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samples of Wombat kimberlite pipe, Northwest Territories,
Canada**

**J.M. Galloway, M. Bringué, S.D. Buryak, A.V. Reyes,
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2022

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FOREWARD

Six samples from various depths from two drill-cores, CH93-29 and DDH00-5, of the Wombat kimberlite pipe, Lac de Gras kimberlite field, Northwest Territories, Canada, were analyzed for palynology for the purpose of biostratigraphic age determination and comparison to a U-Pb age recovered from a partially-altered tephra bed in core DDH00-5. Zircon crystals from this partially-altered tephra bed preserved in core DDH00-5 yielded a laser-ablation inductively-coupled-plasma mass-spectrometry (LA-ICP-MS) $^{206}\text{Pb}/^{238}\text{U}$ date of 82.36 ± 0.44 Ma (weighted-mean; $n=18$ of 34 dated zircon crystals; MSWD = 1.51; uncertainty quoted at 2σ ; Buryak, 2020), placing the material into the lower Campanian.

The palynology results reported here are from samples that overlie and underlie the dated tephra bed, as well as the tephra horizon itself. Pollen and spores are abundant and well preserved in all six samples, and one sample contains abundant and well preserved dinoflagellate cysts (dinocysts).

Characteristics of the Wombat drill core samples herein analyzed are summarized as follows: 1. *Aquilapollenites* and *Wodehousiea* pollen are absent in all of the preparations; 2. *Ulmipollenites*, *Betulaceoipollenites*, *Alnipollenites*, and *Caryapollenites* pollen are dominant angiosperm pollen elements in the preparations; 3. Assemblages are dominated by Cupressaceae-Taxaceae and *Pinuspollenites* pollen, with minor *Cycadopites* and *Metasequoia* pollen; and, 4. The basal sample of core CH93-29 contains abundant (30%) dinocysts, including *Alterbidinium acutulum*, *Isabelidinium cooksoniae*, *Trithyrodinium rhomboideum*, and *Trithyrodinium singhii*. While *Aquilapollenites* is a typical Upper Cretaceous taxon, its occurrence is geographically diachronous and in Alberta, this taxon does not appear until the middle Campanian. *Wodehouseia* is a typical Maastrichtian element. Thus, the absence of both of these taxa in the preparations is consistent with the early Campanian age of the tephra. *Ulmipollenites*, *Betulaceoipollenites*, *Alnipollenites*, and *Caryapollenites* pollen are common elements in Cenozoic strata and while their occurrences are commonly used to argue for a Cenozoic age, their lineages extend into the Mesozoic.

Quantitative palynology was used in the present analysis to infer paleoenvironments during deposition of the studied strata. An absence of dinocysts in all samples except for the basal sample of core CH93-29 suggests limited mixing of xenolithic debris and deposition in a lacustrine environment. Assemblages are dominated by Cupressaceae-Taxaceae and *Pinuspollenites* pollen, with minor *Cycadopites* and *Metasequoia* pollen, suggesting that warm to temperate wet-lowland environments that supported parent plants in mature upland coniferous communities as well as more dynamic lowland settings prevailed in the area surrounding the kimberlite pipe following its emplacement. Abundant dinocysts (30% of the assemblage) in the basal sample of core CH93-29 indicate the deposition and preservation of marine strata in the vicinity of the kimberlite that was reworked. This finding is consistent with previous work in the region that suggests the Western Interior seaway was wider than most models predict in the middle and Late Cretaceous. Dinocysts preserved in the sample range in age from Albian to Maastrichtian, although several taxa suggest a narrower time interval of Albian-Cenomanian. The absence of *Chatangiella* species in the preparation constrains the age of the marine strata to be older than Coniacian.

The dinocyst composition thus provides a biostratigraphic age determination of Albian-Cenomanian for sample 93-29-67-4-64 at 277.1 m VE depth in core CH93-29 based on dinocysts,

but the presence of angiosperm elements in this sample (*Caryapollenites*, Aceraceae) indicate that the Albian-Cenomanian material is reworked. A broad age of Turonian to early Campanian is inferred based on pollen and spore assemblages for all other samples preserved in lacustrine facies, immediately underlying and overlying the dated tephra.

INTRODUCTION

Six samples from various depths from two drill-cores of the Wombat kimberlite pipe, drilled by BHP Billiton in the Lac de Gras kimberlite field, Northwest Territories (NT), Canada (Fig. 1), were prepared and analyzed for palynology for the purposes of biostratigraphic age determination and comparison to a U-Pb age from a recovered bentonite bed in one of the cores. Core DDH00-5 is situated at 64.9168° N, 110.4368° W at an elevation of 449 m asl; it was drilled at an angle of -60° from horizontal and an azimuth of 262°. Core DDH00-5 is lodged at the Geological Materials Storage Facility of the Northwest Territories Geological Survey in Yellowknife, NT. Core CH93-29 is situated at 64.9156° N 110.4311° W at an elevation of 478 m asl; it was drilled at an angle of -45° from horizontal and an azimuth of 110° (Fig. 1). Core CH93-29 was donated to P.A. Siver by BHP Billiton and is lodged at Connecticut College in New London, Connecticut.

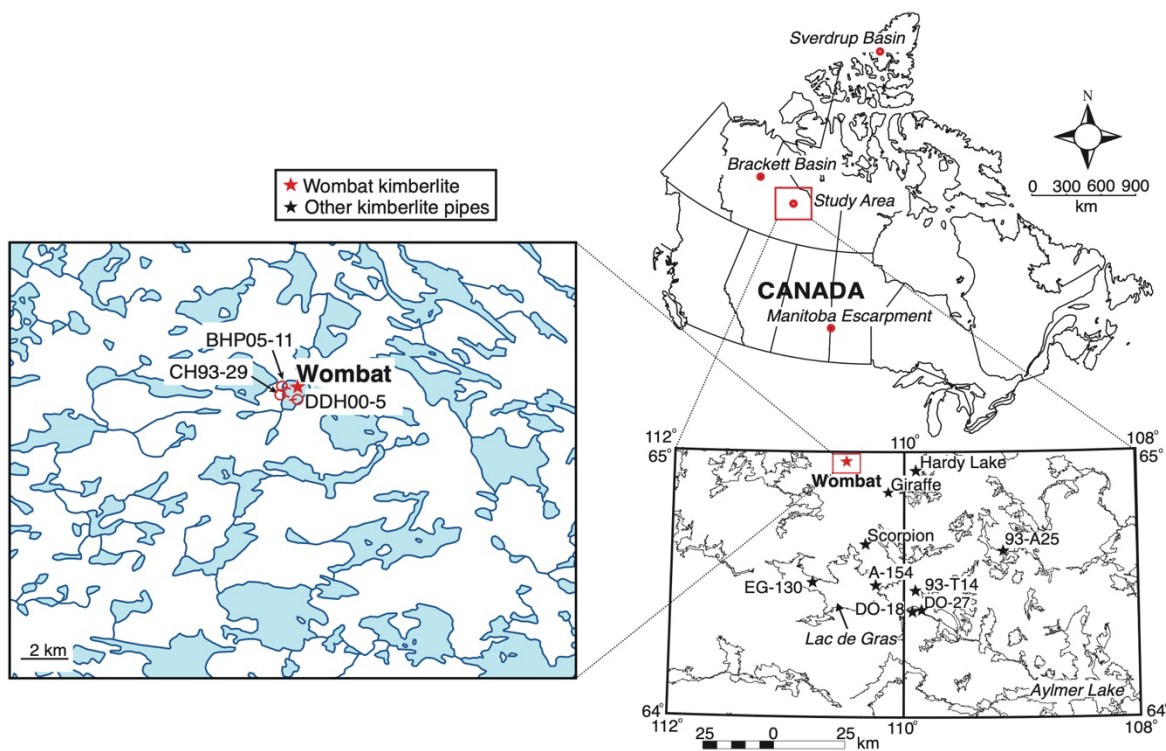


Figure 1. Location map of the Wombat kimberlite pipe locality in the Lac de Gras kimberlite field of the Northwest Territories and location of other selected kimberlite pipes. Open circles on left map are the surface location of Wombat pipe drill cores; single dash on each circle marks drilling azimuth. Closed red circles on map of Canada are generalized locations of basins mentioned in the text or selected kimberlite-bearing basins..

