GEOLOGICAL SURVEY OF CANADA
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1999

Natural Resources Canada
Ressources naturelles Canada

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Catalogue No. M42-543E
ISBN No. 0-660-17809-5

Available in Canada from
Geological Survey of Canada offices:

601 Booth Street
Ottawa, Ontario K1A 0E8

3303-33rd Street N.W.
Calgary, Alberta T2L 2A7

101-605 Robson Street
Vancouver, B.C. V6B 5J3

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Cover Illustration
Joint USGS–GSC field party near Canyon Village, Porcupine River, Alaska. Here the river cuts through 6.6 million year old lake beds, which form the bluffs seen in the distance. GSC 4683-1

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Original manuscript submitted: 1997/04
Approved for publication: 1999/06

PREFACE

This study provides a framework biostratigraphy for pollen and spores in the Neogene and Quaternary of Yukon, adjacent Northwest Territories and Alaska. This biozonation is useful for correlating continental rocks with rocks on the northern continental margin, including the petroliferous Beaufort–Mackenzie Basin. This framework biozonation achieves an absolute chronology based on the study of many continental sections where ages are determined by independent and absolute measures.

The interpretations presented here combine information from several areas of study. There is ample, independent, hemispheric evidence of climate change during the last 18 million years, including evidence derived from marine sedimentology and from the type and isotopic content of marine fossils. Geology has explained the formation of the mountains of Yukon and Alaska, some of the youngest and highest in the world. The close relationship between vegetation and climate is apparent to any modern traveller and has received more than a century of scientific study. Combining and applying these fields of knowledge allows us to refine our understanding of the evolution of the Arctic flora and vegetation through the Neogene and Quaternary.

This work also provides an example in the history of earth of the significance of climatic change to life. Climatic change caused the replacement of the plants adapted to the temperate conditions of the Middle Miocene with plants adapted to the extreme cold and dryness of the Pleistocene and Recent – effectively, the replacement of one ecosystem with another. An argument can be made that concern about anthropogenic climatic change is unwarranted because of the earth's natural climatic variability. Such a statement must be tempered by knowledge that climatic change has had repeated and profound effects on the biosphere.

M.D. Everell
Assistant Deputy Minister
Earth Sciences Sector

PRÉFACE

La présente étude propose une zonation biostratigraphique des pollens et des spores qui couvrirait les 18 millions dernières années (du Miocène au Quaternaire) au Yukon et dans les parties contiguës des Territoires du Nord-Ouest et de l'Alaska. Cette zonation permet d'établir une corrélation entre les roches du continent et celles de la marge continentale septentrionale, dont le bassin de Beaufort–Mackenzie qui renferme des hydrocarbures. La chronologie associée à la zonation est absolue, car elle est fondée sur des coupes où les âges ont été déterminés par des techniques géochronologiques indépendantes.

Ce document décrit également les changements qui se sont produits dans les paléoclimats continentaux des hautes latitudes. D'abondantes études indépendantes, notamment celles du contenu isotopique des fossiles marins et de la nature des sédiments marins, ont démontré que des changements climatiques se sont produits à l'échelle planétaire au cours des 18 millions dernières années. Un événement tectonique de grande envergure s'est produit au cours de cette période de temps, à savoir le soulèvement de la chaîne de l'Alaska et de la chaîne St. Elias, qui sont parmi les montagnes les plus jeunes et les plus hautes au monde. De nos jours, tout voyageur est capable de reconnaître les effets des zones de montagnes sur le climat et l'influence de ce dernier sur la végétation. De nombreuses études scientifiques ont été effectuées sur ces sujets. En se fondant sur ces domaines de connaissances, le climat est interprété comme étant l'élément moteur de l'évolution de la végétation dans l'Arctique au cours du Néogène et du Quaternaire.

Des arguments ont été avancés selon lesquels les préoccupations relatives au changement climatique d'origine anthropique ne sont pas justifiées en raison de la variabilité naturelle du climat de la Terre. De tels arguments doivent être tempérés par les connaissances qui démontrent que les changements climatiques naturels ont eu des incidences marquées sur la biosphère. La présente étude est d'un grand intérêt, car elle met en évidence les conséquences du changement climatique sur les écosystèmes des hautes latitudes à une échelle géochronologique. Les forêts luxuriantes des zones tempérées du Miocène moyen ont été transformées en taïga et en toundra, résistantes aux très grands froids et à la sécheresse qui sévissaient au cours du Pléistocène et de l'Holocène.

M.D. Everell
Sous-ministre adjoint
Secteur des sciences de la Terre

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ABSTRACT

A quantitative pollen and spore zonation for the Neogene and Quaternary of Yukon, western Northwest Territories and central and northern Alaska has been assembled from seven sections and one borehole. The palynological spectra from 163 samples from these sections were grouped and averaged within the groups to produce twenty-one composite spectra that depict the long-term pattern of vegetation change. The oldest record included in the study is estimated to be within the late Early Miocene (ca. 18.3 Ma) and the record extends to the late Quaternary.

Pollen and spores are grouped and summed by environmental tolerances and physiognomy of the modern families and genera of plants to which they are related. Using these groups, pollen and spore ratios are drawn to track environmental parameters – temperature, forest canopy cover, and paludification of the study sites. Biostratigraphic and paleoecological patterns are explained in terms of known changes in global climate and the climatic effects of regional tectonics. Six assemblage zones and five subzones are proposed to describe the palynological succession.

RÉSUMÉ

Une zonation sporopollinique quantitative du Néogène et du Quaternaire du Yukon, de la partie occidentale des Territoires du Nord-Ouest et des parties centrales et septentrionales de l'Alaska a été assemblée à partir de sept coupes et d'un sondage. Les spectres palynologiques obtenus de 163 échantillons prélevés sur ces coupes ont été regroupés et une moyenne a été établie au sein des groupes afin de former 21 spectres composites qui représentent le modèle à long terme de la modification de la végétation. Selon les estimations, les données les plus anciennes comprises dans cette étude remontent à la fin du Miocène inférieur (env. 18,3 Ma); les données s'étendent jusqu'au Quaternaire supérieur.

Les pollens et les spores sont groupés et totalisés en fonction de la tolérance au milieu et de la physionomie des familles et des genres actuels de plantes avec lesquels ils sont associés. En se servant de ces groupes, on détermine des rapports entre les pollens et les spores afin de reconstituer les paramètres du milieu, à savoir la température, le couvert forestier et la turbification des sites étudiés. Les modèles biostratigraphiques et paléoécologiques sont expliqués en termes de changements connus du climat de la Terre et des incidences de la tectonique régionale sur le climat. Six cénozones et cinq sous-biozones sont proposées pour décrire la succession palynologique.

SUMMARY

A quantitative pollen and spore zonation for the Neogene and Quaternary of Yukon, western Northwest Territories and central and northern Alaska has been assembled from seven sections and one borehole. The sections have been dated by K–Ar and ^{39}Ar/^{40}Ar analyses, fission track analyses, paleomagnetic analyses, or by correlation to sections where such age determinations are available. Six assemblage zones and five subzones are proposed to describe the palynological succession. The ages of zonal boundaries are estimated as being half-way between points of age control.

The *Reevesia* Zone (18.3–15.75 Ma) is dominated by Taxodiaceae–Cupressaceae–Taxaceae (T–C–T), Pinaceae and Betulaceae pollen, with a rare occurrence of *Rhus*-type and *Reevesia* pollen. It represents a cool climate of the late early Seldovian stage in the late Early Miocene.

The Fagaceae Zone, T–C–T subzone (15.75–15.05 Ma) is dominated by T–C–T pollen and pollen of thermophilous angiosperms including *Ostrya/Carpinus*, *Carya*, *Juglans*, *Pterocarya*, *Fagus*, *Quercus*, *Castanea*-type, *Liquidambar*, *Ilex*, *Nyssa,* *Tilia*-type and *Ulmus*-type. This zone represents the Middle Miocene, high-latitude temperature maximum and peak canopy density, and, at its end, the beginning of decline in both parameters.

The Fagaceae Zone, *Juglans* subzone (15.05–14.3 Ma) has less pollen of T–C–T, *Fagus* and *Quercus*, but abundant *Juglans*, *Carya*, *Pterocarya* and *Ulmus*-type pollen. A trend of temperature decrease, attributed to global climate, continues in this zone, with increasing canopy openness.

The Betulaceae Zone, Polygonaceae subzone (14.3–12.35 Ma) marks the reduced abundance and last appearance of the most exotic of the thermophilous taxa, including *Osmunda*, *Cercidiphyllum*, *Ilex*, *Fagus*, *Nyssa*, and *Liquidambar*. The spectra are dominated by the Pinaceae taxa *Pinus*, *Picea*, *Tsuga* spp. and the Betulaceae taxa, *Alnus* and *Betula*. Polygonaceae pollen first appears in this zone. The zone indicates continued temperature and canopy density decrease.

The Betulaceae Zone, Transitional subzone (12.35–8.85 Ma) contains the last occurrence of *Acer*, the last, continuous occurrence of *Juglans*, and the first appearance of Caprifoliaceae pollen. The spectra are dominated by Pinaceae and Betulaceae taxa. A temperature decrease and subsequent increase are indicated but not well dated. Canopy density reaches a high value and begins to decline. The onset of a decreasing trend in temperature and canopy density coincides with the beginning of uplift of the Alaska Range and St. Elias Mountains.

The Betulaceae Zone, Cyperaceae subzone (8.85–6.15 Ma) shows rare occurrences of *Carya*, *Castanea*-type and *Ostrya/Carpinus*, and the last occurrence of *Pterocarya*. Pollen of Cyperaceae, *Nuphar* and *Sagittaria* are first recorded in this zone and the Ericales increase in abundance. The upper part of this zone is coeval with the early Messinian.

The Ericales Zone (6.15–4.05 Ma) assemblages are of low diversity. *Sphagnum* spores or *Picea* pollen dominate, Ericales become more abundant, and Caryophyllaceae pollen appears. We consider this zone to represent a cool period and correlate it to the Messinian event, to the onset of glaciation in the Yakataga Formation and to the Akpak–Iperk unconformity in the Beaufort–Mackenzie Basin.

The Poaceae Zone (4.05–2.35 Ma) includes the rare, last occurrences of pollen of some thermophilous taxa including *Juglans*, *Quercus* and *Ulmus*-type, and *Tsuga* sp. In this zone, Poaceae, *Salix* and Cyperaceae pollen and *Sphagnum* become more abundant. Herbs such as Tubuliflorae, Apiaceae, Brassicaceae, *Polemonium*, *Populus* and *Menyanthes* become common or intermittent elements in the assemblages. This zone correlates in part to the mid-Pliocene warm interval, but shows the effects of accelerated uplift of the St. Elias Mountains and the Alaska Range in an increasing continentality, and in greater canopy openess and paludification.

The *Artemisia* Zone 8 (2.35 Ma–present) shows an increased abundance of *Artemisia* pollen and the intermittent presence of *Shepherdia canadensis*. This zone spans the period of Northern Hemisphere glaciation of the late Pliocene and Pleistocene, the climatic effect of which was enhanced by continued uplift to the south.

SOMMAIRE

Une zonation sporopollinique quantitative du Néogène et du Quaternaire du Yukon, de la partie occidentale des Territoires du Nord-Ouest et des parties centrales et septentrionales de l'Alaska a été assemblée à partir de sept coupes et d'un sondage. La datation des coupes a été réalisée par les méthodes K–Ar, $^{39}Ar/^{40}Ar$ et des traces de fission, par des analyses paléomagnétiques ou par corrélation avec des coupes déjà datées. Six cénozones et cinq sous-biozones sont proposées pour décrire la succession palynologique. Les âges des frontières zonales sont estimées comme étant à mi-chemin entres les points du contrôle des âges.

La Zone à *Reevesia* (18,3–15,75 Ma) est dominée par le pollen des Taxodiacées–Cupressacées–Taxacées, des Pinacées et des Bétulacées ainsi que de rares pollens de *Reevesia* et de type *Rhus*. Elle représente le climat plus frais de la fin du début du Seldovien à la fin du Miocène précoce.

La sous-biozone à Taxodiacées–Cupressacées–Taxacées de la Zone à Fagacées (15,75–15,05 Ma) est dominée par le pollen des Taxodiacées–Cupressacées–Taxacées et le pollen d'angiospermes thermophiles, dont *Ostrya/Carpinus*, *Carya*, *Juglans*, *Pterocarya*, *Fagus*, *Quercus*, un type de *Castanea*, *Liquidambar*, *Ilex*, *Nyssa,* ainsi que des types de *Tilia* et d'*Ulmus*. Cette zone représente la période du Miocène moyen de températures maximales des hautes latitudes et de densité maximale du couvert forestier et, à l'extrémité, le début du déclin des deux paramètres.

La sous-biozone à *Juglans* de la Zone à Fagacées (15,05–14,3 Ma) renferme moins de pollen des Taxodiacées–Cupressacées–Taxacées, de *Fagus* et de *Quercus*, mais d'abondants pollens de *Juglans*, de *Carya*, de *Pterocarya* et de type *Ulmus*. Dans cette zone, la tendance à la baisse de la température persiste; elle est attribuable au climat du globe et est accompagnée d'un accroissement de l'ouverture du couvert forestier.

La sous-biozone à Polygonacées de la Zone à Bétulacées (14,3–12,35 Ma) marque la décroissance et la dernière apparition des taxons thermophiles les plus exotiques, notamment *Osmunda*, *Cercidiphyllum*, *Ilex*, *Fagus*, *Nyssa* et *Liquidambar*. Les spectres sont dominés par les taxons de Pinacées, *Pinus*, *Picea*, *Tsuga* spp., et les taxons de Bétulacées, *Alnus* et *Betula*. Le pollen des Polygonacées apparaît d'abord dans cette zone, qui traduit une température constante et une diminution de la densité du couvert forestier.

La sous-biozone transitoire de la Zone à Bétulacées (12,35–8,85 Ma) renferme la dernière occurrence de pollen d'*Acer*, la dernière occurrence continue de pollen de *Juglans* et la première apparition de pollen des Caprifoliacées. Les spectres sont dominés par les taxons de Pinacées et de Bétulacées. On reconnaît une baisse, puis une hausse de température, mais la datation n'est pas précise. La densité du couvert forestier atteint une valeur élevée et commence à diminuer. Le début de la décroissance de la température et de la densité du couvert forestier coïncide avec le début du soulèvement de la chaîne de l'Alaska et de la chaîne St. Elias.

La sous-biozone à Cypéracées de la Zone à Bétulacées (8,85–6,15 Ma) contient de rares occurrences de pollen de *Carya*, de type *Castanea*, d'*Ostrya* et de *Carpin,* ainsi que la dernière occurrence de pollen de *Pterocarya*. Le pollen des Cypéracées, *Nuphar* et *Sagittaria*, est observé pour la première fois dans cette zone et le pollen des Ericacées devient plus abondant. La partie supérieure de cette zone est contemporaine du Messinien précoce.

