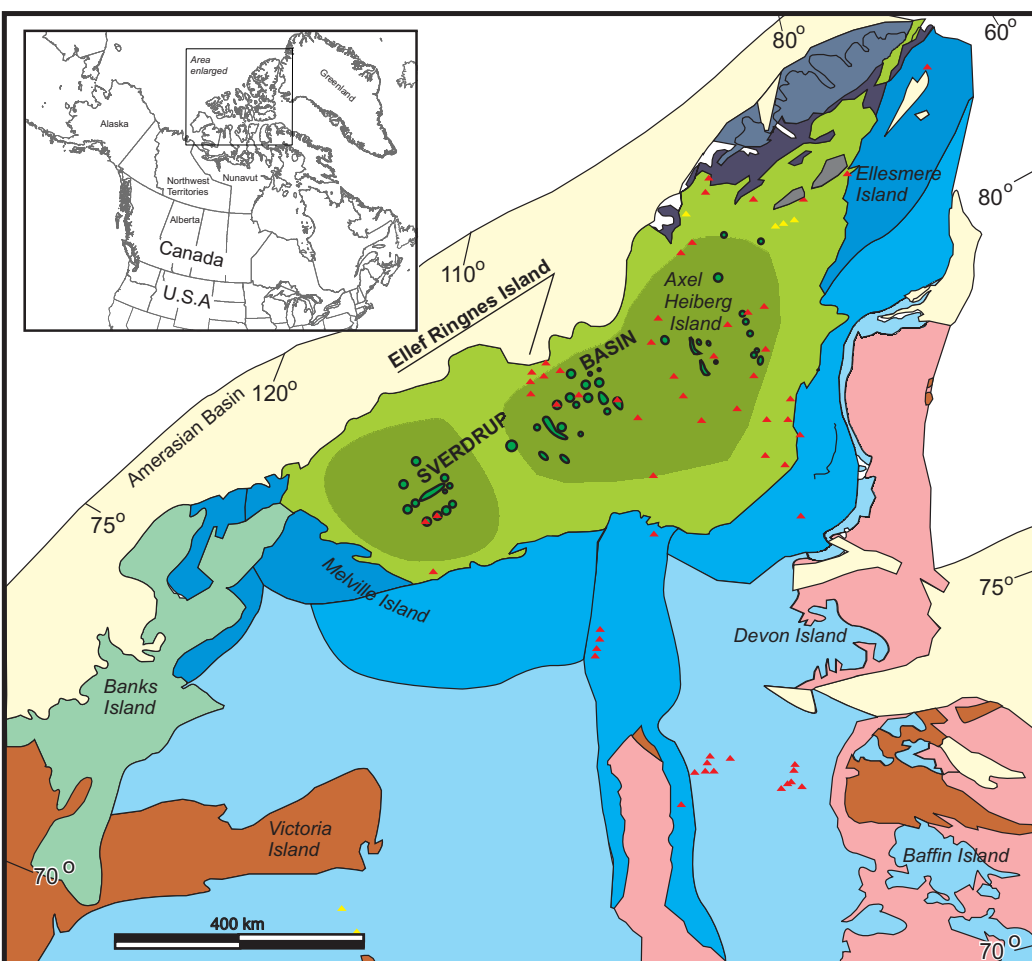
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				<i>Granulatisporites</i>	A.C. Ibrahim 1933
				<i>Dictyophyllidites harrisii</i>	Couper 1958
				<i>Pilososporites verus</i>	Archangelsky and Llorens 2005
				<i>Undulatisporites undulapolus</i>	Brenner 1963
				<i>Foveosporites subtriangularis</i>	Brenner 1963
				<i>Plicifera dicarpoides</i>	(Grigorjeva 1961) Ravn and Witzke 1995
				<i>Gemmatriletes clavatus</i>	Brenner 1963
				<i>Microreticulatisporites uniformis</i>	Singh 1964
				<i>Retitriletes austroclavidites</i>	(Cookson 1953) Döring, Krtzsch, Mai and Schulz in Krtzsch 1963
	Lycopodiopsida	Lycopodiales	Lycopodiaceae	<i>Lycopodiumsporites expansus</i>	Singh 1971
				<i>Lycopodiumsporites indetermined</i>	Delcourt and Sprumont 1955
				<i>Leptolepidites verrucatus</i>	Couper 1953
	Isoetopsida	Selaginellales	Selaginellaceae	<i>Neoraistrickia truncata</i>	(Cookson 1953) Potonie 1956
	incertae sedis			<i>Acanthotriletes varispinosus</i>	Pocock, 1962
	Sphagnopsida	Sphagnales	Sphagnaceae	<i>Stereisporites antiquasporites</i>	(Wilson and Webster 1946) Dettmann 1963
	Hepaticeae	incertae sedis		<i>Aequitriradites spinulosus</i>	(Cookson & Dettmann 1958) Cookson & Dettmann 1961
Bryophyta				<i>Polycingulatisporites radiatus</i>	Zhang & Grant-Mackie 1997
	incertae sedis			<i>Cingulatisporites distaverrucosus</i>	Brenner 1963
	incertae sedis			<i>Matthesisporites tumulosus</i>	Döring 1964
Dinophyta	Dinophyceae	incertae sedis		Dinocysts indetermined	
Dinophyta	Dinophyceae	incertae sedis		<i>Veryhacium</i>	J. Deunff 1954
Chlorophyta	Chlorophyceae	Chlorococcales	Hydrodictyaceae	<i>Pediastrum</i>	Meyen 1829
Chlorophyta or Chomotriletes is incertae sedis (affinity Algal)	Charophyceae	Zygnematales	Zygnemataceae?	<i>Chomotriletes</i>	Naumova 1939 ex Naumova 1953
	incertae sedis			Algae indetermined	
Group Acritarcha	Subgroup Acanthomorphae	incertae sedis		<i>Micrhystridium</i>	Deflandre 1937 emend. Lister 1970
Group Acritarcha	incertae sedis			<i>Pterospermopsis</i>	W. Wetzel 1952
Cyanophycota	incertae sedis			<i>Sigmopolis</i>	Hedlund 1965