The cores DDH00-5 and CH93-29 (Fig. 2) intersect a total of ~195 m (vertical equivalent; VE) of crater lake facies. Grey laminated to massive siltstone with common flattened clay lenses and land plant detritus dominate the lower ~15 m VE of the crater fill. The upper ~180 m VE of the crater fill is mainly dark laminated clay and silt with rare lithic and country rock fragments. Two grey-white-coloured tephra layers are present in the cores at about the same depth intervals at the bottom of the lacustrine sequence, likely indicating stratigraphic overlap between the two cores. The tephra beds include preserved glass shards and some weathered glass pseudomorphs. Zircon crystals from one of the tephra beds yielded a laser-ablation inductively-coupled-plasma mass-spectrometry (LA-ICP-MS) $^{206}\text{Pb}/^{238}\text{U}$ date of 82.36 ± 0.44 Ma (weighted-mean; $n=18$ of 34 dated zircon crystals; MSWD = 1.51; uncertainty quoted at 2σ ; Buryak, 2020). The palynology results reported here are from samples that overlie and underlie the dated tephra bed, as well as the tephra horizon itself.



Figure 2. Representative photo of drill cores CH93-29 (left) and DDH00-5 (right) through Wombat kimberlite pipe lacustrine fill.

METHODS

Five rock samples from drill core DDH00-5 and one rock sample from drill core CH93-29 were selected for analysis (Fig. 3). The samples were processed for palynological analyses following standard techniques (Traverse, 2007) at Global GeoLab Ltd., Medicine Hat, Alberta. Briefly, samples were subjected to hot treatments of hydrochloric and hydrofluoric acids, and oxidation with Schulze's solution and stained with safranin O. Permanent mounts were made in liquid bioplastic. Resulting slides and slurries are archived at the Northwest Territories Geological Survey in Yellowknife, NT. Refer to the Geological Survey of Canada's Sample Management System (SMS) database for further information on the palynological preparations.

Microscopy for the purposes of pollen and spore analysis was conducted by J.M. Galloway using a Leitz Orthoplan transmitted light microscope at 400× and 1000× magnification under oil immersion and in brightfield and differential interference contrast. The botanical authority of identified taxa are provided at the end of this report in Appendix 1. The Thermal Alteration Index (TAI) of pollen and spores was determined after Pearson (1984) and Staplin (1969).

Quantitative analyses of pollen and spores are based on counts of unsieved preparations with mostly greater than 300 spores and pollen enumerated per sample. The relative abundance of each taxon is based on a sum that includes pollen and spores with affinities to terrestrial land plants. Non-terrestrial palynomorphs, including dinocysts, algae, acritarchs, and reworked palynomorphs were also enumerated but excluded from the pollen and spore sum; their abundance is expressed as a proportion of the terrestrial pollen and spore sum.

The one preparation (C-638548, Sample 93-29-67-4-64, 277.1 m VE depth) that contained well-preserved dinocysts was analyzed for their identification. This approach was qualitative. Microscopy for the purposes of dinocyst analysis was conducted by M. Bringué using a Zeiss Axio Imager M2 transmitted light microscope at 400× and 1000× magnification under oil immersion in brightfield, phase contrast, and differential interference contrast. The authority of identified taxa are provided at the end of this report in Appendix 2.

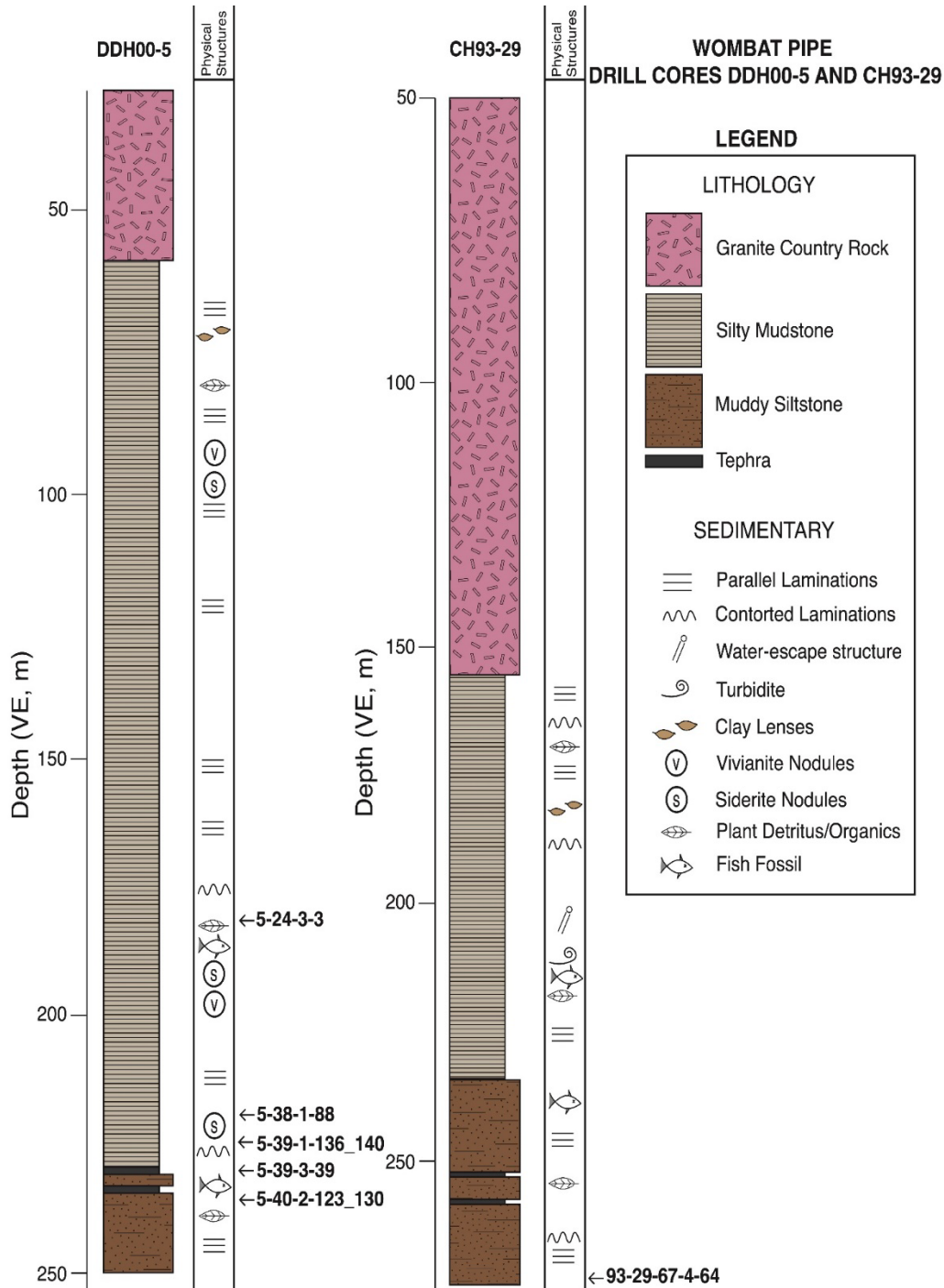


Figure 3. Summary stratigraphic logs of the Wombat drill cores DDH00-5 and CH93-29. Depth in the dipping cores is expressed as vertical equivalent (VE) depth with respect to the surface. The arrows point to the sample locations in the cores. Fish fossils are described in Grande et al. (2022).