Les assemblages de la Zone à éricales (6,15–4,05 Ma) sont peu diversifiés. Les spores de *Sphagnum* ou le pollen de *Picea* sont dominants, les éricales deviennent plus abondants et le pollen des Caryophyllacées fait son apparition. Cette zone représenterait une période de refroidissement et serait en corrélation avec l'événement du Messinien, le début de la glaciation dans la Formation de Yakataga et la discordance Akpak–Iperk dans le bassin de Beaufort–Mackenzie.

La Zone à Poacées (4,05–2,35 Ma) comprend les dernières rares occurrences de pollen de certains taxons thermophiles, dont *Juglans*, *Quercus*, un type d'*Ulmus* et *Tsuga* spp. Dans cette zone, le pollen des Poacées, de *Salix* et des Cypéracées et les spores de *Sphagnum* deviennent plus abondants. Les plantes herbacées telles que les Ubuliflorées, les Apiacées, les Brassicacées, *Polemonium*, *Populus* et *Menyanthes* deviennent des éléments fréquents ou intermittents dans les assemblages. Cette zone est partiellement en corrélation avec l'intervalle chaud du Pliocène moyen, mais montre les conséquences du soulèvement accéléré de la chaîne St. Elias et de la chaîne de l'Alaska dans une continentalité croissante ainsi qu'une ouverture du couvert forestier et une turbification plus importantes.

La Zone 8 à *Artemisia* (92,35 Ma–période actuelle) montre une abondance accrue du pollen d'*Artemisia* et la présence intermittente du pollen de *Shepherdia canadensis*. Elle couvre la période de glaciation de l'hémisphère nord du Pliocène tardif et du Pléistocène, dont les conséquences climatiques ont été accentuées par le soulèvement continu au sud.

INTRODUCTION

This bulletin synthesizes palynological data from sites having good absolute age constraints in the western Northwest Territories, Yukon Territory, and Alaska. These data are used to produce a framework palynological assemblage zonation and paleoclimatic reconstruction for the region. The resulting information is useful for surface and subsurface geological mapping both onshore and on the continental margin of the study area. The reconstruction also contributes to understanding the development of high-latitude vegetation and climate during the Neogene and Quaternary.

Pioneering work established the pattern of late Cenozoic floral evolution and vegetation change for far northwestern North America by the study of megafloral remains from the Kenai Group in Cook Inlet, Alaska (Fig. 1). Wolfe erected the Seldovian, Homerian and Clamgulchian stages, spanning the early Miocene to Pliocene (Wolfe 1966, 1972; Wolfe and Tanai, 1980; Wolfe et al., 1966). These stages have become the structure for discussion of Neogene continental biostratigraphy and paleoclimatology in the region.

In spite of this achievement, there are limitations to the chronological and regional applicability of the megafloral work. The megafloral record for the last 3 million years of the Cenozoic has not been studied at Cook Inlet (Wolfe, 1981). Since the Late Miocene, the uplift in Alaska and Yukon of mountains between the continental interior and the Pacific coast caused differentiation between the biostratigraphic patterns of the interior and coastal regions, rendering the Cook Inlet zonation less useful for regions north of the mountain barrier. Moreover, megafloral assemblages permitting age determinations are rare in surface exposures, and almost impossible to recover from boreholes.

The study of pollen and spores provides a useful biostratigraphic tool for geological mapping and subsurface studies in the Neogene in the western Northwest Territories, the Beaufort Sea, Yukon, and Alaska. The comparative abundance and recoverability of pollen and spores in surface and subsurface sections makes them generally suitable for correlation.

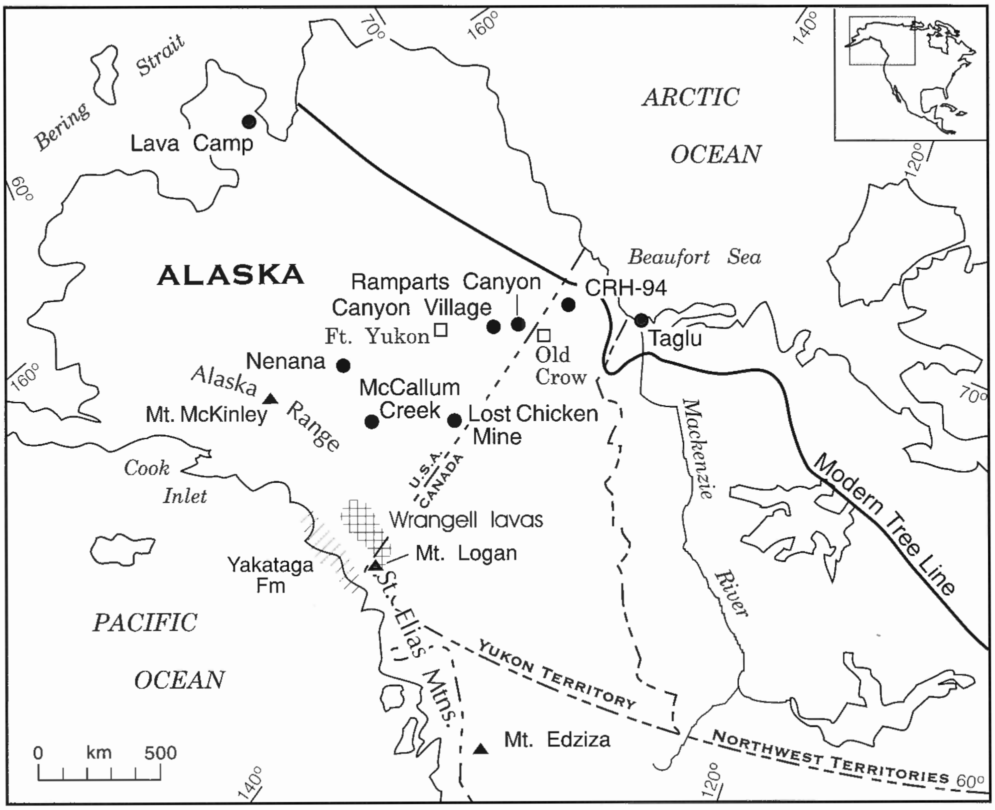


Figure 1. *Location of sections. The sections and their estimated ages are: Taglu borehole, 0–2.4 Ma (Wang and Evans, 1997); CRH-94, 2.4 Ma (Westgate et al., 1995); Lost Chicken Mine, 2.9 Ma (Matthews et al., unpublished manuscript); Lava Camp, 5.7 Ma (Hopkins et al., 1971); Canyon Village, 6.57 Ma (Kunk et al., 1994); Nenana Coalfield, 7.0-16 Ma (Leopold and Liu, 1994); Ramparts Canyon, 18 and 15.2 Ma (Kunk et al., 1994; this work).*

Significant contributions to Neogene regional palynostratigraphy have been made by Wolfe et al. (1966), Leopold (1969), Wahrhaftig et al. (1969) and more recently by Ager et al. (1994), Leopold and Liu (1994) and White and Ager (1994). We further develop the late early Miocene (ca. 18 Ma) to the late Pleistocene continental palynostratigraphy by synthesizing published and unpublished palynological data from investigations in the western Northwest and Yukon territories, and Alaska, north of the St. Elias and Alaska ranges (Fig. 1). The palynostratigraphy developed by our studies can be applied to this region of northwestern Canada and Alaska, where megafloral assemblages are sparse.

It is at least partly a theoretical assertion that development of a mountain barrier south of the study area during the latest Miocene to Pleistocene resulted in increasing differentiation in the biostratigraphic patterns on either side of the barrier. There are no directly comparable records south and north of the divide. Megafossils are rare to the north of the divide, and the last 3 million years remain unstudied to the south (Wolfe et al, 1966). Pollen and spores have not been studied on either side of the divide using the same quantitative techniques (compare Wolfe et al., 1966, and Leopold and Liu, 1994), because of the three-decade span over which the work has been done. However, the above assertion is supported by the marked, modern, coastal–to–interior climate and vegetation differences in Alaska and the Yukon (Burn, 1994), attributed to the formidable topographic barrier of the Alaska and St. Elias mountains. The modern Pacific coast is dominated by cool–moist-adapted species (Sitka spruce, Western hemlock), while cold–dry-adapted species (White spruce) dominate the interior of Alaska and Yukon (Hultén, 1968; Viereck and Little, 1972). The modern latitudinal tree line, which crosses the northern portion of the study area, is also a product of Neogene/Quaternary vegetation development.

An underlying assumption of this study is that the pollen and spore zonation is largely a result of climatic change driving floral and vegetation change. Currie and Paquin (1987) showed that tree species richness is positively correlated to available energy, measured as annual evapotranspiration. The Neogene and Quaternary periods have been a time of dramatic global climatic changes (Haq et al., 1987; Miller et al., 1991, 1996; Wolfe, 1994; White et al., 1997a) with a general cooling trend. The peak warm period of the late Cenozoic occurred in the early Middle Miocene, and was followed by periods of cooling, especially between 15 and 12 Ma, and after 4 Ma. The onset of ice-rafted detritus in the North Atlantic and North Pacific ca. 2.6 Ma (Shackleton et al., 1984; Rea and Schrader, 1985) signaled the onset of major Northern Hemisphere glacial cycles. These changes were in some part dependent on closure of the eastern portal of the Mediterranean and uplift of the Himalayas and Tibetan Plateau (Ruddiman and Kutzbach, 1990; Flower and Kennett, 1994; Kutzbach et al., 1993). Our study shows that a regionally significant factor was uplift of the St. Elias Mountains and the Alaska Range, which caused cooling and increased continentality to their north (Fig. 1; White et al., in press).

GSC–USGS collaboration

A portion of the data used in this study resulted from a joint Geological Survey of Canada–United States Geological Survey program of investigation into Neogene high-latitude biostratigraphy and paleoclimatology (T. Ager, J. White, D. Adam). Fieldwork began in 1990 and substantive results were published in 1994 (Ager et al., 1994). Other authors (H. Jetté, E. Leopold, G. Liu, and C. Schweger) had research programs independent of the USGS–GSC program.

The GSC–USGS program had two stages: first, examination of fossiliferous and independently datable surface sections in order to build a palynostratigraphic and paleoclimatic framework; second, recovery and analysis of a continuously cored borehole from a Neogene, high-latitude sedimentary basin. This paper represents the synthesis of data obtained during the first stage of GSC–USGS investigation, and of data obtained by co-authors. It represents a comprehensive and well-dated overview of evidence from surface sections, which will serve as a guide for dating of core from the borehole obtained in 1995 by the USGS from the Ft. Yukon Basin, Alaska (Fig. 1). The core is anticipated to provide a higher resolution palynostratigraphy and paleoclimatology, and to span the Quaternary to the middle Miocene.

Quantitative database for biostratigraphy and paleoclimatology

The database assembled here is quantitative. A problem that hinders late Cenozoic biostratigraphy is that many common taxa (e.g., *Carya*, *Juglans*, *Pterocarya*, *Ulmus*-type) achieved essentially modern morphology as far back as the Eocene. In the absence of morphological changes in pollen and spores, biostratigraphic successions are best recognized by quantitative abundances, rather than presence/absence data. This analysis shows that even within the time period studied, the stratigraphic ranges of the taxa extend much farther than the interval in which they are common or abundant elements of assemblages. Thus, quantitative representation of data can enhance age interpretations. Quantitative data allow higher resolution paleoclimatic reconstructions than are possible with presence/absence data.

This bulletin is a synthesis of published and unpublished data, originally accumulated for other purposes. Input data from the Usibelli Group were available as percentages by scaling from Figure 8 of Leopold and Liu (1994). For comparison, data in digital files have been converted to percentages. Palynological data from all sections have been summarized with measures of both central tendency (means) and variation (standard deviation). The original palynological count data and taxonomic commentary are available in White et al. (1997b).

Neogene and Quaternary tectonics

In the Alaska Range, fission track analyses indicate rapid uplift of Mount McKinley (elevation 6193 m) and the Alaska Range for the last 5 to 6 Ma, because of a change in relative motion of the North American and Pacific plates (Plafker et al. 1991, Fitzgerald et al., 1993, 1995). The deformation of the upper Tertiary sedimentary rock exposed at McCallum Creek, northern Alaska Range, postdates 5.3 Ma (Weber and Turner, 1977). Pre-uplift mean surface elevations at the site of Alaska Range were about 0.2 km, and interior drainage flowed south across the site until uplift in the Plio-Pleistocene. Presently, the mean elevation is about 3 km (Fitzgerald et al., 1993, 1995; Wahrhaftig, 1987; Wahrhaftig et al., 1969).

The extensive Wrangell lavas were deposited on a surface of low relief. There was no large-scale tectonic deformation during their deposition (Souther and Stanciu, 1975), which has been isotopically dated at between 18 and 10 Ma in southeast Yukon (Skulski et al., 1992). Tectonism that produced the St. Elias Mountains, the highest and youngest in Canada, was concentrated in the Pliocene and Pleistocene (Campbell et al., 1991). Fission track data show that Mount Logan (elevation 5959 m), the largest mountain mass, experienced two Neogene episodes of rapid cooling, ca. 15 Ma and ca. 4 Ma; the latter correlates with compression and underplating of the Yakutat Terrane along the North American plate margin (O'Sullivan et al., 1995). The crustal cooling rates determined for these periods suggest denudation rates of > 0.3 mm/yr. (Parrish, 1981; O'Sullivan et al., 1995). In the Yakataga Formation, on the Pacific side of the St. Elias Mountains, sedimentology and foraminifera indicate that uplift began in the Late Miocene, about 8.5 Ma, initiating tidewater glaciation between 5.0 and 6.7 Ma (Lagoe et al., 1993).

Thus, during most of the Miocene, there apparently was no great topographic barrier to impede the penetration of warm, moist Pacific air to central Alaska–Yukon–Northwest Territories. Significant uplift occurred in the latest Miocene to Pleistocene.

Stratigraphic sections

In the study area, most exposures of Neogene continental rocks represent short intervals of time. Without stratigraphic superposition, correlations are difficult and must be based on assumptions about the direction of floral change. To avoid this problem, the sections used for this study have been dated by K–Ar, ^{39}Ar/^{40}Ar and fission track analyses, often with paleomagnetic support, or by correlation to sections where such age determinations are available. A brief description of the sections studied follows (Fig. 1–3, Table 1).

Table 1
Names and locations of study sites and names of pollen analysts

Section or borehole	Latitude	Longitude	Pollen analyst
Taglu borehole	69°12′	135°20′	H. Jetté
CRH-94	68°04′	139°46′	C. Schweger
Lost Chicken Mine	64°05′	141°55′	D. Adam
McCallum Creek	63°14′	145°37′	J. White
Lava Camp	65°53′	163°07′	J. White
Canyon Village (Loc. 90-7)	67°09′	142°08′	T. Ager
Usibelli Group	63°52′	148°51′	E. Leopold, G. Liu
Upper Ramparts Canyon	67°20′	141°20′	J. White

Where a section or palynological zone to be used for the subsequent analysis is not directly dated by an independent geochronological technique (e.g., Upper Ramparts Canyon, organic bed 1) we discuss the age-constraining evidence in order to derive a working age estimate.