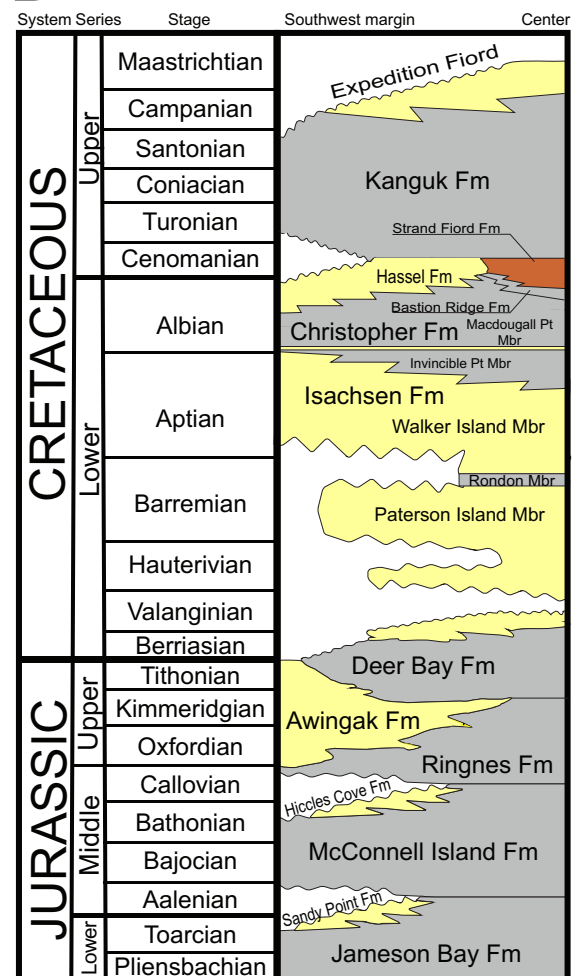
^aTaxonomic authorities not included in the references

Figure 1 Galloway et al.

A



B



CONTINENTAL MARGINS NEOGENE

Sands and gravels

RIFT BASINS JURASSIC - CRETACEOUS

Sandstone and shale

SVERDRUP BASIN CARBONIFEROUS - EOCENE

Shale, evaporite, and sandstone

Carbonate and sandstone

IGNEOUS ROCKS

▲ Cretaceous - Tertiary
▲ Permian

SALT-CORED STRUCTURES

● Diapirs, piercement structures

FRANKLINIAN MARGIN NEOPROTEROZOIC - DEVONIAN

Folded volcanic, deep water strata

Folded deep water strata

Thrust-fold belts in foreland and platform strata

ARCTIC PLATFORM CAMBRIAN - DEVONIAN

Undeformed carbonate evaporite, sandstone, and shale

CANADIAN SHIELD

MID-PROTEROZOIC Sedimentary basins

PEARYA TERRANE MID-PROTEROZOIC - SILURIAN

Volcanic, deep water and shallow water strata

ARCHEAN-PALEOPROTEROZOIC Crystalline basement

LEGEND

■ Mudstone
■ Sandstone
■ Igneous rock

Figure 2 Galloway et al.

