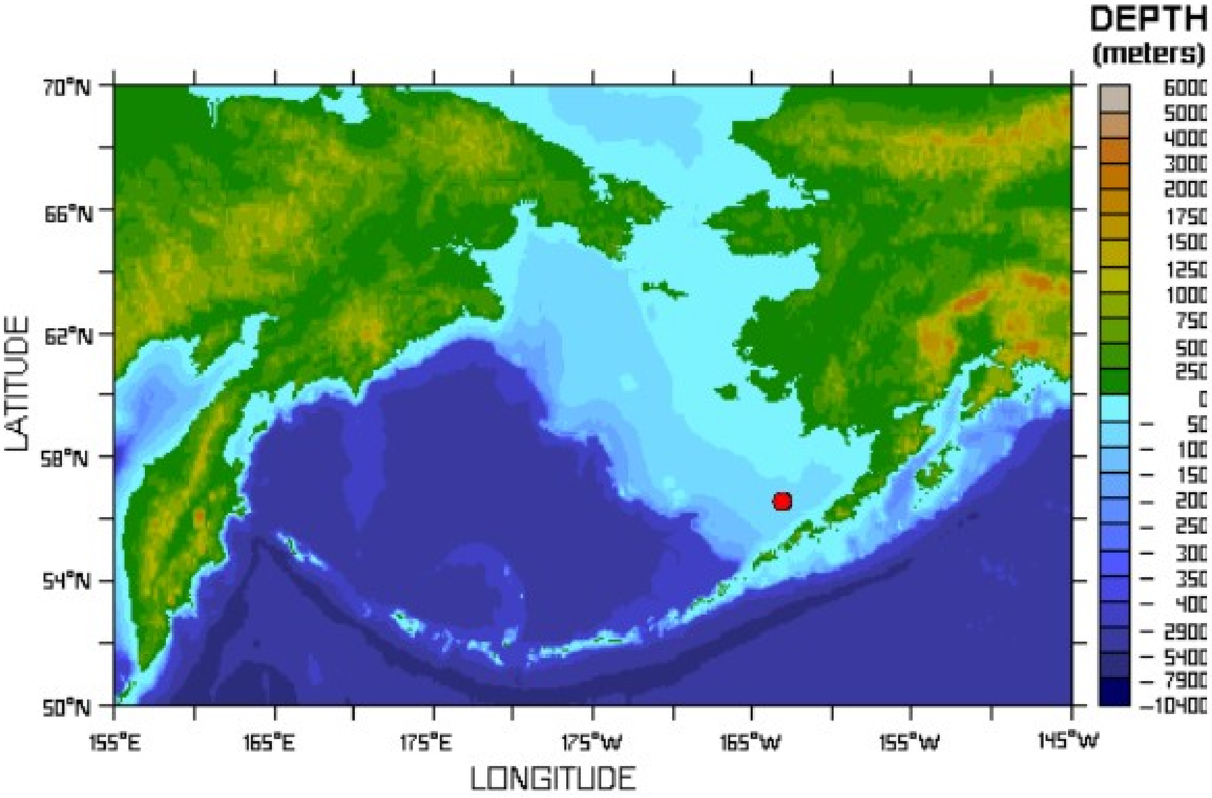
PALYNOLOGICAL BIOSTRATIGRAPHY OF THE NORTH ALEUTIAN SHELF COST NO. 1 WELL



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PALYNOLOGICAL BIOSTRATIGRAPHY OF THE NORTH ALEUTIAN SHELF COST NO. 1 WELL

1. INTRODUCTION

1.1 BACKGROUND

The North Aleutian Shelf COST No.1 well was spudded on September 8, 1982 and was completed on January 14, 1983. The well operator was ARCO, Inc. Water depth at the well site was 277 ft, and KB height above sea level was 85 ft. Well sediment samples were recovered from 1380 to 17,040 ft, MD (TMD = 17,155 ft). Biostratigraphic analysis of the well was undertaken by 'Biostratigraphics Consulting Micropaleontology' (denoted throughout this report as 'BCM') in 1983 and their interpretations were subsequently incorporated by John Larson in MMS Report 88-0089 on the COST well (Turner *et al.*, 1988).

In addition to intense local tectonic and volcanic episodes, the northern North Pacific - Bering Sea region, including the North Aleutian Basin, underwent major plate tectonic, oceanographic and climatic changes during the Cenozoic that strongly affected its biotas, productivity and petroleum source rock potential. Many of these concepts were developed *after* BCM's study was undertaken, more than 25 years ago, and were therefore not included in their interpretation of the well succession.

In addition, the dinoflagellate zonal schemes and most of the zonal markers were not described for the region until the late 1980's in a series of papers by Jonathan Bujak and Kazumi Matsuoka. These markers were not recorded in BCM's study although they do occur in the North Aleutian Shelf COST No. 1 well.

1.2 MATERIAL AND METHODS OF THE PRESENT STUDY

The following report is based on palynological analysis of palynological and kerogen slides were prepared from 174 composite cuttings samples and six core samples (Table 2), plus 78 samples that were picked from coal fragments in cuttings samples (Table 3). All of the cuttings samples were analyzed specifically for this study in 2009 by Jonathan Bujak of Bujak Research International Ltd.

The examined samples are listed on the range charts included in Appendix A of this report and were analysed using a combination of normal transmitted and reflected fluorescence microscopy. This is essential in the Cenozoic section in order to observe the typically pale and often rare specimens of dinoflagellate cysts (dinocysts) and to help distinguish between amorphous sapropel and finely disseminated herbaceous kerogen in the COST well. These applications of fluorescence microscopy are discussed in Bujak & Davies (1982a, b) and illustrated in Plate 1 of this report, which is reproduced from Bujak & Davies (1982a).

1.3 PREVIOUS BIOSTRATIGRAPHIC WORK ON THE COST 1 NO. WELL

The biostratigraphic work on the North Aleutian Shelf COST No. 1 well was primarily based on the analysis of cuttings samples, sidewall cores and 19 conventional cores by Biostratigraphics Consulting Micropaleontology (1983), which is abbreviated as BCM in the remainder of the present report. The examined microfossils included foraminifera, diatoms, silicoflagellates and ebridians, marine and terrestrial palynomorphs including pollen, spores and dinocysts, calcareous nannofossils, ostracodes, and rare radiolaria.

BCM's data and interpretations were extensively reviewed and synthesized by John Larson in MMS Report 88-0089 on the COST well (Turner *et al.*, 1988), who summarized the distribution of microfossils in the well as follows:

> "The biostratigraphy of the Pleistocene, Pliocene, and late Miocene is based primarily on diatoms, with supporting evidence from foraminifera. Calcareous nannofossils and palynomorphs were important for determining the biostratigraphy of the Oligocene, with some support from foraminifera, while palynomorphs were the most important group in the Eocene."

The data available to Larson therefore provided a relatively high resolution biostratigraphy in the upper Miocene to Pleistocene section of the well, down to approximately 3500 ft. However, the age of most of the well, from approximately 3300-17,155 ft (TMD) was less certain, and was based on only a few specimens of pollen, fungi and dinoflagellates recorded by BCM (1983) below about 10,000ft in the section assigned to the Eocene, with subdivision of both the Eocene and Oligocene sections of the well being uncertain.

Larson's interpretation of the COST well biostratigraphy also included data on macrofossils present in conventional cores from the well and ostracodes studied by Elizabeth Brouwers of the U.S. Geological Survey (written communication to Larson, 1985). Interpretation of all other biostratigraphic and geological data were undertaken by Larson, with the exception of siliceous microfossils which were interpreted by Donald Olson of the MMS.

The reader is referred to the original publication of Turner *et al.* (1988) for further details.

1.4 OBSERVATION OF MARINE DINOFLAGELLATE CYSTS

Relatively few dinoflagellate cysts (dinocysts) were recorded from the North Aleutian Shelf COST No. 1 well by BCM (1983). Certain intervals of the well are devoid of these fossils due to nonmarine depositional environment, but the present study indicates that protoperidiniacean dinocysts occur in most samples from the Miocene-Pleistocene section of the well where they are associated with diatoms. This association was first observed in the region by Bujak (1984) and is discussed in Section 3.2 of this report.

Protoperidiniacean dinocysts have a distinctive morphology, with genera such as *Brigantedinium* being spherical to sub-spherical, sometimes resulting in their incorrect identification as spores or thick-walled pollen. However, most specimens, including those in the North Aleutian Shelf COST No. 1 well, possess an intercalary archeopyle that characterizes protoperidiniacean dinocysts - although this may be difficult to observe under low magnification. It is therefore necessary to examine potential specimens under high-power oil immersion in order to confirm their identification.

Marine intervals of the North Aleutian Shelf COST No. 1 well also contain gonyaulacacean dinocysts, although these are generally less common than protoperidiniacean species in the Neogene section. Many of the gonyaulacacean specimens observed in the well are broken and fragmented, so that they may be overlooked, and several species of gonyaulacacean dinocysts are also relatively thin-walled so that they can only be recognized using fluorescence microscopy, as illustrated in Plate 1. Thin-walled specimens may also be dissolved during more vigorous palynological processing. The combined difficulty in recognizing some protoperidiniacean and gonyaulacacean dinocysts, and possible destructive processing may explain the documentation of a larger number of marine dinocysts during the present study than during the study of BCM (1983).

1.5 REPORT FORMAT

The report is divided into the following sections and appendices.

Section 2 discusses the plate tectonic, oceanographic, climatic and lithostratigraphic framework of the North Pacific – Bering Sea region including the North Aleutian Basin.

Section 3 documents the underlying data used to define a composite North Pacific – Bering Sea palynological zonation. These zonal schemes and their age justification are illustrated in Figures 5 to 9 and include zones erected for the Bering Sea / northern North Pacific DSDP Leg 19 by Bujak (1984) and for the Navarin Basin, Norton Sound and the St. George Basin COST wells by Matsuoka & Bujak (1988). Relevant Aleutian and southern Alaskan dinocyst studies by Finzel *et al.* (2009) and Reinink-Smith & Leopold (2005) are also reviewed as they are relevant to the distribution of thermophilic pollen in the COST well. These characterize several warm phases within the Miocene that can be correlated with absolute age determination established by Barron & Baldauf (1990) and Wolfe (1994).

Section 4 and Figures 10 and 11 document the newly erected zonal scheme, including details of the stratigraphic ranges of more than 90 zonal markers. These primarily comprise marine dinocysts, plus several pollen, spore and fungal taxa in the mainly nonmarine Eocene and Oligocene sections of the COST well. Section 4 also discusses thermophilic pollen as these are also important for assigning ages to the Miocene-Neogene interval of the well.

Section 5 summarizes the biostratigraphic results of the present study, including a four-fold degree of confidence given to each zonal assignment, plus absolute ages determined by the occurrence of thermophilic pollen. Some zonal assignments have been adjusted by a few feet to coincide with major stratigraphic breaks or seismic horizons when the observed zonal bioevent is considered to occur slightly low in the well due to poor sample quality or unfavourable depositional environments.

Section 6 gives details of the biostratigraphic subdivision of the well and includes the following subheadings:

- Details of any depth adjustments of the zonal top to coincide with major stratigraphic breaks or seismic horizons.
- Listing of palynomorph bioevents based on the quantitative biostratigraphic data provided in Appendix B as Excel and Stratabugs range charts.
- Listing of absolute age assignments.
- General discussion of the zone.
- Paleobathymetric picks for the zone and discussion of paleoenvironments occurring in the zone.
- Correlation of the zone with other microfossil zones.
- Listing of siliceous microfossil zonal bioevents.
- Discussion of other microfossils occurring in the zone
- Correlation of the zone with seismic sequences and lithostratigraphic picks.

Section 7 lists the consensus well stratigraphy and seismic sequence picks for the well based on discussions with John Larson and Kirk Sherwood of the Alaskan MMS, Anchorage (pers. comm.).

Section 8 discusses paleoenvironmental interpretations for the well based on the present study and previous biostratigraphic study of BCM (1983) and subsequent interpretations of John Larson in MMS Report 88-0089 on the COST well (Turner *et al.*, 1988). Table 2 lists percent values of environmentally sensitive groups of palynomorphs in the COST well.

Section 9 discusses the visual kerogen analysis of key intervals in the COST well. This is particularly important in the interval from 15,620-17,155 ft, for which Dow (1983, in Robertson Research, 1983) reported values of amorphous kerogen exceeding 40%, suggesting a potential oil source, an interpretation that conflicted with other geochemical data as discussed in Turner *et al*. (1988). Table 3 gives percent values of major kerogen types in the COST well based on the present study, indicating that most of the amorphous kerogen recorded by Dow is not sapropelic material, but instead represents the highly disseminated remains of herbaceous plant material with little potential for sourcing oil.

Section 10 discusses kerogen analysis of selected coals in the North Aleutian Shelf COST 1 well. High Hydrogen Index (HI) values of several COST well coals have been previously reported and, if correct, would indicate a possible source for liquid hydrocarbons. The coals were therefore examined during the present study to determine if they include algal remains that would have increased their HI values. Table 3 therefore lists percent values for major palynomorph groups as well as kerogen types in the coals. These indicate that little or no recognizable algal material occurs in the coals, although some do contain up to 40% resinous material that has been proposed as a possible source for waxy oils in the Canadian Beaufort Mackenzie Basin (Snowden, 1982).

A full listing of figures, tables and range charts is provided in the table of contents along with links to correlative electronic document pages.

1.6 DATA FILES

Microsoft Excel and *Stratabugs* digital files are provided with this report (download at MMS website at http://www.mms.gov/alaska/re/reports/rereport.htm) and are also available from Bujak Research International Limited, 288 Newton Drive, Blackpool FY3 8PZ, England; Ph: +44 (1253) 399291; E-mail: jonathan@bujakmudge.com.

2. BIOSTRATIGRAPHY AND CHRONOSTRATIGRAPHY

2.1 BACKGROUND

Figure 5 shows the North Pacific - Bering Sea Cenozoic palynological zones of the this study plotted against the composite oxygen isotope curve of Zachos *et al.* (2001) Mean Annual Temperatures (MAT) of Wolfe (1994) and climatic optima of Barron & Baldauf (1990).

The palynological succession and zonation of the North Aleutian Shelf COST No. 1 well reflects a combination of global, regional and local controls. On a global scale it reflects the shift from a Mesozoic - early Eocene greenhouse state to the modern bipolar glacial icehouse world. This had an enormous effect on marine and nonmarine biotas, particularly in higher latitudes such as the North Aleutian Basin, as the temperature changes were most marked towards the poles.

The second more regional control was imposed by the opening and closing of marine gateways, due to lateral plate tectonic movements. These primarily affected the marine biotas due to changes in oceanic circulation.

The third and more local control was from tectonics in the region of the North Aleutian Basin, which changed the depositional environments during deposition of the COST well succession and hence the relative abundance of marine, brackish water and nonmarine / terrestrial palynomorphs present in the well.

The first two controls are briefly discussed below with less discussion being included on the more local tectonic events because these have been comprehensively discussed in previous publications, including Detterman *et al.* (1996) and Sherwood *et al.* (2006).

2.2 GLOBAL PLATE TECTONIC AND CLIMATIC FRAMEWORK

Paleocene greenhouse conditions were inherited from the Cretaceous, with no appreciable change across the Cretaceous-Tertiary boundary other than the relatively short lived K/T boundary event. Low latitudinal thermal gradients resulted in warm air and sea-surface temperatures extending as far north as the Arctic Ocean, which probably had SST's (sea surface temperatures) that averaged about 10-12^{o}C, resulting in environments totally unknown today due to the combination of warm temperatures and seasonality.

The Paleocene / Eocene Thermal Maximum (PETM) is strongly defined globally by an influx of the subtropical dinocyst *Apectodinium*, reflecting mean Arctic SST values that may have reached about 16^{o}C. This provides a strong chronostratigraphic datum for the inception and end of the event, which lasted for less than half a million years. There is no evidence for the presence of the *Apectodinium* acme event in the North Aleutian Shelf COST No. 1 well, but this may be due to nonmarine deposition in the lowest part of the section or the interval may lie below the base of the well. This is discussed further in Section 5 of the report.

An extensive discussion of the PETM / *Apectodinium* acme event is given in Sluijs *et al.* (2007).

The PETM was succeeded by the early Eocene supergreenhouse world which, apart from the PETM, represented the warmest phase of the Cenozoic and which was succeeded immediately by global cooling and the shift towards the present bipolar glacial icehouse world.

The base middle Eocene *Azolla* event has received considerable attention since it was recovered from ACEX cores on the Lomonosov Ridge. The model proposed by ACEX scientists indicates a highly enclosed basin characterized by episodic surface freshwater layers that were repeatedly colonized by the floating freshwater fern *Azolla* for about 800,000 years. Briefly stated, the model proposes that sequestration of atmospheric carbon by *Azolla* lowered atmospheric CO_2 levels from above 2500 ppm to less that 1000 ppm, shifting the world toward the modern icehouse state.

The *Azolla* interval was succeeded by progressive cooling during the middle and late Eocene, culminating in the Terminal Eocene Event (TEE). The TEE resulted from the following succession of events:

- Plate tectonic separation of Australasia and South America leading to widening and deepening of the Drake Passage.
- Intensification of the Antarctic Circumpolar Current (ACC) which in turn initiated the modern system of deep, cold-water oxygen-rich circulation that extended into the North Atlantic (causing widespread seismically-reflected scouring by contourites.

- Sequestration of atmospheric CO_2 by this new deep-water circulation to below 1000 ppm, which in turn led to global temperature fall.
- Thermal isolation of Antarctica leading to widespread permanent Eastern Antarctic glaciation.
- Global eustatic sea-level fall. Moran *et al.* (2006) have also suggested the development of minor Arctic glaciation at this time based on the presence of ice-rafted material, but this remains to be confirmed by other studies.

Most of the Oligocene was characterized in higher latitudes by a cold phase that removed all cyst-forming dinoflagellates from the Arctic with the exception of the Barents Sea due to inflowing warmer currents from the Norwegian Sea. The northern North Pacific and Bering Sea region also experienced cold sea-surface and air temperatures during most of the Oligocene, which reduced the diversity of dinocyst species as well as angiosperm pollen, with thermophilic species being absent.

The latest Oligocene was marked by a warming event that permitted warmer water dinocysts and thermophilic pollen species to re-migrate into higher latitudes, including the northern North Pacific – Bering Sea region and Arctic. These conditions continued during the Miocene warm phase and reached an optimum in the early part of the middle Miocene between approximately 14 Ma and 16 Ma.

Following the middle Miocene climatic optimum, temperatures began to decrease sharply beginning at about 14 Ma, and were reflected by a sharp decline in thermophilic pollen and warmer water dinocysts. The dinocyst assemblages also show a marked change at this time in the northern North Pacific and Bering Sea region, with protoperidiniacean species becoming abundant at the same time as an increase in diatoms, silicoflagellates and ebridians (Bujak, 1984). Although several relatively short-lived and moderate increases in temperature did occur in the North Pacific region (discussed in the following Section of this report), the general cooling trend continued during the Plio-Pleistocene, culminating in today's climate and temperatures.

2.3 CENOZOIC OCEANOGRAPHY OF THE PACIFIC OCEAN

Ogasawara (2002) divided the Cenozoic history of the Pacific Ocean into seven stages, extending from the Eocene to the Pleistocene (Figures 6 and 7). The first stage was the interval before 43 Ma, which he named the proto-Tasmanian stage, with development of the Tasmanian seaway representing the second stage from 43 to 29 Ma. The third stage (29-23.5 Ma) was the oceanographically most open system because the Pacific was not isolated from the other oceans. The 4th stage resulted from closing of the Bering Strait prior to closure of the Indonesian seaway (23.5-17 Ma) and was followed by the 5th stage during which time the Indonesian and Bering seaways were both closed (17-5 Ma). The 6th stage consisted of a closed Indonesian seaway and an open Bering Strait and Central American seaway (5-2 Ma). The 7th and final stage (post-2.4 Ma) is the modern situation with a closed Central American seaway.

These changes are reflected in Pacific-wide changes in the marine biotas. Major faunal changes across the Eocene – Oligocene boundary reflect the transition from warm-water environments to temperate or cool-water conditions at different latitudes. A dramatic change in the bio-siliceous sedimentation in the early Miocene has been related to diatom floral turnover and closure of the Indonesian seaway, which resulted in formation of the modern northward-flowing Kuroshio Current (Ogasawara, op. cit.), exemplifying the long-distance effects of plate tectonics and gateways on oceanographic change.

2.4 LITHOSTRATIGRAPHY OF THE NORTH ALEUTIAN BASIN

Recent comprehensive discussions of the lithostratigraphic framework are given in Detterman *et al.* (1996) and Sherwood *et al.* (2006), with the following text providing only a brief overview of the lithostratigraphy relevant to the present study.

The North Aleutian Basin, which is also referred to as the Bristol Bay Basin, is a retroarc basin extending from the northwestern margin of the Alaska Peninsula northward beneath the Bering Sea Shelf. More than 6000 m (19,685 ft) of Cenozoic strata are present at its deepest offshore location adjacent to the Alaska Peninsula (Finzel *et al.*, 2005; Kirschner, 1988; Walker *et al.* 2003), with three major phases of Cenozoic subsidence being documented (Finzel *et al.*, 2005; Walker *et al.*, 2003):

1. Fault-controlled subsidence caused by Paleocene and Eocene extensional and strike-slip faulting (the Tolstoi Formation).
2. Late Eocene to middle Miocene flexural subsidence caused by crustal loading due to emplacement of a coeval volcanic arc (the Stepovak, Meshik, and Bear Lake Formations).
3. Late Miocene to Holocene subsidence, which was driven mainly by sediment loading of the southeastern margin as detritus was shed from the Alaska Peninsula (the Bear Lake and Milky River formations)

The Cenozoic succession of the Alaska Peninsula was deposited in a variety of marine and nonmarine environments reviewed by Detterman *et al.* (1996) and Finzel *et al.* (2009).

On the Alaska Peninsula, the Paleocene to Eocene Tolstoi Formation is 659 m (2162 ft) to 1,355 m (4,445 ft) thick at its type and reference sections and mainly comprises fluvial flood-plain and shallow-marine deltaic sediments. The COST well penetrated 2,065 m (6,775 ft) of Tolstoi Formation (Detterman, 1990) but failed to reach its base. The Stepovak Formation comprises about 2000 m (6562 ft) of upper Eocene to Oligocene volcaniclastic deep-water turbidites and shallow-marine sandstone that intertongue with volcanic strata on the southwestern side of the Alaska Peninsula. Detterman (1990) extended the Stepovak Formation to the offshore COST well as a sequence 1,679 m (5,510 ft) in thickness. The upper Oligocene to earliest middle Miocene Unga Formation is only exposed on the Pacific side of the Alaska Peninsula, where it comprises coarse-grained terrestrial strata 275 m (902 ft) in thickness.

