Late Cretaceous winter sea ice in Antarctica?

Vanessa C. Bowman[1], Jane E. Francis[1], James B. Riding[2]

[1]School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

[2]British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK

Email: V.C.Bowman@leeds.ac.uk

ABSTRACT

The Late Cretaceous is generally considered to have been a time of greenhouse climate, with no direct geological evidence for glaciation. We present, indirect evidence from the Maastrichtian sedimentary record for significant, rapid sea-level changes suggests that ice sheets were growing and decaying on Antarctica at that time. Evidence for possible seasonal sea ice during the Maastrichtian [?largely] derives from the palynomorph record of Seymour Island, Antarctica. The small, spine-bearing dinoflagellate cyst *Impletosphaeridium clavus* is dominant, accounting for up to 99% of the marine palynoflora. Its profusion is interpreted as the accumulation of resting cysts from dinoflagellate blooms associated with winter sea ice decay. Peaks and lows of *Impletosphaeridium clavus* abundance represent particularly cold episodes caused by temporary stratification of polar waters, interposed with warmer periods when the ocean was well-mixed. Immediately prior to the Cretaceous-Paleogene boundary, *Impletosphaeridium clavus* decreased dramatically in abundance, interpreted to represent an early expression of warming associated with Deccan Traps volcanism. Terrestrial conditions inferred from spore/pollen data are consistent with the climate interpretations based on *Impletosphaeridium clavus,* and together provide the highest southern paleolatitude expression of global climate during the Maastrichtian. These

palynomorph data, [?]together with $\delta^{18}O$ values from macrofossils, support the presence of ephemeral ice sheets on Antarctica during the Late Cretaceous, and highlight the extreme sensitivity of this region to global climate change.

INTRODUCTION

Following peak warming during the Cretaceous (Turonian) Thermal Maximum (Wilson et al., 2002), global climates cooled during the latest Cretaceous (Friedrich et al., 2012). The well-established, rapid and significant sea level falls at this time requires the [controversial] presence of ephemeral ice sheets on Antarctica (Miller et al., 2005). There is no geological evidence, such as glacial tillites or ice-rafted debris (IRD), of glaciation during the Maastrichtian. Paleobotanical evidence, however, indicates significant cooling in the Antarctic Peninsula region (Francis and Poole, 2002). Here we present new evidence of Maastrichtian climates at 65ºS based on palynology, including evidence of particularly cold episodes, using the dinoflagellate cyst *Impletosphaeridium clavus* Wrenn and Hart,1988 emend. Bowman et al. 2013 as a proxy. We present the first high-resolution, quantitative Maastrichtian to Danian palynomorph dataset from Seymour Island, off the northeast tip of the Antarctic Peninsula (Fig. 1). This is the highest southern paleolatitude exposure of sediments of this age in the world.

METHODOLOGY

A ~1100 m stratigraphic section comprising homogenous, unconsolidated silty-clays and clayey-silts was measured and sampled at high resolution (i.e. every 0.5 to 2 m) throughout the continuous outcrop of the López de Bertodano Formation (LDBF) on Seymour Island (Figs. 1, 2). Eighty-one sediment samples were quantitatively processed for palynomorphs throughout (Table DR1). The age of the section is Maastrichtian to earliest Danian based on magnetostratigraphy and strontium isotope stratigraphy (McArthur et al., 1998; Tobin et al., 2012). Macrofossil, microfossil and palynomorph evidence together with an iridium anomaly at the Cretaceous-Paleogene (K/Pg) boundary support this age model (Elliot et al., 1994; Olivero, 2011; Bowman et al., 2012; Table DR2). Numerical ages herein are based on Gradstein et al. (2012), which place the K/Pg boundary at 66.0 Ma; this is at 1007.5 m in our section.

RESULTS

Dinoflagellate cysts and acritarchs comprise, on average, 70% of the palynofloras below horizon G at 830 m (Table DR1). The small, spine-bearing dinoflagellate cyst *Impletosphaeridium clavus* is dominant, representing up to 99% of the marine palynofloras and attaining up to ~137,000 specimens per gram of sediment. The palynomorph record has been divided by five horizons (A, C, E, G and I; Fig 2) into five intervals (B, D, F, H and J; Fig. 2). Below 830 m, three conspicuous abundance peaks of *Impletosphaeridium clavus* are recorded at horizons A, C and E (143 m, 407 m and 746 m respectively), with intervening intervals of lower concentrations (B, D and F, Fig. 2). The remainder of the marine palynoflora includes typical South Polar Province dinoflagellate cyst genera, such as *Manumiella* spp. (Bowman et al., 2012). Within the same facies, this fluctuating pattern ends abruptly at horizon G with the concentration of *Impletosphaeridium clavus* decreasing to only hundreds of specimens per gram of sediment above 830 m. *Impletosphaeridium clavus* increases again in abundance immediately below the K/Pg boundary, but at relatively low concentrations compared with the lower part of the section.