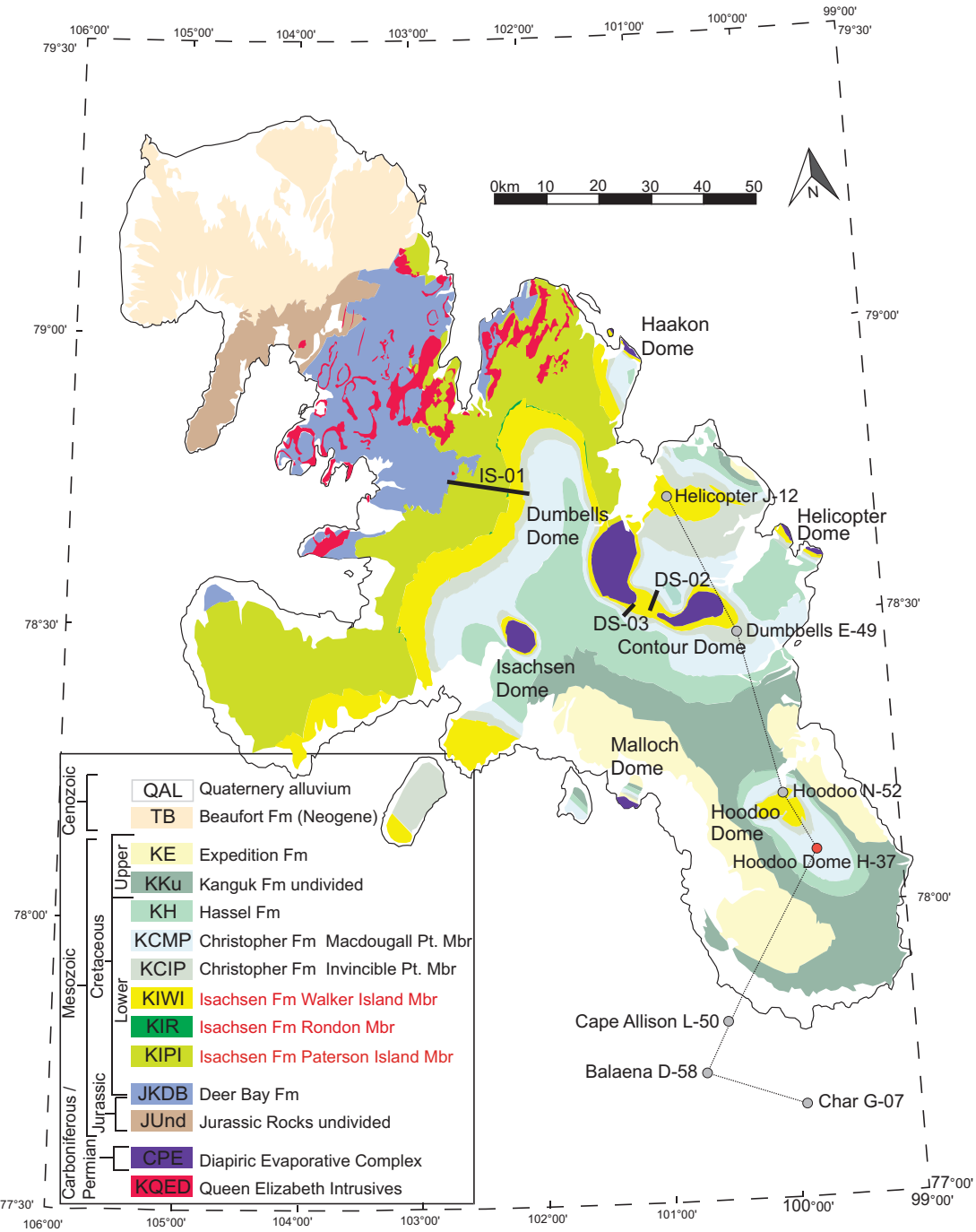


Figure 3 Galloway et al.

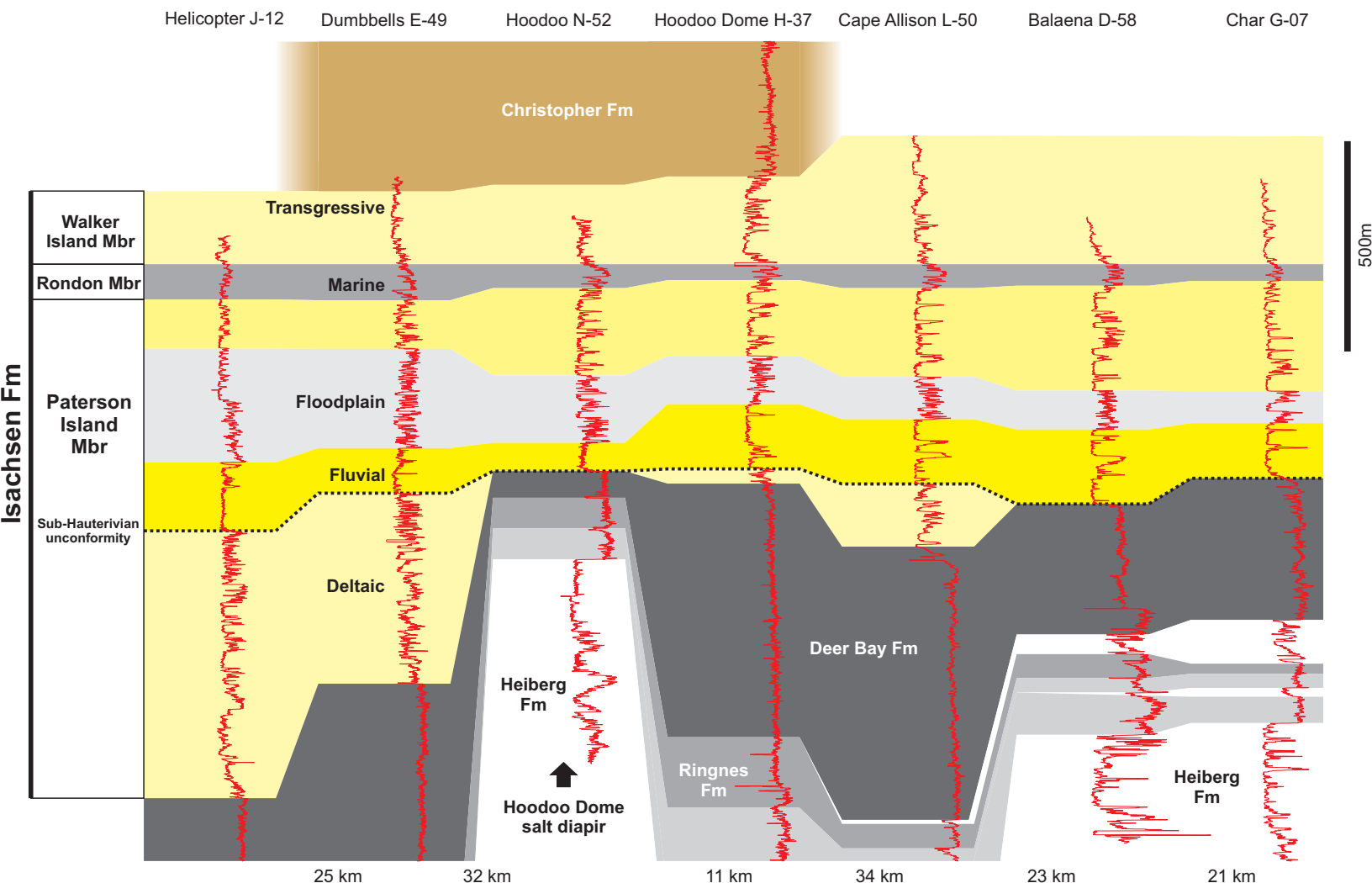


Figure 4A Galloway et al.