RESULTS

Sample Identification is as follows: Geological Survey of Canada Curation Number (C-number), sample collector's code, and core depth expressed as vertical-equivalent (VE) meters below surface. The sample collector's code comprises three or five numbers. Numbers 5 or 93-29 indicate core DDH00-5 or CH93-29, respectively. The next three numbers sequentially represent: the core box number; the channel in the box (with 1 representing the stratigraphically highest channel); and the depth (in cm) of the sample in the channel. Samples C-638543 through to C-638547 were sampled from core DDH00-5 and sample C-638548 was sampled from core CH93-29.

Recovery ranged from poor to good, and preservation of palynomorphs ranged from fair to exceptional. The target count of 300 pollen and spores from obligately terrestrial plants was achieved in four out of five of the samples, and ranged from 206 to 556.

C-638543, Sample 5-24-3-3, 168.1 m VE depth

Processors notes: fair recovery

Thermal Alteration Index: 0

Preservation is excellent. Assemblage is dominated by Cupressaceae-Taxaceae pollen (49%) and *Pinuspollenites* pollen (21%). *Cycadopites* pollen represents 5% of the assemblage. Angiosperms are largely represented by *Caryapollentites* (7%) with *Equisetum* pollen (4%). Spores are rare relative to pollen. Projectate pollen are absent from the assemblage. Dinocysts are absent from the assemblage.

C-638544, Sample 5-38-1-88, 227.5 m VE depth

Processors notes: good recovery

Thermal Alteration Index: 0

Preservation is excellent. Assemblage is dominated by Cupressaceae-Taxaceae pollen (62%) and *Pinuspollenites* pollen (11%). *Metasequoia* pollen represents 8% of the assemblage and *Cycadopites* pollen only 2%. Similar to Sample 5-24-3-3, *Caryapollenites* dominates the angiosperm elements (5%) with *Equisetum* pollen (3%). *Ulmipollenites* pollen is present (1%) but *Alnipollenites* and *Betulaceoipollenites* pollen are absent. Spores and dinocysts are absent.

C-638545, Sample 5-39-1-136_140, 232.1 m VE depth

Processors notes: poor recovery

Thermal Alteration Index: 0

Preservation is excellent. Assemblage is dominated by Cupressaceae-Taxaceae pollen (70%) with *Pinuspollenites* pollen (16%). *Cycadopites* pollen represents 3% of the assemblage. Angiosperm

pollen have higher diversity than the two overlying samples. *Quercoidites*, *Betula*, and *Ulmipollenites* pollen are present, each representing 1% of the assemblage. *Caryapollenites* is the dominant angiosperm element, representing 2% of the assemblage. Spores and dinocysts are absent.

C-638546, Sample 5-39-3-39, 233.9 m VE depth, tephra horizon

Processors notes: fair recovery

Collectors notes: This is a sub-sample from the tephra bed dated by zircon $^{206}\text{Pb}/^{238}\text{U}$ to 82.36 ± 0.44 Ma (weighted-mean; $n=18$ of 34 dated zircon crystals; MSWD = 1.51; Buryak, 2020).

According to the 2020 Geological Time Scale (Gale et al., 2020), 82.36 ± 0.44 Ma falls within the early Campanian, that ranges from 83.65 to 72.17 Ma. However, the base of the Campanian is yet to be ratified with a GSSP.

Thermal Alteration Index: 0

Preservation is excellent. The assemblage is dominated by Cupressaceae-Taxaceae (69%) and *Pinuspollenites* (18%) pollen. *Metasequoia* pollen occurs at 3%. *Caryapollenites* is the dominant angiosperm pollen, representing 3% of the assemblage. *Betulaceoipollenites* and *Ulmipollenites* pollen are present, at 2% and 1%, respectively. *Equisetum* pollen represents only 1% of the assemblage. Spores are rare and dinocysts are absent.

C-638547, Sample 5-40-2-123_130, VE 237.0 m depth

Processors notes: fair recovery

Thermal Alteration Index: 0

Preservation is excellent. This preparation is dominated by Cupressaceae-Taxaceae pollen (69%) and *Pinuspollenites* pollen (13%). *Cycadopites* and *Metasequoia* pollen are present each at 3% of the assemblage. *Caryapollenites* pollen represents 2% of the assemblage. *Betulaceoipollenites* and *Ulmipollenites* pollen are present at 1% each. Spores are rare and dinocysts are absent.

C-638548, Sample 93-29-67-4-64, 277.1 m VE depth

Collectors notes: This sample is the deepest sample provided for analysis.

Processors notes: poor recovery

Thermal Alteration Index: 0

Preservation of palynomorphs in this preparation is poor to fair. The assemblage is distinct from all other preparations in the analyzed set. This assemblage has a lower proportion of Cupressaceae-Taxaceae pollen (only 18%) and comparable *Pinuspollenites* (11%) and *Cycadopites* (4%) pollen

composition. *Perinopollenites elatoides* pollen occurs only in this preparation (5%) and the presence of *Rugubivesiculites* pollen is notable. *Laricoidites magnus* pollen occurs at 4%. *Caryapollenites* pollen occurs with a relative abundance of 4% and *Betulaceoipollenites* pollen is present at 3%. The proportion of spores and their diversity is highest in this preparation. Spores of *Baculatisporites comaumensis* are present at 6%, *Deltoidospora hallei* at 5%, *Osmundacidites wellmannii* at 3%, and *Laevigatosporites ovatus* at 2% of the total assemblage. Of particular significance is the abundance of dinocysts (30%), *Veryhachium* (3%), *Pterospermella* (<1%), and undifferentiated acritarchs (2%).

The dinocyst assemblage of sample C-638548 was analyzed qualitatively. The assemblage is diverse, with 31 cyst taxa identified across 22 genera, including 22 taxa identified at the species level (one informal; see Appendix 2). The sub-family Deflandroidae is well represented with *Alterbidinium acutulium*, *Isabelidinium cooksoniae*, *Trithyrodinium singhii*, *Trithyrodinium ornatum*, *Trithyrodinium rhomboideum*, and *Trithyrodinium suspectum* being relatively abundant. The rest of the assemblage is spread over several (sub)families, including taxa with important biostratigraphic significance such as *Bourkidinium psilatium*, *Dorocysta litotes*, *Florentinia verdieri*, *Luxadinium propatulium*, *Pervosphaeridium* cf. *cenomaniense*, *Tanyosphaeridium* sp. C of Brideaux and McIntyre (1975), *Tenua scabrosa*, and *Wallodinium luna*.