Plant spores and pollen become dominant during interval H (averaging 71% of the entire palynoflora, Table DR1), coincident with the abrupt decrease in concentration of *Impletosphaeridium clavus*. *Laevigatosporites ovatus* (fern) and *Stereisporites* *antiquasporites* (moss) spores, together with *Nothofagidites* spp. (southern beech), *Peninsulapollis gillii* (Proteaceae), *Phyllocladidites mawsonii* and *Podocarpidites* spp. (podocarp conifers) pollen dominate throughout, with rare aquatic fern spores (e.g. *Azolla* spp.) and freshwater algae (e.g. *Botryococcus braunii*). *Nothofagidites* spp. pollen is more abundant and fungal palynomorphs absent at the *Impletosphaeridium clavus* peaks. The distinctive angiosperm pollen species *Tricolpites reticulatus* (Gunneraceae), *Clavamonocolpites polygonalis* (?Chloranthaceae) and *Ericipites scabratus* (Ericaceae) occur rarely between *Impletosphaeridium clavus* peaks A and C, and between peak E and the K/Pg boundary (Figs. 2 and DR1).

DISCUSSION

Evidence from neodymium isotopes suggests that deep-water formation, and consequent mixing of the water column, began in the Southern Ocean during the Campanian (Robinson et al., 2010). A relatively mixed water column at this time is supported by a lower planktic to benthic oxygen-isotope gradient during the Maastrichtian compared with the Cenomanian (Huber et al., 2002). Density-driven overturning and wind-driven upwelling, as in the modern Southern Ocean, would have ventilated the entire water column (Mitchell et al., 1991; Sigman et al., 2004). This scenario of a mixed, oxygen and nutrient-rich water column provides the setting for any oceanic change at the Antarctic margin during the Maastrichtian, and may have been the contextual state of the ocean represented by intervals B, D and possibly F in the *Impletosphaeridium clavus* record from Seymour Island (Fig. 2).

The acmes of *Impletosphaeridium clavus* at A, C and E (Fig. 2) project from the background levels below 830 m, and are interpreted as reflecting accumulations of resting cysts during periods (lasting perhaps tens of thousands of years) of enhanced seasonal bloom activity (rapid population increases) of the parent dinoflagellates. Dinoflagellate blooms occur today in freshwater and marine coastal environments of the low to mid latitudes in response to enhanced nutrient levels and temperature-driven stratification, primarily during the late spring to early summer (Stipa, 2002; Kudela et al., 2005; Michalak et al., 2013). Dinoflagellate blooms are also known to occur in the modern high northern and southern latitudes associated with the melting of seasonal sea ice, followed by the production of vast quantities of resting cysts (Becquevort et al., 1992; Stoecker et al., 1992). These abundant cysts then fall to the sea floor when the ice melts in late spring or early summer (Harland and Pudsey, 1999).

To investigate the striking abundance pattern of *Impletosphaeridium clavus* during the Maastrichtian off the Antarctic margin, we studied geochemical and additional palynofloral data from Seymour Island (Fig. 2). Tobin et al.'s (2012) $\delta^{18}O$ values from macrofossils correlate remarkably well, showing an increase through interval D, then decrease through intervals F and H, mirroring the *Impletosphaeridium clavus* record (Fig. 2). This close correlation of Tobin et al.'s (2012) data with our palynomorph data further strengthens our age model. Overall, heavier $\delta^{18}O$ values correspond to periods of higher abundance of *Impletosphaeridium clavus* (particularly at horizon E, Fig. 2). We infer from this conformity of pattern that blooms of the dinoflagellate that produced the resting cyst *Impletosphaeridium clavus* occurred during periods of particularly cool benthic and intermediate water off the Antarctic Peninsula region during the Maastrichtian.