The Bear Lake Formation comprises up to 1,000 m (3,281 ft) of sediments that locally overlie the Stepovak and Tolstoi formations with a disconformity or sometimes an angular unconformity. At onshore locations on the Alaska Peninsula, the upper part of the Bear Lake Formation is characterized by ‘a complex series of angular unconformities between the locally steeply dipping and tightly folded Bear Lake Formation and the overlying gently dipping Milky River Formation. Publicly available seismic data suggest that this unconformity may be a regional feature, but its characteristics change offshore. There, gently dipping reflectors of the Bear Lake Formation are locally truncated with subtle discordance by an interpreted erosional surface onto which strong reflectors representing clinoforms in the Milky River Formation prograde northwestward.’ (Finzel *et al.*, 2009).

In the Bristol Bay Basin, the Miocene Bear Lake Formation is up to 1,000 m (3,281 ft) thick onshore and approximately 427 m (1,400 ft) in the COST well correlation of Detterman (1990). According to Finzel *et al.* (2009), Helmold & Brizzolara (2005) and Lyle *et al.* (1979), the Bear Lake Formation has the best porosity and permeability values of all the Cenozoic formations in the basin, containing about 63% reservoir sandstone in its total stratigraphic thickness, and is considered to be one of the most promising potential reservoirs in the Bristol Bay Basin.

The overlying Milky River Formation is 465 m (1526 ft) thick at its type section but ranges up to 1,012 m (3,320 ft) in an onshore well and comprises a mixture of primary volcanic and volcaniclastic strata (Detterman *et al.,* 1996; Helmold & Brizzolara, 2005).

3. BIOSTRATIGRAPHIC FRAMEWORK

3.1 BIOSTRATIGRAPHIC BACKGROUND

The biostratigraphic succession of North Aleutian Shelf COST No.1 reported by BCM in 1983 was based on the analysis of palynomorphs, foraminifera, calcareous and siliceous microfossils. Their data were subsequently integrated with studies on megafossils and ostracodes by John Larson in MMS Report 88-0089 (Turner *et al.*, 1988), who observed:

> "The biostratigraphy of the Pleistocene, Pliocene, and late Miocene is based primarily on diatoms, with supporting evidence from foraminifera. Calcareous nannofossils and palynomorphs were important for determining the biostratigraphy of the Oligocene, with some support from foraminifera, while palynomorphs were the most important group in the Eocene."

The data available to Larson provided a relatively high resolution biostratigraphy in the Upper Miocene to Pleistocene section of the well, down to approximately 3500 ft. However, the age of most of the well, from approximately 3960-17,155 ft (TMD) was less certain, and below about 10,000 ft. in the section assigned to the Eocene it was based on only a few specimens of pollen, fungi and dinoflagellates recorded by BCM (1983).

During the period following BCM's 1983 analysis of the North Aleutian COST No.1 well, Jonathan Bujak and Kazumi Matsuoka systematically published details of the dinoflagellate assemblages in the northern North Pacific and Bering Sea region, including DSDP Leg 10, which cored Eocene to Pleistocene sections at 10 sites along the Aleutian Island Arc, plus the Navarin Basin, Norton Sound and St. George Basin COST wells, and the Japanese area to the south:

- Bering Sea (Bujak 1984)
- Navarin Basin, Norton Sound and St. George Basin (Matsuoka & Bujak 1988)
- Japanese area (Matsuoka, Bujak & Shimazaki 1987; Kurita & Obuse, 2003)
- Late Cenozoic of the western and northern Pacific (Bujak & Matsuoka, 1986)

These are summarized below.

3.2 NORTH PACIFIC – BERING SEA DINOCYST ZONAL SCHEMES

Bering Sea (Bujak 1984) (Figures 1, 8)

Bujak (1984) determined the relative abundances of dinoflagellate cysts and acritarchs from the Eocene to Pleistocene cored by Sites 183 to 192, DSDP Leg 19, along the northern and southern sides of the Aleutian Island Arc in the northern North Pacific and Bering Sea (Figure 1). He erected four new genera and 13 new species and defined eight concurrent-rage zones which he calibrated with high-latitude diatom and silicoflagellate-ebridian zonations based on analyses of these microfossil groups recovered at the same DSDP sites (Figure 8):

Spiniferites frigidus (early to late Pleistocene)

Nematosphaeropsis lemniscata (early Pleistocene)

Impagidinium pacificum (early to late Pliocene)

Spiniferites ovatus (late Miocene to early Pliocene)

Gelatia inflata (late Oligocene)

Spiniferites cf. membranaceus (early Oligocene)

Trinovantedinium boreale (early Oligocene)

No zones were erected for the early Miocene to early part of the late Miocene due to the lack of sediments of this age in the DSDP cores examined by Bujak (1984).

In addition to the biostratigraphic framework erected in his study, Bujak (1984) also interpreted a major biofacies change which he related to a significant oceanographic shift of potential significance to petroleum source rocks in the region:

> "Upper Miocene to Recent dinocyst assemblages are dominated by protoperidiniacean cysts which became abundant in the Bering Sea and northern North Pacific at the same time as diatoms because of major changes in oceanic circulation and sedimentation in the Late Miocene."

Modern dinoflagellates that form fossilizable cysts fall into three major groups: ceratiacean, gonyaulacacean and protoperidiniacean dinoflagellates, and the first two groups are almost entirely photosynthetic. In contrast, modern protoperidiniacean dinoflagellates are non-photosynthetic, and utilize dissolved organic material for nutrition or feed directly on diatoms (see review in Bujak & Davies, 1983, and Taylor 1984). They are particularly common in upwelling regions where they are associated today with high diatom productivity, for example off the northeastern coast of Japan (Matsuoka (1976), in the Weddell Sea (Balech & El Sayed, 1965) and the coasts of Peru and western South Africa (Wall *et al.,* 1977).

Navarin Basin, Norton Sound and the St. George Basin (Matsuoka & Bujak, 1988) (Figures 1, 9)

Matsuoka & Bujak (1988) determined the relative abundances of dinoflagellate cysts and acritarchs in 335 samples from the Navarin Basin COST No. 1 well, the Norton Sound COST No. 1 well and the St. George Basin COST No. 2 well and erected local dinoflagellate cyst zones for each well. The composite ranges of dinoflagellate cysts determined for each of the three COST wells were then used by Matsuoka & Bujak (op. cit.) to erect a composite dinoflagellate cyst zonation for the central and eastern Bering Sea.

The six zones were based on a combination of earliest and latest occurrence of a total of 34 genera and 70 species, with four new genera and 23 new species being erected in Matsuoka & Bujak's 1988 paper. The zonation, including key species and correlation of the zones with diatom-silicoflagellate zones is shown in Figure 9:

Filisphaera filifera Zone (late Pliocene to early Pleistocene)

Filisphaera pilosa Zone (early to Pliocene)

Hystrichosphaeropsis variabile Zone (late Miocene)

*Heteraulacacysta campanul*a Zone (latest late Oligocene to early Miocene)

Impagidinium velorum Zone (early Oligocene)

Trinovantedinium boreale Zone (early Oligocene)

Areospheridiujm diktyoplokus Zone (late Eocene)

Sea of Japan (Matsuoka, Bujak & Shimazaki 1987) and DSDP Leg 57, offshore northeastern Japan (Kurita & Obuse, 2003) (Figure 1)

Matsuoka *et al.* (1987) analyzed 53 samples from the Akita and Niigata coastal regions of northern Japan and erected five dinocyst Oppel-zones for the Miocene to Holocene. Age justification for the zones was based on planktonic foraminifera, radiolaria, calcareous nannofossils and diatom zonal determinations that had been previously determined for the same succession.

Matsuoka *et al.'s* (1987) data for the Japanese region were supplemented by Kurita & Obuse (2003) who documented the dinocyst succession in 34 samples from middle Miocene to upper Pliocene sediments from ODP Hole 1141A. Their study did not erect a dinocyst zonation, but updated that of Matsuoka *et al.* by the addition of several species bioevents.

The Japanese dinocyst zonation is only applicable to the Aleutian-Bering Sea region in sediments older than late Miocene due to differences in the stratigraphic ranges in upper Miocene to Recent sediments resulting from increased SST differences between the two regions. The Japanese dinocyst zones that are applicable to the Aleutian-Bering Sea region are:

Operculodinium. echigoense Zone (middle Miocene)

Diphyes latiusculum Zone (middle Miocene)

Late Cenozoic of the western and northern Pacific (Bujak & Matsuoka, 1986)

Bujak & Matsuoka (1986) synthesized dinocyst data previously published by Bujak (1984), Matsuoka & Bujak (1988) and Matsuoka, Bujak & Shimazaki (1987) for the late Cenozoic of the western and northern Pacific. They reviewed the dinocyst zonal calibration against the diatom and silicoflagellate zonations in the northern colder-water areas and the foraminiferal zonations in the southern warmer-water areas.

Bujak & Matsuoka (op. cit.) noted that the local stratigraphic ranges of many dinocyst species reflected changing oceanography and SST, resulting in truncated stratigraphic ranges to the north that reflected the onset of colder surface water conditions during the Neogene. They also noted that the concurrent extinction in the Japanese area of a large proportion of species during the middle Miocene reflected the onset of colder water conditions:

> "During the early middle Miocene, several species disappeared in northern Japan…..where the predominant current system changed from warm to cold-water during the early middle Miocene (Chinzei, 1976; Saito, 1963).

Bujak & Matsuoka (1986) also attributed the local extinction of several species in the Bering Sea to increased cooling:

> "At the end of the late Miocene, many endemic species disappeared in the Bering Sea. The dinoflagellate cyst assemblages subsequently became less diverse with several protoperidiniacean species, such as *Selenopemphix nephroides* and *Xandarodinium variabile* occurring. According to Margulis & Kennett (1971), Bujak (1984), Wolfe (1978), and Wolfe and Tanai (1980), a late Miocene cooling trend occurred in the western and northern Pacific. The disappearances [of dinocyst taxa at this time]….. probably resulted from the paleoceanographic changes that occurred at this time in the northern North Pacific."

Bujak & Matsuoka (1986) concluded that:

> "In the Neogene to Pleistocene of the western and northern North Pacific areas, the stratigraphic ranges of most dinoflagellate cysts were probably controlled primarily by paleoceanographic changes related to water temperature."

The composite dinocyst range chart published by Bujak & Matsuoka (1986) for the western and northern North Pacific did not differentiate the differences in ranges in the colder, northern North Pacific – Bering Sea region from those to the south in the warmer, Japanese region, or variations in species abundance through time. The present report on the North Aleutian Shelf COST No. 1 well therefore includes an updated composite dinocyst range chart for the western and northern North Pacific – Bering Sea in order to distinguish these ranges that are restricted to the Japanese area in red, as well as abundance occurrences of taxa (Figure 10)

Mid to high latitude Pacific Eocene dinoflagellate and miospore ranges

As discussed in Section 3.2 of this report, middle and upper Eocene palynomorph assemblages have previously been documented from the Bering Sea by Bujak (1984) at Sites 183 to 192 of DSDP Leg 19, and by Bujak & Matsuoka (1988) from the Navarin Basin No. 1, Norton Sound No. 1 and George Basin No. 1 COST wells. The only Leg 19 cores that penetrated Eocene strata are at Site 183 where the dinocyst *A. diktyoplokus* has its highest occurrence in core 27, section 4 at 67-69 cm. The youngest occurrence of *A. diktyoplokus* coincides with the top of the Priabonian type section at Priabona in northern Italy and hence the top of the Priabonian

Stage and the top of the Eocene as presently defined. This is discussed in more detail in Section 5.4 of this report. The dinocyst *Trinovantedinium boreale* also occurs at Site 183 where it is restricted to a single sample examined from core 31, section 2 at 51-69 cm.

Bujak (1984) defined the late Eocene *T. boreale* concurrent-range Zone based on the concurrent ranges of eight dinocyst species, but all of these have relatively long stratigraphic ranges except for *A. diktyoplokus* and *T. boreale*. He selected *T. boreale* to name the zone, but the '*Areosphaeridium diktyoplokus* concurrent-range Zone' would have been a better choice because [1] *A. diktyoplokus* occurs at the top of the zone as defined in core 27, section 4 at 67-69 cm, whereas *T. boreale* only occurs in a single sample within the zone in core 31, section 2 at 51-69 cm, and [2] the stratigraphic range of the cosmopolitan dinocyst *A. diktyoplokus* is well-documented whereas that of endemic North Pacific-Bering Sea *T. boreale* is poorly known.

A. diktyoplokus and *T. boreale* were also recorded by Bujak & Matsuoka (1988) in the Bering Sea Navarin Basin and Norton Sound COST wells, with T. *boreale* occurring in younger strata than *A. diktyoplokus* in both wells:

COST well	**top *T. boreale***	**top *A. diktyoplokus***
Navarin Basin No. 1	12,680 ft	12,770 ft
Norton Sound No. 1	8430 ft	12,150 ft

St. George Basin No. 1 well: middle Eocene and lower Oligocene strata absent

Bujak & Matsuoka used these data to define the late Eocene *A. diktyoplokus* Zone and the early Oligocene *T. boreale* Zone, as shown in Figures 9 and 11 of the present report. Based on Bujak & Matsuoka's record of *A. diktyoplokus* and *T. boreale* in the Navarin Basin and Norton Sound COST wells, the occurrence of *T. boreale* at Site 183 in a single sample below the highest occurrence of *A. diktyoplokus* is interpreted to reflect the shallow-water and possible hyposaline environmental preference of *T. boreale*.

Bujak (1984) also defined the *Kallosphaeridium curiosum* Zone in DSDP Site 183, cores 35 to 38 by the concurrent ranges of the dinocysts I*mpagidinium velorum, K. curiosum, Operculodinium centrocarpum, Selenopemphix nephroides, S.* sp. cf. a*rmata sensu* Bujak 1984 and *Selenopemphix* sp. A of Bujak 1984. He assigned an 'undifferentiated middle to late Eocene age' to the zone, based on the oldest occurrence of *S. nephroides* in the type Bartonian of southern England (Bujak, 1980) and its occurrences elsewhere documented in the University of Utrecht dinocyst summer course held in Urbino, Italy: http://www.uu.nl/EN/faculties/science/organisation/depts/biology/research/chairs/BiomarineSciences/People/Henk_Brinkhuis/Pages/default.aspx. The absence of *A. diktyoplokus* from samples at DSDP Site 183 assigned to the *K. curiosum* Zone is puzzling and the *K. curiosum* Zone is not included in the composite North Pacific-Bering Sea zonation erected in the present report (Figure 10) due to this uncertainty and its poor age control. Instead, the following late Paleocene to middle Eocene palynomorph assemblage zones are erected for the North Pacific-Bering Sea region based on a combination of dinocyst, pollen and fungal spore species that occur in the North Aleutian Shelf COST No. 1 well (Figure 10):

Phthanoperidinium distinctum Zone E3 (Bartonian: middle Eocene)

Top defined by the youngest occurrences of:

Phthamoperidinium distinctum (dinocyst)

Pistillipollenites mcgregorii (pollen)

Pesavis tagluensis (fungal spore)

Diphyes colligerum Zone, Subzone E2b (Lutetian: middle Eocene)

Top defined by the youngest occurrences of:

Diphyes colligerum (dinocyst)

Striadiporites sanctaebarbarae (fungal spore)

Diphyes colligerum Zone, Subzone E2a (Lutetian: middle Eocene)

Top defined by the youngest occurrences of:

Ctenosporites wolfei (fungal spore)

Pesavis sp. A of Ioannides & McIntyre, 1980 (fungal spore)

Charlesdowniea columna Zone E1 (Ypresian: early Eocene)

Top defined by the youngest occurrences of:

Areoligera senonensis (dinocyst)

Charlesdowneia edwardsii (dinocyst)

Glaphyrocysta exuberans (dinocyst)

Glaphyrocysta ordinata (dinocyst)

G. exuberans and G. *ordinata* are both temperature-sensitive species with a warmer water preference and ranges that extend upwards into the middle Eocene in the Japanese region, as shown in Figure 10.

Apectodinium homomorphum acme Zone (late Paleocene

Zone defined by an acme of the dinocyst genus *Apectodinium,* reflecting their global migration and abundance coincident with the Paleocene / Eocene Thermal Maximum (PETM), as documented by Bujak & Brinkhuis (1998).

The ranges of dinocyst species listed above are based on their global stratigraphic ranges documented in the University of Utrecht summer dinocyst course held in Urbino, Italy (op. cit.). The ranges of pollen and fungal spore species are based on their ranges established in more than 100 Alaskan and Canadian Arctic wells (Bujak, unpublished personal observations and confidential data), which were correlated with marine dinocysts and benthic foraminifera present in the same well sections.

Taxonomic note: *Charlesdowniea edwardsii* is restricted to the Pacific – Australasian region, but it is very similar in morphology to *C. columna*, which has widespread occurrences in the circum North Atlantic region, including northwest Europe where its established range is the same as that of *C. edwardsii*. Some authors consider that *C. columna* and *C, edwardsii* are conspecific.

3.3 RELEVANT ALEUTIAN AND SOUTHERN ALASKAN PALYNOLOGICAL STUDIES

Finzel et al. (2009): Bear Lake Formation, central Alaska Peninsula (Figures 2, 3, and 4)

Finzel *et al.* (2009) studied the biostratigraphy and depositional environments of the Bear Lake Formation in onshore exposures along the coast and mountains of the central Alaska Peninsula, approximately 100 km to the southeast of the North Aleutian Shelf COST No. 1 well (Figure 2). Figure 3 and Stratigraphic Chart 2 summarizes the ages that they assigned to samples from the following localities, from youngest to oldest:

- Bear Lake 5
- Bear Lake 2
- Sundean / Left Head
- Bear Lake 1
- Bear Lake 4
- Bear Lake 3
- Coal Point

The age assignments of Finzel *et al.* showed that deposition of the Bear Lake Formation began ‘sometime before the middle Miocene (15 Ma) and extended to possibly the earliest Pliocene’, with most deposition occurring during the middle and late Miocene.

Their lithofacies analysis of the formation also indicated that it represented a regional transgressive estuarine depositional system:

> “The lower part of the formation is characterized by trough cross-stratified sandstone interceded with coal and pedogenic mudstone deposited in fluvial and swamp environments of the uppermost parts of the estuarine system. The lower-middle part of the formation is dominated by non-bioturbated, wavy- and flaser-bedded sandstone and siltstone that were deposited in supratidal flat environments. The upper-middle part of the Bear Lake Formation is characterized by inclined heterolithic strata and coquinoid mussel beds that represent tidal channel environments in the middle and lower tracts of the estuarine system. The uppermost part of the formation consists of tabular, bioturbated sandstone with diverse marine invertebrate macrofossil remains. We interpret this part of the section as representing the subtidal tract of the lower estuarine system and possibly the adjacent shallow marine shelf. A comparison of our depositional framework for the Bear Lake Formation with core and well-log data from onshore and offshore wells indicates that similar Miocene depositional systems existed throughout much of the Bristol Bay basin.”

Palynological analyses in the study of Finzel *et al* were undertaken by James White of the Geological Survey of Canada, who analyzed samples from the following three sections:

- Left Head 1 (five samples)

- Bear Lake 1 (six samples)
- Coal Point 1 (six samples)

All of the species listed in Finzel *et al.* are nonmarine pollen and spores, with the exception of the dinoflagellate cyst genus *Cleistosphaeridium*, but a large percentage of 'Undeterminable spp.' were recorded and were particularly high in the Coal Point 1 section, with the value of 'Undeterminable spp.' exceeding 50% of the total palynomorph count in several samples.

Finzel *et al.* based their age determinations of the examined section on the megafossils plus the presence of temperature-sensitive species, which they correlated with temperature changes that occurred during the middle and late Miocene in the Bristol Bay Basin. Temperature-sensitive species that they noted were the thermophilous taxa *Acer, Carya, Pterocarya* and *Ulmus*.

Finzel *et al.* also interpreted assemblages dominated by Taxodiaceae-Cupressaceae-Taxaceae, which they termed T-C-T palynomorphs, as supporting 'deposition during a period of warm climate.

Based on a dominance of T-C-T palynomorphs, Finzel *et al*. concluded that:

> "The Coal Point section, therefore, is apparently older than an interpreted temperature decline that began ca. 15 Ma in the early middle Miocene (White *et al.*, 1997, 1999; Zachos *et al.*, 2001). The reduced abundance of T-C-T pollen, greater Pinaceae, and presence of thermophilous angiosperms that grew in temperate climates in the upper part of the Bear Lake 1 and lower part of the Left Head sections suggest a correlative relationship for these parts of the sections. *Ilex*-type pollen in the upper Bear Lake 1 section suggests a climate with limited frost. These sections are likely correlative with the late middle and early late Homerian stage (Wolfe *et al.*, 1966; Reininck-Smith and Leopold, 2005). The single grass pollen grain in the upper Bear Lake 1 sample is limited evidence, to be treated with caution, but would suggest a correlation to the upper half of the Homerian-type section in Cook Inlet (Reininck-Smith and Leopold, 2005). The upper part of the Bear Lake 1 and lower part of the Left Head sections were likely deposited in the Homerian stage, of middle to early late Miocene age, ca. 11-?8 Ma. Reininck-Smith & Leopold (2005). Detailed restudy of the Holocene in coastal Alaska argues for less cooling in mean annual temperature after the Seldovian and probably less temperature fluctuation during the Homerian than previously described (Wolfe, 1994; White *et al.,* 1997, 1999)."

Integrating macrofossil evidence documented in their study with the palynology discussed above, Finzel *et al.* concluded that deposition of the Bear Lake Formation along the coast and in the mountains of the central Alaska Peninsula initiated sometime before 15 Ma (middle Miocene) and extended possibly into the earliest Pliocene, with the bulk of the formation being deposited during the middle and late Miocene.

Finzel *et al.'s* conclusions are summarized in Figures 3 and 4 which illustrate that the Bear Lake Formation represents a mainly middle and late Miocene transgressive estuarine depositional system in the Bristol Bay Basin:

> "The transgressive package consists of nonmarine, fluvial strata that grade upsection into transitional supratidal strata overlain by subtidal and shelf strata. This progression of facies, combined with the presence of brackish water trace fossils, tidally generated sedimentary structures, and the general lack of wave-generated features, suggests an estuarine depositional environment. Comparison of our depositional framework with core and well-log data from onshore and offshore exploration wells indicates that similar Neogene depositional systems existed throughout much of the Bristol Bay Basin.