Upper Ramparts Canyon (lat. 67° 19.85'N, long. 141° 19.8'W)

The Upper Ramparts Canyon section is on the Porcupine River, Alaska (Fig. 1). Two flood basalts exposed in the Upper Ramparts Canyon overlie and enclose pollen-rich clastic sediments, wood and peat (Fouch et al., 1994). Kunk et al. (1994) concluded from ^{40}Ar/^{39}Ar ages for the basalts and the paleomagnetic data, that the lower and upper flows at locality 90-1 are 15.2 ± 0.1 Ma. Organic bed 2 (o.b. 2), a forest-floor peat with stumps in life position, was engulfed by the lowest basalt, and is thus 15.2 Ma old. Organic beds 3 and 4, a laminated lacustrine shale and a peat, respectively, are enclosed by the two basalts. Organic bed 1 underlies and predates the lowest basalt (White and Ager, 1994).

The peat of o.b. 1 is enclosed in fluvial–lacustrine sand to clay beds and lies 6 m below the lowest basalt flow (Fouch

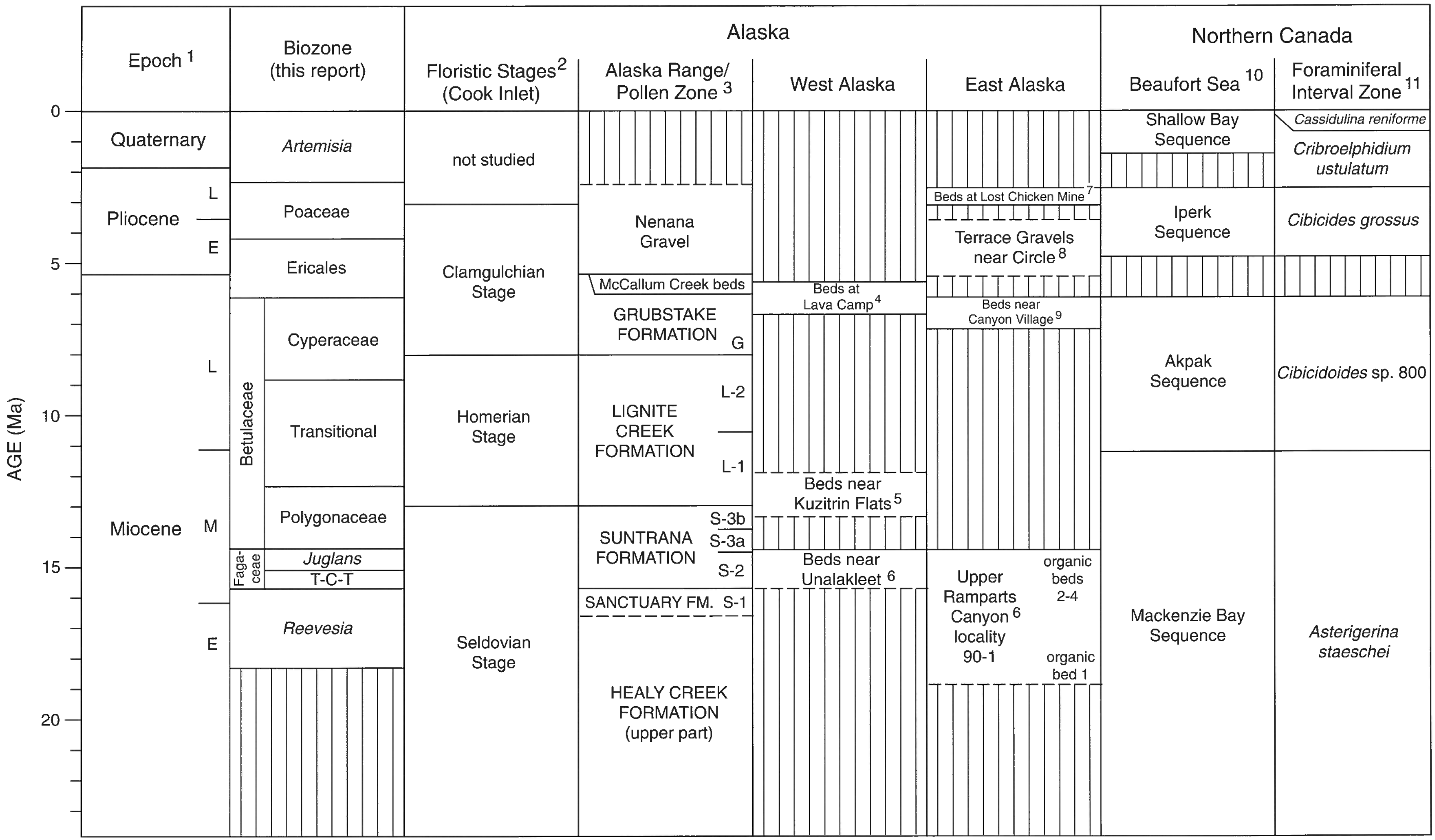


Figure 3. *Correlation diagram. [1]Cande and Kent, 1995. [2]Wolfe et al., 1966; Wolfe and Tanai, 1980; Wolfe, 1981. [3]Wahrhaftig et al., 1969; Wahrhaftig, 1987; Leopold and Liu, 1994, this paper. [4]Hopkins et al., 1971. [5]Ager and Kaufman, 1992; White and Ager, 1994. [6]White and Ager, 1994. [7]Matthews et al., unpublished manuscript; Adam, unpublished manuscript. [8]Ager et al., 1994. [9]Kunk et al., 1994; Ager, Matthews and White, unpublished manuscript. [10]Dixon et al., 1992.*

et al., 1994). Organic bed 1 was interpreted by White and Ager (1994) to be not much older than the overlying o.b. 2 and basalt flows because of the absence of any discernible disconformities between the two organic beds. Reconsidering the evidence, we note that o.b. 1 lacks *Fagus* and *Tilia* pollen in all of the 11 pollen samples analysed. The absence of these two taxa is typical of lower Seldovian samples according to Wolfe and Tanai (1980, p. 7, 8). Thus, an interpretation that o.b. 1 is older than previously estimated and falls in the upper part of the lower Seldovian Stage, older than 18 Ma and of late Early Miocene age (Wolfe, 1981), is more consistent with both the local stratigraphic and regional palynological evidence. We estimate its age at 18.3 Ma, a revision of the 16–17 Ma age estimate found in White and Ager (1994).

The four organic beds of the Upper Ramparts Canyon section each record a relatively short interval of time. Pollen and spores in these beds were analyzed by J. White, and reported in White and Ager (1994).

Usibelli Group (lat. 63°52'N, long. 148°51'W)

The five formations of the Usibelli Group (in stratigraphic order from oldest to youngest – Healy Creek, Sanctuary, Suntrana, Lignite Creek and Grubstake formations) make up the Nenana Coalfield in the north Alaska Range (Wahrhaftig, 1987; Fig. 1). The east–west alignment of folds is crosscut by drainage, providing excellent exposure of long vertical sections, 590 m thick at Suntrana. The Healy Creek Formation is not included here. The Suntrana to Grubstake formations provide a very long stratigraphic and palynological sequence of the continental Neogene of Alaska, spanning the Middle and Upper Miocene.

The Sanctuary and overlying formations, and the uppermost Nenana Gravel, record the warm and then cooling climate of the Miocene, and the reversal of drainage from south-flowing to north-flowing after the uplift of the Alaska Range (Wahrhaftig, 1987; Wahrhaftig, et al. 1969, Leopold and Liu, 1994). Palynological data have been reported in Wahrhaftig et al. (1969) and Leopold and Liu (1994). There are few isotopic dates from this area, and age assignments are based primarily on correlation to Wolfe's stages in the Kenai Group of Cook Inlet in southern Alaska (Triplehorn et al., 1977; Turner et al., 1980; Wahrhaftig, 1987; Wahrhaftig, et al., 1969; Leopold and Liu, 1994). During deposition of the Usibelli Group, the topographic barrier of the Alaska Range was not present between regions of the Usibelli and Kenai Group deposition (Fitzgerald et al., 1993, 1995; Plafker et al., 1991), making correlation between the two areas reliable.

Leopold and Liu (1994) presented a palynological zonation for the Usibelli Group at Suntrana, defining four palynological zones (S-1 to S-3b) in the Sanctuary and Suntrana formations, two zones (L-1, L-2) in the Lignite Creek Formation, and one zone (G-1) in the Grubstake Formation. The correlation of the S-1 and S-2 zones to the Upper Ramparts Canyon organic beds is considered below. This correlation ties the Usibelli Group pollen zonation to an absolute time scale, and serves as a check of chronological arguments derived by correlation to floral stages from Cook Inlet. Correlation of Suntrana Formation Zone S-2 to the Upper Ramparts Canyon organic beds is critical to our analysis.

Correlation of S-2 and organic beds 2, 3, 4

The Suntrana Formation at Coal Creek is 400 m thick and contains six coal beds, individually as much as 13 m thick (Leopold and Liu, 1994). Thus, it represents a considerable span of time. Pollen Zone S-2 occurs in the lower Suntrana Formation (Fig. 3).

The correlation between beds in the Upper Ramparts Canyon section and the Usibelli Group is based on thermophilous taxa. Leopold and Liu (1994) correlated upper Zone S-2 and Zone S3a to beds 2 to 4 of White and Ager (1994) in the Upper Ramparts Canyon section. A slightly different correlation was made by the latter authors, who focused on the maximum relative abundance of *Quercus* and *Fagus* pollen and thus correlated the lower third of the Suntrana Formation (lower Zone S-2) to organic beds 3 and 4 of the Upper Ramparts Canyon section.

In this study, we have divided Zone S-2 into an upper and lower subset of six samples each to improve resolution in biostratigraphy and paleoclimatology. We believe that the lower subset of samples, where the maximum abundance of *Fagus* pollen occurs at sample D-3465J, is penecontemporaneous with o.b. 3 and 4. Zone S-2 records a much longer period of time than the Upper Rampart Canyon beds, so for construction of the composite pollen diagram we have placed the spectra of the lower and upper sample subsets of S-2 above (younger) o.b. 3 and 4, while recognizing that they are in part contemporaneous.

Organic bed 2 spectra are stratigraphically lower than o.b. 3, although within the resolution of our isotopic chronology the beds are contemporaneous. The composite spectrum of o.b. 2 has been placed immediately below o.b. 3.

Correlation of S-1 and organic bed 1

The correlation above leaves the relative order of Zone S-1 and o.b. 1 to be resolved by reference to Wolfe's subdivision of the Seldovian Stage (Wolfe and Tanai, 1980; Wolfe, 1981). Usibelli Zone S-1, underlying S-2, also predates o.b. 2 to 4. Leopold and Liu (1994) correlated the pollen flora of zone S-1 to the lower Seldovian Stage, which is of Early Miocene age (Fig. 2). However, Zone S-1 contains *Fagus* and *Tilia* pollen, which is absent in lower Seldovian Stage samples according to Wolfe and Tanai (1980, p. 7, 8), suggesting that Zone S-1 postdates the lower Seldovian Stage, and is therefore younger than ca. 18 Ma (Wolfe, 1981). This interpretation is supported by the fact that the palynological transition from Zone S-1 to S-2 shows continuities in the percentages of thermophilous taxa (Leopold and Liu, 1994, fig. 9). We have placed S-1 between o.b. 1 and o.b. 3 in our composite zonation. Organic bed 1 was correlated above to the lower Seldovian Stage, at ca. 18.3 Ma.

We have estimated an age of 16 Ma for S-1, with the date on S-2 fixed by correlation to o.b. 2 - 4 at 15.2 Ma. This fits well with Turner et al.'s (1980) average date of 15.8±1.8 Ma for samples on the Chuitna River, which are bracketed by upper Seldovian leaf floras (Turner et al., 1980; Leopold and Liu, 1994).

Climatic interpretations of o.b. 1 and S-1 differ. The exotic *Reevesia* and *Itea*-type pollen are rare in Zone S-1 (Leopold and Liu, 1994), but are absent in the 11 samples from o.b. 1. However, o.b. 1 has more abundant *Pinus* and *Picea* pollen than S-1, the greater Pinaceae abundance suggesting a cooler climate. This pattern suggests a vegetation response to warming from the Early to the Middle Miocene.

The arrangement of the Usibelli Group zones and Upper Ramparts canyon beds, by the reasoning above is, from oldest to youngest: o.b. 1, Zone S-1, o.b. 2, 3, 4, and Zone S-2 (lower and upper subsets). For Zone S-2 and above, order is based on stratigraphic superposition.

Alternative correlation

As noted above, Leopold and Liu (1994) correlated the upper Zone S-2 and Zone S-3a to beds 2 to 4 in the upper Ramparts Canyon section. The interpretation presented here is that the most probable local tie is the lower S-2 to o.b. 2-4. However, Leopold and Liu's alternative correlation also fits the data. In its favour is the fact that the warm–cool–warm climatic pattern in Zone S-2 and lower S-3a (Leopold and Liu, 1994, fig. 7), evident at a time scale of analysis shorter than that used in this reconstruction, makes a cycle comparable to that seen in the marine isotopic Zones M1b and M2 of Miller et al. (1991, 1996). However, two spectra in Zone S-2 dominate the pattern, and it is not certain if the pattern represents events at the same time scale as the marine signal. If Leopold and Liu's correlation is correct, the effect on the biostratigraphic and paleoclimatic reconstruction presented here is to move the datapoint for the lower six spectra in S-2 to between o.b. 2 and S-1.

S-2 to G-1

Pollen zones S-3a and S-3b occur above S-2 in the Suntrana Formation; the top of the S-3b pollen zone is coincident with the top of the Suntrana. The age of the top of the Suntrana Formation is not known isotopically, but is estimated by palynological correlation to Wolfe's Cook Inlet stages. A ^{40}Ar/^{39}Ar date on tephra from within the No. 6 coal is anticipated in the future. Correlation is supported by the percentage of 'exotic' taxa; i.e., taxa not now native to Alaska that occur in the Usibelli and the Kenai groups (Leopold and Liu, 1994).

The Suntrana Formation and its Zones S-2 to S-3b are correlated to the Seldovian Stage of Cook Inlet (Leopold and Liu, 1994, p. 128, 129). The top of the Seldovian Stage is bracketed between the 15.8±1.8 Ma average date on an upper Seldovian flora at Chuitna River and a K–Ar date of 11.3±0.7 Ma from 50 m above the base of the Homerian type section (Turner et al., 1980). The age of the Seldovian–Homerian boundary is interpolated to be 13 Ma (Leopold and Liu, 1994; Wolfe, 1994), and that age is used here as an estimate of the boundary between pollen zones S-3B and L-1.

The ages used for plotting of composite spectra (Fig. 2) have been prorated over the period of time between points of chronological control. Minor adjustments have been made to allow separation of histograms on the plot. The lower six spectra of Zone S-2 have been assigned an age of 15.0 Ma in order to plot just above but nearly contemporaneous with o.b. 2 to 4. The upper six spectra of Zone S-2 have been assigned an age of 14.6 Ma. Zone S-3A has been assigned an age of 14.0 Ma, and S3-B an age of 13.4 Ma.