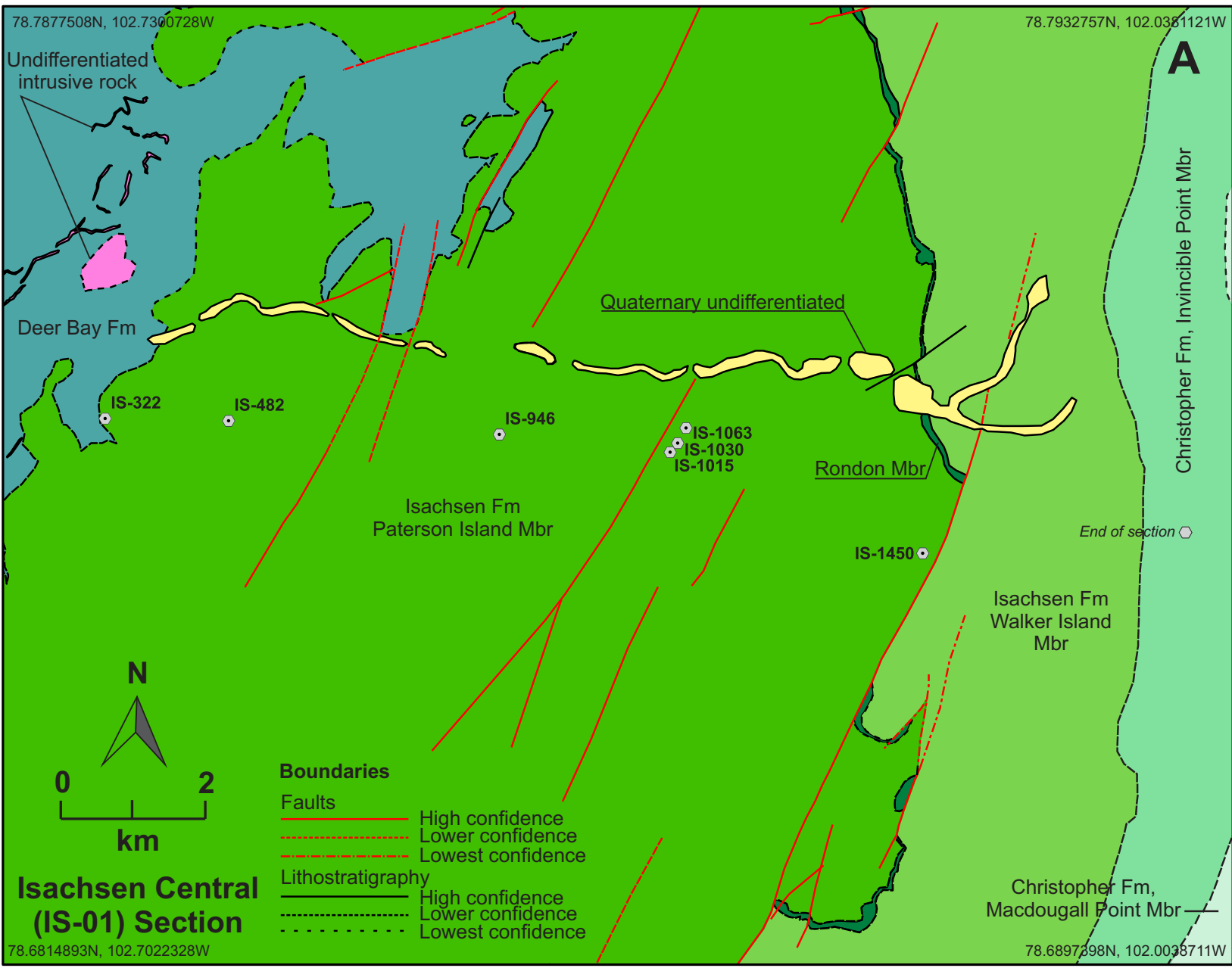


Figure 4B Galloway et al.