No other marine (or terrestrial) palynomorph exhibits a similar abundance pattern to *Impletosphaeridium clavus* (e.g. Thorn et al., 2009), which suggests that there is a unique environmental factor (not otherwise recorded in the sedimentary record), influencing the success of the dinoflagellate that produced this cyst. We infer from the close correlation of the $\delta^{18}O$ record that it preferred cool to cold water temperatures, and may even have tolerated near-freezing conditions based on Tobin et al.'s (2012) lowest annually-averaged estimate of

~4-5°C, close to the *Impletosphaeridium clavus* acme at horizon E. In addition, $\delta^{18}O$ measurements from a belemnite (*Dimitobelus seymouriensis* Doyle and Zinsmeister 1988) correlate to our section immediately below the *Impletosphaeridium clavus* acme at horizon C (open arrow "c", Fig. 2). This suggests a similar intermediate to deep-water mean annual temperature of a cool 6°C at this level with an average annual variability of 5°C (Dutton et al., 2007). These cool intermediate and benthic water temperatures are derived from average annual $\delta^{18}O$ isotope values, and do not preclude surface water temperatures, especially during the Antarctic winter, dropping below freezing and supporting sea ice development.

We infer that the most likely explanation for dinoflagellate blooms in cold, generally well-mixed, shallow marine waters at the Antarctic margin is that they occurred in association with the melting of seasonal sea ice. Although there is no direct modern analogue of *Impletosphaeridium clavus* (Bowman et al., 2013), unsurprising for a cyst from the Late Cretaceous, there are many taxa of small spiny cysts, all comparable in gross morphology, known from sea ice, modern and Quaternary sediment in cold environments of the high southern and northern latitudes (Buck et al., 1992; Stoecker et al., 1992, 1997; Head et al., 2001; Radi et al., 2013). Several of these are characteristic of regions where seasonal sea ice forms (e.g. *Islandinium*? *cezare* (de Vernal et al. 1989 ex de Vernal in Rochon et al. 1999) Head et al. 2001; Fig. 2) and, comparable to the abundance record of *Impletosphaeridium clavus* presented here, some can dominate up to 90% of marine palynomorph assemblages (De Vernal and Rochon, 2011; Radi et al., 2013). The dinoflagellate that produced *Impletosphaeridium clavus* may have had a similar life strategy to that of modern *Biecheleria baltica* Moestrup et al. 2009, a brackish water dinoflagellate (also with a small, spiny resting cyst) associated with sea ice cover in the Baltic Sea (Klais et al., 2011; Warns et al., 2012). *Biecheleria baltica* produces vast quantities of resting cysts, which accumulate in benthic cyst beds (at relatively shallow water depths) and promote intense spring blooms by the motile seeding of the euphotic zone (Klais et al., 2011).

The reconstruction of pre-Quaternary sea ice from the fossil record in both the Arctic and Antarctic has previously relied on the modern analogue interpretation of *Leiosphaeridia* spp. acritarchs, diatoms, foraminifera and terrigenous IRD (St. John, 2008; Davies et al., 2009; Stickley et al., 2009). Diatoms and foraminifera are sparse in the LDBF (e.g. Harwood, 1988). However, the lack of diatoms characteristic of sea ice in the fossil record may be due to a specific paleoecological scenario. For example, early salinity stratification in the modern Baltic Sea favors dinoflagellates over diatoms in the spring blooms associated with sea ice retreat (Klais et al., 2011). No *Leiosphaeridia* spp. or indisputable IRD were recorded from the LDBF. *Leiosphaeridia* spp., which has been used as a proxy for sea ice in the Neogene of Antarctica by Hannah (2006), is present in the Campanian of Humps Island (Wood and Askin, 1992) and may suggest the presence of sea ice in the Antarctic Peninsula region even earlier in the Cretaceous. Habitat difference, e.g. water depth, nutrient availability or levels of oxygenation, may explain their absence in the Maastrichtian record of Seymour Island (Jacobson, 1979).

The lack of IRD in our section is perhaps understandable because, based on the presence of diverse and abundant terrestrial palynomorphs (Askin, 1990), the nearest landmass was vegetated and distant from any potential ice caps at high elevations in the Antarctic continental interior. If sea ice was present it may not have been land-fast, preventing the entrainment of out-sized terrigenous IRD. Manoj et al. (2013) noted that IRD is largely absent in the Holocene of the Indian sector of the Southern Ocean, inferring that this is a result (as in past interglacials) of ice sheet accumulation being mainly restricted to high continental interiors. Similarly, and perhaps for the same reasons, no direct evidence of ice from Late Cretaceous sediments was recovered from Ocean Drilling Program Leg 113 cores in the Weddell Sea (Kennett and Barker, 1990).