DISCUSSION

Previous radiometric age dating of Lac de Gras kimberlite pipes by various methods, including Rb-Sr geochronology of macrocrystal phlogopite (e.g., Creaser et al., 2004) and biostratigraphy (Nassichuk and McIntyre, 1996), generally places the material into the Late Cretaceous to middle Eocene, with eruptive pulses centred at ~48, 51-53, 55-56, and 59-61 Ma (Creaser et al., 2004). Some of these kimberlites contain exceptional preservation of biological material, including, for example, pristine early Eocene wood of *Metasequoia* recovered from the Panda kimberlite dated to 53.3 ± 0.6 Ma (Wolfe et al., 2012). A palynological study of post-eruptive sediments from a core of BHP Billiton's Fifty kimberlite (Ekati property) in the Lac de Gras region reveals an assemblage containing a diversity of pollen from gymnosperms, including Taxaceae-Cupressaceae, and angiosperms including *Momipites*, *Quercoidites*, and *Tiliaepollenites*, which collectively indicate a Paleocene age (Daku, 2014). Daku (2014) used a quantitative approach, and defined two informal palynozones in the Fifty core. A lower zone 1, subdivided into subzones 1a and 1b, is dominated by gymnosperm pollen (>60% *Inaperturopollenites*, *Perinopollenites*, and undifferentiated bisaccate pollen in zone 1b), a variety of spores, and lower angiosperm pollen abundance (~20% in zone 1a and near absence of angiosperm pollen in zone 1b) than in the overlying zone 2. *Sigmopollis*, *Pterospermella*, and dinocysts are present in zone 1. Zone 2 is characterized by decreasing gymnosperm pollen and increasing angiosperm pollen, including *Quercoidites*, *Alnipollenites*, *Tiliaepollenites*, *Caryapollenites*, *Coryluspollenites*, *Momipites*, and *Pterocarya*. *Sigmopollis*, *Pterospermella*, and dinocysts are also present in zone 2. The palynofloral composition constrain the studied sections of the core to be late Paleocene to early Eocene in age. The presence of certain grains, such as *Rugubivesiculites* and *Pistillipollenites* is likely due to reworking of Cretaceous aged xenoliths or sedimentary cover.

Previous palynological work on the Wombat sample suite described herein includes an analysis by Shusheng Hu, of the Yale Peabody Museum of Natural History (Hu et al., 2011). The Hu et al.

(2011) abstract is summarized as follows: Over 140 m of laminated mudstone is preserved in the Wombat kimberlite pipe exploration drill-core from the Slave Geological Province, NT. The crater lake formed after kimberlite emplacement following phreatomagmatic volcanism. The age of the Wombat core is not known. Abundant terrestrial palynomorphs are preserved. The lower and upper Wombat lacustrine facies (assumed herein to be maar deposits) contain two distinct palynological assemblages. The lower assemblage includes *Momipites coryloides*, *M. tenuipolus*, *Triporopollenites bituitus*, *Fraxinoipollenites variabilis*, and *Caryapollenites imparalis*, as well as “8 types of gymnosperm pollen and 1 spore”. The upper assemblage is more diverse with *Ericaceipollenites* sp., *Alnipollenites* sp., *Caryapollenites veripites*, *Betulaceoipollenites* sp. and *Plicatopolis triradiatus*, as well as “10 types of gymnosperm pollen and 9 spores”. The absence of notable Upper Cretaceous palynomorphs such as *Aquilapollenites* and *Wodehouseia* in the material analyzed by Hu (2011) suggest that the sediments are younger than Maastrichtian, and the occurrence of *Ericaceipollenites* and *Alnipollenites* and the absence of the Eocene indicator *Platycarya* suggest a Paleocene age for the Wombat post-eruptive sediments.

Characteristics of the Wombat drill core samples herein analyzed are summarized as follows:

1. *Aquilapollentias* and *Wodehouseia* pollen are absent in all of the preparations;
2. *Ulmipollenites*, *Betulaceoipollenites*, *Alnipollenites*, and *Caryapollenites* pollen are dominant angiosperm elements in the preparations;
3. Assemblages are dominated by Cupressaceae-Taxaceae and *Pinuspollenites* pollen, with minor *Cycadopites* and *Metasequoia* pollen; and,
4. The basal sample (C-638548, Sample 93-29-67-4-64, 277.1 m VE depth) contains abundant (30%) dinocysts, including *Alterbidinium acutulum*, *Isabelidinium cooksoniae*, *Trithyrodinium rhomboideum*, and *Trithyrodinium singhii*.

Below, these characteristics of the assemblages preserved in the studied preparations are discussed, as well as some brief discussions on a few other notable occurrences. Much of the age range information for pollen and spore taxa discussed is sourced from Palynodata (White, 2006). The palynological composition of the Wombat cores show similarities to the detailed analysis of the Fifty core (Daku, 2014), notably the absence of *Aquilapollentias* and *Wodehouseia* pollen, the presence of likely reworked *Rugubivesiculites* pollen, and dominance of Cupressaceae pollen. However, the presence of *Tiliaepollenites* (Maastrichtian or Paleocene – present; as *Tilia*, White, 2006 and references therein) and *Platycarya*, an Eocene indicator taxon in high northern latitudes of North America (Ager et al., 1986; McIntyre, 1986; Spicer et al., 1987; although there are reports of this taxon ranging into the Santonian in Portugal and England; Kedves and Diniz, 1981; Jarzen, 1982a) in the Fifty material, and their absence in the Wombat material studied herein, indicate that post-eruptive sediments of the two kimberlite deposits are of different age.

Absence of *Aquilapollentias* and *Wodehouseia* pollen

U-Pb analysis of zircon isolated from a tephra in sample 5-39-3-39, 233.9 m VE depth in core DDH00-5 provides a weighted mean date of 82.36 ± 0.44 Ma from the youngest cluster of overlapping U-Pb dates ($n=18$ of 34 dated zircon crystals; MSWD = 1.51), including some on crystals with adhered volcanic glass rims (Buryak, 2020). The radiometric date is thus considered a close maximum age for tephra deposition, placing the material in the lower Campanian (Gale et

al. 2020). Previous palynological work on the late Santonian-early Campanian interval in North America has been mainly focused on mid-latitudes. These works include Jarzen and Norris (1975), Norris et al. (1975), Nichols and Jacobson (1982), Nichols and Sweet (1993), Nichols (1994), and Braman (2001), among others.