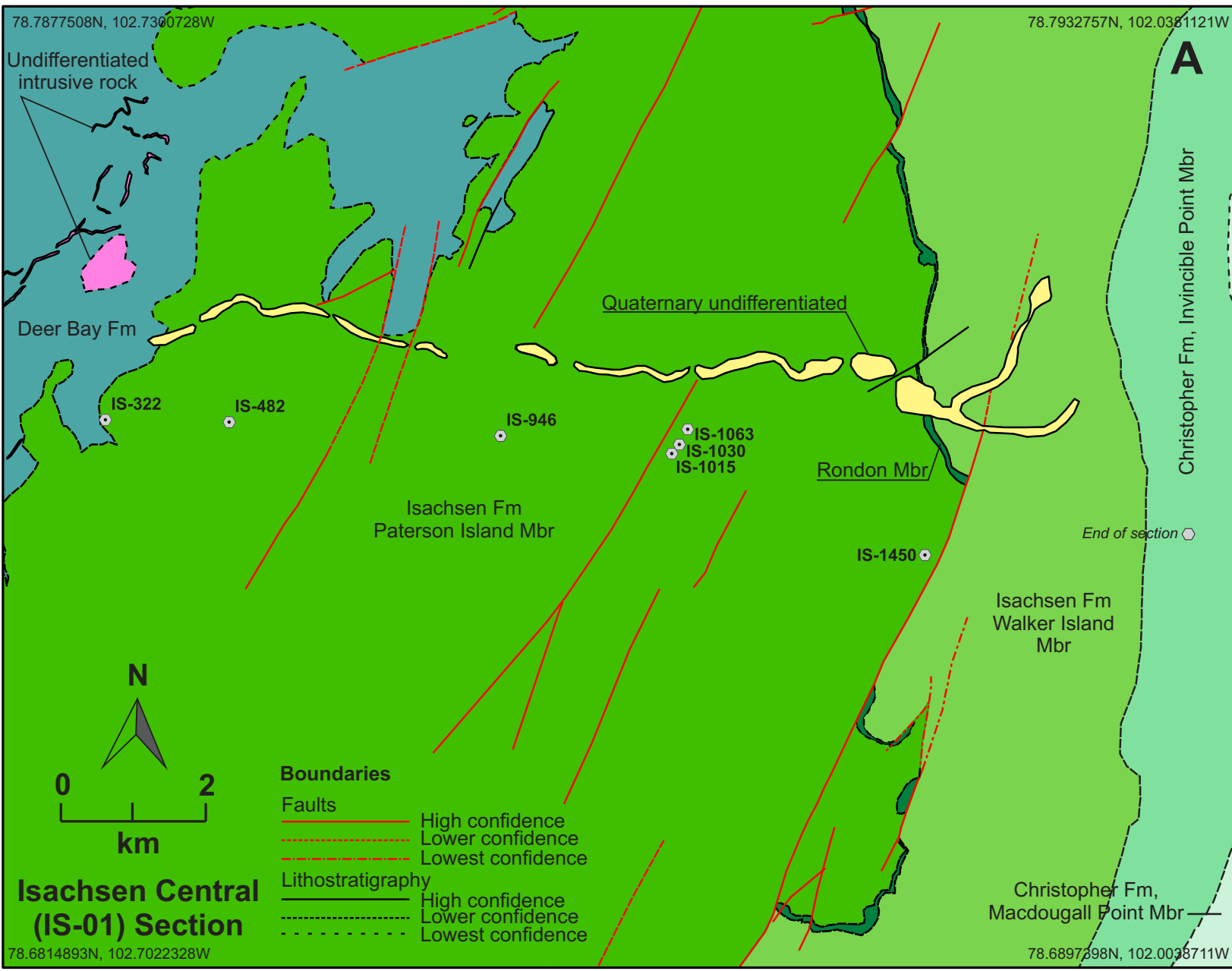


Figure 5 Galloway et al.