The present study on the North Aleutian Shelf COST No. 1 well supports the ages assigned to the Bear Lake Formation by Finzel *et al.* (2009). These were primarily based on the distribution of thermophilic pollen as the onshore sections examined by Finzel *et al.* contained few or no marine palynomorphs (Figures 3 and 4). Miocene sediments of the COST well were deposited in marine environments and contain age-diagnostic marine dinocysts that indicate the same ages as those inferred by Finzel *et al.* (Figure 3; Figure 5), as well as the same succession of thermophilic pollen that they documented. These two sources of COST well data, from [1] nonmarine temperature-sensitive pollen and [2] the ranges of age-diagnostic marine dinocysts that have been calibrated against siliceous microfossils at other North Pacific – Bering Sea locations, independently support the ages assigned by Finzel *et al.* to the Bear Lake Formation at onshore localities, as discussed in Section 6 of this report on 'Biostratigraphic Results'.

Stratigraphic Chart 2 correlates the North Aleutian Shelf COST No. 1 well with the onshore sections examined by Finzel *et al.* (2009). Marine dinocysts present in the COST well indicate an upper Miocene section assigned to the *H. variabilis* Zone from 2510-4080 ft underlain by a section assigned to the middle Miocene *O. echigoense* Zone from 4080-5675 ft. These are broadly correlated as follows with the onshore sections examined by Finzel *et al.*

The upper Miocene section from 2510-4080 ft broadly correlates with the Bear Lake Formation exposed at the Bear Lake 1, Sunbean / Left Head and Bear Lake 2 and 5 localities, to which Finzel *et al.* assigned a late middle Miocene to early Pliocene age. According to the interpretations of Finzel *et al.*, these were deposited in environments that changed upwards from supratidal freshwater marshes and brackish tidal flats at the Bear Lake 1 locality, to brackish-marine intertidal channels and tidal flats at the Sunbean / Left Head locality, and then to marine subtidal channels and sand flats at the Bear Lake 2 and 5 localities.

The middle Miocene section from 4080-5675 ft broadly correlates with the Bear Lake Formation exposed at the Coal Point and Bear Lake 3 and 4 localities, to which Finzel *et al.* assigned an early to middle Miocene age. According to the interpretations of Finzel *et al.*, these were deposited in nonmarine fluvial channels adjacent to overbank environments and swamps or marshes.

The COST well Bear Lake Formation section also shows an upward decrease in nonmarine spores that were transported by water to the COST site. This tentatively supports the transgressive nature of the succession documented by Finzel *et al.,* with fewer of the water-borne spores reaching the COST depositional location as the regression progressed.

Reininck-Smith & Leopold (2005): upper Miocene Homerian type section, southern Alaska

Reininck-Smith & Leopold (2005) studied the palynology of the upper Miocene Homerian type section in the upper Beluga Formation of the Kenai Group in southern Alaska. They documented the presence of 36 pollen and spore genera, but no dinocysts due to the non-marine depositional environment. Their study is relevant because it details the presence and significance of the following thermophilic pollen species that also occur in the North Aleutian Shelf COST No. 1 well:

Generic name	**common name**
Carya	hazel
Corylus	pecan
Fagus	beech

Ilex	holly
Juglans	walnut
Carpinus	hornbeam
Pterocarya	wingnut
Tilia	linden
Ulmus	elm

The presence of these thermophilic pollen species in the COST well provides information regarding the presence of warmer climatic episodes in the well, which can then be correlated with increased paleotemperature episodes documented for the North Pacific region and Beringia by Barron & Baldauf (1990) and Wolfe (1994) respectively.

This is discussed below and in Section 6 of the report on Biostratigraphic Results.

3.4 RECONSTRUCTION OF PALEOTEMPERATURES

Global deep-sea oxygen and carbon isotope records of Zachos et al. (2001) (Figures 5, 6)

Zachos *et al.* (2001) constructed global deep-sea oxygen and carbon isotope records based on data from more than 40 DSDP and ODP sites, with most of the data being derived from the analysis of two common and long-lived benthic taxa, *Cibicidoides* and *Nuttallides*. The oxygen isotope record, which is a general proxi for paleotemperature, is shown in Figures 5 and 6, illustrating the general warm to cool trend during the greenhouse to icehouse shift, including several cold and warm phases in the Oligocene and Miocene.

North Pacific climatic optima of Barron & Baldauf (1990) (Figure 5)

Barron & Baldauf (1990) recognized several oscillations in sea-surface temperature (SST) based on oxygen isotope ratios from *Cibicides* tests obtained from North Pacific marine sediments. They identified three warm intervals, which they named Climatic Optimum 1 (16 to 15 Ma), Climatic Optimum 2 (11.5 to 10.5 Ma), and Climatic Optimum 3 (7.5 to 6.5 Ma) shown in Figure 5.

All three of these Climatic Optima were identified in the North Aleutian Shelf COST No. 1 well, as discussed in Sections 5 and 6 of the report:

- 2730 ft: Climatic Optimum 3
- 3990-4080 ft: Climatic Optimum 2
- 5160-5340 ft: Climatic Optimum 1

Mean Annual Temperatures (MAT) in Beringia (Wolfe, 1994) (Figure 5)

Wolfe (1994) used multivariate analysis of foliar physiognomy to reconstruct the nonmarine climate in Beringia. His studies suggested a gradual decline in MAT from about 12°C to 11°C in the Seldovian, between 18 to 14 Ma, followed by a sharp decrease to about 4°C in the earliest Homerian at 13 Ma. MAT remained between 4°C and 5°C during the remainder of the Homerian and earliest Clamgulchian from 12 to 7 Ma, with two minor increases of about 1°C in MAT at about 11 Ma and 8 Ma (Figure 5).

4. NORTH PACIFIC – BERING SEA BIOSTRATIGRAPHIC ZONATION

4.1 BACKGROUND

The regional North Pacific – Bering Sea palynological zonation used in this report is shown in Figures 10 and 11, and is based on the integration of zonal schemes and species ranges discussed in the preceding sections of this report and shown in Figures 5 to 9. This updates previous work by [1] using the abundances of taxa as well as their ranges, and [2] distinguishing between the ranges of species in the Bering Sea - Aleutian area and those in warmer water of the Japanese region. The colder water ranges shown in black on Figure 10 are applied to the North Aleutian Basin including the COST 1 well.

The palynological zones are primarily based on marine dinocysts, with the addition of several miospore (pollen-spore) and fungal species. Fungi are particularly important in the Eocene section of the COST well, as this comprises predominantly or exclusively nonmarine strata in the North Aleutian Basin. The miospore and fungal ranges are primarily based on Bujak's personal observations of their occurrences in high-latitude marine sections, including the Arctic, plus unpublished and confidential data from the North Pacific region.

Data for the Eocene are mainly provided by the mid to high latitudes ranges of taxa from various sources, summarized in the University of Utrecht Summer School on dinocysts held in Urbino, Italy, for which details can be obtained from Dr Henk Brinkhuis: http://www.uu.nl/EN/faculties/science/organisation/depts/biology/research/chairs/BiomarineSciences/People/Henk_Brinkhuis/Pages/default.aspx.

4.2 DEFINITION OF ZONES

Zones are concurrent range zones defined by a combination of first (earliest) and last (latest) stratigraphic occurrences and abundances of species. The succession of first and last occurrences bioevents that define each zone are tabulated in Figure 10. Age justification and correlation of the zones with other microfossil zonations are discussed in the preceding sections of this report and are tabulated in Figures 5 to 8. Zonal names are based on one of the taxa that define the zone and are also indicated by an alphanumeric notation indicating the Stage / Age in which the zone occurs.

The palynological zones defined in this report are, in order of increasing depth:

Spiniferites frigidus Zone PL2 (Pleistocene: Ionian)

Nematosphaeropsis lemniscata Zone PL1 (Pleistocene: Calabrian)

Impagidinium pacificum Zone P2 (late early and late Pliocene: late Zanclean, Piacenzian and Gelasian)

Spiniferites ovatus Zone P1 (early Pliocene: early and middle Zanclean)

Hystrichosphaeropsis variabilis Zone M3 (latest middle and late Miocene: late Serravalian, Tortonian and Messinian)

- Subzone M3b (late Miocene: late Tortonian and Messinian)
- Subzone M3b (latest middle and late Miocene: late Serravalian and early and middle Tortonian)

Operculodinium echigoense Zone M2 (middle Miocene: Langhian and early to middle Serravalian)

- Subzone M2b (middle Miocene: early to middle Serravalian)
- Subzone M2a (middle Miocene: Langhian)

Heteraulacacysta campanula Zone M1 (early Miocene: Burdigalian and Aquitainian)

Gelatia inflata Zone O3 (late Oligocene: Chattian)

Spiniferites cf. *membranaceus* Zone O2 (early Oligocene: Rupelian)

Trinovantedinium boreale Zone O1 (earliest Oligocene: early Rupelian)

Areosphaeridium diktyoplokus Zone E4 (late Eocene (Priabonian)

Phthanoperidinium distinctum Zone E3 (middle Eocene: Bartonian)

Diphyes colligerum Zone E2 (middle Eocene: Lutetian)

- Subzone E2b (middle Eocene: late part of the Lutetian)
- Subzone E2a (middle Eocene: early part of the Lutetian)

Charlesdowniea columna Zone (early Eocene: Ypresian)

Apectodinium homomorphum Zone (latest Paleocene: late Thanetian)

4.3 CALIBRATION WITH ABSOLUTE TIME

Two methods are used to assign specific depths in the North Aleutian Shelf COST No. 1 well to absolute time:

1. Correlation of palynomorph bioevents and zonal boundaries with ages established using other fossil groups or in references sections, which is discussed above in Section 3.1 of the report.
2. Correlation with paleotemperature changes documented by Barron & Baldauf (1990) for the North Pacific and by Wolfe (1994) for Beringia using shifts in the pollen assemblages observed in the COST well. These are reflected in the occurrence and abundance of thermophilic angiosperm and gymnosperm pollen in the well. Details of this methodology are given in Section 3.4 of this report.

4.4 ABSOLUTE TIME SCALE

The IUGS absolute time scale is used throughout this report (2009 International Commission on Stratigraphy: http://www.stratigraphy.org/upload/ISChart2009.pdf).

4.5 NOTES ON TAXONOMIC NOMENCLATURE

The dinocyst taxonomic nomenclature used in this report follows the Lentin and Williams index of fossil dinoflagellates, 2004 edition (Williams & Fensome, 2004).

Fossil pollen and spore nomenclature is complicated by the use of several systems of nomenclature by palynologists. These include the application of:

- Modern plant nomenclature such as the pollen genus *Pterocarya* to denote the pollen produced by the parent plant, in this example, wingnut.
- Modern pollen and spore nomenclature such as the use of the genus *Pterocaryapollenites* to denote the pollen produced by the parent plant.
- A purely morphological system, for example the genus *Polyatriopollenites* for pollen specimens that resemble or are identical to modern *Pterocaryapollenites* pollen. This

system is preferred by some palynologists in order to avoid indications of plant affinity for the pollen, particularly in older Cenozoic or Mesozoic strata where affinities area more tenuous than in Neogene sections.

The nomenclatural confusion also applies to specific assignments of pollen and spore, so that several generic and specific names have been applied to identical pollen in the fossil record in publications and other reports, leading to confusion in interpreting data for non-palynologists (as well as many palynologists).

In order to provide consistency with the previous data of Finzel *et al.* (2009), the present report uses pollen and spore nomenclature that is similar to that used by James White of the GSC in Calgary, in Finzel *et al.* (2009). The following listing is provided to facilitate comparisons of the data in Finzel *et al.* with those of the present report for the COST well:

Finzel *et al.* (2009)	**This report**
Abies sp.	*Abiespollenites* spp.
Alnus sp. with 4 to 7 pores	*Alnipollenites verus*
Aremarrhena sp.	not recorded
Artemisia sp.	*Artemisia-Taraxacum* spp.
Baculatisporites pimarius	*Baculatisporites / Osmundacidites* spp.
Betula 20 microns or less	*Betulaceoipollenites* spp. 20 microns or less
Betula greater than 20 microns	*Betulaceoipollenites* spp. greater than 20 microns
Boisduvalia clavatites	*Boisduvalia clavatites*
Carya sp.	*Caryapollenites* spp.
Cedrus sp.	*Cedripites* spp.
Cryptogramma sp.	not recorded
Cystopteris sp.	not recorded
Deltoidospora sp.	*Deltoidospora* spp.
Ericales undifferentiated	*Ericipites antecursorioides* and *E. compactipolleniatu*s
Fagus sp.	*Faguspollenites* spp.
Fractisporonites sp.	not recorded
Hypoxylonites sp.	not recorded
Ilex-type	*Ilexpollenites* spp.

Laevigatosporites sp.	*Laevigatosporites ovatus*
Liliaceae undifferentiated	not recorded
Lycopodium sp.	*Lycopodiumsporites* spp.
Nuphar sp.	not recorded
Osmunda sp.	*Baculatisporites / Osmundacidites* spp.
Picea sp.	*Piceaepollenites* spp.
Pinaceae undifferentiated	*Pinaceae* undifferentiated
Pinus koraiensis-type	*Pinuspollenites koraiensis*-type
Pinus sp.	*Pinuspollenites* spp.
Poaceae undifferentiated	not recorded
Podocarpus-type	*Podocarpidites* spp.
Polypodiaceae/Dennstaedtiaceae	Polypodiaceae / Dennstaedtiaceae spp.
Pterocarya sp.	*Pterocaryapollenites* spp.
Tsuga canadensis-type	*Tsugaepollenites canadensis*
Tsuga heterophlycta-type	*Tsugaepollenites heterophlycta*
Reticolporopollenites sp.	*Reticolporopollenites* spp.
Retitricolpites sp.	*Retitricolpites* spp.
Salix sp.	*Salixpollenites* spp.
Sphagnum sp.	*Sphagnumsporites* spp.
Taxodoaceae-Cupressaceae-Taxa	*Taxodiaceaepollenites* spp.
Tricolpites sp.	*Tricolpites* spp.
Triporopollenites sp.	*Triporopollenites* spp.
Ulmus-type	*Ulmipollenites* spp.

5. SUMMARY OF RESULTS: NORTH ALEUTIAN SHELF COST NO. 1 WELL

5.1 PALYNOLOGICAL ZONAL ASSIGNMENTS *

1390 ft: highest examined sample

1390-1590(1) ft: *Nematosphaeropsis lemniscata* Zone PL1 (early Pleistocene) [1]

1590(1)-2370 ft: *Impagidinium pacificum* Zone P2 (latest early to late Pliocene) [3]

2370-2510(2) ft: *Spiniferites ovatus* Zone P1 (early Pliocene) [1]

***(Bracketed numbers -** See notes on zonal assignments, Section 5.3 below)

---hiatus---

2510(2)-4080 ft: *Hystrichosphaeropsis variabilis* Zone M3 (late Miocene) [3]

- 2510-3090 ft: *H. variabilis* Zone Subzone M3b (late Miocene) [3]
- 3090-4080 ft: *H. variabilis* Subzone M3a (late Miocene) [3]

4080 -5675(3) ft: *Operculodinium echigoense* Zone M2 (middle Miocene) [2]

- 4080-4890 ft: *O.* echigoense Zone, Subzone M2b (middle Miocene) [2]
- 4890-5675(3) ft: *O.* echigoense Zone, Subzone M2a (middle Miocene) [2]

---hiatus---

5675(3)-7900(4) ft: *Spiniferites* cf. *membranaceus* Zone O2 (early Oligocene) [4]

7900(4)- 9555(5) ft: *Trinovantedinium boreale* Zone O1 (early Oligocene) [4]

9555(5)-10,380 ft *Areosphaeridium diktyoplokus* E4 Zone (late Eocene) [2]

---hiatus---

10,380-15,420 ft: *Diphyes colligerum* Zone E2 (middle Eocene) [3]

- 10,380-11,820 ft: *D. colligerum* Zone E2 Subzone 2b (middle Eocene) [2]
- 11,820-15,420 ft: *D. colligerum* Zone E2 Subzone 2a (middle Eocene) [2]

15,420-17,150 ft (TD): *Charlesdowniea columna* Zone E1 (early Eocene) [2]

5.2 ADJUSTMENTS TO DEPTHS OF ZONAL TOPS

The following adjustments were made to coincide with a major stratigraphic break or seismic horizon when the observed zonal bioevent is considered too depressed and to occur slightly low in the well due to poor sample quality or unfavourable depositional environments.

(1) Depth adjusted from the cuttings sample at 1650-1740 ft to the top of the Milky River Formation at 1590 ft.

(2) Depth adjusted from the cuttings sample at 2550-2640 ft to Seismic Horizon A, the top of Seismic Sequence II, and the top of the Bear Lake Formation at 2510 ft.

(3) Depth adjusted from the cuttings sample at 5700-5790 ft to Seismic Horizon B, the top of Seismic Sequence III, and the top of the Stepovak Formation at 5675 ft.

(4) Depth adjusted from the cuttings sample at 8040-8130 ft to the top of the Seismic Horizon C at 7900 ft.

(5) Depth adjusted from the cuttings sample at 9570-9650ft to the top of lithological sequence D2 at 9555 ft.

5.3 NOTES ON ZONAL ASSIGNMENTS

1. The zonal listing shows the highest examined sample in which zonal marker species were observed. This may result in the biostratigraphic picks differing slightly from stratigraphic datums indicated by log or seismic correlations. Where these depths are occasionally integrated (e.g., the top of the Milky River Formation), this reconciliation is noted in the text.
2. The degree of confidence is shown in square brackets [1-4] after each zonal assignment:

Confidence level 1:	highest confidence level
Confidence level 2:	medium confidence level
Confidence level 3:	lower confidence level
Confidence level 4:	lowest confidence level

5.4 ABSOLUTE AGE ASSIGNMENTS

The methods used to assign the ages for specific depths in the North Aleutian Shelf COST No. 1 well discussed in Section 4.3 and in Stratigraphic Charts 1 & 2 of this report provide the following determinations:

1390 ft: > 0.78 Ma for the highest examined sample in the *Nematosphaeropsis lemniscata* Zone equivalent to Calabrian interval = 0.78 to 1.8 Ma.

1590(1) ft: 1.8 Ma for the top of the *Impagidinium pacificum* Zone P2 Zone as top of zone = top Pliocene (*sensu* top Gelasian dated as 1.8 Ma).

2010 ft: 2.4 to 2.6 Ma (average age = 2.5 Ma) for the top consistent / *in situ* occurrence of *Tsugaepollenites* (hemlock), corresponding to intra-P2 cooling event coincident with expansion of Arctic ice sheet.

2370 ft: 3.5 Ma for the top common / abundant occurrence of *Tsugaepollenites* (hemlock), coincident with early development of Arctic ice sheet.

2370 ft: Approximate 3.5 Ma for the top of the *Spiniferites ovatus* Zone.

2510 ft: Approximate 3.4 to 5.3 Ma hiatus corresponding to seismic horizon A as the lowermost Pliocene is probably absent, assuming constant sedimentation rate in the early Pliocene *Spiniferites ovatus* Zone.

2550 ft: 5.33 Ma for the top of Subzone M3b of the *Hystrichosphaeropsis variabilis* Zone, which correlates with the top Miocene.

2730 ft: 6.5 to 7.5 Ma (average = 6.0 Ma) corresponding to North Pacific climatic optimum CO3 of Barron & Baldauf (1990).

3090 ft: Approximate 9 Ma for the top of Subzone M3a of the *Hystrichosphaeropsis variabilis* Zone.

3990ft: 10.5 to 11.5 Ma (average = 11.0 Ma) corresponding to North Pacific climatic optimum CO2 of Barron & Baldauf (1990).

3990ft: 11 Ma corresponding to a minor temperature increase documented by Wolfe (1994).

4080 ft: 11.61 Ma for the top of Subzone M2b of the *Operculodinium echigoense* Zone, which correlates with the top middle Miocene.

4890 ft: 14 Ma corresponding to an abrupt temperature decline documented by Wolfe (1994).

4890ft: Approximate 14 Ma for the top of Subzone M2a of the *Operculodinium echigoense* Zone, within the middle Miocene.

5160-5340 ft: 15.0 to 16.0 Ma based on the correlation with North Pacific climatic optimum CO1 of Barron & Baldauf (1990) which occurred from 15 to 16 Ma.

5675 ft: The youngest established age for the base of the Miocene section in the North Aleutian Shelf COST No. 1 well is 15 Ma and the oldest age is 16 Ma, as discussed above. The youngest age of Oligocene strata immediately below the hiatus at 5675 ft is 28.4 Ma (= top of the lower Oligocene). Its oldest age is less certain because the age of the base of the *S.* cf. *membranaceus* Zone has not been firmly established. Preliminary estimates indicate its base at 32.9, based on a possible duration of 1 Ma for the underlying *T. boreale* Zone. The restricted dinocyst assemblages in the *T. boreale* Zone indicate that the *T. boreale* Zone may equate with a sharp cooling phase in the earliest Oligocene (Figure 5), so that its 1 Ma duration is calculated from its base at the Eocene-Oligocene boundary at 33.9 Ma) This gives a minimum duration for the hiatus between the Oligocene and Miocene sections of the well of 12.4 Ma (28.4 minus 16 Ma) and a possible maximum duration of 17.9 Ma (32.9 minus 15 Ma). The hiatus between the Miocene and Oligocene and Miocene section in the COST well corresponds to Seismic Event B and the hiatus between Bear Lake and Stepovak formations (see discussion of the *S.* cf. *membranaceus* Zone for details).
9555 ft: 33.5 Ma based on the youngest global occurrence of the dinocyst *Areosphaeridium diktyoplokus* (Brinkhuis, 1994; Brinkhuis & Visscher, 1995; and the University of Utrecht dinocyst summer course held in Urbino, Italy: http://www.uu.nl/EN/faculties/science/organisation/depts/biology/research/chairs/BiomarineSciences/People/Henk_Brinkhuis/Pages/default.aspx.

The bioevent also characterizes the top of the Priabonian type section as originally defined at Priabona in northern Italy, but there have been recommendations to redefine the top of the Priabonian, and hence the top of the Eocene at the deeper paleowater Massignano section in central Italy, primarily tied into the occurrences of Hantkeninid foraminifera, and this would place the top of the Eocene slightly below the last occurrence of *A. diktyoplokus*. Irrespective of this possible redefinition, the youngest occurrence and hence the top of the *A. diktyoplokus* Zone indicates an absolute age of 33.5 Ma for the COST well at 9555 ft as there is no evidence of a hiatus immediately above this horizon in the well.

10,380 ft: Possible minimum duration of missing section in hiatus at 10,380 ft of 3.2 Ma based on Priabonian strata no older than 37.2 Ma overlying Lutetian strata with fungal spore markers no younger than 40.4 Ma. This correspondes to Seismic Event D and the break between the Stepovak and Tolstoi formations.

15,420 ft: 48.6 Ma based on the youngest occurrence of the dinocyst *Charlesdowniea columna* at the top of the Ypresian.