If, as we contend, fossil *Impletosphaeridium clavus* abundances may be used as a proxy for seasonal sea ice, an explanation is required for the episodic, vast accumulations of this cyst that peak at horizons A, C and E (Fig. 2). Dinoflagellates bloom today at the retreating sea ice margin, so variation in the accumulation of fossil resting cysts through geological time in the LDBF must reflect an overprint of an additional longer-term climate or habitat change. One suggestion is these periods of enhanced production of resting cysts may reflect particularly cold climatic phases where the water column became more stratified on the shallow marine shelf, as suggested for deeper waters in the Southern Ocean during the Pliocene (Sigman et al., 2004). These phases, straddling the *Impletosphaeridium clavus* abundance peaks, perhaps lasted tens of thousands of years, and may reflect variations in orbital cyclicity. [agreed – it is a tad speculative – JBR]

On the LDBF shelf, which had a slightly fresher surface layer due to riverine inflow, a climatic cooling may have diminished the influence of background temperature-driven mixing, thereby allowing the establishment of a more stable water column in the basin influenced by salinity stratification. During the spring, the formation of an oxygen-rich surface layer, with increased light levels (due to less mixing), and nutrients replenished via buoyant terrestrial inflow and the sea ice melt, would have promoted monospecific blooms of habitat-specific dinoflagellates. Dinoflagellates would still have bloomed during sea ice retreat between these colder spells (i.e. during the middle of intervals B, D and F, Fig. 2), but with less stratification, the light levels would have been lower and the incoming nutrients more diluted throughout the water column, resulting in lower numbers of dinoflagellates and their resting cysts.

Additional evidence for Maastrichtian climatic change comes from the terrestrial palynomorph record of Seymour Island, which indicates that the region was forested with southern beech (*Nothofagus* spp.) and conifers (mainly *Podocarpidites* spp.). Most modern relatives of the southern beech grow in wet, cool to cold environments (Read et al., 2010). Below the K/Pg boundary, *Nothofagidites* spp. abundance was lowest during phase H and highest below G, peaking alongside the *Impletosphaeridium clavus* acmes at horizons A, C and E (Fig. 2, Table DR1). By contrast, *Nothofagidites* spp. abundance was lower, although variable, in the intervening warmer phases B and D (Fig. 2). Furthermore, pollen representing specific thermophylic plants such as Gunneraceae (*Tricolpites reticulatus*) appears first during warmer phase B, and much more frequently above horizon E as the region warmed again towards the latest Maastrichtian (Fig. 2, Table DR3). The presence of fungal remains during warm phases B and D, their absence during cold episodes A, C and E, and their increase in frequency of occurrence following E supports evidence for pre-K/Pg warming (Fig. 2). This is consistent with an increase in saprophytic degradation of the terrestrial biomass which grew during the warmer climate. In addition, from the marine macrofossil record, the restricted stratigraphic occurrences of the belemnite *Dimitobelus seymouriensis* Doyle 1988 and the ammonite *Zelandites varuna* Forbes 1846 support our interpretation of short-term warmer intervals (Zinsmeister, 2001; Fig. 2).

Previous research supports a generally cool climate in this region during the Maastrichtian. Dicotyledonous wood analysis suggests mean annual terrestrial temperatures of 7°C (Francis and Poole, 2002) and marine molluscan extinction patterns indicate Campanian to Maastrichtian cooling associated with regional shallowing (Crame et al., 1996). Additionally, chemical weathering and sediment maturity suggest probable cold temperate or sub-polar conditions for the Antarctic interior during the Maastrichtian (Dingle and Lavelle, 1998).

With no change in facies, the abrupt decrease in abundance of *Impletosphaeridium clavus* across horizon G in the LDBF is interpreted as representing rapid warming that lasted until the K/Pg boundary, which prevented the build-up of winter ice in the northern Antarctic Peninsula region. This coincides with lower abundances of *Nothofagidites* spp. and an increase in the occurrence of thermophylic plants and saprophytic fungal remains through phase H, all suggesting warming. *Impletosphaeridium clavus* increases again in abundance across the K/Pg boundary, but irregularly and in low numbers. Similarly, *Nothofagidites* spp. again increases in abundance into the Danian. This may indicate slight cooling associated with disturbed environments and an erratic recovery period from the K/Pg catastrophe.