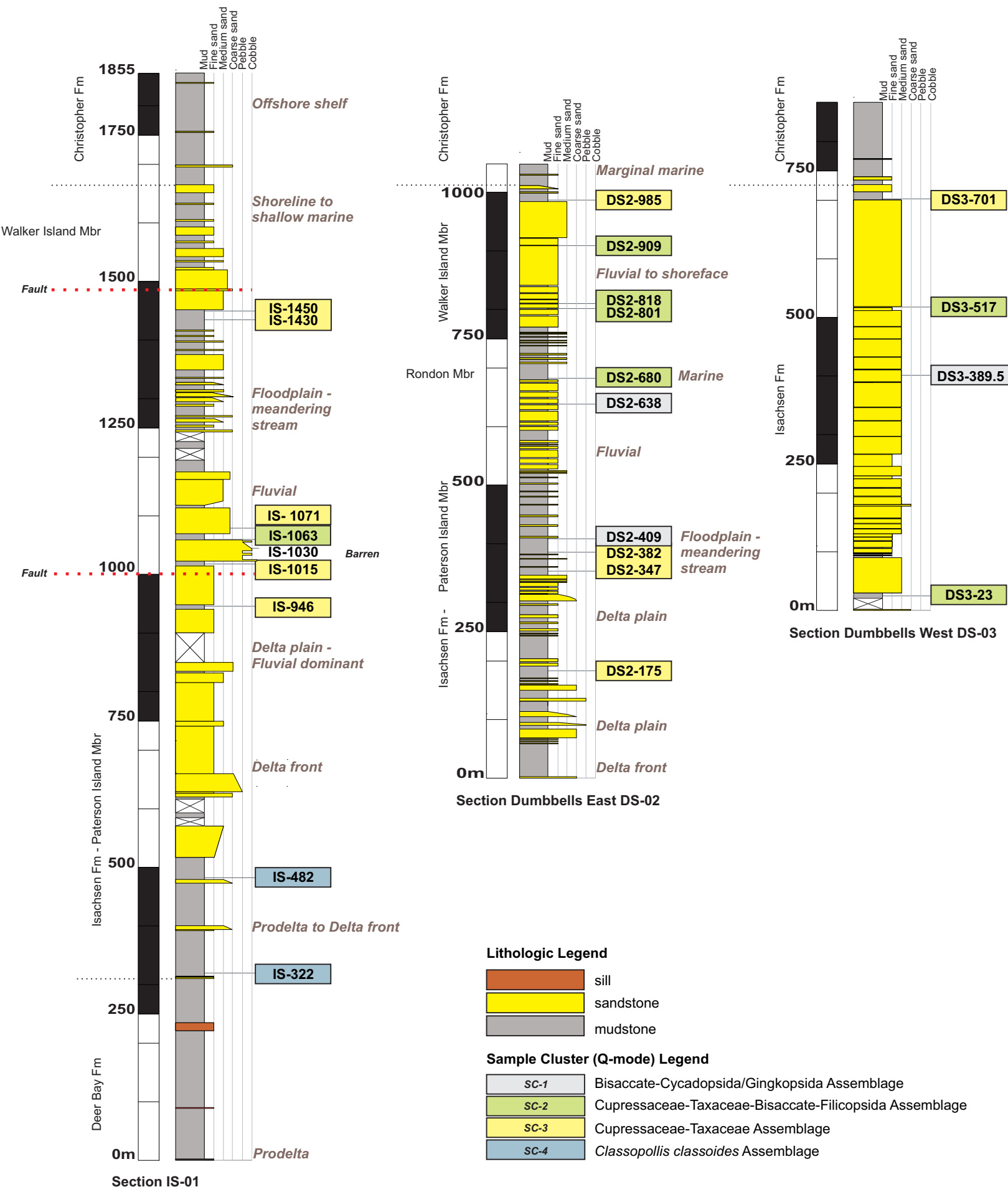
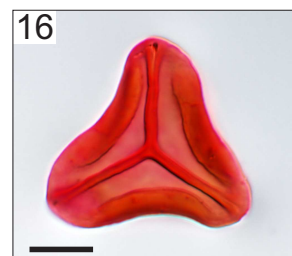
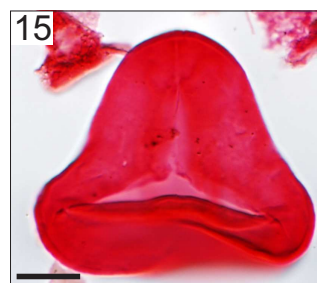
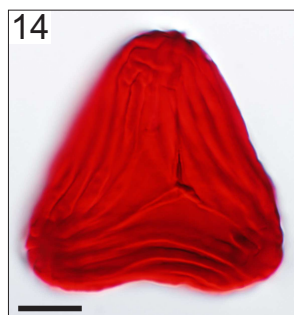
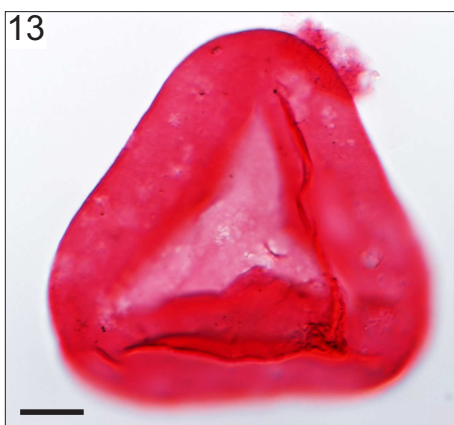
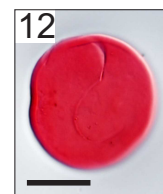
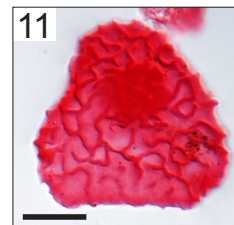
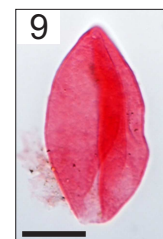
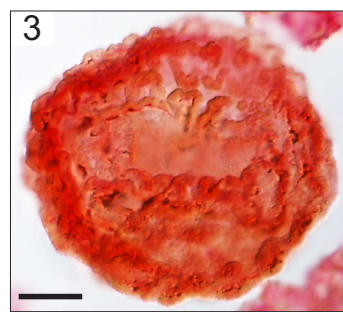
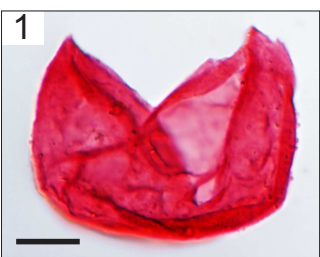
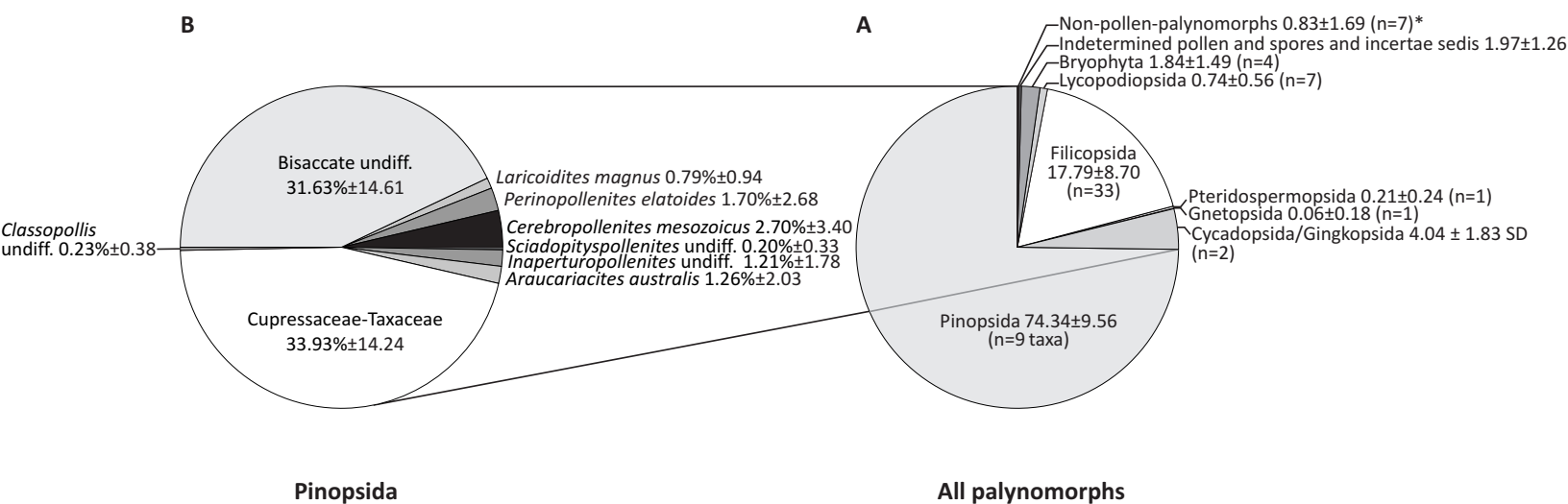


Figure 6 Galloway et al.