6. BIOSTRATIGRAPHIC RESULTS: N. ALEUTIAN SHELF COST NO. 1 WELL

6.1 INTRODUCTION

1. This section of the report discusses the biostratigraphic succession interpreted from the palynological data shown on the stratigraphic and species occurrence charts in Appendices A and B of the report.
2. The zonal subdivision of the well is documented below in order of increase depth, using the zonal scheme shown in Figure 10.
3. Each zonal and subzonal name is followed by its zonal abbreviation and age, for example, the *Spiniferites frigidus* Zone PL2 (Pleistocene).
4. A confidence level is assigned to each zone in square brackets from 1 (highest) to 4 (lowest). Zonal bioevents listed within each zone or subzone are followed by the type of microfossil in curved brackets, i.e., (A) algae, (D) dinocysts, (F) fungi, (P) pollen, and (S) spores.
5. The zone characterized by each species' highest occurrence is shown in square brackets [---] after the species name and microfossil type; for example:

   1390 ft *Filisphaera filifera* (D) [PL2]

   In this example the species *Filisphaera filifera* is a dinocyst that has its highest occurrence at 1390 ft and in the North Pacific – Bering Sea zonal scheme defined in this report and its highest occurrence characterizes Zone PL2 (Pleistocene *Spiniferites frigidus* Zone).

6.2 BIOSTRATIGRAPHIC SUBDIVISION: N. ALEUTIAN SHELF COST 1 WELL

1390 ft: highest examined sample

1390-1590$^{(1)}$ ft: *Nematosphaeropsis lemniscata* Zone PL1 (early Pleistocene) [1]

(1) Depth adjusted from the cuttings sample at 1650-1740 ft to the top of the Milky River Formation at 1590 ft.

Diagnostic palynomorph bioevents:

1390 ft	*Brigantedinium* spp. (D) [PL2]
	Filisphaera filifera (D) [PL2]
	Halodinium major (A) [PL2]
	Halodinium minor (A) [PL2]
	Spiniferites ramosus (D) [PL2]
	Xandarodinium variabile (D) [PL1]
1470 ft	*Selenopemphix nephroides* (D) [PL1]
	Spiniferites frigidus (D) [PL2]

Absolute age assignment:

1390 ft:	highest examined sample in the *Nematosphaeropsis lemniscata* Zone PL1 Zone (zone equivalent to Calabrian = 0.78 to 1.8 Ma) (1780 ft sample age > 0.78 Ma)

Discussion: Eight algal and dinocyst species confirm the Pleistocene age of this interval, with *Selenopemphix nephroides* and *Xandarodinium variabile* indicating a relatively confident assignment [level 1] to the early Pleistocene *Nematosphaeropsis lemniscata* Zone.

Paleobathymetry: The following paleobathymetric depths were given for this interval (1390-1590) in Sherwood *et al.* (2006) and Turner *et al.* (1988), with additional interpretations being given below in the section on 'paleoenvironment'.

- 1390-1560 ft: middle to outer neritic

- 1560-1590 ft: outer neritic

Paleoenvironment: Marine dinocysts comprise 3% to 5% of the total palynomorph assemblages), with rare brackish-freshwater algal species of *Halodinium* probably being transported to the marine depositional site, and the relatively low abundance of dinocysts is probably due to their dilution by nonmarine miospores also being transported to the depositional site. Protoperidiniacean species comprise more than 50% of marine dinocyst, reflecting periods of high productivity, often associated with diatom abundance, as discussed in Bujak (1984) and Section 2.3 of this report. However, it is probable that the North Aleutian Shelf area drilled by the COST well was not the center of high productivity as a larger number of protoperidiniacean cyst remains would have been deposited in sediments at the COST well location. It is more likely that the areas of high productivity were some distance away and the cysts were transported to the COST well location, or that a relatively small number of protoperidiniacean dinoflagellates occupied the COST well location and formed cysts that sank to the sea-floor and were incorporated into the COST well sediments. As discussed below, Protoperidiniacean cysts are the most common dinocyst type, but occur in relatively low number compared to miospores throughout the COST well middle Miocene to Pleistocene section, so that a similar scenario is suggested for all of this time.

The miospore assemblages in this interval reflect a climate similar to today's, comprising long-ranging spores and gymnosperm data plus low-diversity angiosperm pollen including *Betulaceoipollenites* (birch) and *Alnipollenites* (alder). *In situ* thermophilic species are absent and the rare specimens that do occur are interpreted to be reworked.

Correlation with other microfossil zones: The following siliceous microfossil zones have their tops in the early Pleistocene N. *lemniscata* Zone as documented in Turner *et al.* (1988):

1380 ft	*Actinocyclus oculatus* Zone (Pleistocene)

Siliceous microfossil zonal markers bioevents (J. Larson in Turner *et al.*, 1988):

1380 ft	*Rhizosolenia curvirostris* (no samples examined above 1380 ft)
	Thalassiosira nidulus (no samples examined above 1380 ft)
1470 ft	top *Actinocyclus oculatus*
	top *Pseudopyxilla americana*

Other microfossils: High-latitude, cold-water shelf foraminifera occur with no observed age-diagnostic species. No ostracodes or calcareous nannofossils were recovered from this interval of the well.

Seismic and lithostratigraphy: The early Pleistocene N. *lemniscata* Zone corresponds to the following seismic and lithostratigraphic units of Sherwood *et al.* (2006) and Turner *et al.* (1988):

- Lower part of the ‘unnamed Quaternary unit which occurs from 0-1590 ft
- Middle part of Seismic Sequence I which occurs from 0-2510 ft
- Middle part of lithostratigraphic Unit A which occurs from 1000-2510 ft

1590(1)-2370 ft: *Impagidinium pacificum* Zone P2 (latest early to late Pliocene) [1]

(1) Depth adjusted from the cuttings sample at 1650-1740 ft to the top of the Milky River Formation at 1590 ft.

Diagnostic palynomorph bioevents:

1560 ft	*Lejeunecysta fallax* (D) [P2]
	Selenopemphix crenata (D) [P2]
	Selenopemphix quanta (D) [P2]
1650 ft	*Nematosphaeropsis lemniscata* (D) [P2]
	Tectatodinium pellitum (D) [P2]
1830 ft	*Impagidinium pallidum* (D) [P2]
	Impagidinium velorum (D) [P2]
2190 ft	*Impagidinium japonicum* (D) [P2]
2280 ft	*Impagidinium pacificum* (D) [P2]

Absolute age assignments:

1590(1): 1.8 Ma for the top of the *Impagidinium pacificum* Zone P2 Zone as top of zone = top Pliocene (*sensu* top Gelasian dated as 1.8 Ma).

2010 ft: 2.4 to 2.6 Ma (average age = 2.5 Ma) for the top consistent / *in situ* occurrence of *Tsugaepollenites* (hemlock), corresponding to intra-P2 cooling event coincident with expansion of Arctic ice sheet.

Discussion: Nine dinocyst species confirm the Pliocene age of this interval, indicating a relatively confident assignment [level 1] to the latest early to late Pliocene *Impagidinium pacificum* Zone.

Paleobathymetry: The following paleobathymetric depths were given for this interval (1590-2370 ft) in Sherwood *et al.* (2006) and Turner *et al.* (1988), with additional interpretations being given below in the section on 'paleoenvironment'.

- 1590-1740 ft: outer neritic
- 1740-2160 ft: middle to outer neritic
- 2160-2370 ft: middle neritic

Paleoenvironment: Marine dinocysts occur in all samples from this interval, comprising between 3% and 4% of palynomorphs indicating fully marine deposition, with protoperidiniacean species comprising from 64% to 75% of marine dinocyst, reflecting periods of high productivity, often associated with diatom abundance. The miospore assemblages are similar to those in the overlying interval and *in situ* thermophilic species are absent except for the rare specimens that are interpreted to be reworked. However, the highest consistent occurrence of *Tsugaepollenites* (hemlock) within the interval at 2010 ft, is interpreted to correspond to intra-P2 cooling event coincident with expansion of Arctic ice sheet at approximately 2.4 to 3.6 Ma.

Correlation with other microfossil zones: The following siliceous microfossil zones have their tops in the late Pliocene *I. pacificum* Zone as documented in Turner *et al.* (1988):

1560 ft	*Denticulopsis seminae fossilis* Zone (late part of the late Pliocene)
2190 ft	*D. seminae fossilis – D. kamtschatica* Zone (early part of the late Pliocene)

Siliceous microfossil zonal markers bioevents (J. Larson in Turner *et al.*, 1988):

1560 ft	top *Rhizosolenia barboi* (defines top of the *D. seminae fossilis* Zone) top *Stephanopyxis horridus*

1760 ft		top *Thalassiosira zabelinae*

2190 ft		top common *Denticulopsis kamtschatica*

Other microfossils: High-latitude, cold-water shelf assemblage with no observed age-diagnostic species, with faunal abundance decreasing downhole. Ostracodes support general Pliocene age for this interval (Elizabeth Browers, written communication to John Larson, op. cit).

Seismic and lithostratigraphy: The latest early to late Pliocene *I. pacificum* Zone corresponds to the following seismic and lithostratigraphic units of Sherwood *et al.* (2006) and Turner *et al.* (1988):

- Middle and upper part of the Milky River Formation, which occurs from 1590-2510 ft (as defined in the present study)
- Lower part of Seismic Sequence I which occurs from 0-2510 ft
- Middle part of lithostratigraphic Unit A which occurs from 1000-2510 ft

2370-2510(2) ft: *Spiniferites ovatus* Zone P1 (early Pliocene) [2]

(2) Depth adjusted from the cuttings sample at 2550-2640 ft to Seismic Horizon A, the top of Seismic Sequence II, and the top of the Bear Lake Formation at 2510 ft.

Diagnostic palynomorph bioevents:

2370 ft		*Spiniferites ovatus* (D) [P1]

Absolute age assignment:

2370 ft:	3.5 Ma for the top common / abundant occurrence of *Tsugaepollenites* (hemlock), coincident with early development of Arctic ice sheet.

2370 ft:	Approximate 3.5 Ma for the top of the *Spiniferites ovatus* Zone.

Discussion: The early Pliocene top *Spiniferites ovatus* Zone is defined primarily on the highest occurrence of the dinocyst *S. ovatus,* which occurs in low numbers in both samples from this interval. The sample at 2370 ft marks the highest common occurrence of *Tsugaepollenites* (hemlock). This is correlated with early development of Arctic ice sheet between 6.5 to 7.5 Ma and slightly warmer climate in the North Aleutian shelf region than that of the overlying interval. Protoperidiniacean species comprise more than 67% to 73% of marine dinocyst, reflecting periods of high productivity, often associated with diatom abundance, as discussed in the section of the report on the Pleistocene *N. lemniscata* Zone.

Paleobathymetry: The following paleobathymetric depths were given for this interval (2370-2510 ft) in Sherwood *et al.* (2006) and Turner *et al.* (1988), with additional interpretations being given below in the section on 'paleoenvironment'.

- 2370-2510 ft: inner to middle neritic

Paleoenvironment: Marine dinocysts occur in both samples from this interval, comprising approximately 3% of palynomorphs indicating marine deposition, with protoperidiniacean species comprising from 67% to73% of marine dinocyst, reflecting periods of high productivity, often associated with diatom abundance. The miospore assemblages are similar to those in the overlying interval but the highest common to abundant occurrence of *Tsugaepollenites* (hemlock) is interpreted to correspond to early development of Arctic ice sheet at approximately 3.5 Ma.

Correlation with other microfossil zones: The following siliceous microfossil zones have their tops in the early Pliocene *S. ovatus* Zone as documented in Turner *et al.* (1988):

2370 ft	*D. kamtschatica* Zone Subzone 'b' (early Pliocene)

Siliceous microfossil zonal markers bioevents (J. Larson in Turner *et al.*, 1988):

2370 ft	top *Cosmiodiscus insignis*
	top *Coscinodiscus temperi*

Other microfossils: Extremely rare high-latitude, cold-water shelf assemblage of foraminifera occur with no observed age-diagnostic species. Ostracodes are absent from this interval of the well.

Seismic and lithostratigraphy: The early Pliocene *S. ovatus* Zone corresponds to the following seismic and lithostratigraphic units of Sherwood *et al.* (2006) and Turner *et al.* (1988):

- Lower part of the Milky River Formation which occurs from 1590-2510 ft (as defined in the present study)
- Lower part of Seismic Sequence I which occurs from 0-2510 ft

- Lower part of lithostratigraphic Unit A which occurs from 1000-2510 ft

The base of the Zone corresponds to Seismic Event A

2510$^{(2)}$-4080 ft: *Hystrichosphaeropsis variabilis* Zone M3 (late Miocene) [3]

(2) Depth adjusted from the cuttings sample at 2550-2640 ft to Seismic Horizon A, the top of Seismic Sequence II, and the top of the Bear Lake Formation at 2510 ft.

2510$^{(2)}$-3090 ft: *H. variabilis* Zone Subzone M3b (late Miocene) [2]

Diagnostic palynomorph bioevents:

2550 ft	*Spiniferites aquilonius (*D) [M3b]
2730 ft	*Hystrichosphaeropsis variabile* (D) [M3b]
	Leujeunecysta globosa (D) [M3b]

Absolute age assignment:

2510 ft:	Approximate 3.4 to 5.3 Ma hiatus corresponding to seismic horizon A as the lowermost Pliocene is probably absent, assuming constant sedimentation rate in the early Pliocene *Spiniferites ovatus* Zone.
2550 ft:	5.33 Ma for the top of Subzone M3b of the *Hystrichosphaeropsis variabilis* Zone, which correlates with the top Miocene.
2730 ft:	6.5 to 7.5 Ma (average = 6.0 Ma) corresponding to North Pacific climatic optimum CO3 of Barron & Baldauf (1990).

Discussion: Three dinocyst species indicate assignment to the late Miocene *H. variabilis* Zone, indicating a fairly confident assignment [level 2]. The miospore assemblages include an influx of thermophilic angiosperm pollen from 2730-2820 ft, which is interpreted to correspond to North Pacific climatic optimum CO3 of Barron & Baldauf (1990) dated at 6.5Ma to 7.5 Ma.

Paleobathymetry: The following paleobathymetric depths were given for this interval (2510-3090 ft) in Sherwood *et al.* (2006) and Turner *et al.* (1988), with additional interpretations being given below in the section on 'paleoenvironment'.

- 2510-3090 ft: inner to middle neritic

Paleoenvironment: Marine dinocysts occur in all samples from this interval, comprising between 3% and 4% of palynomorphs indicating marine deposition. Protoperidiniacean species comprise up to than 70% of the marine dinocysts, reflecting periods of high productivity, often associated with diatom abundance, as discussed in the section of the report on the Pleistocene *N. lemniscata* Zone.

Correlation with other microfossil zones: The following siliceous microfossil zones have their tops in the late Miocene *H. variabilis* Zone as documented in Turner *et al.* (1988):

2670 ft	*Denticulopsis kamtschatica* Zone Subzone 'a' (late Miocene)
2970 ft:	*Denticulopsis hustedtii* Zone Subzone 'b' (late part of the late Miocene)

Siliceous microfossil zonal markers bioevents (J. Larson in Turner *et al.*, 1988):

2670 ft base *Thalassiosira oestrupii*

2870 ft (estimated depth): top *Triceratium condecorum*

2970 ft base *Denticulopsis kamtschatica*

Other microfossils: Extremely rare high-latitude, cold-water shelf assemblages of foraminifera occur that are possibly caved from the overlying interval, with no observed age-diagnostic species. Ostracodes occur in isolated intervals and support a general Miocene age for this interval.

Seismic and lithostratigraphy: Subzone M3b of the late Miocene *H. variabilis* Zone corresponds to the following seismic and lithostratigraphic units of Sherwood *et al.* (2006) and Turner *et al.* (1988):

- Upper part of the Bear Lake Formation which occurs from 2510-5675 ft (as defined in the present study)
- Upper part of Seismic Sequence II which occurs from 2510-5675 ft
- Upper part of lithostratigraphic Unit B1 which occurs from 2510-4110 ft

The top of the Subzone corresponds to Seismic Event A.

3090-4080 ft: *Hystrichosphaeropsis variabilis* Subzone M3a (late Miocene) [1]

Diagnostic palynomorph bioevents:

3090 ft	*Hystrichosphaeropsis arctica* (D) [M3a]
	Operculodinium wallii (D) [M3a]
	Operculodinium alsium (D) [M3a]
3180 ft	*Spiniferites frigidus* (D) [M3a]
	Spiniferites hexatypicus (D) [M3a]
	Spiniferites reductus (D) [M3a]
3180 ft	*Tectatodinium minutum* (D) [M3a]
3270 ft	*Spiniferites ellipsoideus* (D) [M3a]
	Spiniferites nortonensis (D) [M3a]
3900 ft	*Tuberculodinium rossignolae* (D) [M3a]

Absolute age assignment:

3090 ft: Approximate 9 Ma for the top of Subzone M3a of the *Hystrichosphaeropsis variabilis* Zone.

3990ft: 10.5 to 11.5 Ma (average = 11.0 Ma) corresponding to North Pacific climatic optimum CO2 of Barron & Baldauf (1990).

3990ft: 11 Ma corresponding to a minor temperature increase documented by Wolfe (1994).

Discussion: The late Miocene *Hystrichosphaeropsis variabilis* Subzone M3a is indicated by the highest occurrence of 10 dinocyst species in this interval, indicating a high level of confidence (level 1) for the zonal assignment. The miospore assemblages include an influx of thermophilic angiosperm pollen at 3990 ft, which is interpreted to correspond to North Pacific climatic optimum CO2 of Barron & Baldauf (1990) dated at 10.5 to 11.5Ma and a minor temperature increase documented in Beringia by Wolfe (1994) at 11 Ma. Protoperidiniacean species generally comprise up to 75% of marine dinocyst, reflecting periods of high productivity, often associated with diatom abundance, as discussed in the section of the report on the Pleistocene *N. lemniscata* Zone.

Paleobathymetry: The following paleobathymetric depths were given for this interval (3090-4080 ft) in Sherwood *et al.* (2006) and Turner *et al.* (1988), with additional interpretations being given in the discussion below on 'Paleoenvironment'.

- 3090-3130 ft: inner to middle neritic
- 3130-3310 ft: transitional
- 3310-3900 ft: transitional to inner neritic
- 3900-4080 ft: inner neritic

This has been amended as follows based on observation of marine dinocysts during the present study:

- 3090-3130 ft: inner to middle neritic
- 3130-4080: inner neritic

Paleoenvironment: The presence of marine dinocysts in all samples from this interval indicates marine depositional environments. However, the relative abundance of dinocysts is lower and a larger number of spores occur relative to the lighter and more easily transported angiosperm pollen as compared to the overlying interval. This may be have been caused by the transgressive trend noted by Finzel e*t al.* (2009) in coeval strata of the Bear Lake Formation exposed on the central Alaska Peninsula from (from older to younger) [1] nonmarine fluvial channels adjacent to overbank environments and swamps or marshes (corresponding to middle Miocene Subzone M2a), to [2] supratidal freshwater marshes and brackish tidal flats(corresponding to middle Miocene Subzone M2b), to [3] brackish-marine intertidal channels and tidal flats (corresponding to late Miocene Subzone M3a), to marine subtidal channels and sand flats (corresponding to late Miocene Subzone M3b.) This is illustrated in Stratigraphic Chart 2 in Appendix A of the report. Protoperidiniacean species comprise up to 75% of marine dinocysts, reflecting periods of high productivity, often associated with diatom abundance, as discussed in the section of the report on the Pleistocene *N. lemniscata* Zone.

Correlation with other microfossil zones: The following siliceous microfossil zones have their tops in the late Miocene *H. variabilis* Zone Subzone M3a, as documented in Turner *et al.* (1988):

3500 ft *Denticulopsis hustedtii* Zone Subzone 'a' (early part of the late Miocene)

3960 ft 'Indeterminate zone' (early to middle Miocene)

Siliceous microfossil zonal markers bioevents (J. Larson in Turner *et al.*, 1988):

3500 ft base *Coscinodiscus insignis*

top *Stephanopyxis schenckii*

Other microfossils: Above 3900 ft, foraminifera comprise extremely rare high-latitude, cold-water shelf assemblage possibly caved from the overlying interval, with no observed age-diagnostic species. Foraminifera occur in moderate abundance below 3900 ft, with *Porosorotalia* cf. *P. clarki* at 4050 ft supporting a Miocene age. Ostracodes occur in isolated intervals and support a general Miocene age for this interval.

Seismic and lithostratigraphy: Subzone M3a of the late Miocene *H. variabilis* Zone corresponds to the following seismic and lithostratigraphic units of Sherwood *et al.* (2006) and Turner *et al.* (1988):

- Middle part of the Bear Lake Formation which occurs from 2510-5675 ft (as defined in the present study)
- Middle part of Seismic Sequence II which occurs from 2510-5675 ft
- Lower part of lithostratigraphic Unit B1 which occurs from 2510-4110 ft

4080-5675(3) ft: *Operculodinium echigoense* Zone M2 (middle Miocene) [2]

(3) Depth adjusted from the cuttings sample at 5700-5790 ft to Seismic Horizon B, the top of Seismic Sequence III and the top of the Stepovak Formation at 5675 ft.

Discussion: The *O. echigoense* Zone is subdivided into its two subzones in the COST well.

4080-4890 ft: *Operculodinium echigoense* Zone, Subzone M2b (middle Miocene) [2]

Diagnostic palynomorph bioevents:

4080 ft *Impagidinium cornutum* (D) [M3a]

Impagidinium manumii (D) [M3a]

Operculodinium echigoense (D) [M2b]

Absolute age assignment:

4080 ft: 11.61 Ma for the top of Subzone M2b of the *Operculodinium echigoense* Zone, which correlates with the top middle Miocene.

Discussion: The middle Miocene *Operculodinium echigoense* Zone Subzone M2b is defined primarily on the highest occurrence of the dinocyst *O. echigoense,* in the northern North Pacific - Bering Sea region and this species is persistent in this interval, indicating fairly confident (level 2) assignment to the subzone. Protoperidiniacean species comprise up to 50% of marine dinocyst, reflecting periods of high productivity, often associated with diatom abundance, as discussed in the section of the report on the Pleistocene *N. lemniscata* Zone.

Paleobathymetry: The following paleobathymetric depths were given for this interval (4080-4890 ft) in Sherwood *et al.* (2006) and Turner *et al.* (1988), with additional interpretations being given in the discussion that following on 'Paleoenvironment'.

- 4080-4110 ft: middle neritic
- 4110-4870 ft: inner to middle neritic
- 4870-4890 ft: inner neritic

Paleoenvironment: Marine dinocysts are rare but persistent in this interval indicating marine depositional environments, but they are strongly diluted by spores and pollen transported to the depositional site. The significance of this is outlined in the previous discussion in this report on the *H. variabilis* Zone Subzone M3a.