Pollen Zones L-1 and L-2 are from the Lignite Creek Formation in the Usibelli Group. The Lignite Creek is correlated to the Homerian Stage at Cook Inlet, and thus spans the interval 13 Ma to 8 Ma. The age of the Homerian/Clamgulchian Stage boundary is estimated at 8 Ma. This date is derived from K–Ar dates of 8.8±0.9 and 8.1±0.7 Ma in the Homerian type section and Clamgulchian reference section, respectively. These dates are supported by zircon fission-track ages of 8.1±1.0 and 7.6±0.7 Ma (Turner et al., 1980). For plotting, the composite spectra from Zones L-1 and L-2 have been assigned mean ages of 11.3 and 9.7 Ma, respectively.

The Grubstake Formation and pollen zone G in the Usibelli Group are considered transitional between the Homerian and Clamgulchian stages (Leopold and Liu, 1994, p. 129). A date of 8.3±0.4 Ma has been obtained from an ash at the base of the Grubstake Formation at the type section on Tatlanika Creek (Wahrhaftig, 1987). Therefore, we have assigned an age of 8 Ma to the composite pollen spectra from Zone G-1.

Canyon Village (locality 90-7, lat. 67°8'48"N, long. 142°8'24"W)

Two sections near Canyon Village are on the Porcupine River in northeast Alaska, downstream of the Ramparts Canyon section. Exposures of Miocene lacustrine sediment occur in adjacent sections 90-7 and 90-8, which are contemporaneous. Section 90-7 comprises 38 m of Late Miocene lacustrine and fluvial sediment (Fouch et al., 1994). A tephra enclosed in the sequence has been dated at 6.57±0.02 Ma (Kunk et al., 1994). A palynological and macrobotanical report is in preparation (Ager et al., unpublished manuscript). The palynological counts by T.A. Ager, from 90-7, the longest section, are used here. The data are plotted at 6.6 Ma.

Lava Camp (lat. 65°53'N, long. 163°07'W)

Hopkins et al. (1971) described a Pliocene flora and fauna in strata by a gold mine in the valley of the Inmachuk River, Seward Peninsula, Alaska. Here a basaltic lava flowed over wet ground with small ponds. Rooted stumps engulfed by the lava, and a lack of soil development below the basalt indicate that the sediments are only slightly older than the basalt. The basalt is dated by K–Ar at 5.7±0.2 Ma (Hopkins et al., 1971). Samples 1190-B and E from the Lava Camp Mine, collected by J.V. Matthews, are stored in the collection of T.A. Ager and were provided to J.M. White for analysis. Lava Camp is the westernmost of the sites in this study, and probably the most removed from the effects of Neogene/Quaternary uplift to the south. The Bering Strait probably did not exist during the time of deposition of the Lava Camp sediments.

McCallum Creek (lat. 63°13'35"N, long. 145°36'55"W)

This section of upper Tertiary sedimentary rock lies on the north slope of a valley on a tributary of McCallum Creek, 1.5 km east-northeast of the junction of the McCallum Creek road and the Richardson Highway, Mount Hayes A-4 Quadrangle, Alaska. This area was visited by a joint USGS–GSC field party in 1991. Weber and Turner (1977) described a lower Tertiary unit of lignitic sandstone and shale with some conglomerate and ash, 150 to 300 m thick. An upper unit comprises several thousand metres of conglomerate. A fault visible in the McCallum Creek valley has thrust Pennsylvanian and Permian sedimentary rocks southward over Tertiary sedimentary rocks, the latter of which are deformed in broad, slightly overturned folds (Weber and Turner, 1977).

A 100 m thick section of the lower unit is exposed, containing a tephra approximately 2 m thick, which thins out to the north. One pollen sample from dark siltstone underlies the tephra by 0.5 m and one sample from mudstone with vitreous charcoal overlies the tephra by 2.5 m. The impoverished pollen assemblage was analysed by J.M. White. Kunk (1995) reported ages of 5.23±0.05 Ma plateau, 5.10±0.15 Ma isochron, and 5.37 Ma total gas – which are similar to a K–Ar date of 5.26 Ma on hornblende from the lower unit, reported by Weber and Turner (1977). We have plotted the data at 5.2 Ma.

Lost Chicken Mine (lat. 64°4'30"N, long. 141°54'52"W)

The hamlet of Chicken is on the Taylor Highway in northeast Alaska. Gold-bearing, fluvial gravel deposits have been mined along Lost Chicken Creek, a tributary of the Fortymile River. The upper placer pit contains fluvial gravels, silts, peats, and trees in life position, now preserved in permafrost. These deposits are at least 100 m above the Fortymile River. Manuscripts are in preparation describing the stratigraphy (Carter el al., unpublished manuscript), palynology (Adam, unpublished manuscript), and paleobotany and geochronology (Matthews et al., unpublished manuscript). A tephra from John Matthews' station 91-2 has been dated by J. Westgate at 2.9±0.2 Ma using fission tracks (Mathews, pers. comm.).

The data presented here are the average of spectra from thirty-two, relatively homogeneous palynological samples (Adam, in prep.).

CRH-94 (lat. 68°3'30"N, long. 139°46'25"W)

CRH-94 is a cutbank exposure, about 40–50 m high, in a meander of the Old Crow River in the northern Old Crow Basin (Fig. 1). The section consists of a sequence of fine grained, alluvial, lacustrine and reworked lacustrine sediments capped by upper Pleistocene lacustrine clays. The Little Timber Tephra, 25 cm thick, is found at the downstream end at the base of the bluff in a 7.8 m thick lacustrine unit of massive, dark brown, clay-rich silt with concretions. The tephra has been dated to 2.29±0.25 Ma by the isothermal plateau fission track method (Westgate et al., 1995). Paleomagnetic samples from 0.5 m above and 1.0 m below the tephra are reversed, consistent with the tephra's age.

The results of analysis by C.E. Schweger of 11 samples from above and below the tephra are averaged here to create one representative spectrum. Three samples from within the tephra, which show vegetation disturbance resulting from tephra, deposition were excluded.

Taglu Borehole (lat. 69°11'37"N, long. 135°20"27"W)

The Taglu borehole on Richards Island, Mackenzie River delta was drilled in March and April, 1992 to a depth of 451.1 m, and most of the section penetrated above 372 m was recovered in core. The core has been logged, described and lithological and paleoecological analyses have been done (Dallimore and Matthews, 1997). Paleontological analyses indicate the presence of a probable unconformity in a section of unrecovered core between 375 and 411 m, the sediment below being Middle Miocene and older, and above latest Miocene to Pleistocene (Dallimore and Matthews, 1997). Paleomagnetic analyses (Wang and Evans, 1997) define the placement of paleomagnetic chrons, the shifts taking place over short intervals of core. For this analysis, the mean paleomagnetic boundary positions are used, with associated ages following Cande and Kent (1992, 1995): Brunhes–Matuyama boundary, 152.3 m (0.78 Ma); the Jaramillo normal subchron, 204.1–216.1 m (0.99–1.07 Ma); the Olduvai normal subchron 308.1– 316.9 m (1.77–1.95 Ma); and, the Matuyama–Gauss boundary, 356.0 m (2.60 Ma) (Wang and Evans, 1997).

Pollen samples were analysed by H. Jetté. The samples are divisible stratigraphically into four groups, within which the sample percentages were averaged. Mean ages for the groups were estimated by pro-rating their stratigraphic midpoints relative to the paleomagnetic boundaries. The group depth limits, estimated age and number of palynological samples is: 5.0–70.7 m, 0.2 Ma, five samples; 75.7–119.9 m, 0.6 Ma, five samples; 169.9–263.4 m, 1.0 Ma, six samples; 332.8–349.8, 2.4 Ma, five samples.

The Taglu borehole is composed mainly of paralic and fluvial sediments, and is the northernmost of the sites, located north of the Brooks Range and British Mountains. In environment and location it is unlike the other sites. The geographic effect on the palynological record will not be known until the analysis of more southern, contemporaneous sites. The proximity of the site to Eocene outcrop in the Caribou Hills (Ioannides and McIntyre, 1980) makes it possible that some of the palynomorphs counted were recycled.

METHOD

Composite spectra

Pollen and spore counts were used to create the composite zonation. Seven palynologists counted the samples. The number of grains counted varied with workers' objectives and because it was more difficult to achieve a desired count in some samples than in others. Nonetheless, the count was usually between 200 and 600 a sample, less in only a few impoverished samples. "Rare" taxa are those that did not appear in a count to the predetermined pollen sum for each sample, but were identified during a scan of the uncounted portion of the slide. Their occurrence beyond the count sum allows an assessment of their maximum relative frequency, normally less than 0.5 per cent. Rare taxa were added to the compiled pollen and spore database and their relative abundance estimated at 0.1 per cent.

Raw count-data were used to generate the percentages from all sections except the Usibelli Group, for which percentage data have been scaled from Figure 8 of Leopold and Liu (1994). Scaling introduces some error in the estimates, but it is considered random and inconsequential because the results from several samples are averaged.

In order to make the composite pollen diagram, the palynological spectra have been averaged to provide a "typical" spectrum from each section, or pollen zone within a section (Usibelli Group), or increment in a borehole (Taglu well). The 163 palynological samples from these sections have been grouped and averaged within the groups to produce 21 composite spectra, using the statistical functions of QuattroPro for Windows. No less than two samples, and as many as 32, are summed to make up each composite spectrum, thus decreasing stochastic variation in the percentage estimates by increasing sample size, and reducing the effect of short-term climatic or edaphic variation. The population standard deviation of the percentages has been calculated to provide a measure of the variation around the average value (Table 2).

The 21 composite spectra depict the long-term pattern of vegetation change. The average resolution is about one composite record per million years, more frequent in the middle Miocene and Pleistocene, and less in between.

Taxonomic harmonization

Authors vary in their use of taxonomy. We have not re-examined all specimens included in the tables, but taxonomic usage was harmonized by amalgamating some taxa at a higher level when the databases were being integrated (by JMW). Taxa chosen for representation in Figure 2 and Table 3 are morphologically distinct at the given taxonomic level, and have stratigraphic and/or environmental utility. Other taxa are included because they are commonly abundant though they may show only generalized patterns of relative abundance change.

Identifications of Middle and Late Miocene taxa used in this paper follow those illustrated in White and Ager (1994) and Leopold and Liu (1994). Atlases of modern pollen from the Northern Hemisphere (Adams and Morton, 1972, 1974, 1976, 1979; Bassett et al., 1978; Bobrov et al., 1983; Erdtman et al., 1963; Huang, 1972; Kuprianova and Alyoshina, 1972, 1978; Lieux, 1980a,b, 1983; Lieux and

Table 2
Sections, Usibelli Group pollen zones or Taglu well increments and associated number of spectra; and estimated age of biozone boundaries. The data are listed from youngest to oldest

Section or zone	No. of spectra from section	Composite spectra mean ages (Ma)	[1]Estimated zone boundary (Ma)	Palynomorph assemblage	
				Zone	Subzone
			0		
Taglu borehole, 5.0–70.7 m	5	0.20			
Taglu borehole, 75.7–119.9 m	5	0.60		Artemisia	
Taglu borehole,169.9–263.4 m	6	1.00			
CRH-94	11	2.30			
			2.35		
Taglu borehole, 332.8–349.8 m	5	2.40		Poaceae	
Lost Chicken Mine	32	2.90			
			4.05		
McCallum Creek	2	5.20		Ericales	
Lava Camp	2	5.70			
			6.15		
Canyon Village (Loc. 90-7)	23	6.60		Betulaceae	
Usibelli Group, Zone G	6	8.00			Cyperaceae
			8.85		
Usibelli Group, Zone L-2	7	9.70		Betulaceae	
Usibelli Group, Zone L-1	7	11.30			Transitional
			12.35		
Usibelli Group, Zone S-3b	6	13.40		Betulaceae	
Usibelli Group, Zone S-3a	6	14.00			Polygonaceae
			14.3		
Usibelli Group, Zone S-2 (upper)	6	14.60		Fagaceae	
Usibelli Group, Zone S-2 (lower)	6	15.00			Juglans
			15.05		
Upper Ramparts Canyon, o.b. 4	4	15.10		Fagaceae	
Upper Ramparts Canyon, o.b. 3	7	15.20			T–C–T
Upper Ramparts Canyon, o.b. 2	3	15.50			
			15.75		
Usibelli Group, Zone S-1	3	16.00		Reevesia	
Upper Ramparts Canyon, o.b. 1	11	18.20			
			18.3		
Sum of spectra	163				

[1] The estimated ages of zone boundaries are arithmetic means between the ages of adjacent points, and represent the best estimate of the ages of the transitions between different assemblages, but do not imply double digit accuracy.

Godfrey, 1982; Moriya, 1978; Nilsson et al., 1977; McAndrews et al., 1973; Richard, 1970a,b,c; Shimakura, 1973) and specialized systematic overviews of modern taxa are appropriate references for the Miocene and, especially, the Pliocene and Pleistocene taxa.

In some cases there is ambiguity in using a modern taxon to represent a pollen type because morphologically similar pollen is produced by more than one modern plant – most notable is pollen from the families Taxodiaceae, Cupressaceae and Taxaceae. *Corylus*-type might represent *Myrica* or *Corylus*. *Larix*-type could also be *Pseudotsuga*. *Picea* spp., *Pinus* spp. and *Tsuga* spp. all merit closer taxonomic study, because morphological variation suggests that several types may be present in these generic categories.

Article 11.7 of the International Code of Botanical Nomenclature (Greuter et al., 1994) indicates that the names of plants based on a non-fossil type have priority over names of the same rank based on a fossil type. Following the principle of priority of names of Recent taxa, we use modern botanical names where it is clear that a palynomorph can be confidently assigned to a modern family or genus. Modern generic names are consistent with nomenclature applied to fossil leaf floras of Neogene age from the region (e.g., Wolfe, 1966; Wolfe and Tanai, 1980).

Zonal scheme and chronology

This bulletin provides a first overview and palynostratigraphic framework for the Neogene and Pleistocene in the study area. Many of the pollen taxa have stratigraphic ranges extending from the Eocene to the present, but show distinct variations in relative abundance in the study area during the Neogene and Pleistocene. Thus, biostratigraphy relies on a scheme combining assemblage zones and informal abundance zonation (North American Commission on Stratigraphic Nomenclature, 1983). Abundance zones are the standard biozonal unit of Quaternary palynology.

We have also adopted a standard practice, as used for Quaternary biostratigraphy, of drawing zonal boundaries midway between datapoints (e.g., Moore and Webb, 1978, p. 89-96). Our chronological boundaries between the zones are arithmetic midpoints between the estimated ages of composite pollen spectra within the zones. The two-decimal-point precision in the age estimates of the zonal boundaries does not imply that level of precision or accuracy. Indeed, we expect that further work will substantially revise the zonal scheme and the chronology.

An additional consideration is that the stratigraphic ranges of pollen taxa represented here do not necessarily correspond to the true stratigraphic ranges of the plants. The data presented here show the representation of the flora in the pollen rain. Many factors influence the representation of plants in the palynological record.

Outside of the zonal scheme, we have assessed the value for age determinations of long-ranging and relatively abundant taxa (plotted to the right on Fig. 3) by ternary diagram manipulations of their percentages. These results are found in the ternary diagrams of Figures 4 to 8.