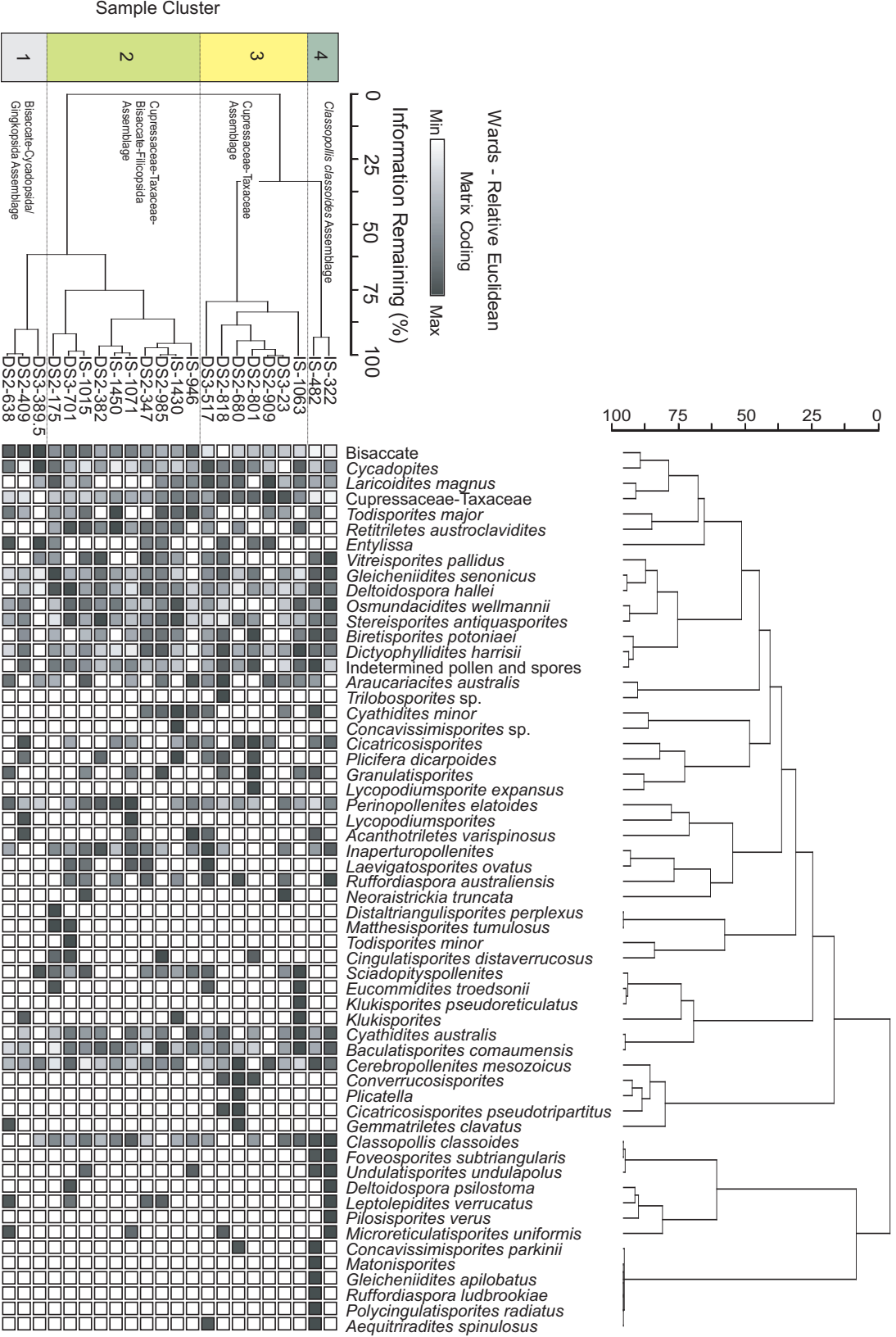


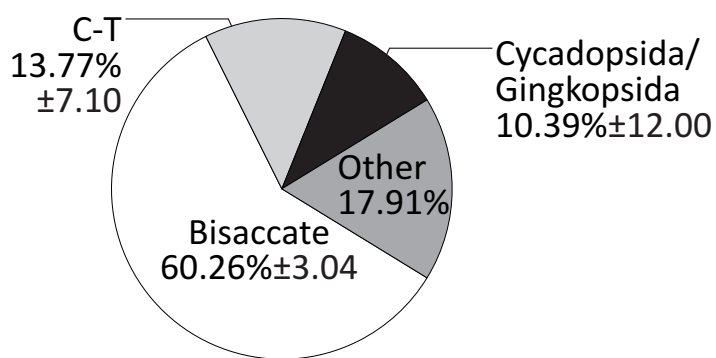
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Figure 7 Galloway et al.

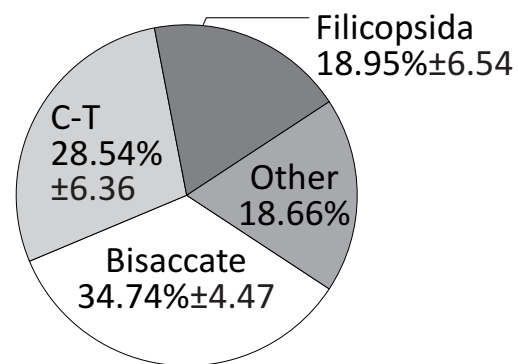


Relative abundance of pollen and spore sum (n=22 samples)
 *Relative abundance non-pollen palynomorphs not included in main pollen and spore sum
 Sigmopollis not included because semi-quantitative data
 Does not add to 100 due to rounding