Correlation with other microfossil zones: No siliceous microfossil zonal tops were recognized in this interval.

Siliceous microfossil zonal markers bioevents (J. Larson in Turner *et al.*, 1988):

3960 ft	base *Thalassiosira nidulus*

Other microfossils: Foraminifera occur in moderate abundance below 3900 ft, with *Porosorotalia* cf. *P. clarki* at 4050 ft supporting a Miocene age. Ostracodes occur in isolated intervals and support a general Miocene age for this interval.

Seismic and lithostratigraphy: Subzone M2b of the middle Miocene *O. echigoense* Zone corresponds to the following seismic and lithostratigraphic units of Sherwood *et al.* (2006) and Turner *et al.* (1988):

- Middle part of the Bear Lake Formation which occurs from 2510-5675 ft (as defined in the present study)
- Middle part of Seismic Sequence II which occurs from 2510-5675 ft
- Lithostratigraphic Unit B2 which occurs from 4110-4870 ft

4890-5675⁽³⁾ ft: *Operculodinium echigoense* Zone, Subzone M2a (middle Miocene) [2]

(3) Depth adjusted from the cuttings sample at 5700-5790 ft to Seismic Horizon B, the top of Seismic Sequence III, and the top of the Stepovak Formation at 5675 ft.

Diagnostic palynomorph bioevents:

4890 ft	*Diphyes latiusculum* (D) [M2a]
	Gelatia inflata (D) [O4] single specimen interpreted to be reworked

Absolute age assignment:

4890 ft: 14 Ma corresponding to an abrupt temperature decline documented by Wolfe (1994).

4890ft: Approximate 14 Ma for the top of Subzone M2a of the *Operculodinium echigoense* Zone, within the middle Miocene.

5160-5340 ft: 15 to 16 Ma (average 5200 ft and 15.5 Ma) corresponding to North Pacific climatic optimum CO1 of Barron & Baldauf (1990).

Discussion: The middle Miocene *Operculodinium echigoense* Zone Subzone M2a is defined primarily on the highest occurrence of the dinocyst *D. latiusculum,* in the northern North Pacific - Bering Sea region and this species is persistent in this interval, indicating fairly confident (level 2) assignment to the subzone. A single specimen of *Gelatia inflata* is interpreted to be reworked at 4890 ft, but if in place it would indicate the presence of upper Oligocene strata in the well. The miospore assemblages include an influx of thermophilic angiosperm pollen below between 5160-5340 ft, which is interpreted to correspond to North Pacific climatic optimum CO1 of Barron & Baldauf (1990) dated at 15.5(?) Ma. A marked decrease in thermophilic pollen above 4890 ft is also correlated with the 14 Ma abrupt temperature decline documented by Wolfe (1994) and the 14 Ma (?) global cooling phase documented by Zachos *et al.* (2001).

Paleobathymetry: The following paleobathymetric depths were given for this interval (4890-5675 ft) in Sherwood *et al.* (2006) and Turner *et al.* (1988), with additional interpretations being given in the discussion that following on 'Paleoenvironment'.

- 4890-5460 ft: inner neritic
- 5460-5675 ft: inner to middle neritic

Paleoenvironment: The presence of rare marine dinocysts in most samples from this interval indicates marine depositional environments, with the marine assemblages being diluted by abundant transported palynomorphs. Interpreted changes in depositional environments during the Miocene are outlined in this report in the discussion on the *Hystrichosphaeropsis variabilis* Zone, Subzone M3a. The relative abundance of protoperidiniacean species shows a marked change through this interval, from 10% in the lowest sample at 5610 ft to 35% in the highest sample at 4890 ft, and then increasing further in the overlying Subzone M2b to up to 50%. As discussed earlier the high relative abundance of protoperidiniacean species reflects periods of high productivity and is often associated with diatom abundance. Gonyaulacacean dinoflagellates are primarily photosynthetic and are not associated with diatom occurrences or blooms, unlike protoperidiniacean dinoflagellates which are primarily carnivorous and have been observed feeding on animal remains and ingesting entire diatoms. Bujak (1984) therefore related the shift from gonyaulacacean-dominance to protoperidiniacean dominance to a significant oceanographic shift of potential significance to petroleum source rocks in the region:

> "Upper Miocene to Recent dinocyst assemblages are dominated by protoperidiniacean cysts which became abundant in the Bering Sea and northern North Pacific at the same time as diatoms because of major changes in oceanic circulation and sedimentation in the Late Miocene."

The shift from gonyaulacacean to protoperidiniacean dominance may therefore have occurred in the middle Miocene, during deposition of Subzone M2a and this might be explained by the parallel uphole increase in siliceous microfossil prey, including diatoms in the same middle Miocene section of the well.

Correlation with other microfossil zones: No other microfossil zones were recognized in this interval.

Siliceous microfossil zonal markers bioevents (J. Larson in Turner *et al.*, 1988): None

Other microfossils: Foraminifera occur in moderate abundance but with no age-diagnostic species. Ostracodes occur in isolated intervals and support a general Miocene age for this interval.

Seismic and lithostratigraphy: Subzone M2a of the middle Miocene *O. echigoense* Zone corresponds to the following seismic and lithostratigraphic units of Sherwood *et al.* (2006) and Turner *et al.* (1988):

- Lower part of the Bear Lake Formation which occurs from 2510-5675 ft (as defined in the present study)
- Lower part of Seismic Sequence II which occurs from 2510-5675 ft
- Lithostratigraphic Unit B3 which occurs from 4870-5675 ft

5675(3)-9210 ft: *Spiniferites* cf. *membranaceus* Zone O2 (early Oligocene) [3]

(3) Depth adjusted from the cuttings sample at 5700-5790 ft to Seismic Horizon B, the top of Seismic Sequence III, and the top of the Stepovak Formation at 5675 ft.

Diagnostic palynomorph bioevents:

5700 ft	*Gelatia inflata* (D) [O3] highest interpreted *in situ* occurrences
	Spiniferites cf. *membranaceus sensu* Bujak 1984 (D) [O2]
6330 ft	*Hystrichostrogylon membraniphorum* (D) [O2]

Absolute age assignment:

5675 ft: The youngest established age for the base of the Miocene section in the North Aleutian Shelf COST No. 1 well is 15 Ma and the oldest age is 16 Ma. The youngest age of Oligocene strata immediately below the hiatus at 5675 ft is 28.4 Ma (= top of the lower Oligocene). Its oldest age is less certain because the age of the base of the *S.* cf. *membranaceus* Zone has not been firmly established. Preliminary estimates indicate its base at 32.9, based on a possible duration of 1 Ma for the underlying *T. boreale* Zone. The restricted dinocyst assemblages in the

T. boreale Zone indicate that the *T. boreale* Zone may equate with a sharp cooling phase in the earliest Oligocene (Figure 5), so that its 1 Ma duration is calculated from its base at the Eocene-Oligocene boundary at 33.9 Ma) This gives a minimum duration for the hiatus between the Oligocene and Miocene sections of the well of 12.4 Ma (28.4 minus 16 Ma) and a possible maximum duration of 17.9 Ma (32.9 minus 15 Ma). The hiatus between the Miocene and Oligocene and Miocene section in the COST well corresponds to Seismic Event B and the hiatus between Bear Lake and Stepovak formations (see discussion of the *S.* cf. *membranaceus* Zone for details).

Discussion: The early Oligocene assignment of the *S.* cf. *membranaceus* Zone is based on the presence of *S.* cf. *membranaceus* at 5700 ft and *H. membraniphorum* at 6330 ft, with *G. inflata* also indicating a general Oligocene age for the sample at 5700 ft. The confidence level for the zonal pick is fairly low (= 3) because these and other marine dinocysts are rare throughout the interval, reflecting restricted marine or nonmarine deposition, with no nonmarine palynomorphs presently being known that characterize the zone. Although *G. inflata* occurs in this interval in the COST well, its stratigraphic range encompasses both the *G. inflata* and *S.* cf *membranaceus* zones in the North Pacific and Bering Sea region, so that its occurrence does not conflict with assignment to the latter zone.

Detterman *et al.* (1996) defined two members of the Stepovak Formation: an overlying sandstone member, which was deposited on a shallow water shelf, and an underlying siltstone member, which was deposited as a succession of deep-water turbidites. The predominantly shallow water marine to nonmarine deposition of the Stepovak Formation in the COST well would be consistent with an early Oligocene age for the section and correlation with the onshore Sandstone member. However, assignment to the early Oligocene *S.* cf. *membranaceus* Zone of the present study is less confident than picks for the overlying Miocene-Pleistocene sections and the possibility that it may be in part late Oligocene cannot be discounted. In this case, part of the Stepovak section in the COST well would be equivalent to the Siltstone member of the Stepovak Formation. It is therefore possible that palynological zones O3 and O2 may be correlative with the sandstone member onshore, whilst zones O1 and E4 may be correlative with the siltstone member.

It may also be relevant that the Stepovak Formation is 2,028 ft thick in the type area onshore (Detterman et al, 1996, p. 47) but 4,705 ft or more at the COST well, indicating a much thicker and possibly more complete section in the COST well. This interpretation would suggest that the early Oligocene picks for the well may be too high, but in the absence of other strong biostratigraphic evidence, a low confidence (3) is assigned to the early Oligocene age interpretation of the *S.* cf. *membranaceus* Zone of this report.

Assignment to the *S.* cf. *membranaceus* Zone, if correct, indicates a relatively long hiatus between the Stepovak and Bear Lake formations, corresponding to Seismic Event B at 5675 ft, as discussed above.

Paleobathymetry: The following paleobathymetric depths were given for this interval (5675-7900 ft) in Sherwood *et al.* (2006) and Turner *et al.* (1988), with additional interpretations being given in the discussion that follow on 'Paleoenvironment'.

- 5675-5860 ft: inner to middle neritic
- 5860-6120 ft: inner neritic
- 6120-6470 ft: transitional
- 6470-7900 ft: nonmarine to transitional
- 7900-8190 ft: transitional to inner neritic
- 8190-9210 ft: nonmarine to inner neritic

This has been amended as follows based on observation of marine dinocysts during the present study:

- 5675-5860 ft: inner to middle neritic
- 5860-6120 ft: inner neritic
- 6120-6330 ft: transitional
- 6330-8190 ft: transitional to inner neritic
- 8190-9210 ft: nonmarine to inner neritic

Paleoenvironment: Marine dinocysts occur sporadically and in low numbers throughout the interval, indicating environments that fluctuated from non marine to inner neritic. Non-thermophilic angiosperm pollen indicating a relatively cool climate characteristic of the Oligocene cold phase, as discussed above.

Correlation with other microfossil zones: No other microfossil zones were recognized in this interval.

Siliceous microfossil zonal markers bioevents (J. Larson in Turner *et al.*, 1988): None

Other microfossils: Foraminifera occur in moderate abundance down to 6120 ft and include *Rotalia beccarii* (equivalent to *Ammonia japonica* according to J. Larson in Turner *et al.*, 1988), which indicates an Oligocene to earliest Miocene age based on its occurrence in other Bering Sea COST wells. Foraminifera are extremely rare from 6120-7900 ft and become more common below 7900 ft but with no marker species being observed, possibly due to the poor preservation of specimens. *In situ* ostracodes are extremely rare in this interval and no age-diagnostic species were observed.

Seismic and lithostratigraphy: The early Oligocene *S.* cf. *membranaceus* Zone corresponds to the following seismic and lithostratigraphic units of Sherwood *et al.* (2006) and Turner *et al.* (1988):

- Middle and upper part of the Stepovak Formation which occurs from 5675-10,380 ft (as defined in the present study)
- Seismic Sequence III which occurs from 5675-7900 ft
- Upper part of seismic Sequence IV which occurs from 7900-10,380 ft
- Lithostratigraphic Units C1 and C2 which occur from 5675-6470 ft and 6470-7900 ft respectively
- Middle and upper part of lithostratigraphic Unit D1 which occurs from 7900-9555 ft

9210-9555(5) ft: *Trinovantedinium boreale* Zone O1 (early Oligocene) [1]

(5) Depth adjusted from the cuttings sample at 9570-9650ft to the top of lithological sequence D2 at 9555 ft.

Diagnostic palynomorph bioevents:

9210 ft	*Trinovantedinium boreale* (D) [O1]
	Phthanoperidinium bennetii (D) [O1]
	Phthanoperidinium comatum (D) [O1]

Absolute age assignment: There is little data available at present to indicate the absolute age of the top of the *T. boreale* Zone, although the absence of thermophilic pollen indicates that the entire zone occurs within the Oligocene cold phase and it is possible that the zone corresponds entirely to the marked temperature decrease that followed the 33.5 Ma TEE before temperature recovered slightly in the subsequent part of the Oligocene cold phase.

Discussion: This zone was originally defined by Bujak (1984) in North Pacific – Bering Sea DSDP Leg 19 sites where it is characterized by low-diversity dinocyst assemblages dominated by *T. boreale.* The same situation occurs in the COST well with *T. boreale* as the dominant dinocyst species. *T. boreale* also ranges down into the underlying late Eocene *Areosphaeridium diktyoplokus* Zone, where it is less common and co-occurs with several late Eocene dinocyst species, discussed below.

The zonal assignment is supported by the presence of *Phthanoperidinium bennetii* and *Phthanoperidinium comatum*. Data from the Bering Sea and Japanese areas indicate that neither of these species ranges above the earliest Oligocene in the northern North Pacific, but that *P. comatum* ranges to the top of the early Oligocene in the Japanese area due to warmer SST (K. Matsuoka, pers. comm. to J. Bujak), as shown in Figure 10. Both of these species are found in fully marine dinocyst assemblages, but probably have a tolerance of hyposalinity as discussed below.

Paleobathymetry: The following paleobathymetric depths were given for this interval (9210-9555 ft) in Sherwood *et al.* (2006) and Turner *et al.* (1988), with additional interpretations being given in the discussion that following on ‘Paleoenvironment’.

- 9210-9555 ft: nonmarine to inner neritic

Paleoenvironment: The present study broadly agrees with the environment shown on the bathymetric curve in Sherwood *et al.* (2006), although marine dinocysts are slightly more abundant than in the overlying interval, indicating environments that were transitional to nearshore marine without an evidence of entirely nonmarine deposition.

Correlation with other microfossil zones: No other microfossil zones were assigned to this interval.

Siliceous microfossil zonal markers bioevents (J. Larson in Turner *et al.*, 1988): None

Other microfossils: Foraminifera are common in this interval but with no marker species being observed, possibly due to the poor preservation of specimens.

Seismic and lithostratigraphy: The early Oligocene *T. boreale* Zone corresponds to the following seismic and lithostratigraphic units of Sherwood *et al.* (2006) and Turner *et al.* (1988):

- Middle part of the Stepovak Formation which occurs from 5675-10,380 ft (as defined in the present study)
- Middle part of seismic Sequence IV which occurs from 7900-10,380 ft
- Lower part of lithostratigraphic Unit D1 which occurs from 7900-9555 ft

9555(5)-10,380 ft: *Areosphaeridium diktyoplokus* Zone E4 (late Eocene) [2]

(5) Depth adjusted from the cuttings sample at 9570-9650ft to the top of lithological sequence D2 at 9555 ft.

Diagnostic palynomorph bioevents:

9570 ft	*Areosphaeridium diktyoplokus* (D) [E4]
	Adnatosphaeridium multispinosum (D) [E4]
	Lentinia serrata (D) [E4]
	Phthanoperidinium levimurum(D) [E4]
9750 ft	*Cordosphaeridium gracile* (D) [E4]
	Glaphyrocysta semitecta (D) [E4]
9930 ft	*Cordosphaeridium exilimurum* (D) [E4]
	Cordosphaeridium inodes (D) [E4]

Absolute age assignment: The youngest occurrence of *Areosphaeridium diktyoplokus* is a global dinocyst datum that is well established at 33.5 Ma (see discussions and data for example in Brinkhuis, 1994; Brinkhuis & Visscher, 1995; and the University of Utrecht dinocyst summer course held in Urbino, Italy (web address given on page 35). The bioevent also characterizes the top of the Priabonian type section as originally defined at Priabona in northern Italy; however there have been recommendations, primarily tied into the occurrences of Hantkeninid foraminifera, to redefine the top of the Priabonian, and hence the top of the Eocene, at the deeper paleowater Massignano section in central Italy, that would place the top of the Eocene slightly below the last occurrence of *A, diktyoplokus*. Irrespective of this possible redefinition, the youngest occurrence and hence the top of the *A. diktyoplokus* Zone indicates an absolute age of 33.5 Ma for the COST well at 9555 ft as there is no evidence of a hiatus immediately above this horizon in the well.

Discussion: Although several biomarkers for the late Eocene *Areosphaeridium diktyoplokus* Zone occur in this interval, the level of confidence is downgraded from [1] (highest level of confidence) to [2] because it is possible that the specimens are reworked from the underlying Eocene section of the well, as discussed below.

A late Eocene age assignment was also indicated in BCM 's 1983 report on the COST well, based primarily on the presence of *Areosphaeridium diktyoplokus*. However, other species recorded as being present in the same interval by BCM do not range into the late Eocene, indicating either reworking or incorrect species identifications. If the reworking interpretation is correct, then it is possible that other specimens such as *A. diktyoplokus* are also reworked, suggesting that the interval is lowermost Oligocene and contains common Eocene reworking. The Eocene – Oligocene boundary would then be coincident with Seismic Horizon D at 10,380 ft.

Assessment of BCM's species assignments in this interval is therefore crucial in order to determine the age of this interval and whether the dinocyst biomarkers are reworked or in place.

BCM (1983) recorded a species in the conventional core at 9969.3 ft as the peridiniacean dinocyst species *Deflandrea* cf. *D wetzelli. D. wetzelli* (which has now been reassigned to the genus *Cerodinium)* does not range above the Lutetian and, if it were in place and correctly identified, it would indicate the presence of a hiatus at about 9969.3 ft, with lower Oligocene strata directly overlying a middle Eocene (Lutetian section), and both the Bartonian and Priabonian being absent.

No specimens of either *C. wetzelii* or related species that could be assigned to *C.* cf. *wetzelii* were observed during the present study, and the only peridiniacean dinocyst with similar morphology that occurs in this interval is the species *Trinovantedinium boreale. T. boreale* superficially resembles *C. wetzelli*, but differs in several features including not having pericoels beneath its apical and antapical horns – a feature that is highly characteristic of *C. wetzelii. T. boreale* was described for the first time and a new species erected by Bujak in 1984, the year after BCM's (1983) report on the COST well, and this may explain BCM's incorrect identified the specimens of *T. boreale* as *D*. cf. *wetzelli*.

BCM also recorded dinocysts from this interval that they identified as *Glaphyrocysta exuberans*, which does not range above the Lutetian. No specimens of *G. exuberans* were observed from this interval during the present study, but the distinctive species *Glaphyrocysta semitecta* does occur. *G. semitecta* is a temperature-sensitive species that was erected by Bujak (in Bujak *et al.,* 1980) from the type Bartonian of southern England. It has a diachronous range, reflecting strong SST control, last occurring in the Priabonian in mid to high latitudes such as the North Sea and northern North Pacific - Bering Sea regions, but ranging into the earliest Oligocene in lower latitudes in Tethyan localities including central and northern Italy (Brinkhuis 1994). Its presence in this interval of the COST well is therefore consistent with a late Eocene age assignment and BCM's record of G. *exuberans* is interpreted to be a misidentification of *G. semitecta*.

Another species considered to be incorrectly indentified in this interval by BCM is *Adnatosphaeridium reticulense* in the conventional core at 9978.1 ft and it is probable that its correct identification is *Adnatosphaeridium multispinosum*, which was observed in the present study and which ranges to the top of the Eocene.

BCM recorded *Apectodinium homomorphum* in the conventional core at 10,328.9 ft. This species forms part of a plexus with related species such as *Apectodinium parvum* intergrading into forms with short horns and spinal ornament. These superficially resemble *T. boreale* and it is possible that BCM's record of *A. homomorphum* represents specimens of *T. boreale*.

BCM also recorded *Deflandrea cf. D. phosphoritica* in this interval, but no specimens attributable to the distinctive species *D. phosphoritica* were observed in the COST well during the present study.

In summary, data from the present study and the species identifications discussed above are consistent with a late Eocene (Priabonian) assignment for the interval from 9555-10,380 ft and this interpretation consistent with paleoenvironmental interpretations based on the palynomorph assemblages in the interval.

Paleobathymetry: The following paleobathymetric depths were given for this interval (9555-10,380 ft) in Sherwood *et al.* (2006) and Turner *et al.* (1988), with additional interpretations being given in the discussion that following on 'Paleoenvironment'.

- 9555-10,230 ft: inner to middle neritic
- 10,230-10,380 ft: transitional to inner neritic

This has been amended as follows based on observation of marine dinocysts during the present study:

- 9555-10,380 ft: inner to middle neritic

Paleoenvironment: The palynological succession in this interval shows evidence of upward shallowing, with fully marine dinocysts becoming less common upwards and brackish-tolerant species of *Phthanoperidinium* and the fresh to brackish water alga *Paralecaniella indentata* becoming relatively more common. This is consistent with strong evidence for a global glacioeustatic sea-level fall associated with the Terminal Eocene Event (TEE). The TEE is often characterized by a hiatus or a shift towards less marine conditions around basin margins. The TEE began with increased development of the Antarctic Circumpolar Current (ACC) due to plate tectonic separation of the Antarctic landmass from South America and Australasia. Increased ACC then triggered the onset of vigorous, oxygen-rich deep-water circulation, which then sequestered large amounts of CO_2 at the Eocene/Oligocene transition, with atmospheric levels falling below 1000 ppm. The reduced pCO_2 resulted in major Antarctic glaciation and glacioeustatic sea-level fall. At the same time, the more vigorous deep-water circulation caused bottom-water scouring and a corresponding seismic event extending, for example, into the North Atlantic. It is therefore possible that the regression indicated by palynology in the interval from 10,380 ft to 9555 ft was related to the TEE, although local tectonic factors may have also contributed.

Correlation with other microfossil zones: No other microfossil zones were recognized in this interval.

Siliceous microfossil zonal markers bioevents (J. Larson in Turner *et al.*, 1988): None

Other microfossils: Foraminifera are common in this interval but with no marker species being observed, possibly due to the poor preservation of specimens. Ostracodes are very rare and probably represent caved specimens. Rare echinoid fragments and pyritised diatoms occur but are not age-diagnostic.

Seismic and lithostratigraphy: The late Eocene *A. diktyoplokus* Zone corresponds to the following seismic and lithostratigraphic units of Sherwood *et al.* (2006) and Turner *et al.* (1988):

- Lower part of the Stepovak Formation which occurs from 5675-10,380 ft (as defined in the present study)
- Lower part of seismic Sequence IV which occurs from 7900-10,380 ft
- Lithostratigraphic Unit D2 which occurs from 9555-10,380 ft

The base of the Zone corresponds to Seismic Event D at 10,380 ft.