While *Aquilapollenites* is a typical Upper Cretaceous taxon, its occurrence is geographically diachronous. *Aquilapollentites* is first documented in mid-paleolatitude strata in the Turonian, but is later represented in palynofloras by a diversity of forms in the Campanian and Maastrichtian in high northern latitudes (Stanley, 1970; Batten, 1984). Diachroneity of its occurrence is also noted within strata of western Canada (e.g., Braman, 2001). For example, the Milk River Formation material analyzed by Braman (2001) ranges in age from late Santonian to possibly early Campanian (based on ^{40}Ar - ^{39}Ar ages and magnetostratigraphy that is used to infer an age for the Milk River Formation of 84.5 to 83 Ma; Obradovitch and Cobban, 1975; Obradovitch, 1993; Leahy and Lerbekmo, 1995; Montgomery et al., 1998). Species of *Aquilapollenites* pollen do not appear until within the fully marine Campanian Pakowki Formation and younger units in southern Alberta, where they become characteristic of the Pakowki and Foremost formations across much of the Western Interior Basin. Thus, only poor correlations are possible in Canada within the *Aquilapollenites* floral province of eastern Russia and northern China for this time interval (Braman, 2001). *Wodehousiea* pollen is a typical Maastrichtian element in North America and eastern Asia (Nichols and Jacobson, 1982 and references therein; Nichols et al., 2010), but in the USSR ranges into the late Campanian (Budrin, 1969), Coniacian (Zaklinskaya, 1970), or the Cenomanian (Chlonova, 1971). A Canadian Arctic record (Hopkins, 1973) documents this taxon ranging from the Campanian to Maastrichtian in strata from Amund and Ellef Ringnes islands in the Sverdrup Basin. *Aquilapollentites* and *Wodehousiea* range into the Paleocene or Eocene in North America (References in White, 2006).

The absence of *Aquilapollenites* and *Wodehousiea* pollen in the sample suite herein analyzed is consistent with an early Campanian age determination based on the geochronology of the tephra at 233.9 m depth in core DDH00-5. The absence of *Aquilapollenites* pollen suggests an age older than middle Campanian, while the absence of *Wodehousiea* pollen suggests an age older than Maastrichtian. Alternatively, their absence could suggest an age younger than Paleocene or Eocene.

Dominant angiosperm elements

Ulmipollenites, *Betulaceoipollenites*, *Alnipollenites*, and *Caryapollenites* pollen are the dominant angiosperm pollen elements in the preparations analyzed. *Equisetum* pollen is also common. While these pollen types are common elements in Cenozoic strata, and as such, while their occurrences are commonly used to argue for a Cenozoic age, their lineages extend into the Mesozoic.

Ulmipollenites

While Ulmaceae has a Late Cretaceous origin (Maastrichtian; Muller, 1981), its pollen (i.e., *Ulmus*) does not become common in the rock record until the Cenozoic (e.g., see records in White, 2006). Rare records of Upper Cretaceous Ulmoid pollen from Germany exist (Thiergart, 1942, 1949). *Ulmipollenites* is documented in strata as old as broadly Upper Cretaceous in Brazil

(Srivastava, 1967) and as old as Maastrichtian in Alberta (Srivastava, 1969) and Wyoming (Kauffman, 1973; Farabee, 1984). Spicer (1989) classifies this taxon as spanning from the Late Cretaceous to Early Paleocene in the mid-continental USA. Most typically, however, the majority of records of *Ulmipollenites* begin in the Cenozoic (White, 2006). Spicer (1989) notes an absence of taxa with close affinities to putatively more advanced Hamamelididae (e.g., Ulmaceae, Betulaceae, Fagaceae, and Myricaceae) in Upper Cretaceous floras of Alaska where Ulmaceae, Fagaceae, Betulaceae, and Juglandaceae do not appear until the Paleocene (Wolfe et al., 1966). The presence of *Ulmipollenites* therefore provides evidence for a Cenozoic age, but the possibility of an older occurrence for this taxon cannot be eliminated.

Betuloideae (Alnus, Betula)

Leaves of probable Betulaceae are widespread in Maastrichtian and Paleocene floras (La Motte 1952; Takhtajan 1982; Crane and Stockey, 1987). Betulaceae probably originated in temperate areas of Laurasia during the Late Cretaceous (Chen et al., 1999). Plants with diagnostic features of modern *Betula* are present in middle Eocene strata and early phases of evolution of this lineage likely occurred in the earliest Cenozoic or Late Cretaceous (Crane and Stockey, 1987), possibly as early 80 Mya during the Santonian in the Cretaceous (Bousquet et al., 1992).

Triporate grains with vestibulate pores first appear in the “Senonian” (informal; the final part of the Cretaceous comprising the Coniacian-Campanian and possibly Maastrichtian; *Betulaceoipollenites*; Jarzen and Norris 1975; Miki 1977). *Betulaceoipollenites* is documented in strata as old as broadly Late Cretaceous in mid-latitudes of North America, Europe, and China (Hofmann, 1950; Norford et al., 1973; Zhang, 1993) and becomes common in the latest Cretaceous and Paleocene (e.g., Manum 1962; Stanley 1965). Other records document *Betula* pollen in strata as old as “middle Cretaceous” in the Ural Mountains (former USSR; Pokrovskaya, 1950) or Turonian in the former USSR (Bondarenko, 1958; Boytsova et al., 1960). However, occurrences this old are very rare and *Betula* and *Betula*-type pollen is typically not reported until the Cenozoic (see White, 2006).

Pollen of *Alnipollenites* occurs in the Santonian and Campanian in Japan (Takahashi, 1974; Miki, 1977) and there are numerous Maastrichtian and Paleocene records of *Alnus*-like pollen from North America and Europe (Stanley 1965; Elsik 1968; Norton and Hall, 1969; Oltz 1969; Snead 1969; Felix and Burbridge 1973; Srivastava 1975; Jarzen 1982; Crane and Stockey, 1987). Pollen characteristic of *Alnus* dates back to the Santonian (Hickey et al., 1983), late Maastrichtian (Hopkins, 1973), or Paleocene (McIntyre and Ricketts, 1989) in the Canadian Arctic, the Santonian or Turonian of Alberta (Jarzen and Norris 1975), and as old as Albian in the USSR (Sedova, 1964; Panova, 1964).

The occurrence of *Alnipollenites* and *Betulaceoipollenites* is consistent with an early Campanian age provided by the U-Pb geochronology, but taken on their own, the occurrence of these taxa is more typical for a latest Cretaceous to Paleocene or younger age.

Caryapollenites

Caryapollenites is documented in strata of Santonian age in the Canadian Arctic (Hickey et al., 1983) but most records of this pollen in the Arctic (e.g., Spicer et al., 1987; Norris and Miall, 1984a,b) or mid-latitudes of North America (e.g., Jarzen, 1982b; Demchuk et al., 1987) are in strata dated as Paleocene in age. Its occurrence is therefore consistent with a Campanian age.

Dominance of Cupressaceae-Taxaceae and *Pinuspollenites* pollen with minor *Cycadopites* and *Metasequoia*

Quantitative palynology was used in the present analysis to infer paleoenvironments during deposition of the material. An absence of dinocysts in all samples except for the basal sample of core CH93-29 (C-638548; 93-29-67-4-64; 277.1 m VE depth) suggests limited mixing of xenolithic debris. Assemblages are dominated by Cupressaceae-Taxaceae and *Pinuspollenites* pollen, with minor *Cycadopites* and *Metasequoia* pollen. Taxodiaceae are interpreted to have been hygrophilous plants that thrived in warm to temperate wet-lowland environments (Vakhrameev, 1991; Pelzer et al., 1992; Dejax et al., 2007). Plant macrofossils with affinities to the Cupressaceae (*Cupressinoxylon*) are reported from Aptian–Albian strata of Axel Heiberg and Ellesmere islands, where mean annual temperature is inferred to have been 3–10°C (Harland et al., 2007). In modern environments, Cupressaceae pollen is generally well dispersed and occurs with frequencies of 10–40% in late Holocene lacustrine and marine sediments where parent plants are dominant vegetation components (Galloway et al., 2010). Relative abundances of >50% of Cupressaceae–Taxaceae pollen in Wombat core samples therefore suggests that parent plants were dominant in regional forests, and that climate was cool-temperate and moist.