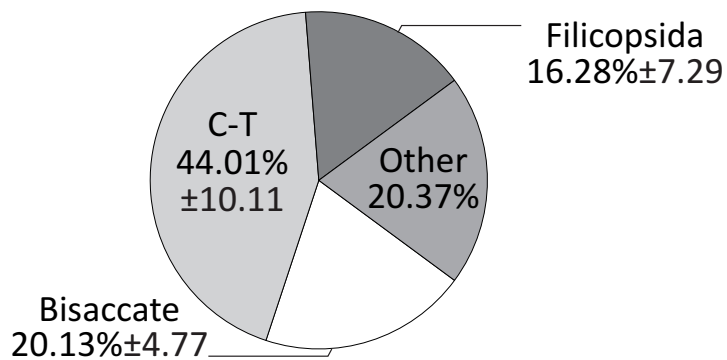




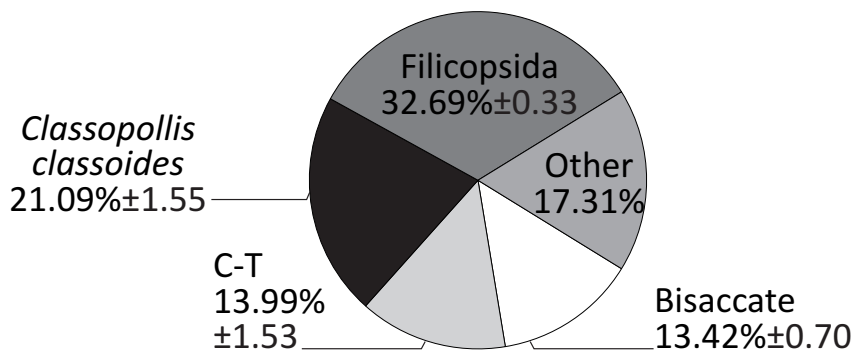
SC-1 Bisaccate-Cycadopsida/
Gingkopsida Assemblage



SC-2 Cupressaceae-Taxaceae-
Bisaccate-Filicopsida
Assemblage

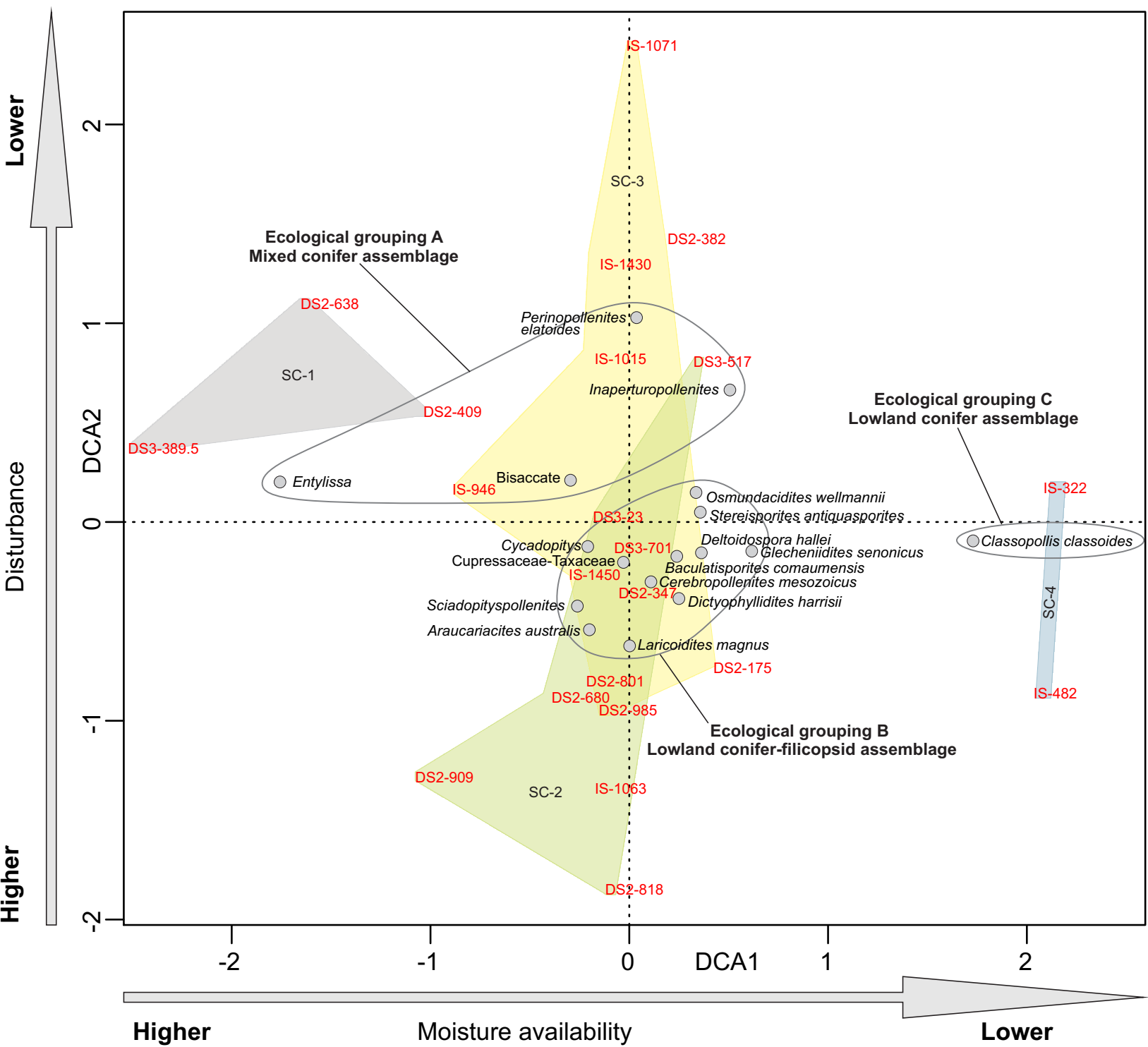


SC-3 Cupressaceae-Taxaceae
Assemblage



SC-4 *Classopollis classoides*
Assemblage

Figure 9 Galloway et al.



Supplementary Material Appendix A B

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