10,380-15,420 ft: *Diphyes colligerum* Zone E2 (middle Eocene) [2]

Discussion: The *Diphyes colligerum* Zone E2 Zone is separated in the COST well into late Lutetian Subzone 2b from 10,380-11,820 ft and the early Lutetian Subzone 2a from 11,820-15,420 ft.

10,380-11,820 ft: *Diphyes colligerum* Zone E2 Subzone 2b (middle Eocene) [2]

Diagnostic palynomorph bioevents:

10,380 ft	*Pesavis tagluensis* (F) [E3]
	Striadiporites sanctaebarbarae (F) [E2b]
10,470 ft	single questionable *Pesavis* sp. A, Ioannides & McIntyre 1980 (F) [E2a]

Absolute age assignment: Assignment to the middle Eocene *Diphyes colligerum* Zone E2 Subzone 2b is based on fungal spores and the pollen *Pistillipollenites mcgregorii* with reference to their ranges established by unpublished and confidential studies on Arctic, North Pacific and Norwegian-Greenland sections. These indicate their relatively synchronous ranges across the entire area with little or no diachronism due to temperature gradients within the late part of the Lutetian. This interpretation indicates that the Bartonian is absent from the COST well, indicating the presence of a hiatus with a minimum duration between the Priabonian that has a base established at 37.2 Ma and the top of the Lutetian at 40.4 Ma. This minimum duration for the hiatus of 3.2 Ma corresponds to Seismic Event D 10,380 ft between seismic sequences III and IV, and the break between the Stepovak and Tolstoi formations.

No major glacioeustatic sea-level fall is known during the late Lutetian and Bartonian and it is probable that the hiatus reelects local tectonic-volcanic events rather than global glacioeustacy. This is supported by the following information summarized by Kirk Sherwood (personal communication to J. Bujak, November 2009):

> "According to Detterman et al (1996, p. 42), the Tolstoi Formation ranges from Late Paleocene (~59 Ma?) to Mid-Eocene in age. Offshore, the basement horsts in the North Aleutian basin began to rise at this time, and the Tolstoi is the principal fill in the intervening grabens. Onshore, the Tolstoi is overlain unconformably (in both cases) by either the 30-40 Ma Meshik volcanics or the Oligocene Stepovak Formation (Detterman et al, 1996, p. 40-41).
>
> At about 50 Ma, the reorganized interactions with the Kula and Pacific plates produced a new mid-ocean Aleutian volcanic arc (previously located along the Bering shelf margin) and initiated the strike-slip faulting through the Bering shelf that controlled the subsidence and block faulting in the North Aleutian, St. George, and Navarin basins (Worrall, 1991, fig. 22). The oldest rocks found in the modern Aleutian arc are about 46-55 Ma (Jicha *et al.,* 2006; Scholl *et al.,* 1987) and this is used to establish the age of origin of the arc in its present location. However, based upon onshore age data for the Tolstoi Formation (Detterman et al, 1996, p. 42), the sediment fill in the North Aleutian basin can be inferred to be a little older, extending back into the late Paleocene (~59 Ma).
>
> A major outpouring of volcanic rocks and related intrusives occurred across the Alaska Peninsula from 22-48 Ma, with most dates falling in the range from 30-40 Ma. This event is referred to as the "Meshik arc" (Wilson 1985) and the volcanics are called the Meshik Formation. One large Meshik volcanic center was sited in the eastern part of the North Aleutian basin and divides the basin into two subbasins. Sherwood *et al.* (2006, figs. 18, 19). The volcanic and tectonic activity associated with the Meshik arc may well be the driver for the 37.2-40.4 Ma (Late Eocene) uplift and erosion event (seismic horizon D) at 10,380 ft md in the COST well"

Discussion: If the single questionable specimen of *Pesavis* sp. A, Ioannides & McIntyre 1980 at 10,470 ft is in place and correctly identified, it would indicate penetration of early Lutetian Subzone 2a at 10,470 ft. However, the preferred interpretation is that it is reworked based on its corroded preservation which contrasts with the good preservation of the *in situ* assemblage.

Paleobathymetry: The following paleobathymetric depths were given for this interval (10,380-11,820 ft) in Sherwood *et al.* (2006) and Turner *et al.* (1988), with additional interpretations being given in the discussion that following on 'Paleoenvironment'.

- 10,380-10,590 ft: transitional to inner neritic
- 10,590-10,830 ft: nonmarine to transitional
- 10,830 -11,820 ft: nonmarine

Paleoenvironment: J. Larson (personal communication to J. Bujak, November 2009) reviewed evidence for marine deposition in the Tolstoi Formation:

> "Proceeding downward in the section, the last vestiges of marine environment (transitional marine) down to 10,830 feet on the paleoenvironmental curve are based on an occurrence of *Ostrea* (oysters) in the conventional core at 10,326.2-10,333.3 and on sporadic very rare foram occurrences (*Cribronion* sp?, *Textularia*?? (fragment), *Elphidium*? (fragment) and *Elphidiella* sp.) in the ditch samples. *Elphidium* sp. was the last unfragmented foram observed, at 10,590'. An *Elphidium*? fragment occurs at 10,710'.
>
> Below this horizon, foraminiferal evidence becomes exceedingly rare and ultimately disappears altogether. Caving or reworking of foram material seems likely. At 11,030-11,040' there was a fragmentary internal mold. At 11,700' a very worn fragment occurs that is tentatively assigned to *Cyclammina* and at 11,910' a possible *Haplophragmoides* fragment occurs. Sidewall cores in the 12,284' to 12,947' interval yielded fine arenaceous tubules of uncertain affinity (12,284' and 12,375'), and a crushed possible foraminiferal test, plus a possible Rotalid fragment at 12,437'. A sand-cast/mold of a quinqueloculinid or a globobuliminid foraminifera was observed at 12,947' and the deepest potential foraminifera fragment observed (*Elphidiella*?) is in the cuttings sample at 13,500-13,530'. Molluscan fragments were noted at 15,000-15,060', 16,080-140' and 16,470-16,560'."

There is no confident evidence from the present study to indicate the presence of marginal marine or marine strata in this interval. Rare dinocysts observed in the uppermost part of the section are not age-diagnostic and may be caved from the overlying upper Eocene interval.

Correlation with other microfossil zones: No other microfossil zones were recognized in this interval.

Siliceous microfossil zonal markers bioevents (J. Larson in Turner *et al.*, 1988): None

Other microfossils: Foraminifera are rare in this interval and no specimens were observed below 10,760 ft except for probably caved specimens.

Seismic and lithostratigraphy: Subzone 2b of the middle Eocene *D. colligerum* Zone corresponds to the following seismic and lithostratigraphic units of Sherwood *et al.* (2006) and Turner *et al.* (1988):

- Upper part of the Tolstoi Formation penetrated in the COST well which occurs from 10,380-17,155 ft (TD)
- Upper part of seismic Sequence V penetrated in the COST well which occurs from 10,380-17,155 ft (TD)
- Upper part of lithostratigraphic Unit E which occurs from 10,380-15,620 ft

The top of the Zone corresponds to Seismic Event D at 10,380 ft.

11,820-15,420 ft: *Diphyes colligerum* Zone E2 Subzone 2a (middle Eocene) [3]

Diagnostic palynomorph bioevents:

11,820 ft	*Pesavis* sp. A of Ioannides & McIntyre, 1980 (F) [E2a]
12,450 ft	*Ctenosporites wolfei* (F) [E2a]

Discussion: Assignment to the *Diphyes colligerum* Zone Subzone 2a is indicated by the presence of the fungal spores *Pesavis* sp. A of Ioannides & McIntyre (1980) and *Ctenosporites wolfei.* As with the overlying Subzone 2b, in the absence of *in situ* dinocysts and age-diagnostic miospores, assignment to Subzone 2a is based on fungal spores and their ranges established by unpublished and confidential studies on Arctic, North Pacific and Norwegian-Greenland sections.

Paleobathymetry: The following paleobathymetric depths were given for this interval (11,820-15,420 ft) in Sherwood *et al.* (2006) and Turner *et al.* (1988), with additional interpretations being given in the discussion that following on 'Paleoenvironment'.

- 11,820-15,420 ft: nonmarine

Paleoenvironment: There is no evidence from the present study to indicate the presence of marginal marine or marine strata in this interval.

Correlation with other microfossil zones: No other microfossil zones were recognized in this interval.

Siliceous microfossil zonal markers bioevents (J. Larson in Turner *et al.*, 1988): None

Other microfossils: Other microfossils: Extremely rare radiolaria occur within the Eocene section of the well, but no age-diagnostic forms were observed.

Seismic and lithostratigraphy: Subzone 2a of the middle Eocene *D. colligerum* Zone corresponds to the following seismic and lithostratigraphic units of Sherwood *et al.* (2006) and Turner *et al.* (1988):

- Middle part of the Tolstoi Formation penetrated in the COST well which occurs from 10,380-17,155 ft (TD)
- Middle part of seismic Sequence V penetrated in the COST well which occurs from 10,380-17,155 ft (TD)
- Lower (but not the lowest) and middle part of lithostratigraphic Unit E which occurs from 10,380-15,620 ft

15,420-17,155 ft (TD): *Charlesdowniea columna* Zone E1 (early Eocene) [2]

Diagnostic palynomorph bioevents:

15,420 ft	*Charlesdowniea columna* (D) [E1]
15,600 ft	*Areoligera senonensis* (D) [E1]

Absolute age assignment:

15,420 ft: 48.6 Ma based on the youngest occurrence of the dinocyst *Charlesdowniea columna* at the top of the Ypresian.

Discussion: The dinocyst *C. edwardsii* is restricted to the Pacific – Australasian region, but is very similar in morphology to *Charlesdowniea columna* and some authors consider that *C. columna* and *C, edwardsii* are conspecific. *C. columna* has widespread occurrences in the circum North Atlantic region, including northwest Europe where its youngest occurrence is well established at 48.6 Ma almost at to the top of the Ypresian. The range of *C. edwardsii* is less well established, but there is no reliable evidence to indicate its presence in middle Eocene strata in the Northern Hemisphere. The range of *Areoligera senonensis* is less well-resulting in intergradation within the *Areoligera coronata-medusettiformis-senonensis* plexus leading to confused speciation in the literature. Assignment to the early Eocene *C. columna* Zone is therefore based on the occurrence of *C. columna* at 15,420 ft.

Although the lowest part of the well, from 15,610-17,155 ft (TD) is included in the early Eocene *C. columna* Zone, it is possible that it includes Paleocene strata because no palynological bioevents were observed in that section of the well to indicate either an Eocene or a Paleocene age.

Paleobathymetry: The following paleobathymetric depths were given for this interval (15,420-17,155 ft: TD) in Sherwood *et al.* (2006) and Turner *et al.* (1988), with additional interpretations being given in the discussion that following on 'Paleoenvironment'.

- 15,420-17,255 ft (TD): nonmarine

This has been amended as follows based on observation of marine dinocysts during the present study:

- 15,420-15,690 ft: nonmarine to transitional
- 15,690 ft-17,255 ft (TD): nonmarine

Paleoenvironment: *C. columna* and *A. senonensis* both represent species that were probably hyposalinity-tolerant, so that their presence does not necessarily indicate fully marine conditions. Their presence in the mudstone between approximately 15,420 ft and 15,610 ft may therefore reflect marginal marine conditions, possibly associated with tidal mud flats, embayments or brackish water lagoons, or alternatively they may have been transported to a nonmarine location by storm surges.

Correlation with other microfossil zones: No other microfossil zones were recognized in this interval.

Siliceous microfossil zonal markers bioevents (J. Larson in Turner *et al.*, 1988): None

Other microfossils: None

Seismic and lithostratigraphy: The early Eocene C. *columna* Zone corresponds to the following seismic and lithostratigraphic units of Sherwood *et al.* (2006) and Turner *et al.* (1988):

- Lower part of the Tolstoi Formation penetrated in the COST well which occurs from 10,380-17,155 ft (TD)
- Lower part of seismic Sequence V penetrated in the COST well which occurs from 10,380-17,155 ft (TD)
- Lowest part of lithostratigraphic Unit E which occurs from 10,380-15,620 ft, and lithostratigraphic Units F and G which occur from 15,620-16,652 ft and 16,652-17,155 ft (TD) respectively.

7. LITHOSTRATIGRAPHY AND SEISMIC SEQUENCES

7.1 LITHOSTRATIGRAPHIC PICKS

The following lithostratigraphic picks are based on a consensus reached by John Larson and Kirk Sherwood of the Alaskan MMS, Anchorage (pers. comm.) and the present study.

0 ft	**unnamed Quaternary**
1590 ft	**Milky River Formation**
2510 ft	**Bear Lake Formation**
5675 ft	**Stepovak Formation**
10,380 ft	**Tolstoi Formation**
17,155 ft	**Total Depth in Tolstoi Formation**

7.2 SEISMIC SEQUENCE PICKS

The following seismic stratigraphic picks are based on data documented in Sherwood *et al.* (2006).

0 ft Seismic Sequence I

--Seismic Horizon A---

2510 ft Seismic Sequence II

--Seismic Horizon B---

5675 ft Seismic Sequence III

--Seismic Horizon C---

7900 ft Seismic Sequence IV

--Seismic Horizon D---

10,380 ft Seismic Sequence V

8. PALEOEBATHYEMETRIC LISTING

Paleobathymetry: The following paleobathymetric depths were given for this interval in Sherwood *et al.* (2006) and Turner *et al.* (1988), with additional paleoenvironmental interpretations being given in discussion of the individual zones in Section 6 of this report on ‘Biostratigraphic Results’:

- 1390-1560 ft: middle to outer neritic
- 1560-1740 ft: outer neritic
- 1740-2160 ft: middle to outer neritic
- 2160-3000 ft: middle neritic
- 3000-3130 ft: inner to middle neritic
- 3130-3310 ft: transitional
- 3310-3900 ft: transitional to inner neritic
- 3900-4080 ft: inner neritic
- 4080-4110 ft: middle neritic
- 4110-4870 ft: inner to middle neritic
- 4870-5460 ft: inner neritic
- 5460-5860 ft: inner to middle neritic
- 5860-6120 ft: inner neritic
- 6120-6470 ft: transitional
- 6470-7900 ft: nonmarine to transitional
- 7900-8190 ft: transitional to inner neritic
- 8190-9555 ft: nonmarine to inner neritic
- 9555-10,230 ft: inner to middle neritic
- 10,230-10,590 ft: transitional to inner neritic
- 10,590-10,830 ft: nonmarine to transitional
- 10,830-17,155 ft (TD): nonmarine

The paleobathymetric depths listed above from Sherwood *et al.* (2006) and Turner *et al.* (1989) are amended below to include new paleoenvironmental interpretations discussed in the individual zones in the Sections of this report on 'Biostratigraphic Results':

- 1390-1560 ft: middle to outer neritic
- 1560-1740 ft: outer neritic
- 1740-2160 ft: middle to outer neritic
- 2160-3000 ft: middle neritic
- 3000-3130 ft: inner to middle neritic
- 3130-4080: inner neritic
- 4080-4110 ft: middle neritic
- 4110-4870 ft: inner to middle neritic
- 4870-5460 ft: inner neritic
- 5460-5860 ft: inner to middle neritic
- 5860-6120 ft: inner neritic
- 6120-6330 ft: transitional
- 6330-8190 ft: transitional to inner neritic
- 8190-9555 ft: nonmarine to inner neritic
- 9555-10,380 ft: inner to middle neritic
- 10,380-10,590 ft: transitional to inner neritic
- 10,590-10,830 ft: nonmarine to transitional
- 10,830-15,420 ft: nonmarine
- 15,420-15,690 ft: nonmarine to transitional
- 15,690 ft-17,155 ft (TD)

9. VISUAL KEROGEN ANALYSIS OF POSSIBLE AMORPHOUS SAPROPEL IN KEY INTERVALS (TABLE 3)

Turner *et al.* (1988, fig. 93, p. 187) reviewed the North Aleutian Shelf COST No. 1 well kerogen data of Dow (1983, in Robertson Research, 1983), who reported amorphous kerogen with some values exceeding 40% of the total amorphous-exinite-vitrinite-inertinite mix in the interval from 15,620-17,155 ft. Based on Dow's description of relatively high amounts of amorphous kerogen, Sherwood *et al.*, 2006, p. 24-26 informally termed the section from 15,620-17,155 ft as the "amorphous interval".

Amorphous sapropelic kerogen *sensu stricto* is a primary source for liquid hydrocarbons. It is typically formed by algae, and primarily comprises the remains of marine phytoplankton in oil-prone source rocks such as the Kimmeridgian Clay of the North Sea and the Miocene Monterey Formation of California, although it may be occasionally formed in freshwater bodies by non-marine algae in other regions. Its possible presence as reported by Dow (1983) is therefore crucial for assessing the hydrocarbon potential of the COST well as its common occurrence would significantly increase the oil potential of the North Aleutian Basin.

Marine microfossils are absent or extremely rare in the COST well "amorphous interval" and the presence of relatively common amorphous kerogen in the interval is inconsistent with both pyrolysis and elemental data shown in Turner *et al.* (1988, fig. 93). Robertson Research (1983) also noted this discrepancy and speculated that the kerogen documented as amorphous material represents the oxidized relicts of original amorphous kerogen or alternatively that the kerogen was incorrectly identified by Dow (1983).

Flett (in Turner *et al.*, 1988, p. 191) and Dow (1983) also speculated that non-algal material was a possible origin for the "amorphous" kerogen in this interval as a possible way to reconcile the conflicting geochemical data.

Bujak *et al.* (1977a, b, 1978, 1979) undertook visual kerogen analyses using transmitted light microscopy in more than 100 wells from the Canadian east coast Scotian Shelf, Grand Banks and Labrador Shelf. These authors noted the difficulty in sometimes distinguishing between true amorphous sapropelic kerogen and the highly fragmented and finely disseminated remains of plant material, including cuticle generally classified within their grouping of "herbaceous kerogen".

Bujak *et al.* (op. cit.) also noted that finely disseminated herbaceous kerogen could be distinguished from amorphous sapropelic by careful observation under high power transmitted light microscopy. Under high power and with oil-immersion of the microscope objective, the original structure of herbaceous kerogen can be discerned as distinct walls with angular structure surrounding the finely disseminated herbaceous material. This contrasts with the fully amorphous character of sapropelic kerogen which reflects its origin from the semi-liquid contents of algal cells.

Distinguishing the two types of kerogen is also aided by fluorescence microscopy which is discussed by Bujak & Davies (1982a, b) and illustrated in Plate 1 of the present report. This technique can be used to continuously observe the kerogen in the same field of view under both normal transmitted light and reflected fluorescence emission and therefore provides a practical and rapid method to determine kerogen type.

The combination of normal transmitted light and fluorescence microscopy was therefore used in to the present study of the COST well and indicated that no amorphous sapropelic kerogen, or only very small amounts (less than 5%), occur in the “amorphous interval”, which in contrast contains relatively high amounts of finely disseminated herbaceous material. This indicates that the interval is primarily gas prone with little potential for sourcing oil.

Results of the kerogen analysis of this interval are shown in Table 3, which uses the four-fold kerogen classification of Bujak *et al.* (op. cit.), plus the addition of “resinous kerogen” discussed in the following section of this report.

10. COMPOSITION OF COALS WITH REPORTED HIGH HI VALUES (TABLE 4)

Table 4 lists sidewall and conventional core samples with a reported Hydrogen Index (HI) exceeding 150 by Dow (1983, in Robertson Research, 1983) and Exlog (1983). Most of the samples contain coals.

It is possible that the high HI values observed in coals from the middle and lower parts of the well result from the coals including algal material. In order to confirm whether 'algal coals' occur at these horizons, kerogen analyses and the determination of major palynomorph groups were undertaken on coal fragments picked and processed from the intervals and the results are presented in Table 3. The following categories of kerogen type were recognized:

- resin
- amorphous sapropelic material
- herbaceous kerogen, including plant cuticle and cells
- wood
- inertinite, representing black opaque kerogen resulting from either high thermal alteration or oxidation which may be associated with weathering

The following palynomorph types were determined:

- saccate gymnosperm pollen including bisaccate pollen and *Tsugaepollenites*
- angiosperm pollen
- spores
- *Taxodiaceaepollenites* pollen
- fungal remains
- miscellaneous algae listed on the range chart included with this report
- dinoflagellate cysts (dinocysts)

These data indicate that algal remains are absent or very rare in all of the examined samples, indicating that the high HI values previously recorded are not due to the presence of algal material.

Resin is relatively abundant in several intervals of the well, and may be a possible source for waxy oil source in the Canadian Beaufort Mackenzie Basin as it is identical to the kerogen classified as ‘resinite’ by Snowden (1980), who suggested that it might be a possible waxy oil source in the Canadian Beaufort Mackenzie Basin. Common to abundant resin is confined to the Tolstoi and Stepovak Formation sections of the COST well and corresponds to previously reported high HI values in the sidewall core at 10,832.0 ft and the cuttings sample at 15,420-15510 ft which both contain 40% resin.

11. REFERENCES

Balech, E. & El Sayed, S.Z. 1965. Microplankton of the Weddell Sea. In: Biology of the Antarctic Seas II. Antarctic Research Series 5, Amer. Geophy. Union, 1965, pp. 107-124.

Barron, J.A. 1998. Late Neogene changes in diatom sedimentation in the North Pacific. Journal of Asian Earth Sciences, vol. 16, pp. 85-95.

Barron J.A. & Baldauf, J.G. 1990. Development of biosiliceous sedimentation in the North Pacific during the Miocene and early Pliocene. In: Tsuchi, T. (ed.), Pacific Neogene Events. University of Tokyo Press, pp. 43-63.

Biostratigraphics Consulting Micropaleontology. 1983. ARCO North Aleutian Shelf COST No. 1 Well, Bering Sea, Alaska. Ventura, California, Biostratigraphics, a unit of McClelland Engineers, 6 parts, 139 pp. Available online at MMS website at: http://www.mms.gov/alaska/re/reports/nascostbio/nascostbpr.htm.

Brinkhuis, H., 1994, Late Eocene to Early Oligocene dinoflagellate cysts from the Priabonian type-area (Northeast Italy): biostratigraphy and paleoenvironmental interpretation. Palaeogeography, Palaeoclimatology, Palaeoecology 107, pp. 121-163.

Brinkhuis, H. and Visscher H., 1995. The upper boundary of the Eocene series: a reappraisal based on dinoflagellate cysts bio-stratigraphy and sequence stratigraphy. Society of Economic Paleontologists and Mineralogists, Special Publication 54, Tulsa, pp. 295-304.