The palynomorph record from the LDBF of Seymour Island strongly suggests a pattern of at least three particularly cold episodes during the Maastrichtian, followed by an abrupt warming immediately prior to the K/Pg event. This is consistent with other records of Maastrichtian climate trends, which indicate overall cooling until a sudden warming before the K/Pg boundary (Barrera and Savin, 1999; Abramovich and Keller, 2003). From the mid Campanian to ~500 ka prior to the K/Pg boundary, oxygen and carbon isotope excursions indicate two significant cooling episodes (Barrera and Savin, 1999; Friedrich et al., 2012) superimposed on a long-term cooling trend of intermediate waters, particularly in the high latitudes. The first of these, the Campanian-Maastrichtian Boundary Event (CMBE, base of C32N1 to upper C31R), is characterized by a significant global negative carbon isotope excursion, associated with climatic cooling and sea level fall (Friedrich et al., 2009; Jung et al., 2012). Based on magnetostratigraphy, the end of the CMBE correlates with the lower ~500 m of our section, encompassing the cold episodes interpreted at horizons A and C (Fig. 2). The second cooling episode recognized from the deep sea occurred from uppermost C31N to the top of C30N (Barrera and Savin, 1999) bracketing the final *Impletosphaeridium clavus* acme during the Maastrichtian (horizon E, Fig. 2). The causes of these oceanic cool phases remain controversial; they have been related to short-term changes in thermohaline circulation and/or the development of ephemeral ice sheets on Antarctica in association with global regressions (Miller et al., 2005; Koch and Friedrich, 2012). Further evidence supporting intervening warmer phases comes from $\delta^{13}C$ and $\delta^{18}O$ analysis of paleosol carbonates (Nordt et al., 2003; correlated to interval B, Fig. 2) and bulk carbonate (Voigt et al., 2012; interval D, Fig. 2).

The earliest records of abundant *Impletosphaeridium clavus* in the James Ross Basin supports the timing of the onset of cold climates in Antarctica during the Campanian evidenced by neodymium isotopes, and the coeval extinction of inoceramid bivalves (Dolding, 1992; Crame and Luther, 1997; Robinson et al., 2010; Bowman et al., 2013). The switch to deep-water production at the Antarctic margin at this time (Robinson et al., 2010) strengthens the link made here between abundant *Impletosphaeridium clavus* and the presence of seasonal sea ice in the Cretaceous because the formation of cold deep waters on the Antarctic shelf today is intrinsically linked to winter sea ice formation (Withworth et al., 1998).

Our data interpretations suggest climate may have been cold enough periodically to initiate short-term glaciations of Antarctica, probably restricted to high elevations in the continental interior, during the Maastrichtian. Modeling exploring Cenozoic glaciation corroborates this theory by predicting that significant sea ice forms only in the Southern Ocean *after* the initiation of ice sheets in central Antarctica (DeConto et al., 2007). Hong and Lee (2012) concurred that the Maastrichtian was cold enough to have allowed Antarctic glaciation using estimates of *p*CO2 levels below 500 ppm from low latitude pedogenic carbonates.

Analysis of our data suggests that a latest Maastrichtian climatic warming (beginning after horizon E, Fig. 2) probably prevented the survival of seasonal sea ice at this paleolatitude, even in the coldest winters. One explanation for this is that at the Antarctic margin, ~2 Ma prior to the K/Pg boundary, the marine and terrestrial fossil record has recorded the beginning of a latest Maastrichtian greenhouse event. Globally, warming through ~500 ka prior to the K/Pg boundary, has been attributed to outgassing associated with the main pulse of Deccan Traps volcanism (Barrera and Savin, 1999; Abramovich and Keller, 2003; Nordt et al., 2003). The earliest (albeit minor) eruptive phase of Deccan Traps volcanism began at the base of C30N (Chenet et al., 2009), coincident with significant changes in the fossil record on Seymour Island. At this level, the final decline in *Impletosphaeridium clavus* numbers began prior to the K/Pg boundary, *Nothofagidites* spp. pollen abundance began to decrease, warmth-loving angiosperm taxa suddenly appeared, saprophytic fungal spores became more prevalent and a decrease in $\delta^{18}O$ isotope values from macrofossils occurred (Tobin et al., 2012) (Fig. 2). We contend that our data from this expanded Maastrichtian section highlight the extreme sensitivity of the Antarctic paleoenvironment to global climatic change.