Paleovegetation patterns and paleoclimatology

In Figure 9, taxa are grouped and summed by environmental tolerances and physiognomy, and ratios drawn to track environmental parameters: temperature, T_{est} (warm/cool

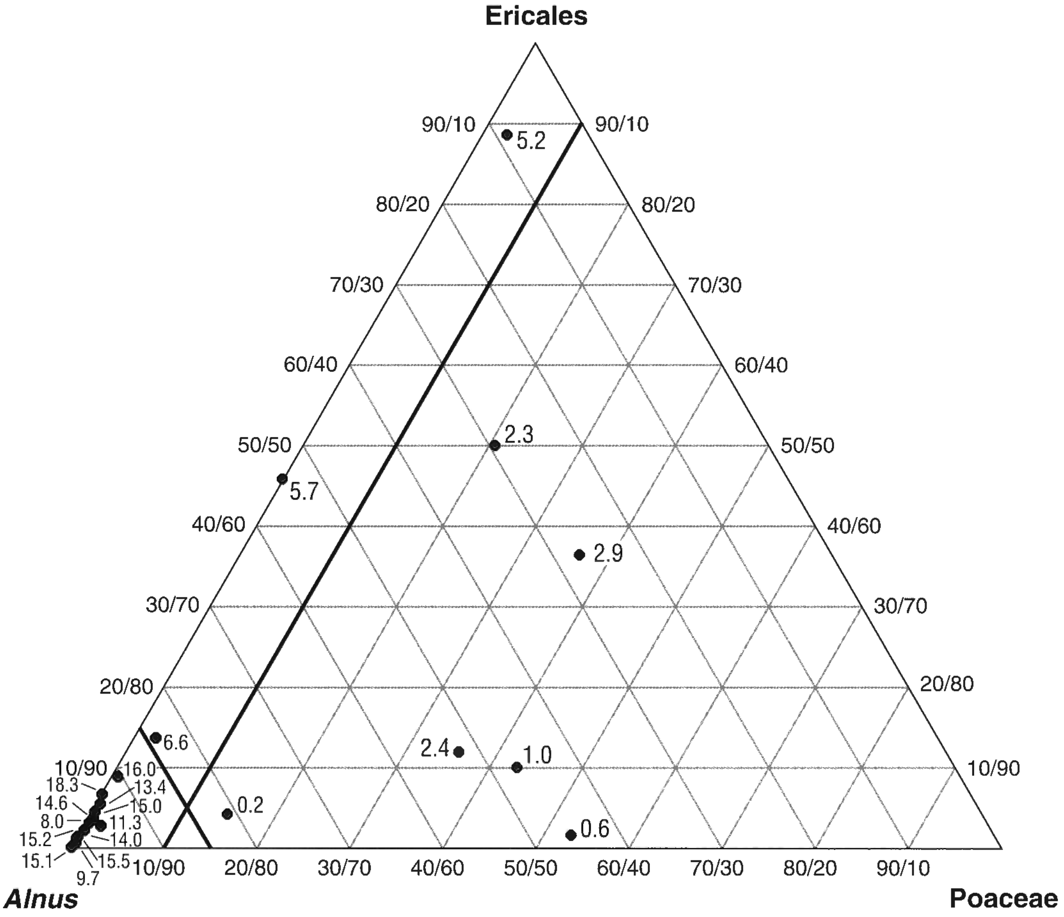


__Figure 4.__ Ternary diagram of relative abundances of __Alnus__, Ericales and Poaceae (see p. 22 for discussion).

trees), an indication of relative climatic temperature; canopy, C_{est} ((shrubs + herbs)/trees), an indication of the relative area of forest canopy to space occupied by shade-intolerant taxa; and paludification, P_{est} (terrestrial angiosperms/*Sphagnum),* an index of the paludification of the study sites (coverage by saturated organics). Summations are based on modern botanical affinities and climatic tolerances, although these are broad at the family or genus level of determination, and may be less appropriate for the older assemblages. The ratios in Figure 9 are not linear measures of the parameters they describe. Our interpetations are based on the direction of change of the ratios, rather than on their absolute values.

RESULTS

Zonation

Figure 3 shows long-term patterns of relative abundance of 77 taxa from approximately 18 Ma to the late Quaternary. Table 2 shows the means and population standard deviations (STD) for the plotted taxa, which account for 65 to 100 per cent of the sum of pollen in the samples (Table 3: S-2 upper sums to 101.9 per cent, because of the addition of rare taxa at 0.1 per cent and to error in scaling the data from the published pollen diagram). The most abundant taxon omitted is Undifferentiated Bisaccates.

Taxa now absent in the interior parts of Yukon and Alaska north of the coastal ranges are plotted to the left on Figure 3, by last stratigraphic appearance. Taxa extant in that region are plotted by apparent first appearance in the middle of Figure 3. Taxa extant in the study area do not always appear in the uppermost samples for stochastic or climatic reasons, but at the given level of taxonomic differentiation, representatives are found in the modern flora (Scoggan, 1978a, b, c, 1979; Hultén, 1968). Other morphologically distinctive but long-ranging taxa have been plotted to the right of Figure 3. The latter may or may not show generalized patterns of change in relative abundance.

Ratios depicting paleoclimatic and paleovegetation changes associated with this zonation are found on Figure 9.

Reevesia Zone, 18.3–15.7 Ma

The *Reevesia* Zone is made up of 11 spectra from o.b. 1, Upper Ramparts Canyon, and three spectra from the Zone S-1, Sanctuary Formation, Usibelli Group. The rare presence

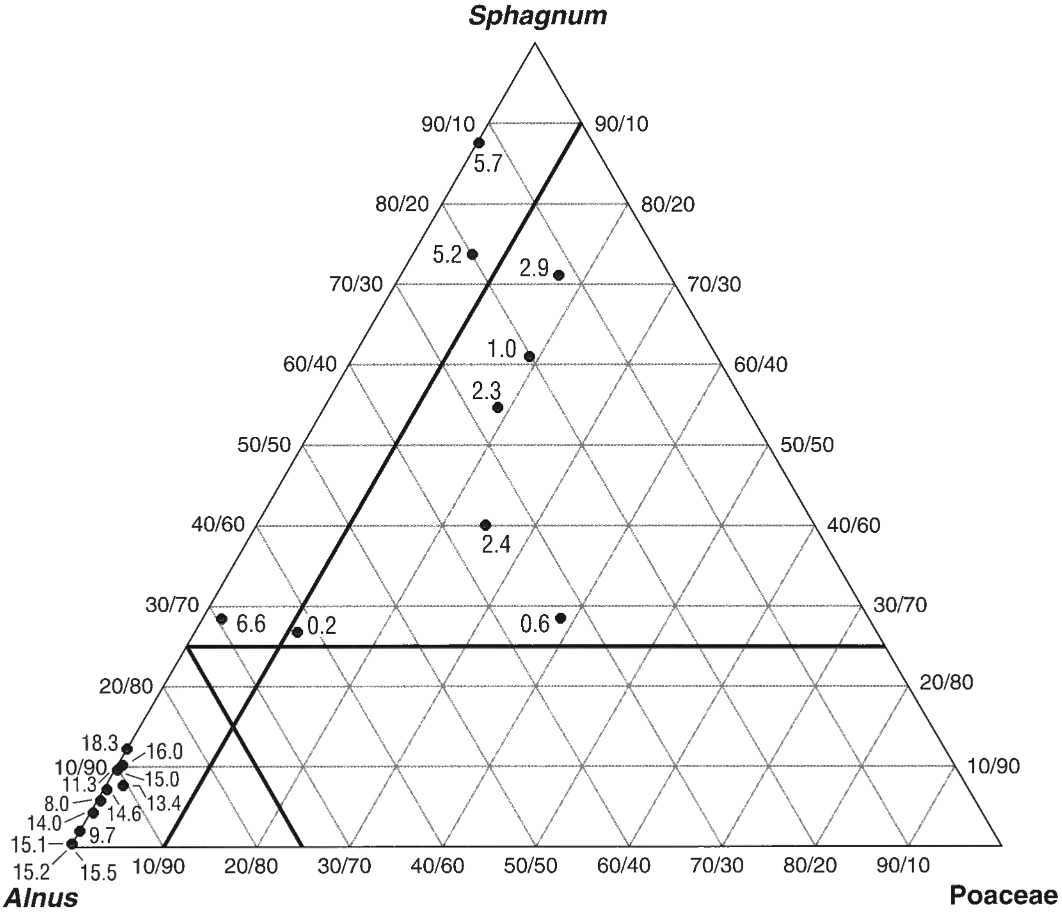


Figure 5. *Ternary diagram of relative abundances of* ***Alnus, Sphagnum*** *and Poaceae (see p. 22 for discussion).*

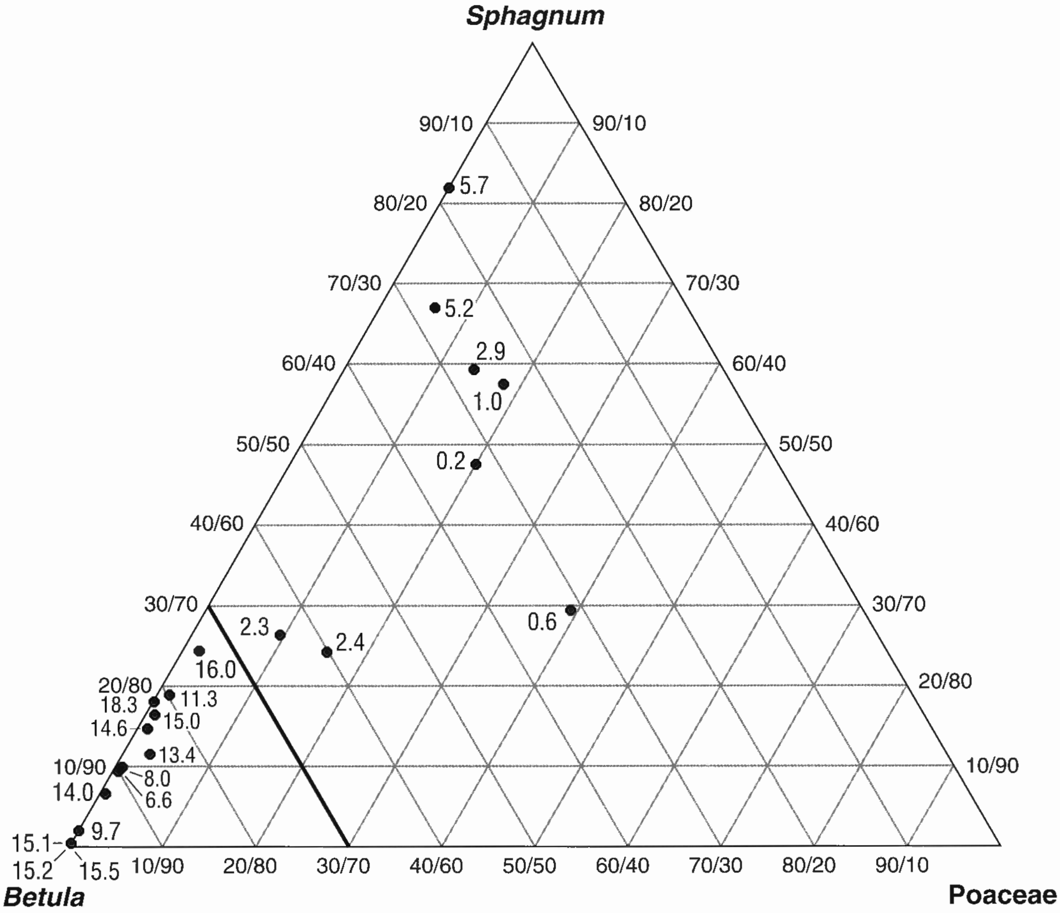


Figure 6. *Ternary diagram of* ***Betula, Sphagnum*** *and Poaceae (see p. 22 for discussion).*

of *Reevesia* is exclusive both to this zone, and to the Sanctuary Formation (S-1) within it. The use of the very rare taxon, *Reevesia*, to name the zone is not entirely satisfactory, but the zone lacks other distinguishing taxa, although it is separable from the subsequent Fagaceae Zone by its relative impoverishment in Fagaceae pollen. The zonal name is considered a provisional measure, and, considering that the ages of the data comprising this zone are more poorly constrained than subsequent zones, further work may considerably revise the interpretation presented here.

The zone has small amounts of *Rhus*-type pollen, *Ilex*, *Quercus*, *Juglans*, and *Carya*, in both sections. *Fagus*, *Nyssa*, *Tilia*-type and *Castanea*-type pollen occur in the Usibelli Zone 1 spectra. This zone has no *Liquidambar* or *Ostrya/Carpinus* pollen. T–C–T pollen and Pinaceae pollen (especially *Picea* and *Pinus)*, and Betulaceae pollen (*Alnus* and *Betula*) are important floral elements. The fluctuation in the C_{est} ratio at S1 towards more open canopy is due to an increase in *Corylus*-type and Ericales pollen, the ecological significance of which is not clear.

Fagaceae Zone, 15.7–14.3 Ma

The *Fagaceae* Zone is characterized by the high relative abundance of T–C–T pollen, and the consistent presence of a rich flora of thermophilous taxa, including *Ilex*, *Quercus*, *Fagus*, *Nyssa*, *Juglans*, *Tilia*-type, *Carya* and *Castanea*-type. These taxa have high relative abundance in comparison with their relative abundance in other zones (Table 3). *Liquidambar* and *Ostrya/Carpinus* pollen occur. The zone is subdivided into T–C–T and *Juglans* subzones.