Bujak, J.P. 1980. Dinoflagellate cysts and acritarchs from the Eocene Barton Beds of southern England; in Bujak, J.P., Downie, C., Eaton G.L., & Williams, G.L., Dinoflagellate cysts and acritarchs from the Eocene of southern England; The Palaeontological Association, Special Papers in Palaeontology, no. 24, pp. 36-91.

Bujak, J.P. 1984. Cenozoic dinoflagellate cysts and acritarchs from the Bering Sea and northern North Pacific, DSDP Leg 19. Micropaleontology, vol. 30, pp. 180-212.

Bujak, J.P., Barss, M.S. & Williams, G.L. 1977a. Offshore eastern Canada Part I. Offshore east Canada's organic type and colour and hydrocarbon potential. Oil and Gas Journal, vol. 75, pp. 198-202.

Bujak, J.P., Barss, M.S. & Williams, G.L. 1977b. Offshore eastern Canada Part II. Offshore east Canada's organic type and color and hydrocarbon potential. Oil and Gas Journal, vol. 75, pp. 96-100.

Bujak, J.P., Barss, M.S. & Williams, G.L. 1978 . Organic type and colour and hydrocarbon potential, offshore eastern Canada. Canadian Society of Petroleum Geologists; Reservoir, vol. 5, pp. 1-2.

Bujak, J.P., Barss, M.S. & Williams, G.L. 1979 . Organic type and colour and hydrocarbon potential, offshore eastern Canada. Atlantic Geoscience Society, Biennial Colloqium, Current Research in the Maritimes, Fredericton, New Brunswick, January 1979; Abstracts.

Bujak, J.P. & Brinkhuis, H. 1998. Global warming and dinocyst changes across the Paleocene/Eocene boundary. *In:* Paleocene/Eocene Boundary Events (Lucas, S.G., Berggren, W. & Aubry, M.-P., eds), Columbia University Press, pp. 277-295.

Bujak, J.P. & Davies. E.H. 1982a. Initial and acquired fluorescence of palynomorphs. Proceedings of the Third North American Palynological Convention, pp. 102-106; Montreal, August 1982; Abstracts.

Bujak, J.P. & Davies. E.H. 1982b. Fluorescence and the search for petroleum. BIO Review '82; Publication of the Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada, pp. 54-57.

Bujak, J.P. & Davies, E.H. 1983. Modern and fossil Peridiniineae. American Association of Stratigraphic Palynologists Contribution Series No. 13, pp. 1-203.

Bujak, J.P., Downie, C., Eaton, G.L. and Williams, G.L., 1980. Dinoflagellate cysts and acritarchs from the Eocene of southern England. The Palaeontological Association, Special Paper in Palaeontology 24, pp. 1-100.

Bujak, J.P. & Matsuoka K. 1986. Late Cenozoic dinoflagellate cyst zonation in the Western and Northern Pacific. American Association of Stratigraphic Palynologists, Contribution Series Number 17: "Neogene dinoflagellates". A.A.S.P. Symposium, New York, October 1986, pp. 7-25.

Bujak, J.P. & Matsuoka, K. 1986. Taxonomic reallocation of dinoflagellate cysts from Japan and the Bering Sea. Palynology, vol. 10, pp. 235-241.

Detterman, R.L., 1990, Correlation of exploratory wells, Alaska Peninsula: U.S. Geological Survey Open file Report OF 90-279, 2 plates.

Detterman, R.L., Case, J.E. Miller, J.W., Wilson, F.H. & Young, M.E., 1996. Stratigraphic framework of the Alaska Peninsula: Geologic Studies on the Alaska Peninsula. U.S. Geological Survey Bulletin 1969-A, 74 p.

Dow, W.G. 1983. Chemical analysis of North Aleutian Shelf, COST No. 1 well. In: Alaska Report No.823/135: Houston, Texas, Robertson Research (U.S.), Inc., 315 p. [report prepared for ARCO).

Exlog (Exploration Logging Inc. of U.S.A.), 1983, Geochemical final well report, ARCO Exploration Company, North Aleutian Shelf C.O.S.T. Well No. 1, September 1982-January 1983: Report to ARCO Exploration Company and Industry Consortium by Exlog. Available as public well file, Minerals Management Service, 949 E. 36th Ave., Suite 300, Anchorage, AK 99503, 40 p.

Finzel, E.S., Reifenstuhl, R.R., Decker, P.L. & Ridgway, K.D. 2005. Sedimentology, stratigraphy and hydrocarbon reservoir-source rock potential. Using surface and subsurface data, of Tertiary and Mesozoic strata, Bristol Bay Basin and Alaska Peninsula. Alaska Division of Geological & Geophysical Surveys Preliminary Interpretive Report 2005-4, 67 p.

Finzel, E.S., Ridgway, K.D., Reifenstuhl, R.R., Blodgett R.B., White, J.M. & Decker, P.L. 2009. Stratigraphic framework and depositional environments of the Miocene Bear Lake Formation, Bristol Bay, Alaska: Onshore equivalents to potential reservoir strata in a frontier gas-rich basin. AAPG Bulletin, v. 93, no. 3, p. 379-405.

Helmold, K.P. & Brizzolara, D.W. 2005. Reservoir quality of Tertiary sandstones from Bristol Bay Basin, Alaska Peninsula: Preliminary Report. Alaska Division of Oil and Gas Technical Report, 32 p.

Hite, D. 2004. Bristol Bay Native Corporation – Hydrocarbon potential of Native Lands in the Bristol Bay area, southern Alaska. Bristol Bay Native Corporation files, Data Set Index No. 774, 8 p.

Ioannides, N. S. & McIntyre, D. J. 1980. A preliminary palynological study of the Caribou Hills outcrop along the Mackenzie River, District of Columbia. Geological Survey of Canada, Paper 80−1A, pp 197−208,

Jicha, B.R., Scholl, D.W., Singer, B.S., Yogodzinski, G.M., and Kay, S.M., 2006, Revised age of Aleutian Island arc formation implies high rate of magma production: Geology, v. 34, no. 8, p. 661-664; doi: 10.1130/G22433.1.

Kennett, J.P. & Barker, P.F. 1990. Late Cretaceous to Cenozoic climate and oceanographic development in the Weddell Sea, Antarctica. An ocean-drilling perspective. In: Proceedings of the Ocean Drilling Program, Scientific Results: College Station, TX, Texas A & M University, Ocean Drilling Program, vol. 113, pp. 937-960.

Kirschner, C.L. 1988. Map showing sedimentary basins of onshore and continental shelf area, Alaska. U.S. Geological Survey Miscellaneous Investigations Series 1-1873, scale 1:2,500,000, 1 sheet.

Kurita, H. & Obuse, A. 2003. Middle Miocene-uppermost Lower Pliocene dinoflagellate cyst biostratigraphy, ODP Leg 186 Hole 1151A, off Sanriku coast, northern Japan, northwestern Pacific. In: Proceedings of the Ocean Drilling Program, Scientific Results, vol. 185.

Margolis, S. V. & Kennett, J.P. 1971. Cenozoic postglacial history of Antarctica recorded in sub-Antarctic deep-sea cores. American Journal of Science, vol. 271, pp. 1036.

Matsuoka, K. 1976. Recent thecate and fossilized dinoflagellates off Hachinohe coast, northeastern Japan. Publ. Seto Mar. Biol. Lab., vol. 23, pp. 351-369.

Matsuoka, K. & Bujak, J.P. 1987. Neogene dinoflagellate cyst biostratigraphy in the central and eastern Bering Sea. Abstracts, 94th Annual Meeting of the Geological Society of Japan, Osaka, Japan, April 1987.

Matsuoka, K. & Bujak, J.P. 1988. Cenozoic dinoflagellate cysts from the Navarin Basin, Norton Sound and St. George Basin, Bering Sea. Bulletin of the Faculty of Liberal Arts, Nagasaki University, Natural Science, vol. 29, pp. 1-147.

Moran, K. *et al*. 2006. The Cenozoic paleoenvironment of the Arctic Ocean. Nature, volume 444, no. 1, pp. 601-605.

Maiya, S. 1978. Late Cenozoic planktonic foraminiferal biostratigraphy of the oil-field region of northeast Japan. In: Huzita, K., *et al.* Eds., Cenozoic Geology of northeast Japan. Professor N. Ikebe Memorial Volume, Osaka, pp. 35-60.

Matsunaga, T. 1963. Benthonic smaller foraminifera from the oil fields of northern Japan. Tohoku University, Science Report, 2nd Series, no. 2, pp. 67-122.

Matsuoka, K., Bujak, J.P. &, Shimazaki, T. 1987. Late Cenozoic dinoflagellate cyst biostratigraphy in the Sea of Japan off North Japan. Micropaleontology, vol. 33, no. 3, pp. 214-229.

Moran, K. *et al.* (multiple authors not listed here). 2006. The Cenozoic palaeoenvironment of the Arctic Ocean. Nature, June 1, 2006, pp. 601-609.

Nagaseko, K. & Sugano, K. 1973. Neogene radiolarian zonation in Japan. Geological Society of Japan, Memoir no, 8, 23-33.

Ogasawara, K. 2002. Responded of Japanese Cenozoic mollusks to Pacific gateway events. Revista Mexicana de Ciencias Geologicas, vol. 19, no. 3, pp. 206-214.

Reininck-Smith, L.M & Leopold, E.B. 2005. Warm climate in the late Miocene of the south coast of Alaska and the occurrence of Podocarpaceae pollen. Palynology, v. 29, p. 205-262.

Robertson Research (U.S.), Inc.,, see Dow, 1983.

Scholl, D.W., Vallier, T.L., and Stevenson, A.J., 1987, Geologic evolution and petroleum geology of the Aleutian ridge: in Scholl, D.W. et al, eds., *Geology and Resource Potential of the Continental margin of Western North America and Adjacent Ocean Basins—Beaufort Sea to Baja California*, Circum Pacific Council for Energy and Mineral Resources, Houston, TX, p. 123-155.

Sherwood, K.W., Larson, J., Comer, C.D., Craig, J.D. & Reitmeier, C. 2006. North Aleutian Basin outer continental shelf planning area: Assessment of undiscovered technically-recovered oil and gas as of 2006. Anchorage, Alaska, U.S. Department of the Interior Minerals Management Service, Alaska Outer Continental Shelf Region, 139 p. Available online at MMS website at: http://www.mms.gov/alaska/re/reports/NAB06/nab2006.htm.

Sluis, A., Bowen, G.J., Brinkhuis, H., Lourens, I.J. & Thomas, E. 2007. The Paleocene – Eocene Thermal Maximum super greenhouse: biotic and geochemical signatures, age models and mechanisms of global change. In: Williams, M., Haywood, A.M., Gregory, F.J & Schmidt, D.N. (eds). Deep-Time Perspective on Climate: Marrying the Signal from Computer Models and Biological Processes. The Micropaleontological Society, Special Publications. The Geological Society of London, pp. 323-349.

Snowden, L.R., 1980. Resinite - potential petroleum source in Beaufort–Mackenzie basin. In: Miall, A.B. (Ed.), Facts and Principles of World Petroleum.

Taylor, F.J.R. 1984. The biology of dinoflagellates. Bot. Monogr., 20. Oxford, England: Blackwell.

Turner, R.F., McCarthy, C.M., Lynch, M.B., Hoose, P.J., Martin, G.C., Larson, J.A., Flett, T.O., Sherwood, K.W., and Adams, A.J., 1988, Geological and operational summary, North Aleutian shelf COST No. 1 well, Bering Sea, Alaska: Minerals Management Service OCS Report MMS 88-0089, 266 p. Available online at MMS website at: http://www.mms.gov/alaska/reports/1980rpts/akpubs80s.HTM (scroll down to MMS 88-0089).

Walker, K.T., McGeary, S/.E. & Klemperer, S.L. 2003. Tectonic evolution of the Bristol Bay Basin, southeast Bering Sea: Constraints from seismic reflection and potential field data. Tectonics, vol. 22, no. 5, p. 1049.

Wall, D., Dale, B., Lohnmann, G.P. & Smith, W.K. 1977. The environmental and climatic distribution of dinoflagellate cysts in modern marine sediments from regions in the North and South Atlantic Oceans and adjacent seas. Marine Micropaleontology, vol. 2, pp. 121-200.

White, J.M., Ager, T.A., Adam, D.P., Leopold, E.B., Liu, G., Jette, H. & Schweger, C.E. 1997. An 18 million year record of vegetation and climate change in northwestern Canada and Alaska: Tectonic and global climatic correlations. Paleogeography, Paleoclimatology and Palecology, v. 130, p. 293-306.

White, J.M., Ager, T.A., Adam, D.P., Leopold, E.B., Liu, G., Jette, H. & Schweger, C.E. 1999, Neogene and Quaternary quantitative palynostratigraphy and paleoclimatology from sections in Yukon and adjacent Northwest Territories and Alaska. Geological Survey of Canada Bulletin, v. 543, 30. p.

Wilson, F.H., 1985, The Meshik arc – an Eocene to earliest Miocene magmatic arc on the Alaska Peninsula: Alaska Division of Geological and Geophysical Surveys Professional Report 88, 14 p.

Williams, G.L. & Fenzome, R.A. 2004. The Lentin and Williams index of fossil dinoflagellates – 2004 Edition. Available for download at
https://payment.palynology.org/index.php?main_page=product_info&products_id=309

Wolfe, J.A. 1978. A paleobotanical interpretation of Tertiary climates in the Northern Hemisphere. American Scientist, vol. 66, pp. 694-703.

Wolfe, J.A. 1994. An analysis of Neogene climates in Beringia. Paleogeography, Paleoclimatology and Palecology, v. 108, p. 207-216.

Wolfe, J.A., Hopkins, D.M. & Leopold, E.B. 1966. Tertiary stratigraphy and paleobotoany of the Cook Inlet region, Alaska, U.S. Geological Survey Professional Paper 980, 29 p.

Wolfe, J.A. & Tanai, T. 1980. The Miocene Seldovia Point flora from the Kenai Group, Alaska. US Geological Survey Professional Paper 1105, pp. 1-52.

Worrall, D.M., 1991, Tectonic history of the Bering Sea and the evolution of Tertiary strike-slip basins of the Bering Sea: Geological Society of America Special Paper 257, 120 p.

Zachos, J., Pagani, M., Sloan, L., Thomas, E. & Billups, K. 2001. Trends, Rhythms and aberrations in global climate 65 Ma to Present. Science v. 292, p. 686-693

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1st stage: Proto-Tasmanian Seaway	
55-56 Ma:	Increased greenhouse gases due from Greenland Mantle Plume volcanism resulting in Paleocene Eocene Thermal Maximum (PETM). India-Asia contact initiating Himalayan uplift.
50-51.5 Ma:	Early Eocene climatic optimum.
50 Ma:	Arctic Azolla Event reducing $p\mathrm{CO}_2$ levels (? to less than 2000 ppm.) and initiating the shift towards the modern icehouse climate.
49-50 Ma:	Initiation of eastern Antarctic glaciation resulting in glacioeustatic sea-level fall.
43 Ma:	Preliminary onset of the Tasman Seaway. Moving direction of the Pacific Plate changes from NNW to WNW.
2nd stage: Tasmanian Seaway	
38 Ma:	Tethys closes between the Mediterranean and Indian Oceans.
33-34 Ma	Terminal Eocene Event. Major opening of the Tasmanian seaway between Antarctica and Tasmania leading to increased development of the Antarctic Circumpolar Current (ACC) triggering the onset of vigorous, oxygen-rich deep-water circulation and sequestration of atmospheric CO_2 at the Eocene/Oligocene transition. Lowered $p\mathrm{CO}_2$ levels (to less than 1000 ppm) resulting in major Eastern Antarctic glaciation and glacioeustatic sea-level fall up to 350m.
30-31 Ma	Increased opening of the Drake Passage between Antarctica and South America
25 Ma:	late Oligocene warming.
3rd stage: Tasman-Drake Seaways	
23.5 Ma:	Drake Passage opens between Antarctica and South America. Intensification of ACC. Mi-1 glaciation of Zachos (2001)
4th stage: Indo-Pacific separation	
21-17 Ma:	Initiation of Andean uplift, and acceleration of Himalayan uplift.
5th stage: Indo-Pacific connection	
17 Ma:	Closing of Indonesian seaway
15-17 Ma:	Mid Miocene climatic optimum
14.5-15 Ma:	Onset of middle-Miocene cooling
11-14 Ma:	Major expansion of Eastern Antarctic Ice Sheet
9 Ma:	Shoaling of Panama Isthmus
7-8 Ma:	Asian monsoons intensify
6.5 Ma:	Establishment of Western Antarctic ice sheet
6.5-6.2 Ma:	Diatom accumulation rate (MAR) increase in California (6.5 Ma) and in high latitudes (6.2 Ma)
6 Ma:	Minor warming event N7b of Tsuchi (1992)
6th stage: Bering Strait	
5 Ma:	Messinian salinity crisis
4.5 Ma:	Diatom sedimentation increases in NW Pacific and decreases in California-Japan (Diatom event C of Barron, 1998)
3.5 Ma:	Ice sheet development in Arctic Ocean (Kennett & Barker, 1990)
3.5-2 Ma:	Closing of American Seaway (Panama Isthmus)
2.4 Ma:	Expansion of Arctic Ice Sheet

Table 1. Global oceanographic-climatic events and Pacific gateway stages after Ogasawara (2002).

North Aleutian Shelf COST No. 1

			PERCENT OF TOTAL PALYNOLOGICAL ASSEMBLAGE (onshore and paralic palynomorph are potentially transported into marine environments towards the right of the chart)													
			nonmarine								paralic / brackish		marine			
upper sample depth (ft)	lower sample depth (ft)	sample type	% bisaccate gymnosperms	% Tsugaepollenites	% pollen excluding thermophilic taxa	% thermophilic pollen	% spores	% fungi	% Taxodiaceaepollenites	% freshwater algae	% brackish water algae	% brackish water dinocysts	% marine algae	% Gonyalacacean dinocysts	% Protoperidiniacean dinocysts	TOTAL COUNT (counts less than 500 are due to low palynomorph recovery)
1390	1470	cuttings	63.7		13.7		20.7						1.7	1.0	1.0	300
1470	1560	cuttings	55.0		15.7		27.7						1.3	0.7	1.0	300
1560	1650	cuttings	62.3		12.7		22.7						2.7	0.3	2.0	300
1650	1740	cuttings	70.0		4.3		22.0		1.7				0.3	0.7	1.3	300
1740	1830	cuttings	63.0		3.0		29.0		2.3				1.0	0.7	2.0	300
1830	1920	cuttings	60.7		2.7		33.0		1.0				1.0	1.3	1.3	300
1920	2010	cuttings	65.3		2.3		28.0		0.7				1.0	1.7	2.0	300
2010	2100	cuttings	67.0	1.0	2.0		26.7						0.3	1.3	2.0	300
2100	2190	cuttings	67.1	0.7	3.0		24.9		2.3				0.7	0.3	1.7	300
2190	2280	cuttings	71.8	0.8	1.6		24.2							0.8	0.8	500
2280	2370	cuttings	68.4	1.0	1.2	0.2	25.4		2.8				0.2	0.4	0.6	500
2370	2460	cuttings	67.6	3.0	1.8		24.2		2.0					0.6	0.8	500
2460	2550	cuttings	63.4	3.8	2.0	0.2	24.4	0.4	2.8					2.2	1.2	500
2550	2640	cuttings	64.7	2.2	1.8		25.7		3.4					1.6	0.6	500
2640	2730	cuttings	64.4	3.0	2.6	0.6	22.8		4.0				0.2	1.4	1.2	500
2730	2820	cuttings	60.2	4.4	1.4	3.4	23.8		4.6					0.8	1.4	500
2820	2910	cuttings	57.6	4.0	1.6	2.0	28.4		3.6				0.2	1.4	1.4	500
2910	3000	cuttings	60.0	3.2	1.8	0.6	28.4		3.2					1.2	1.6	500
3000	3090	cuttings	53.0	4.2	3.0		34.8		2.8					0.6	1.6	500
3090	3180	cuttings	55.6	5.2	3.2		32.0	0.2	2.2					0.8	1.0	500
3180	3270	cuttings	51.0	6.0	3.2	0.2	33.4	0.8	3.4					0.6	2.7	500
3270	3360	cuttings	56.2	6.2	2.4		29.6	2.0	2.8				0.2	2.0	0.8	500
3360	3450	cuttings	55.6	7.4	2.6		29.0	2.2	3.6				0.4	1.4	0.4	500
3450	3540	cuttings	52.0	6.6	2.6	0.2	33.0	0.6	4.2					1.2	0.2	500
3540	3630	cuttings	53.8	4.2	4.0	0.6	31.0	1.0	4.8					1.0	0.6	500
3630	3720	cuttings	58.8	3.8	3.4	2.0	27.2	0.4	3.6					1.0	0.2	500
3720	3810	cuttings	59.6	2.8	4.2	1.2	27.6	0.8	3.0				0.2	1.4	0.2	500
3810	3900	cuttings	54.0	2.6	4.6	2.0	30.8	1.6	5.0					1.0		500
3900	3990	cuttings	51.2	2.4	2.4	4.4	32.4	0.2	5.4					1.0	0.8	500
3990	4080	cuttings	43.2	3.4	2.4	7.4	38.8	0.6	4.4					0.2	0.2	500
4080	4170	cuttings	48.6	3.6	2.4	5.8	34.6	0.2	2.6					1.8	0.6	500
4170	4260	cuttings	44.7	5.8	4.0	4.3	37.1	0.3	2.8					1.0	0.5	400
4260	4350	cuttings	42.0	6.3	3.3	2.5	40.8		3.5					0.9	0.9	400
4350	4440	cuttings	41.5	7.5	4.0	2.5	40.0	0.3	2.5					1.8	0.3	400
4440	4530	cuttings	45.5	5.8	3.0	1.3	40.5	0.3	2.3					1.3	0.5	400
4530	4620	cuttings	40.3	8.8	2.3	3.5	41.3	0.5	2.8					0.8	0.5	400
4620	4710	cuttings	49.4	5.6	3.6	3.0	35.0	0.8	2.8					0.4	0.2	500
4710	4800	cuttings	45.6	4.0	4.0	3.8	39.0	1.6	3.0					0.4	0.2	500
4800	4890	cuttings	48.2	3.8	2.8	5.8	36.0	0.6	2.4					0.6	0.4	500
4890	4980	cuttings	37.6	4.8	2.2	12.2	40.6	0.2	2.0					0.4	0.2	500
4980	5070	cuttings	38.0	5.0	0.8	15.0	37.2		2.8					0.4	0.8	500
5070	5160	cuttings	37.8	5.6	2.0	15.4	36.4		2.4						0.2	500
5160	5250	cuttings	41.8	4.2	2.6	17.8	31.2	0.2	1.8					0.4	0.2	500
5195.3		core	61.0		1.7	0.7	32.7		4.0							300
5250	5340	cuttings	45.4	4.8	2.4	14.0	30.8	0.8	1.6					0.8	0.2	500
5340	5430	cuttings	48.2	4.4	2.2	13.2	29.2	0.4	2.0					0.2	0.6	500
5430	5520	cuttings	47.0	5.0	2.8	12.4	29.4	0.2	2.8					0.4	0.2	500
5520	5610	cuttings	22.5	7.0	3.3	19.0	42.0	1.8	4.0					2.0	0.3	400
5610	5700	cuttings	21.0	5.8	2.0	20.0	43.2	0.8	4.5					3.0	0.3	400
5700	5790	cuttings	46.0	2.0	2.5	2.0	41.0	0.5	3.0					3.5		200
5790	5880	cuttings	17.0	5.0	7.0	1.0	56.0	8.0	9.0					5.0		100

Table 2. Percent values of environmentally sensitive groups of palynomorphs in the COST well.