CONCLUSIONS

We provide the first evidence endorsing the presence of seasonal sea ice during the Late Cretaceous at the Antarctic margin. The profusion of *Impletosphaeridium clavus* from the Maastrichtian succession of Seymour Island is considered to represent dinoflagellate blooms and subsequent accumulation of their resting cysts related to winter sea ice decay, much like those produced in abundance today by sea ice dinoflagellates in the Southern Ocean. We consider this as a novel potential proxy for seasonal sea ice and thus Antarctic paleoclimate. Superimposed on a cooling Maastrichtian climate and a generally well-mixed water column, *Impletosphaeridium clavus* acmes suggest particularly cold episodes during temporary stratification of shallow marine waters, interposed with slightly warmer periods when temperature-driven mixing was re-established. Climate interpretations of the terrestrial palynomorph record and $\delta^{18}O$ isotope analyses from macrofossils support these interpretations. Based on our age model, the palynomorph record herein represents the highest southern paleolatitude expression of global Maastrichtian climate events, including evidence for the end of cooling and perhaps early expression of warming in the latest Cretaceous associated with Deccan Traps volcanism. The Seymour Island palynomorph record of seasonal sea ice for most of the Maastrichtian, in turn, strongly supports year-round glaciation at elevation in the interior of the continent. This agrees with the controversial notion of ephemeral Late Cretaceous ice caps on Antarctica as a causal mechanism for eustatic change and highlights the extreme sensitivity of the high southern paleolatitudes to global climate change.

ACKNOWLEDGMENTS

We thank J.A. Crame, A.M. Haywood, S.J. Hunter, J. Witts and R. Raiswell for discussions, and the British Antarctic Survey and HMS Endurance for logistics during Antarctic fieldwork. Crispin Day, Bruce Mortman and Matt Priestman provided field support. This work was funded by a Natural Environment Research Council (NERC) Antarctic Funding Initiative project (Grant NE/C506399/1). VCB received additional funds from the TransAntarctic Association and an Antarctic Science Bursary. JBR publishes with the approval of the Executive Director, British Geological Survey (NERC).

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FIGURE CAPTIONS

Figure 1. Location map of Seymour Island, Antarctica, using modern geography.

Figure 2. The abundance of key Maastrichtian palynomorphs from Seymour Island (this study), $\delta^{18}O$ isotope values and key occurrences of macrofossils (Tobin et al., 2012; Zinsmeister, 2001) and their interpretation regarding regional paleoclimate and possible sea ice presence. Timescale based on the correlation of magnetostratigraphy (Tobin et al., 2012) and strontium isotope stratigraphy (McArthur et al. 1998; Vonhof et al., 2011) to our section using the K/Pg boundary as a datum (updated to Gradstein et al., 2012). Age model verified using biostratigraphical data cited in Table DR2 and an iridium anomaly found at the K/Pg boundary along strike (Elliot et al., 1994). Open arrow "a", *Pycnodonte* cf. *P. vesiculosa* (Sowerby 1823), 0 m (relative to K/Pg); open arrow "b", *Linotrigonia pygoscelium* [Van – I

could not find the author citation for this one – J], bivalve, -200 m; open arrow “c”, *Dimitobelus seymouriensis*, belemnite, -636 m (McArthur et al., 1998). Palynomorph events A to J are discussed in the text. Photomicrograph, i, *Impletosphaeridium clavus*, D5.930.1A, England Finder W65-1; ii, modern *Islandinium? cezare*, holotype, Saint-Césare, Quebec (SC 86-09, slide UQP 199-3B, B15-4; courtesy of Martin J. Head, Brock University). Brown triangles and black dots denote the presence of fungal palynomorphs and pollen comparable with modern angiosperm pollen from plants typical of warm, humid environments (Fig. DR1; Table DR3). The snowflake symbols indicate particularly cold climatic episodes as interpreted from the acmes of *Impletosphaeridium clavus*. *, Chenet et al. (2007, 2009); Robinson et al. (2009).

[1]GSA Data Repository item 20xxxxx, Figure DR1, Tables DR1, DR2 and DR3, and additional references are available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.