Fagaceae Zone, T–C–T subzone, 15.7–15.05 Ma

The *Fagaceae* Zone is made up of three spectra from o.b. 2 in the Upper Ramparts Canyon section, seven from o.b. 3, and four from o.b. 4. The dominance of T–C–T pollen is this subzone's most distinctive feature. The wet forest assemblage of o.b. 2 produces the highest T–C–T percentages, but samples from the lacustrine shales of o.b. 3 also yield high T–C–T values. Wood and leaf identification indicates that the T–C–T pollen derives, at least in part, from

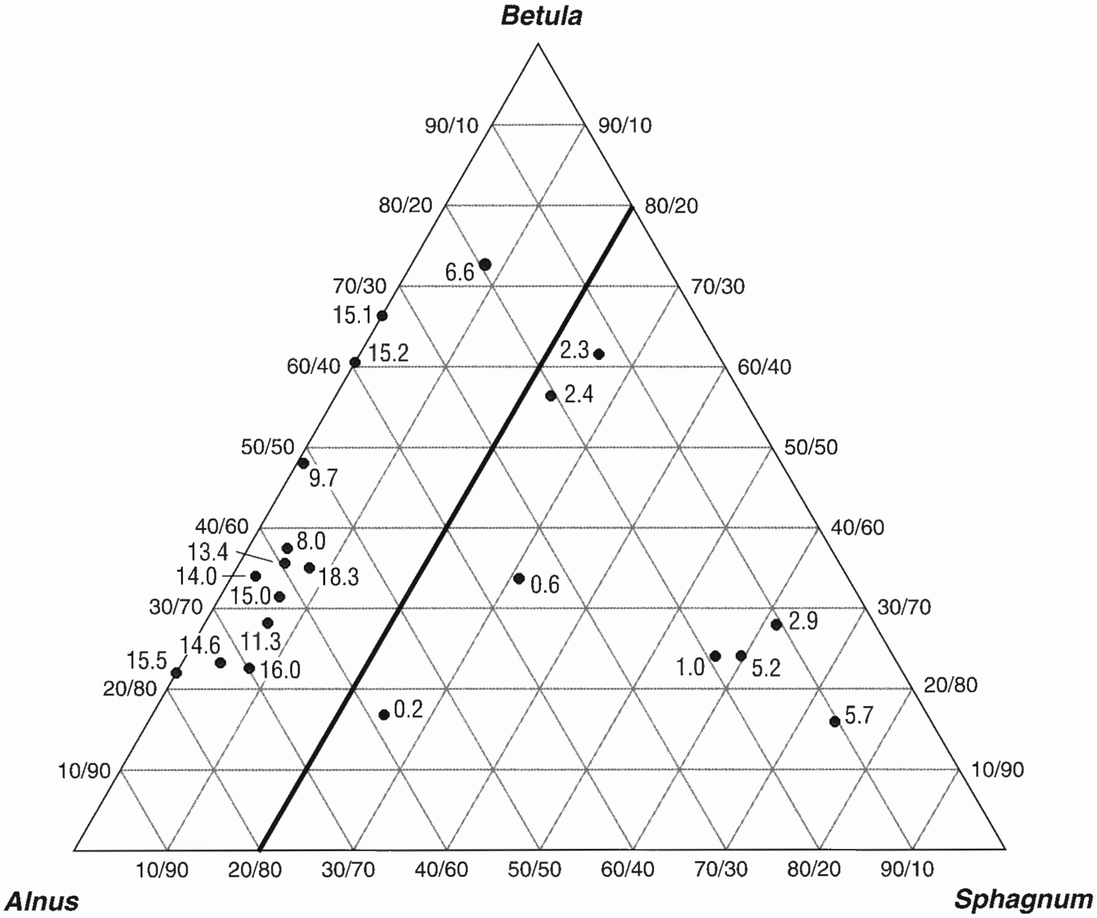


Figure 7. *Ternary diagram of* ***Alnus, Betula,*** *and* ***Sphagnum*** *(see p. 22 for discussion).*

the Taxodiaceae. *Metasequoia*-type pollen and leaves are present (White and Ager, 1994). *Quercus* and *Fagus* pollen have their highest representations in this subzone, about 8 per cent each in the uppermost two spectra. *Juglans*, *Carya* and *Ulmus*-type pollen are present. Peak warmth and a high canopy density are interpreted by the flora in this subzone.

Fagaceae Zone, Juglans subzone, 15.05–14.3 Ma

The *Juglans* subzone is made up of 12 spectra from Usibelli Group Zone S-2, subdivided into upper and lower groups because of the long time represented by the thick Suntrana Formation. The *Juglans* subzone differs from the T–C–T subzone in the following features: it has the first rare occurrences of *Diervilla/Weigela*, Liguliflorae, *Artemisia* and Chenopodiineae pollen; *Quercus*, *Fagus* and *Castanea*-type pollen are less abundant, and T–C–T much less abundant than in the T–C–T subzone; and *Carya*, *Pterocarya* and Nyssa are more abundant. *Juglans*, *Carya*, *Pterocarya* and *Ulmus*-type reach their highest percentages in the composite zonation. This subzone contains the last consistent occurrence of *Sciadopitys* pollen, although there is a late appearance at the Canyon Village site, and the last occurrence of pollen of *Engelhardtia/Alfaroa*.

The decline in T–C–T pollen does not appear to be due to local edaphic factors because coals, representing wet environments similar to Upper Ramparts Canyon o.b. 2, are well represented in the samples from the Suntrana Formation. Climatic cooling occurred during this time.

Although we have shown the *Juglans* subzone as overlying the T–C–T subzone, it should be recalled that the lower composite spectrum of the *Juglans* subzone is interpreted as being, in part, contemporaneous with the T–C–T subzone (above). The pollen spectra from the Suntrana Formation represent a much longer period of time than those from the Upper Ramparts Canyon section, so we have portrayed *Juglans* subzone as overlying the T–C–T subzone.

A decrease in canopy density and declining temperatures are associated with this subzone.

It is appropriate to remember that the true picture is more complicated than our long-term reconstruction. Averaging

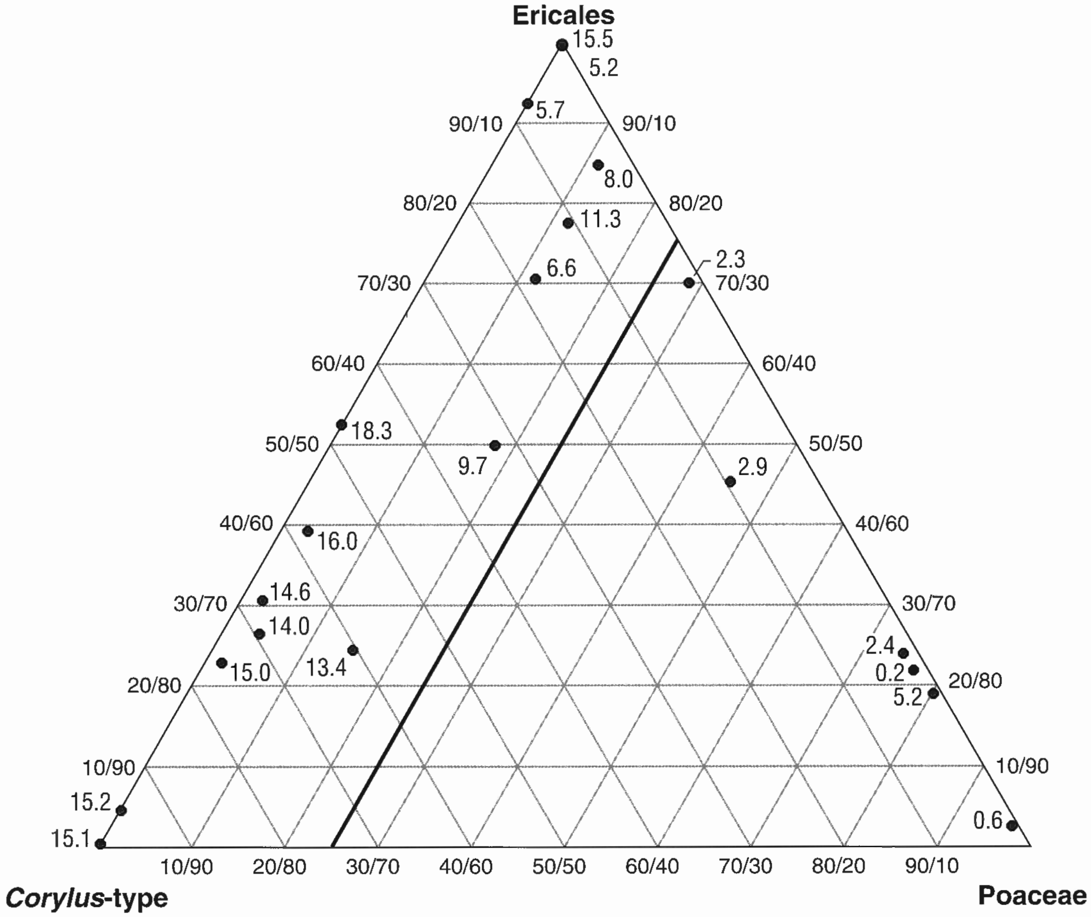


Figure 8. *Ternary diagram of* ***Corylus****-type, Ericales and Poaceae (see p. 22 for discussion).*

Figure 9 *(opposite page). Ratios of palynomorph sums drawn from the full dataset in order to characterize climatic and environmental parameters. As a result of several factors, including differential pollen productivity of taxa, the ratios are not linear measures of the underlying parameters.*

Taxa are summed in the following categories.

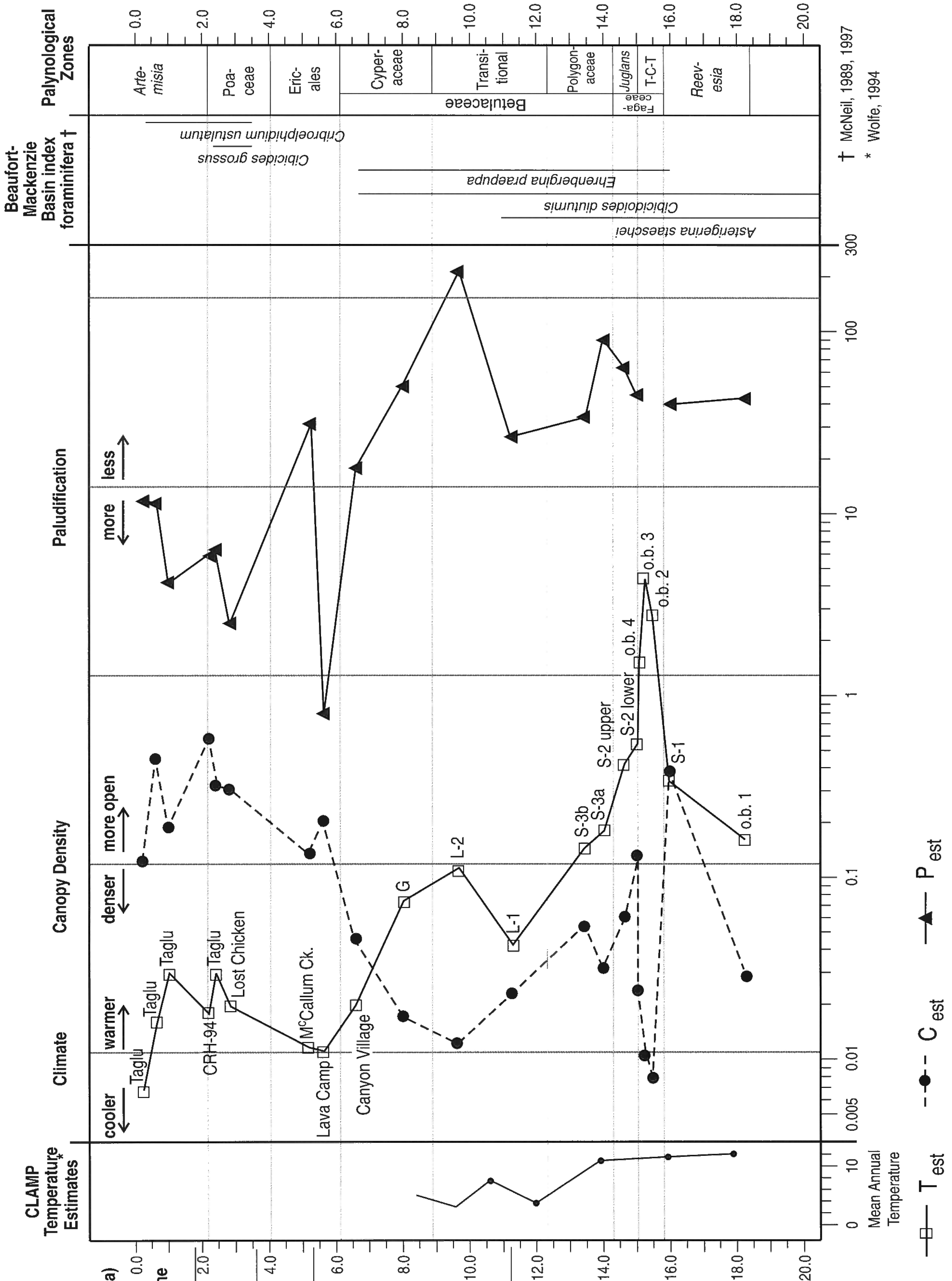
Warm trees: Abies*,* ***Acer****,* ***Carya****,* ***Castanea****-type,* ***Cedrus****,* ***Cercidiphyllum****,* ***Englehardtia/Alfaroa****,* ***Fagus****,* ***Ilex****,* ***Juglans****,* ***Liquidambar****,* ***Metasequoia****-type,* ***Nyssa****,* ***Ostrya/Carpinus****,* ***Pinus koraiensis****-type,* ***Pinus*** *(robust corpus),* ***Pterocarya****,* ***Quercus****,* ***Reevesia****,* ***Rhus****-type,* ***Sciadopitys****, Taxodiaceae–Cupressaceae–Taxaceae,* ***Tilia****-type,* ***Tsuga canadensis****-type,* ***Tsuga heterophylla****-type,* ***Tsuga*** *sp.,* ***Ulmus****-type.*

Cool trees: ***Alnus*** *(4–7 pore),* ***Betula*** *(all sizes),* ***Larix/Pseudotsuga****,* ***Picea*** *spp.,* ***Pinus*** *spp.,* ***Populus****,* ***Salix****,* ***Tsuga mertensiana****.*

Shrubs and herbs: Ambrosia*, Apiaceae (Umbelliferae),* ***Artemisia****, Asteraceae (Compositae) Liguliflorae, Asteraceae (Compositae) Tubuliflorae, Brassicaceae (Cruciferae), Caprifoliaceae, Caryophyllaceae, Chenopodiineae,* ***Corylus****-type,* ***Diervilla/Weigela****,* ***Epilobium****, Ericales,* ***Eriogonum****, Fabaceae (Leguminosae),* ***Myrica/Comptonia****, Onagraceae,* ***Plantago****, Poaceae (Gramineae),* ***Polemonium****, Polygonaceae,* ***Polygonum persicaria****,* ***Polygonum*** *sp.,* ***Polygonum viviparum****, Ranunculaceae, Rosaceae,* ***Rumex****,* ***Shepherdia canadensis****,* ***Valeriana****.*

Bryophytes: Sphagnum

Temperature estimates are from Wolfe's Climate–Leaf Analysis Program (1994). Beaufort–Mackenzie Basin index foraminifera are from McNeil (1989).


Age (Ma)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
Pleistocene
Pliocene
L
E
Miocene
L
M
E
CLAMP Temperature Estimates*
0
10
Mean Annual Temperature
Climate
cooler
warmer
Canopy Density
denser
more open
Paludification
more
less
0.005
0.01
0.1
1
10
100
300
Taglu
Taglu
Taglu
Taglu
CRH-94
Lost Chicken
McCallum Ck.
Lava Camp
Canyon Village
G
L-2
L-1
S-3b
S-3a
S-2 upper
S-2 lower
S-1
o.b. 1
o.b. 2
o.b. 3
o.b. 4
Beaufort-Mackenzie Basin index foraminifera †
Cribroelphidium ustulatum
Cibicides grossus
Ehrenbergina praepupa
Cibicidoides diutumis
Asterigerina staeschei
Palynological Zones
Arte-misia
Poa-ceae
Eric-ales
Cyper-aceae
Transi-tional
Polygon-aceae
Juglans
T-C-T
Faga-ceae
Betulaceae
Reev-esia
† McNeil, 1989, 1997
* Wolfe, 1994
T est
C est
P est

masks the true variability of the floral record. Moreover, our datapoints are too few to record the variation in climate and vegetation that existed in the middle Miocene (Flower and Kennett, 1994). For example, Leopold and Liu (1994) recorded a very low-diversity sample in their rich Zone S-2, suggesting a cool climatic oscillation. The warmest type of assemblage from the Middle Miocene temperature maximum is probably that represented by the T–C–T subzone.