Macrofossil evidence from the Lower Cretaceous strata of the Canadian Arctic suggests that Pinaceae were common in high northern latitude forests, with constituents that were similar to modern *Pinus*, *Picea*, *Larix*, and *Pseudotsuga* (Harland et al., 2007). A component of the bisaccate pollen, particularly *Pinuspollenites* pollen, may therefore have been produced by parent plants with broad ecologies similar to extant *Pinus*. Modern *Pinus* species can grow on soils of fluvial origin and are early pioneers of disturbed habitats but can also form edaphic climax.

Most fossil pollen of the Ginkgoales and Cycadales belong to the genera *Monosulcites* or *Cycadopites*. Some pollen of the extinct Bennettitales may also belong to the *Monosulcites*–*Cycadopites* group (Abbink et al., 2004). Extant Cycadales grow in tropical regions and are adapted for drought, suggesting tolerance of dry summer seasons for Mesozoic ancestors. Mesozoic Cycadales were a diverse group that included extinct taxa (e.g., Nilsoniaceae) that grew in lowland subtropical areas (Abbink et al., 2004, and references therein), but Cycadales are in general interpreted to have been mesoxerophilous plants and probably grew in well-drained upslope habitats (Dejax et al., 2007), and were widely distributed in the Arctic during the Cretaceous (Galloway et al., 2013, 2015, 2021).

The overall assemblage preserved in the Wombat drill core material represents pollen from mature upland coniferous communities that grew in well-drained substrate with infrequent disturbance as well as pollen derived from plants adapted to more dynamic environments.

Dinocysts

Abundant dinocysts (30% of the assemblage) are preserved in the basal sample of core CH93-29 (C-638548, sample 93-29-67-4-64, 277.1 m VE depth). Dinocysts are mostly found in marine depositional environments. Their abundance in this sample suggests that marine strata occurred near this site.

During the Late Cretaceous the Western Interior seaway cut across North America. By 65 Ma the seaway had become an epicontinental sea. Nassichuk and McIntyre (1995) studied Ekati kimberlites and found Upper Cretaceous marine fish fossils and numerous marine dinocysts preserved in them. This led them to conclude that the Western Interior Seaway was likely wider than most models predict at the end of the Cretaceous.

Samples from BHP-Dia Met Joint Venture, and those from pipes closer to Yamba Lake, contain fossil dinocysts, pollen, spores, and teleost fish remains ranging in age from Albian to Paleocene (Nassichuk and McIntyre, 1996). Emplacement of the pipes had to predate the youngest fossils in the pipes. The presence of marine fossils of Cretaceous age in Lac de Gras kimberlites provided the first evidence to prove that Mesozoic and Cenozoic rocks were deposited above the Precambrian rocks of the Slave Geological Province, and the age of these marine strata range from Albian to Maastrichtian (Nassichuk and McIntyre, 1996).

Several dinocyst taxa identified in sample C-638548 were also reported from the Lac de Gras kimberlite pipes by Nassichuk and McIntyre (1996). Notably, the presence of *Luxadinium propatum*, *Trithyrodinium singhii* (as *Ginginodinium evitii*), and *Trithyrodinium ornatum* (as *Ginginodinium ornatum*), is consistent with the material preserved in the samples examined by Nassichuk and McIntyre (1996). *Aquilapollenites* and *Wodehouseia* pollen are present in some of their material that they date to be Maastrichtian in age. These authors also report the presence of *Caryapollenites* and *Carya* spp., *Alnus* spp., and *Momipites* spp. and use their presence to determine a Paleocene age for strata containing them.

Known ranges for the dinocysts observed in sample C-638548 are shown in Figure 4. Overall, the age interpretation of Albian to Maastrichtian (for dinocysts alone) is consistent with the ages provided by Nassichuk and McIntyre (1996). However, several cyst taxa indicate a much narrower time interval (Fig. 4), including *Bourkidinium psilatium* (Singh, 1983), *Dorocysta litotes* (Davey, 1970; McIntyre in Dixon, 1996), *Florentinia verdieri* (Singh, 1983), *Luxadinium propatum* (Brideaux and McIntyre, 1975), *Trithyrodinium rhomboideum* (Singh, 1983), and *Wallodinium luna* (Cookson and Eisenack, 1960), suggesting that most deposition (or reworking of source material and re-deposition) at the site occurred during the late Albian to Cenomanian. Furthermore, the absence of *Chatangiella* species in sample C-638548, which are particularly abundant in Upper Cretaceous (starting in the Coniacian) strata associated with the deposits of the Western Interior Seaway in the region (e.g., McIntyre, 1974, 1975), suggests a depositional age older than Coniacian.

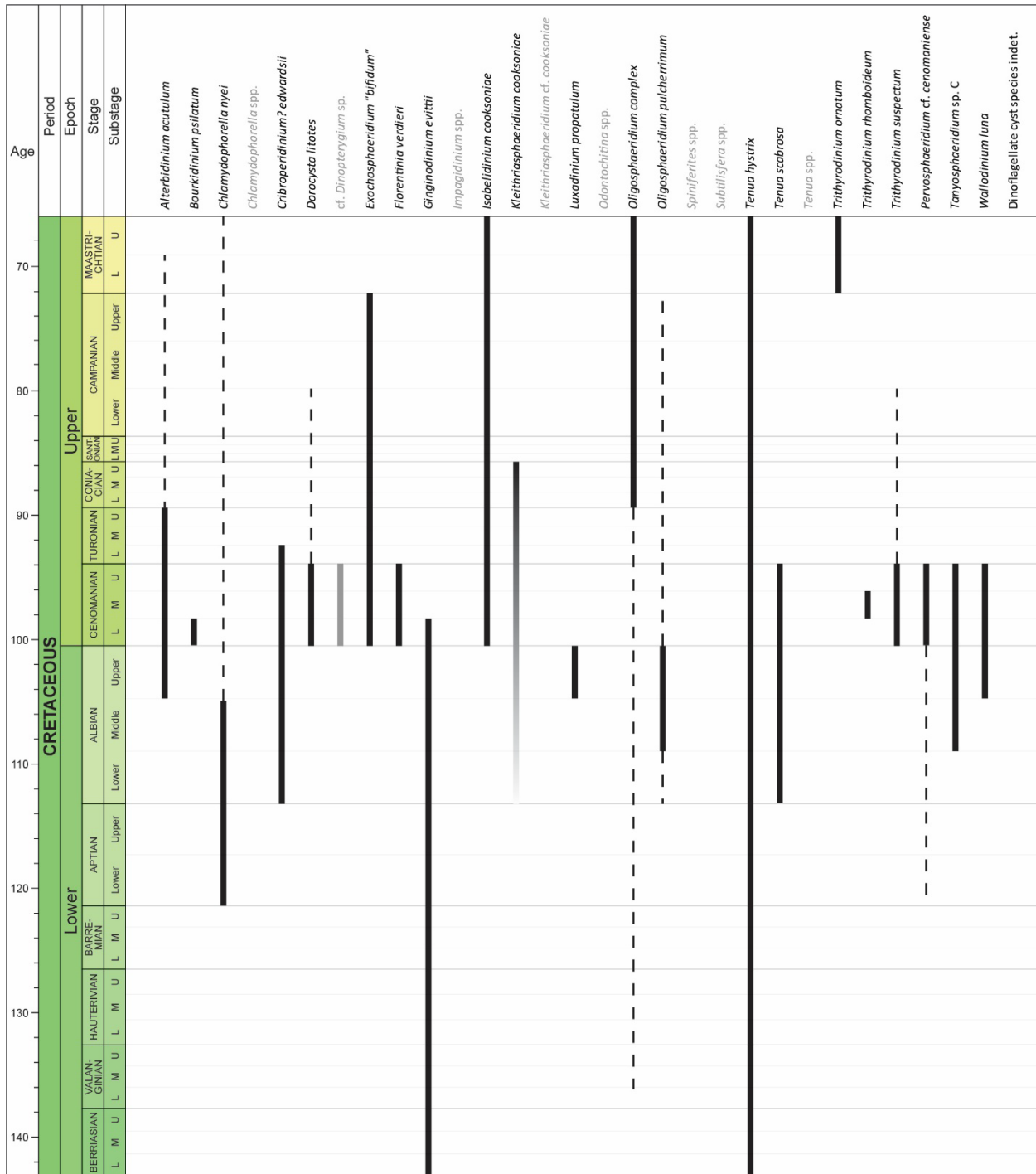


Figure 4. Dinocyst age ranges for taxa identified in sample CH93-29 (C-638548; 93-29-67-4-64; 277.1 m VE depth). Time scale of Gale et al. (2020) used, with age in Ma.

Pollen, spores, and dinocysts of Late Cretaceous age may have been sourced from sedimentary xenoliths from now eroded sedimentary cover that may have been dispersed into the mudstone deposited in the lacustrine setting of the maar. Miospores and dinocysts and associated organic debris from country rock commonly mixes into kimberlite during eruptions and subsequent fall-

back of rim deposits into the crater, and can affect age interpretations and result in admixtures of fossils indicative of different ages. This phenomenon can lend valuable evidence itself. For example, Sweet et al. (2006) documented the occurrence of Albian through early Paleocene clasts from now eroded sedimentary cover within kimberlite of the Lac de Gras area based on dinocyst and miospore assemblages in the rock fragments, and inferred the timing of hiatuses and changes in thickness and depositional environments coincident with cycles of kimberlite emplacement and resulting localized uplift. Comparison to the kimberlite fields of north-central Alberta (Buffalo Head Hills and Birch Mountain) where Cretaceous host rock cover still exists permitted them to correlate more precisely to adjacent areas without past kimberlite activity. Their evaluation of vertical shifts in palynological datums and lithological markers shows that in a setting of normally flat-lying topography, hiatuses of deposition occurred broadly coincident with kimberlite emplacement, leading them to suggest that kimberlite emplacement is associated with local structural bulges and depressions, possibly related to extensional tectonics.

Other comments

Rugbisvesiculites

The presence of *Rugbisvesiculites* pollen in the deepest sample, C-638548, suggests an Albian-Cenomanian age (Staplin, 1967; Brideaux, 1973; Norris, 1976; Hickey et al., 1977; Galloway et al., 2012), although this taxon ranges into the Late Cretaceous or Cenozoic (see White, 2006). This taxon is only present in the basal sample that also contains dinocysts, suggesting the possibility of provenance from xenoliths of now eroded sedimentary cover.

Echniosporis

The Lycopsid (Isoetaceae) genus *Echniosporis* first appears in the Late Cretaceous to Paleocene in Patagonia (Barreda et al., 2012). Members of this genus appear in the Hauterivian of the USSR (Bai et al., 1983), Cenomanian in China (Zhang and Zhan, 1991), and Maastrichtian, in Germany (Wolf, 1963).

Arctic biostratigraphic heterochroneity

Heterochroneity exists at least to some degree in all biostratigraphy; all taxa do not appear in all locations at precisely the same time. Forms originate, and then must migrate to colonize new locations, and then become locally or more broadly extinct. The success and pace of migration depends on many factors, including ecological characteristics of the taxa (e.g., the concept of K or R strategists) combined with the environmental and climatological parameters of new regions, the success of ecological competition with existing taxa living in the new habitats, and/or geophysical barriers to migration (Herman, 2002, 2011; Galloway et al., 2012).

In Upper Cretaceous Alaskan floras, paleoenvironments appeared to have been important in controlling colonization by early angiosperms, as most taxa new to Alaska first appear, or are more abundant in, fluvial rather than swamp/lacustrine environments where Taxodiaceae and ferns were common (Spicer et al., 1987). Such disturbed areas may have provided a competitive advantage to angiosperms with early successional ecology (Galloway et al., 2012). As a result of the

constellation of these effects, impoverished floral communities existed in high northern latitudes close to richly diverse communities (Herman, 2002, 2007a, 2007b, 2011; Galloway et al., 2012). In general, low angiosperm pollen abundance and diversity in high northern latitude deposits are interpreted to reflect a low and mid-latitude origin (Spicer et al., 1987; Herman, 2002; Spicer and Herman, 2010) followed by a diachronous dispersal pattern northward of early angiosperms (Stanley, 1967; Traverse, 2007; Galloway et al., 2012). However, some high northern latitude floras, such as Albian-Cenomanian assemblages in northern Alaska and north-eastern Asia, are highly diverse (Smiley, 1969; Spicer and Parrish, 1986; Parrish et al., 1998; Spicer and Herman, 2001, 2010; Herman, 2002; Spicer et al., 2002; Herman and Spicer, 2010). In part, based on this diversity, alternative hypotheses to polar angiosperm origins have been proposed, such as the Arctic origin hypothesis (Hickey et al., 1983) or Arcto-Tertiary geoflora (Chaney, 1938, 1959). Hickey et al. (1983) considered that many divergences of angiosperm lineages have occurred in the Arctic, although this hypothesis is disputed based on the quality of the dinocyst and paleomagnetic data and their interpretation (see Spicer et al., 1987; Norris and Miall, 1984a,b; and Kent et al., 1984). Of note is Hickey's sample 67A, inferred by Hickey et al. (1983) to be Santonian to early Campanian in age and containing an assemblage that included *Alnipollenites*, *Ericaceipollenites*, and *Ulmipollenites* pollen. Based on Spicer et al.'s (1987) re-interpretation of Hickey's data, they suggest that the assemblage (pollen and dinocysts; Choi, 1983) is consistent with a Paleocene age.

Other notable differences exist in the composition of flora between high northern latitude settings (Galloway et al., 2012). For example, Cycadophytes, a typically wide-ranging group, were not found on the Arctic Slope following the Cenomanian, although they occur in the Campanian of the Alaska Peninsula (Hollick, 1930), and in the Sverdrup Basin in the middle Cretaceous (Galloway et al., 2012, 2013, 2015). The Alaskan region did not receive some migrants from more southern regions at all, and consequently, some major types that typify mid-latitudes are absent in Alaskan Upper Cretaceous floras (Spicer et al., 1987). Vegetation of the Alaskan Late Cretaceous can largely be described as a polar deciduous forest and most aspects of the physiognomy of this vegetation are not present in modern forests (Wolfe, 1985). The composition of these forests may have resulted from a combination of meso-thermal climate coupled with high latitude light regime.