Betulaceae Zone, 14.3–6.15 Ma

The pollen specta of the Betulaceae zone are dominated by *Alnus* and *Betula* pollen.

Betulaceae Zone, Polygonaceae subzone, 14.3–12.35 Ma

The *Polygonaceae* subzone is based on six spectra from Zones S-3a and S-3b of the Suntrana Formation, Usibelli Group. Pollen of the Polygonaceae family (*Polygonum persicaria, Polygonum* sp.) first appear in this zone. These assemblages are marked by overall reduced abundances and the last occurrences of the exotic taxa, *Cercidiphyllum*, *Ilex*, *Fagus*, *Nyssa*, and *Liquidambar*. *Osmunda* and *Quercus* occur only rarely above this subzone. The spectra are dominated by Betulaceae (*Alnus* and *Betula*) and Pinaceae (*Pinus*, *Picea*, *Tsuga* spp., *Abies*, *Larix*-type).

This zone contains the last appearance of the most thermophilous of the exotic taxa, and indicates continued climatic cooling.

Unlike the *Fagaceae* Zone, *Ilex*, *Quercus*, *Fagus*, *Nyssa*, *Liquidambar*, *Carya* and *Pterocarya* occur only in trace amounts.

Betulaceae Zone, Transitional subzone, 12.35–8.85 Ma (Zone 4)

The Transitional subzone is made up of seven spectra from each of Usibelli Group Zones L-1 and L-2 (Leopold and Liu, 1994). This zone has the first trace amounts of *Ambrosia*-type pollen. However, it is most aptly characterized as having a transitional assemblage. Most thermophilous taxa have disappeared – this subzone has no *Cercidiphyllum*, *Ilex*, *Quercus*, *Fagus*, *Nyssa*, *Liquidambar*. *Sciadopitys*, *Carya*, *Castanea*-type and *Ostrya/Carpinus* pollen, although they were found in trace amounts in younger sections. It contains the last occurrence of *Acer*, and the end of the continuous record of *Juglans*, which occurs at least once above the zone. Betulaceae and Pinaceae taxa dominate the spectra, as in the underlying Polygonaceae subzone. However, the herbaceous taxa, which are important elements of younger assemblages, are not significant in this zone. It is as if the long period of decline in temperatures from the early Middle Miocene reduced the community to the hardiest of elements, while the herbaceous elements, which become more dominant in younger assemblages, were not yet important. The canopy density curve of Figure 7 suggests that the canopy may have been too dense to allow niches for herbs.

A temperature minimum is indicated at 11.3 Ma, followed by a subsequent warming and increase in canopy density at ca. 9.7 Ma. (estimated time based on correlation as per discussion above).

Betulaceae Zone, Cyperaceae subzone, 8.85–6.15 Ma

The *Cyperaceae* subzone is made up of eight spectra from Zone G-1 of the Grubstake Formation, Usibelli Group, and 23 spectra from Canyon Village, Locality 90-7.

The first rare occurrences of Cyperaceae, *Nuphar* and *Sagittaria* pollen occur in the Cyperaceae subzone. *Pinus* species reach the highest percentages recorded in the composite spectra and the Ericales begin to make up higher percentages of the spectra. *Trapa* pollen was found only in this zone, but this may be due to the lacustrine sample site. The Cyperaceae subzone contains pollen of *Sciadopitys*, which also occurs in the *Reevesia* and Fagaceae zones. *Carya*, *Castanea*-type and *Ostrya/Carpinus* occur in this zone in low to trace percentages, well above the end of their consistent occurrence in the Polygonaceae subzone (there is only one other higher occurrence of *Carya* at Lost Chicken Mine). This zone contains the last occurrence of *Pterocarya*, and it contains no *Juglans* or *Acer* pollen, although a rare occurrence of *Juglans* is noted in the *Poaceae* Zone. The spectra are dominated by Betulaceae pollen.

The pollen of thermophilous taxa may have been deposited by airborne transport from the south, or the trees may have grown locally in restricted, south-facing microhabitats. The Cyperaceae subzone reflects the continuing long-term trend of declining temperature and the beginning of a late Neogene trend of decreasing canopy density. An erratic trend toward increasing paludification begins in this subzone.

Ericales Zone, 6.15–4.05 Ma

The Ericales Zone is based on a small set of samples from two geographically dispersed sites: Lava Camp on Seward Peninsula (5.7 Ma), and McCallum Creek in the Alaska Range (ca. 5.2 Ma). Ericales are considerably more abundant, whereas *Alnus* and *Betula* pollen are much less abundant than in lower zones. This zone has the first, rare record of Caryophyllaceae pollen. The sample size is smaller than for any other zone, which may account for the lack of many species. This zone has no records of T–C–T, *Tilia*-type, *Sciadopitys*, Carya, *Pterocarya*, *Castanea*-type, *Ostrya/Carpinus*, *Diervilla/Weigela*, or *Ulmus*-type pollen.

Both assemblages are relatively impoverished in taxa but significant differences exist between them. *Sphagnum* spores are a very important element in the Lava Camp spectrum, and *Picea* dominates the McCallum Creek spectra. This zone has the lowest temperature ratio for the whole record, except for the Pleistocene, and the flora indicates an open canopy.

No data are available between the uppermost section of the Ericales Zone (McCallum Creek, 5.2 Ma) and the lowermost section of the Poaceae Zone (Lost Chicken Mine, 2.9 Ma).

Poaceae Zone, 4.05–2.35 Ma

The Poaceae (Gramineae) Zone is made up of 32 spectra from the Lost Chicken Mine, and five spectra from the Taglu borehole interval (depth 332.8–349.8 m). Poaceae pollen is relatively abundant in the Poaceae Zone although it is present in lower zones. The zone contains the first appearances of *Polemonium* and *Menyanthes* pollen and pollen of the Brassicaceae (Cruciferae) and Apiaceae (Umbelliferae). Asteraceae (Compositae) pollen is more consistently present (though not abundant) than in lower zones, including *Artemisia* pollen, which begins to be a regular element in the assemblages. There is a diversity of Polygonaceae pollen, and relatively abundant Cyperaceae pollen. The increase in Poaceae and *Artemisia* pollen and the disappearance of *Tsuga* probably indicate increasing dryness.

Rare occurrences of thermophilous pollen, T–C–T, *Carya*, *Juglans*, *Quercus*, *Tilia*-type, *Ulmus*-type and *Tsuga* sp. are found in this zone, and in this respect it resembles the underlying Ericales Zone and Cyperaceae subzone assemblages. However, the Poaceae Zone is distinguishable from the Cyperaceae subzone, Ericales Zone and older zones by the rich development of the herbaceous taxa, described above.

The last appearance of thermophilous taxa raises the question of recycling of pollen from older deposits. *Juglans* and *Quercus* are found in spectra from the Lost Chicken Mine. Cenozoic rocks in the area containing *Castanea*-type, *Carya*, *Juglans-Pterocarya*, *Tilia*, *Ulmus* and *Quercus*, were concluded to be of early Tertiary to Early Miocene age (Foster and Igarashi, 1990), but the presence of herbaceous taxa suggests that some of the rocks containing thermophilous taxa may be penecontemporaneous with the deposits at Lost Chicken Mine. Although no Paleogene or Miocene taxa that demonstrate recycling have been reported from Lost Chicken Mine, the proximity of such deposits makes it possible. Likewise, Paleogene rocks outcrop near the Taglu borehole (Ioannides and McIntyre, 1980) and the presence of Cretaceous and Paleogene recycled palynomorphs in the Taglu borehole is known (Davies, pers. comm.; Dallimore and Matthews, 1997; White, unpublished data) but it is not known if recycling accounts for the *Carya*, *Tilia*-type and *Ulmus*-type pollen observed in the Taglu borehole interval 332.8–349.8 m. Local growth of thermophilous taxa seems unlikely at either site. The rare occurrences of pollen of thermophilous taxa are possibly rare airborne pollen grains from the south. During the Pliocene, plant macrofossils show that three species of *Pinus*, and *Sciadopitys* grew on Meighen Island at 80°N (Matthews and Ovenden, 1990; Fyles, 1990). Considering the evidence for forests 16° north of Chicken and 11° north of the Taglu site, the rare presence of airborne pollen of thermophilous taxa seems reasonable at these sites during the mid-Pliocene. Airborne transport of pollen to these sites would reflect climatic warming, if they are not recycled material.

Assuming that the thermophilous taxa are not recycled, the Poaceae Zone shows a warming climatic trend from the Ericales Zone, but a continuous trend toward a more open canopy.

Artemisia Zone, 2.35 Ma–Present

The *Artemisia* Zone is made up of 11 spectra from CRH-94, and six, five and five spectra from Taglu borehole intervals 263.4–169.9, 119.9–75.7, and 70.1–5 m, respectively. The mean age estimate for the uppermost Taglu interval, 70.7–5.0 m, is 0.2 Ma, but the top sample is of Holocene age. In this zone the datapoints probably reflect only interglacial conditions; the site is at high latitude and near or within the limits of continental glaciations (Duk-Rodkin and Hughes, 1995). Even if not ice covered, little could likely grow during the full glacial periods.

Artemisia pollen becomes a more abundant and consistent element of the assemblages both at CRH-94 and at the Taglu borehole. *Shepherdia canadensis* also occurs intermittently. Betulaceae, *Pinus* and *Picea* are important elements of the assemblages.

The flora indicate fluctuating canopy density, and an initial temperature increase followed by continuous decline.

The base of this zone more-or-less coincides with the onset of ice-rafted detritus and major northern hemisphere glaciation (Shackleton et al., 1984; Rea and Schrader, 1985). A temperature peak and decline are evident in this zone, and a puzzling increase in canopy density.

Biostratigraphic patterns of commonly occurring taxa

Taxa categorized as long-ranging in Figure 3, including *Alnus* and those to its right, occur consistently in spectra from the Neogene and Quaternary. They have no sharply defined biostratigraphic patterns, although several exhibit long-term changes in relative abundance. The possible utility of these patterns for stratigraphic palynology has been investigated by the creation of ternary diagrams. The datapoints, being calculated from the composite spectra, represent average values, and thus the effect of stochastic, short-term climatic or edaphic factors, which affect individual samples, is minimized. The relative abundances of the three taxa in each of Figures 4 to 8 are unconstrained by the values of taxa not included in the figures, because they are calculated as percentages of the sum of the percentages of the taxa in Figure 3 and Table 3.

Two patterns emerge amongst *Alnus*, Ericales, and Poaceae pollen (Fig. 4): 1) all spectra where *Alnus* constitutes more than 85 per cent of the sum are greater than 6.6 Ma in age; 2) all spectra in which Poaceae is more than 10 per cent of the sum are 2.9 Ma in age or younger.

The patterns for *Alnus*, *Sphagnum* and Poaceae pollen (Fig. 5), are similar to those above. In Figure 5: 1) all spectra where *Alnus* constitutes more than 75 per cent of the sum are greater than 6.6 Ma in age; 2) all spectra in which Poaceae is more than 10 per cent of the sum are 2.9 Ma or younger; 3) all spectra in which *Sphagnum* is greater than 25 per cent of the sum are 6.6 Ma or younger in age. Figure 5 shows more definitive patterns than Figure 4.

Amongst *Betula*, *Sphagnum* and Poaceae (Fig. 6), all spectra where *Betula* constitutes more than 70 per cent are greater than 5.7 Ma in age.

Amongst *Alnus*, *Betula* and *Sphagnum* (Fig. 7), all spectra in which *Sphagnum* is greater than 20 per cent of the sum are 5.7 Ma or younger in age.

Amongst *Corylus*-type, Ericales and Poaceae (Fig. 8) all spectra in which Poaceae is greater than 25 per cent of the sum are 2.9 Ma in age or younger. The ambiguity in separating the triporate pollen *Myrica*, *Corylus,* and *Comptonia* makes this distinction less useful than the previous.

Note that in Figures 4 and 5 there are small areas on the diagrams that satisfy more than one percentage/age criterion and any datapoints falling in these areas would be open to conflicting interpretation. The age distinctions indicated by the pollen and spore abundances are guidelines only, limited by the chronological continuity of the datapoints we have for this study.

The patterns in Figures 4 to 8 reflect the Late Miocene to Pleistocene development of pollen and spore assemblages with abundant shrub and herb components, reduced tree cover, and increasing paludification.

DISCUSSION

Vegetation and climatic change

The climatic record presented here (Fig. 9) has been discussed in White et al. (1997a), and is discussed here in relation to the pollen zones defined above.

Early and Middle Miocene

The T–C–T subzone, constrained at 15.2 Ma, contains our warmest flora, fitting best in the early zone Mi2 temperature peak of Miller et al. (1991). White and Ager (1994) estimated a Mean Annual Temperature (MAT) of 9°C for o.b. 3. This agrees with Wolfe's (1994) MAT estimate of 11.5°C for Cook Inlet at 15 Ma, considering the 7° latitude difference and using his latitudinal temperature gradient of 0.4^{o}C per degree of latitude.

Relative to the temperature peak in the T–C–T subzone, the *Reevesia* Zone shows cooler Early Miocene temperatures, unlike the pattern depicted in Wolfe (1994) in which the MAT at 18 Ma is about 12°C. Without significant topographic barriers, the Cook Inlet pattern should be similar to the interior. Our pattern and chronology fit quite well with the marine isotope signal in Miller et al.'s (1991) zones Mi1 and Mi2.

The Usibelli data show the pattern of dramatic cooling indicated by marine δ^{18}O decline and sea-level fall after 14.8 Ma, which is at least partly due to Antarctic glaciation (Haq et al., 1987; Miller et al., 1991; Flower and Kennett, 1994) and is probably linked to changes in tectonics and the carbon cycle (Raymo, 1994).

Middle and Late Miocene

A low-temperature interval is inferred in the Betulaceae Zone, lower Transitional subzone, based on the assemblage from the L1 zone of the Usibelli Group, dated at about 11.3 Ma. Late in the Transitional subzone a warmer period is recorded, followed in the Cyperaceae subzone by a stong cooling trend, a more open forest canopy, and paludification at the study sites.

An interesting feature of the T_{est} curve (Fig. 9) through the Middle and Late Miocene (*Juglans* subzone to Cyperaceae subzone) is that it shows a two-stage temperature decrease, similar to the two-stage $\delta^{18}O$ pattern described by Miller et al. (1991), and ascribed to glacioeustatic lowering associated with Antarctic ice volume increase. However, within this interval our chronology is by correlation and interpolation, and a considerable latitude of error must be admitted. Our chronological estimate for the T_{est} low at L1 coincides with Miller et al.'s (1991) placement of the Mi5 event at 11.3 Ma, but we really cannot be sure whether the proper fit is to the Mi5 event or to the Mi4 event (ca. 12.6 Ma). Our L1 event is not synchronous with Barron and Baldauf's (1990) Climate Optimum 2, which they estimate to occur between 11.5 to 10.4 Ma.