Due to the complex interplay of biological, ecological, climatological, and geographical factors controlling plant evolution, diversity, migration, and extinction, local range-zones (topozones or teilzones) of palynomorphs are needed to interpret the biostratigraphy of a given area, but application of local range-zones are not possible until they are developed. Thus, total ranges composited from occurrence data in other regions must be cautiously applied. Several authors attest to constraints on occurrence of fossils in a given area, including patterns of evolution, migration, and differential extinction (e.g., Kauffman, 1981) that affect the precision with which total-range biostratigraphic data can be applied locally (Nichols and Jacobson, 1982). Thus, the comparison of floras between high and lower latitudes at any given time is complex. Differences in floral composition likely reflect a combination of location of origin, migration pathways and barriers, disturbance ecology, local climate and edaphic factors, combined with extremes in polar light regime.

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Appendix 1

The table below provides the list of pollen and spore taxa and their authorities identified in the analyzed samples listed according to their parent plant classifications. Taxonomic authorities are not listed in the References.

Taxon	Authority
Gymnosperms	
<i>Pinuspollenites</i>	Raatz 1938
<i>Abiespollenites</i>	Thiergart, 1937 ex Raatz 1937
<i>Araucaricites</i>	Cookson, 1947 ex Couper 1953
<i>Cerebropollenites mesozoicus</i>	(Couper 1958) Nilsson 1958
Cupressaceae-Taxaceae	
<i>Cycadopites follicularis</i>	Wilson and Webster 1946
<i>Laricoidites magnus</i>	(Potonié 1931) Potonié et al. 1958 nom. cons.
<i>Metasequoia</i>	Miki 1941
<i>Perinopollenites elatoides</i>	Couper 1958
<i>Piceapollenites</i>	Pautsch 1958
<i>Podocarpidites</i>	Cookson 1947 ex Couper 1953
<i>Rugubivesiculites</i>	Pierce 1961
Undiff. bisaccate pollen	
Undiff. non-bisaccate gymnosperm pollen	
<i>Vitreisporites pallidus</i>	Nilsson 1958
Angiosperms	
<i>Quercoidites</i>	Potonié, Thomson, Thiergart 1960
Aceraceae	
<i>Alnipollenites</i>	Potonié 1931
Amaranthaceae	
<i>Betulacoipollenites</i>	Potonié 1951
<i>Caryapollenites</i>	Potonié 1960
<i>Equisetum</i>	L.
Ericaceae	
<i>Liliacidites</i>	Couper 1953
<i>Liquidambar</i>	L.
<i>Momipites</i>	Wodehouse 1933
<i>Penetetrapites</i>	Hedlund and Norris 1968
<i>Retitricolpites</i>	van der Hammen 1956 ex. Pierce 1961
<i>Ulmipollenites</i>	H. Wolff 1934
Undiff. papillate triporate pollen	
Undiff. psilate periporate pollen	
Undiff. angiosperm pollen	
Undiff. psilate triporate pollen	
Undiff. tricolpate pollen	
Undiff. tricolporate pollen	
Undiff. triporate pollen	
Ferns and allies	
<i>Laevigatosporites ovatus</i>	Wilson and Webster 1946
<i>Baculatisporites comaumensis</i>	(Cookson 1953) Potonié 1956
<i>Bireteisporites potonieae</i>	Delcourt and Sprumont 1955
<i>Cicatricosisporites</i>	Potonié and Gelletich 1933
<i>Cingulitriletes clavus</i>	(Balme 1957) Dettmann 1963
<i>Cyathidites australis</i>	Couper 1953
<i>Deltoidospora hallei</i>	Miner 1935
<i>Echinosporis</i>	Krutzsch 1967
<i>Gleicheniidites senonicus</i>	Ross 1949
<i>Osmundacidites wellmannii</i>	Couper 1953
<i>Stereisporites antiquasporites</i>	(Wilson and Webster 1946) Dettmann 1963
Indet. pollen and spores	
Non-pollen palynomorphs	
Undiff. dinoflagellate cysts	
<i>Veryhachium</i>	Deunff 1954
Undiff. acritarchs	
<i>Pterospermella</i>	Eisenack 1972

Appendix 2

The table below provides the list of dinoflagellate cyst taxa and their authorities identified in sample C-638548, sample 93-29-67-4-64, 277.1 m VE depth, listed alphabetically. Taxonomic authorities are not listed in the References.

Taxon	Authority
<i>Alterbidinium acutulum</i>	(Wilson, 1967) Lentin and Williams, 1985; Emend. Khowaja-Ateequzzaman et al., 1991
<i>Bourkidinium psilatam</i>	Singh, 1983
<i>Chlamydophorella nyei</i>	Cookson and Eisenack, 1958
<i>Chlamydophorella</i> spp.	Cookson and Eisenack, 1958; Emend. Duxbury, 1983
<i>Cribroperidinium? edwardsii</i>	(Cookson and Eisenack, 1958) Davey, 1969
<i>Dorocysta litotes</i>	Davey, 1970
cf. <i>Dinopterygium</i> sp.	Deflandre, 1935; Emend. Stover and Evitt, 1978; Fensome et al., 2009
<i>Exochosphaeridium "bifidum"</i>	(Clarke and Verdier, 1967) Clarke et al., 1968; Emend. Davey, 1969
<i>Florentinia verdieri</i>	Singh, 1983
<i>Ginginodinium evittii</i>	Singh, 1983
<i>Impagidinium</i> spp.	Stover and Evitt, 1978
<i>Isabelidinium cooksoniae</i>	(Alberti, 1959) Lentin and Williams, 1977
<i>Kleithriasphaeridium cooksoniae</i>	(Singh, 1971) Fensome et al., 2009
<i>Kleithriasphaeridium</i> cf. <i>cooksoniae</i>	(Singh, 1971) Fensome et al., 2009
<i>Luxadinium propatum</i>	Brideaux and McIntyre, 1975
<i>Odontochitina</i> spp.	Deflandre, 1937; Emend. Davey, 1970; Bint, 1986; El Mehdawi, 1998; Núñez-Betelu and Hills, 1998
<i>Oligosphaeridium complex</i>	(White, 1842) Davey and Williams, 1966b
<i>Oligosphaeridium pulcherrimum</i>	(Deflandre and Cookson, 1955) Davey and Williams, 1966
<i>Spiniferites</i> spp.	Mantell, 1850; Emend. Sarjeant, 1970
<i>Subtilisfera</i> spp.	Jain and Milleped, 1973; Emend. Lentin and Williams, 1976
<i>Tenua hystrix</i>	Eisenack, 1958; Emend. Sarjeant, 1985
<i>Tenua scabrosa</i>	(Cookson and Eisenack, 1970) Fensome et al., 2019
<i>Tenua</i> spp.	Eisenack, 1958; Emend. Sarjeant, 1968; Pocock, 1972; Sarjeant, 1985
<i>Trithyrodinium rhomboideum</i>	Singh, 1983
<i>Trithyrodinium ornatum</i>	(Felix and Burbridge, 1973) Lentin and Williams, 1976
<i>Trithyrodinium suspectum</i>	(Manum and Cookson, 1964) Davey, 1969
<i>Pervosphaeridium</i> cf. <i>cenomaniense</i>	(Norvick, 1976) Below, 1982
<i>Tanyosphaeridium</i> sp. C	Brideaux and McIntyre, 1975
<i>Wallopinium luna</i>	(Cookson and Eisenack, 1960) Lentin and Williams, 1973
Dinoflagellate cyst species indet.	