Messinian event

The late Cyperaceae subzone assemblage from Canyon Village, and the low diversity Ericales zone assemblages from Lava Camp and McCallum Creek fall within, and possibly just after, the Messinian, 7.10 to ca. 5.33 Ma (Krijgsman et al., 1994; Hilgen and Langereis, 1993; adjusted to Cande and Kent, 1995). T_{est} indicates a cool climate interval. Canyon Village strata are early Messinian, a time when high-frequency, low-amplitude $\delta^{13}C$ and $\delta^{18}O$ oscillations have been recorded. Strata at Lava Camp and possibly McCallum Creek are late Messinian, a time of low-frequency, high-amplitude oscillations (Aharon et al., 1993). During the Messinian, extensive evaporites were deposited in the Mediterranean Sea, due both to tectonic activity at Gibraltar and eustatic fluctuations from Antarctic glaciation (Adams et al., 1977; Roberts et al., 1994; Clauzon et al., 1996). Messinian temperature effects are probably evident in the temperature decline and increase in canopy openness in the Lava Camp and McCallum Creek assemblages, which have notably impoverished pollen and spore assemblages.

There are several correlative events in northwestern North America. There is a first-order sequence boundary separating the Akpak Sequence and overlying Iperk Sequence in the Beaufort–Mackenzie Basin, marking a shift from cool–temperate to boreal–arctic benthic foraminifera (Dixon et al., 1992; McNeil et al., 1994). McNeil et al. (1982) interpret this erosional unconformity as correlating with an eustatic drop in sea level. Haq et al. (1987) show a type 1 sequence boundary at 5.5 Ma, a result of increased downdraw from the long-term sea-level decline of about 150 m. The sub-Iperk unconformity surface was, in part, subaerially exposed continental margin. Subsidence subsequent to that time is equivalent to slightly more than the thickness of the Iperk Sequence, which is up to 4000 m in the east Beaufort Sea. Subsidence in the nearshore, subaerially exposed margins is less. The prodelta/shelf and slope deposits of the Akpak Sequence, with widespread clinoforms in the outer shelf area (Dixon et al., 1992) are probably indicative of deposition during a period of declining sea levels, likely attributable to the Messinian events. By this correlation, the Iperk Sequence was deposited during the subsequent eustatic rise.

Lagoe et al. (1993) described the first evidence of tidewater glaciation on the south coast of Alaska in the Yakataga Formation dated between 6.7 and 5.0 Ma. Although they attribute the onset of glaciation to uplift, the temperature decline identified by our data must have contributed to glaciation.

Late Pliocene–Pleistocene

In spite of regional uplift, the global late Pliocene warm period (ca. 3.0 Ma; Dowsett et al., 1994; Cronin et al., 1994), is reflected in the Poaceae Zone. Although we have no datapoints indicating the onset of the Pliocene peak warmth, the Lost Chicken Mine assemblage falls within or just after the 3.15 to 2.85 Ma interval targeted by PRISM for reconstruction of the paleoclimate of the middle Pliocene warm interval (Dowsett et al., 1994). The lowest Taglu interval, in the Poaceae Zone, and CRH-94, in the *Artemisia* Zone, follow shortly after 3 Ma and therefore reflect the warm event.

Higher sea levels (Dowsett et al., 1994) contributed to the opening of the Bering Strait at about 3.0 Ma, the site of which had been a barrier beween the Arctic and Pacific oceans since the Cretaceous. Many more North Pacific invertebrates invaded the Arctic Ocean than the reverse (Fyles et al., 1991), suggesting that the main current flow was northward. Heat transfer through the Bering Strait is a small component of the Arctic heat budget (Barry, 1989) but the event may have warmed and moderated the adjacent Arctic Ocean and the climate of the study area. Dowsett et al. (1994) concluded that the Arctic Ocean had much less ice, and was at least seasonally ice free at this time.

T_{est} values for the Lost Chicken Mine assemblages and the lowest two Taglu intervals are higher than for adjacent datapoints. It is conceivable that this represents a real climatic warm event, which would be consistent with global data, but it is also possible that thermophilous taxa were recycled from older rocks and contribute to the temperature signal.

A pattern of temperature decline dominates the record of the *Artemisia* Zone. North Atlantic and North Pacific ice-rafted detritus indicates the onset of major Northern Hemisphere glaciation near the Matuyama–Gauss boundary (Shackleton et al., 1984; Rea and Schrader, 1985) at 2.58 Ma (Cande and Kent, 1995). In North America, glaciation occurred in the Gauss chron in central Yukon (Duk-Rodkin and Barendregt, 1997) and central Rocky Mountains (Cioppa et al., 1995). Evidence from Upper Pliocene strata exists for the presence of permafrost in the northern Yukon

(Burn, 1994) and for mid-continental glaciation (Boellstorff, 1978).

Our data reflect the high-latitude climate deterioration of the Late Pliocene and Pleistocene. Relative abundance increases of Cyperaceae and *Sphagnum* occurred after 3 Ma, and of *Artemisia* after 2.3 Ma. Cyperaceae, *Sphagnum* and *Artemisia* are apparently contradictory indicators, the former two suggesting edaphic moisture and the latter edaphic dryness. Increasing climatic continentality may explain the paradox. *Sphagnum* probably thrived in standing water from spring run-off and protected from winter desiccation by freezing. The Cyperaceae may have occupied wetland or poorly vegetated upland habitats. *Artemisia* probably grew on summer-dry upland sites. The co-occurrence of these taxa is consistent with the modern ecology of the area. All suggest the decline of forest canopy cover. The temperature during the growing season at the time must have been greater than 10°C, and the region must have had rainfall of more than 40 mm to sustain peat formation in wetlands (Lottes and Ziegler, 1994).

In northwestern Europe, the Praetiglian cool period, and the correlative Mediterranean moist zone PIII (Suc and Zagwijn, 1983), which occurred about 2.3 Ma (Zagwijn, 1992), is time-equivalent to CRH-94. Our data between 2.3 and 1.0 Ma may correlate to the first two of the warm–cool–warm temperature cycles in northern Europe (Reuverian–Praetiglian–early Tiglian) and to the first two of the dry–humid–dry moisture cycles in the Mediterranean (PII–PIII–PIV/Pl.I) (Suc and Zagwijn, 1983). However, the chronology from the Taglu borehole suggests that our upper warm cycle is an interglacial interval younger than the early Tiglian and PIV/Pl.I interval.

The temperature–vegetation record in the upper three Taglu intervals reflects vegetation development only during interglacials. The T_{est} decline may reflect the effect on vegetation of thicker and more persistent permafrost from the high-amplitude glacial cycles of the late Pleistocene (Ruddiman and Raymo, 1988; Henrich and Baumann, 1994; Dwyer et al., 1995). South of the study area, there is evidence at Mount Edziza of glacial ice flow from the northern Coast Range of British Columbia at 1.1 Ma (Spooner et al., 1995).

Correlation to foraminiferal zones of Beaufort–Mackenzie Basin

Late Cenozoic palynostratigraphy in the Beaufort–Mackenzie Basin has been difficult because of the dominance of the spectra by long-ranging pollen and spore taxa, recycling of Paleogene pollen of essentially modern morphology, and the contamination of cuttings samples by caving (White, 1989). This present work establishes a palynostratigraphic framework for the Beaufort-Mackenzie Basin, a framework that could not be established convincingly from samples taken within the Basin. Correlations are made here to McNeil's (1989) foraminiferal interval zones of the Beaufort–Mackenzie Basin, based on absolute age estimates of the zones and comparison of climatic interpretations.

McNeil's (1989) *Asterigerina staeschei* Interval Zone occurs in Lower to Middle Miocene strata in rocks of the Mackenzie Bay Sequence. The foraminifera suggest warm water conditions, consistent with our results. We do not have data that correlate to the basal *A. staeschei*, but our *Reevesia* Zone to Polygonaceae subzone and the lower part of the Transitional subzone spanning 18.3 Ma to ca. 10 Ma, correlate to the upper *A. staeschei* Zone. The palynological data show that the continental temperatures were variable within this time interval, with peak temperatures occurring at about 15.2 Ma, followed by an abrupt temperature decline. White and Ager (1994) estimated a MAT of 9°C for the Upper Ramparts Canyon Beds 2–4, and Liu and Leopold (1994) have estimated a MAT of 7–9°C for the equivalent warmest interval in the Suntrana Formation.

White and Ager (1994) correlated the Upper Ramparts Canyon Beds 2–4 with intervals in the Mackenzie Bay Sequence (Issungnak O-61 well, 1605–1625 m; Ulalerk C-50 well, 1676–1737 m), based on the presence of *Juglans* pollen. Current data (Fig. 2, Table 2) show that *Ilex*-type, *Quercus*, *Fagus*, *Nyssa* and *Liquidambar* have more restricted stratigraphic ranges in the Miocene than *Juglans*, and are better indicators. However, the presence of a pollen taxon in offshore sediments is determined both by its abundance in the pollen rain of the source vegetation and its ability to be transported and preserved, therefore the indicators with the most restricted stratigraphic ranges may not always be present. The proposed correlation to the Issungnak O-61 well stands, based on the presence of *Ilex*-type, *Fagus*, *Quercus*, and probably *Liquidambar* (White and Ager, 1994). In the Ukalerk C-50 well, *Ilexpollenites* occurs above *Juglanspollenites,* and *Liquidambarpollenites* sp. occurs higher in the section, not far below cf. *Polemonium* (McNeil et al., 1982) This stratigraphic pattern is not consistent with our work, and suggests that recycling is a significant complicating factor in the Ulakerk C-50 well, rendering the proposed correlation less certain.

The Transitional subzone correlates to the lower part of McNeil's (1989) *Cibicidoides* sp. 800 Interval Zone. The Cyperaceae subzone and the Ericales Zone correlate to the mid- and upper *Cibicidoides* sp. 800 Interval Zone. The top of *Cibicidoides* sp. 800 Interval Zone is coincident with the Akpak Sequence, ending at the Akpak–Iperk unconformity. The unconformity has been correlated by McNeil to the Messinian crisis, in agreement with our Ericales Zone interpretation. No climatic interpretations are otherwise attached to the foraminiferal zones.

The Poaceae Zone correlates to McNeil's (1989) *Cibicides grossus* Interval Zone, the end of which corresponds to the onset of northern hemisphere continental glaciation in the late Pliocene. The *Artemisia* Zone correlates with the *Cribroelphidium ustulatum* Interval Zone and the overlying *Cassidulina reniforme* Interval Zone, which represent cold arctic climatic conditions and glacial fluctuations. Climatic interpretation of the Poaceae and *Artemisia* zones agrees with the foraminiferal zones, but the palynomorph zones also resolve the Pliocene warm interval.

Orogenic versus global climatic influence

The climatic change in the study area is the result of an interplay between global climatic changes and regional tectonics. The regional uplift chronology and regional paleoclimatic record are incomplete but correlations are possible. What cannot be attributed to regional tectonics we assume to result from the global changes.

Significant uplift in the Alaska Range and St. Elias Mountains did not begin until the latest Miocene. Thus, we have no firm evidence that our Middle Miocene cooling and the L1 to L2 warming event are due to anything other than global events.

By 8.5 Ma, uplift was probably underway in southeast Alaska, creating a regionally extensive barrier to the south, but the elevations were surely much lower than today and the Alaska Range had not begun to rise. The trends in our data of temperature decline, increasing canopy openness and site paludification in Alaska–Yukon between 9.7 and 7 Ma, including the Messinian-correlative events, are most likely attributable to global climatic events because they apparently preceded major regional uplift.

In the Late Miocene, global ecological change is indicated by expansion of C_4 grasslands at about 7–6 Ma, which may be explainable by climatic changes (possibly Asian monsoon intensifiation) or $p\mathrm{CO}_2$ changes. The changes may have been driven by tectonic activity, especially the uplift of the Himalayas (Quade et al., 1989; Cerling et al., 1993; Quade and Cerling, 1995; Quade et al., 1995; Filippelli, 1997; Latorre et al., 1997). The onset of Greenland glaciation at about 7 Ma (Larsen et al., 1994) suggests climatic cooling was involved in the paleoecological/paleoclimatic changes. Thus global climatic and local tectonic events are implicated in causing the trends towards climatic cooling, more open canopy and paludification seen in the study area at about 6–7 Ma.

During the main phase of regional uplift, after 6 Ma, it is likely that climatic and vegetation changes in the study area were most influenced by rising southern mountain barriers, blocking the Pacific influence on the interior climate. The differentiation between coastal and interior vegetation must have been established during this time. Nonetheless, the influence of the global mid-Pliocene warm period (Dowsett et al., 1994) is evident in strata in the Lost Chicken and the lowest Taglu intervals. The opening of the Bering Strait about 3 Ma may also have moderated the continentality of the region and contributed to the expression of the late Pliocene warm period in the study region.

A mechanism proposed to partly explain late Neogene high-latitude cooling is orogeny in the Tibetan Plateau, Himalayas, and western North America. Such uplift influences the position of planetary waves and seasonal heating and cooling over plateaux (Ruddiman and Raymo, 1988; Ruddiman and Kutzbach, 1990; Kutzbach et al., 1993). Ruddiman and Kutzbach's (1990) model predicted a cooler Arctic, but a warmer winter in interior Alaska as a result of northward-advected warmth; they speculated that this contradiction with paleobotanical evidence is due to the lack of narrow mountain ranges in their models. Our findings show that uplift of the Alaska and St. Elias ranges is a partial explanation for changing vegetation and climate to their north in the latest Miocene to Pleistocene, although we can not rule out possible significant influence from fluctuations in atmospheric CO_2 concentrations. The climatic significance of local uplift is enhanced if the Himalayan and Tibet region achieved near-present elevations and extent by 8 Ma (Harrison et al., 1992; Coleman and Hodges, 1995), as dramatic climatic changes in our study area occur after that time.

We conclude that the significant vegetation and climatic changes from about 18 Ma to 9 Ma were responses to global climatic changes. From 9 to about 6 Ma, the response may have been to global and local tectonic developments. After 6 Ma, regional uplift was a significant cause of cooling and continentality, although the global signal of the late Pliocene warm interval was still expressed in the study area. One wonders if late Pliocene–Pleistocene uplift in southern Yukon and Alaska, by blocking atmospheric heat transport into the Arctic, was itself a significant contributor to large-scale Arctic cooling and the development of northern latitude continental glaciation. Improved chronological resolution of uplift and vegetation–climatic change, and climate modelling, are required to understand the possible significance of regional tectonics on the Arctic climate.

Evolution of the Arctic Ecosystem

Aspects of modern Holarctic vegetation can be seen in these Neogene and Quaternary pollen and spore assemblages. In the latest Miocene beds at Canyon Village (6.57 Ma), *Picea*, Ericales and *Sphagnum* covary with each other, and inversely with thermophilous elements (Ager et al., unpublished manuscript). An association of shrubs and herbs including *Salix*, Ericales, Cyperaceae, Poaceae and Asteraceae dominates pollen and spore assemblages in the late Pliocene Poaceae Zone. In the latest Pliocene and Pleistocene *Artemisia* Zone, the abundance of both *Sphagnum* and *Artemisia*, typical of the modern vegetation of the study area, is evident.

The palynological evidence suggests that the floristic elements required to form boreal forest and tundra ecosystems were established in the region by 2.3 Ma. Wolfe (1985; citing Sher et al.) noted that the first evidence of tundra is in the Kolyma Lowland in the Pliocene.

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