North Aleutian Shelf COST No. 1			PERCENT OF TOTAL PALYNOLOGICAL ASSEMBLAGE (onshore and paralic palynomorph are potentially transported into marine environments towards the right of the chart)													TOTAL COUNT (counts less than 500 are due to low palynomorph recovery)
			nonmarine								paralic / brackish		marine			
upper sample depth (ft)	lower sample depth (ft)	sample type	% bisaccate gymnosperms	% Tsugaepollenites	% pollen excluding thermophilic taxa	% thermophilic pollen	% spores	% fungi	% Taxodiaceaepollenites	% freshwater algae	% brackish water algae	% brackish water dinocysts	% marine algae	% Gonyalacacean dinocysts	% Protoperidiniacean dinocysts	
5880	5970	cuttings	27.0	4.0	10.0	2.0	50.0	3.0	6.0					1.0		100
5970	6060	cuttings	60.0	1.5	5.5	2.0	30.5	2.0						0.5		200
6060	6150	cuttings	50.0	2.0	4.0	2.5	37.5	0.5	3.5					0.5		200
6150	6240	cuttings	41.0	1.0	13.0	2.0	40.0		3.0							100
6240	6330	cuttings	26.0		28.0	6.0	38.0	2.0	2.0							50
6330	6420	cuttings	6.0	2.0	20.0		56.0		10.0					6.0		50
6420	6510	cuttings	30.0		16.0	2.0	42.0		8.0		2.0					50
6510	6600	cuttings	34.0		12.0		40.0		12.0					2.0		50
6600	6690	cuttings	43.0	1.0	7.5	1.0	45.0		2.0		0.5					200
6690	6780	cuttings	22.0	8.5	18.5		47.5		2.5		1.0					200
6780	6870	cuttings	30.0	8.0	17.5		38.0		4.0		2.0			0.5		200
6870	6960	cuttings	40.0	8.5	13.5		35.0		1.5		1.5					200
6960	7050	cuttings	27.5	6.5	22.0		41.5				1.0			1.5		200
7050	7140	cuttings	24.5	5.5	25.5		43.0		1.0		0.5					200
7140	7230	cuttings	29.5	4.0	21.0	0.5	43.5		1.0					0.5		200
7230	7320	cuttings	33.5	5.5	16.0	1.5	42.5		0.5		0.5					200
7320	7410	cuttings	44.5	6.5	16.0	0.5	31.0		0.5		1.0					200
7410	7500	cuttings	34.5	8.5	21.5		34.0				1.5					200
7500	7590	cuttings	29.0	5.5	23.0		39.5		1.0		2.0					200
7590	7680	cuttings	23.0	7.0	27.5		41.0		0.5		1.0					200
7680	7770	cuttings	23.0	9.0	26.5	0.5	38.5		1.0		1.5					200
7770	7860	cuttings	32.0	8.5	20.5		36.5		2.0		0.5					200
7860	7950	cuttings	21.5	10.5	19.0	0.5	48.0		0.5							200
7950	8040	cuttings	17.5	14.5	25.0		41.0		1.5		0.5					200
8040	8130	cuttings	11.5	10.5	27.0	0.5	47.5		2.5					0.5		200
8130	8220	cuttings	13.0	13.0	24.5	0.5	46.5		2.0		0.5					200
8220	8310	cuttings	9.3	10.0	19.3		58.7		1.3		0.7			0.7		150
8310	8400	cuttings	16.5	8.5	23.5	0.5	48.5		1.0		1.0			0.5		200
8400	8490	cuttings	27.5	7.0	13.5	0.5	46.5		2.5		1.5			1.0		200
8490	8580	cuttings	22.0	14.0	11.0		48.5		4.0		0.5					200
8580	8670	cuttings	11.0	17.0	8.5		57.5		5.5					0.5		200
8670	8760	cuttings	11.5	17.5	26.5		37.0	0.5	7.0		0.5					200
8760	8850	cuttings	10.5	14.0	28.0		42.0	1.0	4.5		0.5			0.5		200
8850	8940	cuttings	5.0	15.0	29.0	0.5	45.5	0.5	3.5		1.0			0.5		200
8940	9030	cuttings	8.5	19.0	25.5	0.5	43.0	2.5	2.0		0.5			1.0		200
9030	9120	cuttings	22.0	8.0	24.5	1.0	40.0	5.0	1.0		0.5	3.0				200
9120	9210	cuttings	13.5	9.0	24.0	1.0	43.5	1.5	1.5		0.5	6.5		0.5		200
9210	9300	cuttings	16.5	6.5	19.5	0.5	46.0	2.0	2.5		1.0	2.0		5.5		200
9300	9390	cuttings	6.5	9.0	23.5	1.0	53.0		1.5		2.0	2.0		1.5		200
9390	9480	cuttings	6.5	11.5	22.5	0.5	50.5	5.5	1.0		1.5	4.5		1.5		200
9480	9570	cuttings	14.0	5.5	21.0	0.5	53.0	5.5	2.0	6.0		3.0		1.0		200
9570	9660	cuttings	53.0	4.4	11.8	0.2	26.0	0.2		1.4		1.0		1.2		500
9660	9750	cuttings	49.2	5.6	11.0	0.4	30.4	0.6	1.0	1.6		1.0				500
9750	9840	cuttings	53.0	5.4	10.6	0.2	27.2	0.2	0.4	1.2				1.6		500
9840	9930	cuttings	53.0	3.8	11.8	0.2	27.6	0.2	0.8	0.6	0.2	0.6		0.8		500
9930	10020	cuttings	49.6	3.8	11.0		26.8	1.0	1.0	0.8		4.6		2.6		500
9978.1		core	54.0	4.8	9.4		27.2	0.4	1.0	0.6		0.2		2.6		500
9982.5		core	53.8	5.0	8.8		28.0		0.6	0.2		0.8		2.4		500
10020	10110	cuttings	50.4	4.0	8.8	0.2	31.2	1.2	1.4			0.4		3.4		500
10110	10200	cuttings	46.6	3.2	9.2	0.2	35.2	2.4	1.6	0.2				3.8	0.2	500
10200	10290	cuttings	52.6	2.2	9.2		32.0	0.8	0.8	0.2				2.4	0.6	500

Table 2. Percent values of environmentally sensitive groups of palynomorphs in the COST well.

North Aleutian Shelf COST No. 1

PERCENT OF TOTAL PALYNOLOGICAL ASSEMBLAGE (onshore and paralic palynomorph are potentially transported into marine environments towards the right of the chart)

			nonmarine								paralic / brackish		marine			
upper sample depth (ft)	lower sample depth (ft)	sample type	% bisaccate gymnosperms	% Tsugaepollenites	% pollen excluding thermophilic taxa	% thermophilic pollen	% spores	% fungi	% Taxodiaceaepollenites	% freshwater algae	% brackish water algae	% brackish water dinocysts	% marine algae	% Gonyalacacean dinocysts	% Protoperidiniacean dinocysts	TOTAL COUNT (counts less than 500 are due to low palynomorph recovery)
10290	10380	cuttings	58.6	2.8	9.4		26.8	1.2	1.0					0.8	0.4	500
10380	10470	cuttings	36.5	5.0	14.5	6.5	36.0	8.0	1.5							200
10470	10560	cuttings	40.0	3.0	18.0	9.0	27.5	11.0	2.5							200
10560	10650	cuttings	16.5	3.5	15.5	14.0	47.0	13.5	3.0		0.5					200
10650	10740	cuttings	29.0	2.0	15.5	9.0	42.5	6.5	1.5		0.5					200
10730.0		core	34.0	1.5	16.5	7.5	39.5	4.5	1.0							200
10740	10830	cuttings	33.5	1.0	19.5	4.5	39.0	8.5	2.0		0.5					200
10830	10920	cuttings	33.5	0.5	12.5	7.5	44.5	6.0	1.0	0.5	0.5					200
10920	11010	cuttings	19.0	0.5	16.0	10.0	50.0	9.5	3.0		1.0					200
11010	11100	cuttings	36.0	0.5	16.5	2.0	42.0	8.5	1.5		1.5					200
11100	11190	cuttings	28.5	1.5	12.5	6.5	47.0	6.5	3.0	0.5	0.5			0.5		200
11190	11280	cuttings	33.5	1.0	13.0	6.0	45.5	1.5		0.5	0.5					200
11280	11370	cuttings	38.0	1.5	9.5	8.0	41.0	2.5	1.0		0.5					200
11370	11460	cuttings	38.5	0.5	9.0	8.0	43.5	2.0			0.5					200
11460	11550	cuttings	29.5	1.0	9.0	12.5	47.5	1.0			0.5					200
11550	11640	cuttings	24.5	3.0	14.0	12.5	44.5	2.5	1.5							200
11640	11730	cuttings	23.0	1.5	13.0	14.0	46.5	4.0	2.0							200
11730	11820	cuttings	36.0	1.0	10.5	7.0	44.0	4.5	1.0		0.5					200
11820	11910	cuttings	33.0	1.5	13.0	7.5	44.0	8.5	1.0							200
11910	12000	cuttings	17.5	1.5	16.0	12.0	50.5	10.0	1.5		1.0					200
12000	12090	cuttings	20.5	0.5	16.5	10.5	50.5	8.5	1.0		0.5					200
12090	12180	cuttings	16.5	0.5	14.5	11.0	55.5	8.0	2.0							200
12180	12270	cuttings	20.0		18.0	12.5	48.0	6.0	1.0		0.5					200
12270	12360	cuttings	23.5		16.0	11.0	48.0	3.5	1.5							200
12360	12450	cuttings	25.0		13.0	9.0	51.5	6.5	1.0		0.5					200
12450	12540	cuttings	31.0		12.5	8.0	47.5	8.5	1.0							200
12540	12630	cuttings	21.0		16.5	9.0	51.0	6.0	2.5							200
12630	12720	cuttings	19.5		13.5	13.0	52.0	5.5	1.5		0.5					200
12720	12810	cuttings	16.5	0.5	12.0	12.5	56.5	6.0	1.5		0.5					200
12810	12900	cuttings	10.5		12.5	19.0	54.5	8.0	3.0		0.5					200
12900	12990	cuttings	13.0		13.5	21.0	48.5	4.0	4.0							200
12990	13080	cuttings	21.5		12.0	17.5	45.5	5.5	3.0	0.5	0.5					200
13080	13170	cuttings	18.5		13.0	13.5	51.0		2.5		1.0					200
13170	13260	cuttings	18.5		13.0	13.0	52.0	1.5	1.5	0.5	2.0					200
13260	13350	cuttings	17.5		12.0	11.0	56.5	0.5	1.0		1.5					200
13350	13440	cuttings	16.0	1.0	12.0	10.0	60.0	0.5	0.5		0.5					200
13440	13530	cuttings	12.5	0.5	9.0	9.5	68.0		0.5							200
13530	13620	cuttings	18.0	1.0	9.0	7.5	63.0		1.0		0.5					200
13620	13710	cuttings	18.5	1.5	10.0	9.5	58.0	0.5	1.5		1.0					200
13710	13800	cuttings	16.0	0.5	14.5	8.5	58.5	1.5	2.0							200
13800	13890	cuttings	14.0	1.0	17.0	8.0	56.0	2.5	3.5		1					200
13890	13980	cuttings	11.0	0.5	13.0	11.5	61.5	2.0	2.0		0.5					200
13980	14070	cuttings	19.5		9.5	12.0	57.0	3.0	1.5		0.5					200
14070	14160	cuttings	18.0		13.0	9.5	57.5	1.0	2.0							200
14160	14250	cuttings	13.0		11.5	10.0	64.5	2.5	1.0							200
14186.1		core	22.0		12.5	8.0	55.5	4.5	2.0							200
14250	14340	cuttings	23.5		9.0	7.5	58.0	3.0	1.5		0.5					200
14340	14430	cuttings	24.5		6.0	5.5	63.0	3.5	0.5		0.5					200
14430	14520	cuttings	19.5		4.0	5.5	70.5	5.0	0.5							200
14520	14610	cuttings	24.0		4.0	4.0	67.5	2.5	0.5							200
14610	14700	cuttings	33.0		6.0	4.0	56.5	6.0			0.5					200

Table 2. Percent values of environmentally sensitive groups of palynomorphs in the COST well.

North Aleutian Shelf COST No. 1

PERCENT OF TOTAL PALYNOLOGICAL ASSEMBLAGE (onshore and paralic palynomorph are potentially transported into marine environments towards the right of the chart)

			nonmarine								paralic / brackish		marine			
upper sample depth (ft)	lower sample depth (ft)	sample type	% bisaccate gymnosperms	% Tsugaepollenites	% pollen excluding thermophilic taxa	% thermophilic pollen	% spores	% fungi	% Taxodiaceaepollenites	% freshwater algae	% brackish water algae	% brackish water dinocysts	% marine algae	% Gonyalacacean dinocysts	% Protoperidiniacean dinocysts	TOTAL COUNT (counts less than 500 are due to low palynomorph recovery)
14700	14790	cuttings	29.0		8.0	4.0	58.5	0.5			0.5					200
14790	14880	cuttings	29.5		6.5	5.5	58.5	3.5								200
14880	14970	cuttings	20.5		6.0	2.5	69.5	0.5	0.5		1.0					200
14970	15060	cuttings	19.0		7.5	4.0	69.0	1.0			0.5					200
15060	15150	cuttings	21.5		9.5	5.0	59.5	2.0	3.0		1.5					200
15150	15240	cuttings	20.5		7.0	5.5	64.5	4.5	1.5		1.0					200
15240	15330	cuttings	21.5		10.5	5.0	62.0	2.0	1.0							200
15330	15420	cuttings	12.5		9.5	8.5	67.0	8.5	2.0		0.5					200
15420	15510	cuttings	12.5		7.0	12.5	63.0	7.5	3.5		0.5			1.0		200
15510	15600	cuttings	12.5		6.0	10.5	67.0	13.0	2.0		1.5			0.5		200
15600	15690	cuttings	23.0		8.5	5.5	57.0	9.5	1.5		1.0			3.5		200
15690	15780	cuttings	60.0				30.0	20.0	8.0		2.0					50
15780	15870	cuttings	50.0			2.0	48.0	36.0								50
15870	15960	cuttings	46.0				54.0	34.0								50
15960	16050	cuttings	50.0		2.0		46.0	22.0			2.0					50
16050	16140	cuttings	50.0				50.0	36.0								50
16140	16230	cuttings	20.0		2.0		78.0	22.0								50
16230	16320	cuttings	42.0			2.0	56.0	26.0								50
16320	16410	cuttings	36.0		2.0		60.0	30.0			2.0					50
16410	16500	cuttings	30.0			2.0	68.0	38.0								50
16500	16590	cuttings	26.0		2.0		72.0	36.0								50
16590	16680	cuttings	40.0				60.0	28.0								50
16680	16770	cuttings	30.0			2.0	66.0	42.0	2.0							50
16715.0		core	44.0				52.0	26.0	4.0							50
16770	16860	cuttings	40.0				60.0	28.0								50
16860	16950	cuttings	30.0		2.0		66.0	26.0	2.0							50
16950	17040	cuttings	24.0				70.0	38.0	6.0							50

Table 2. Percent values of environmentally sensitive groups of palynomorphs in the COST well.

North Aleutian Basin COST 1 well coal samples: kerogen types and major palynomorph groups			KEROGEN TYPE (%)						PALYNOMORPH TYPE (%)						
			RESIN	AMORPHOUS	HERBACEOUS	PALYNOMORPHS	WOODY	INERTINITE	SACCATE GYMNOSPERM POLLEN	ANGIOSPERM POLLEN	SPORES	TAXODIACEAEPOLLENITES	FUNGI	ALGAE	DINOCYSTS
2640	2730	cuttings			15	10	65	10	30	38	30	2			
2730	2820	cuttings			10	75	15		5	15	78	2			
2820	2910	cuttings	5		75	5	10	5	INDETERMINATE (TOO RARE)						
2910	3000	cuttings	5		80	5	10		INDETERMINATE (TOO RARE)						
3000	3090	cuttings			65	20	15		35	33	25	2	5		
3090	3180	cuttings			60	30	10		15	35	43	2	5		
3180	3270	cuttings			60	25	15		20	25	43	2	10		
3270	3360	cuttings			65	25	10		30	20	33	2	15		
3360	3450	cuttings	5		60	15	20		20	15	57	3	5		
3450	3540	cuttings			25	10	55	10	15	40	37	3	5		
3540	3630	cuttings			15	10	65	10	10	35	45	5	5		
3630	3720	cuttings	5		50	5	40		INDETERMINATE (TOO RARE)						
3720	3810	cuttings			65	10	20	5	10	35	48	2	5		
3810	3900	cuttings			25	10	55	10	15	40	35	5	5		
3900	3990	cuttings			40	10	40	10	10	35	48	5	2		
8130	8220	cuttings			65	5	30		INDETERMINATE (TOO RARE)						
8220	8310	cuttings	5		55	10	30		15	35	45		5		
8310	8400	cuttings	10		50	10	35		10	35	54	1			
8400	8490	cuttings	15		45	10	30		5	45	48	2			
8580	8670	cuttings	10		35	15	35	5	10	40	45	5			
8670	8760	cuttings	20		40	5	35		INDETERMINATE (TOO RARE)						
8760	8850	cuttings	5		60	15	20		35	25	30	5	5		
8850	8940	cuttings	20		45	5	30		INDETERMINATE (TOO RARE)						
8940	9030	cuttings	35		35	5	25		INDETERMINATE (TOO RARE)						
9030	9120	cuttings	30		40	5	25		INDETERMINATE (TOO RARE)						
10,470	10,560	cuttings	70		15	5	10		INDETERMINATE (TOO RARE)						
10,560	10,650	cuttings	65		20	5	10		INDETERMINATE (TOO RARE)						
10,740	10,830	cuttings	60		25	2	13		INDETERMINATE (TOO RARE)						
10,830	10,920	cuttings	45		25	2	28		INDETERMINATE (TOO RARE)						
10,832.0		swc	40		20	5	35								
10,920	11,010	cuttings	55		20	2	23		INDETERMINATE (TOO RARE)						
11,010	11,100	cuttings	5		60	20	15		10	45	40	1	4		
11,100	11,190	cuttings	5		60	25	10		5	49	40	1	5		
11,190	11,280	cuttings	10		65	20	5		10	60	25	3	2		
11,280	11,370	cuttings	5		60	20	10	5	10	59	25	5	1		
11,820	11,910	cuttings	10		70	10	10		25	35	30	5	5		
11,910	12,000	cuttings	20		60	10	10		25	30	35	5	5		
12,360	12,450	cuttings	5		80	10	5		15	40	25	15	5		
12,450	12,540	cuttings	5		75	10	10		15	45	25	10	5		
12,540	12,630	cuttings	15		65	10	10		20	40	25	10	5		

Table 3. Percent values of major kerogen types and major palynomorph groups in COST well coals based on the present study.

North Aleutian Basin COST 1 well coal samples: kerogen types and major palynomorph groups			KEROGEN TYPE (%)						PALYNOMORPH TYPE (%)						
			RESIN	AMORPHOUS	HERBACEOUS	PALYNOMORPHS	WOODY	INERTINITE	SACCATE GYMNOSPERM POLLEN	ANGIOSPERM POLLEN	SPORES	TAXODIACEAEPOLLENITES	FUNGI	ALGAE	DINOCYSTS
12,630	12,720	cuttings	35		45	5	15		INDETERMINATE (TOO RARE)						
12,720	12,810	cuttings	45		35	10	15		20	35	35	5	5		
12,810	12,900	cuttings	25		60	5	10		INDETERMINATE (TOO RARE)						
12,900	12,990	cuttings	10		55	25	10		38	30	25	5	2		
12,990	13,080	cuttings	5		80	10	5		20	50	20	5	5		
13,080	13,170	cuttings			75	20	5		10	45	35	10			
13,260	13,350	cuttings			75	20	5		20	40	35	5			
13,350	13,440	cuttings	5		60	30	5		15	44	35	5	1		
13,440	13,530	cuttings	10		70	15	5		10	45	40	5			
13,530	13,620	cuttings	5		70	15	10		10	40	40	10			
13,620	13,710	cuttings			75	15	10		20	40	34	5	1		
13,710	13,800	cuttings			65	10	20	5	15	35	38	10	2		
13,800	13,890	cuttings			75	20	5		20	38	35	5	2		
13,890	13,980	cuttings	15		55	10	15	5	10	35	49	5	1		
13,980	14,070	cuttings	5		60	15	20		10	40	43	5	2		
14,070	14,160	cuttings	15		65	10	10		15	44	35	5	1		
14,160	14,250	cuttings	5		65	25	5		10	39	40	10	1		
14,250	14,340	cuttings	25		60	5	10		INDETERMINATE (TOO RARE)						
14,340	14,430	cuttings	15		70	5	10		INDETERMINATE (TOO RARE)						
14,430	14,520	cuttings			75	15	10		20	38	35	5	2		
14,520	14,610	cuttings	55		25	10	10		5	73	15	5	2		
14,610	14,700	cuttings	75		15	5	5		INDETERMINATE (TOO RARE)						
14,700	14,790	cuttings	15		65	10	10		10	35	50		5		
14,790	14,880	cuttings	5		60	25	10		40	30	25		5		
14,880	14,970	cuttings	15		45	30	10		25	39	35		1		
14,970	15,060	cuttings	15		55	20	10		20	44	35		1		
15,060	15,150	cuttings	10		60	15	15		15	44	40		1		
15,150	15,240	cuttings	30		45	5	20		INDETERMINATE (TOO RARE)						
15,240	15,330	cuttings	35		40	10	15		5	39	55		1		
15,420	15,510	cuttings	40		45	5	10		INDETERMINATE (TOO RARE)						
15,510	15,600	cuttings	60		33	2	5		INDETERMINATE (TOO RARE)						
15,600	15,690	cuttings	65		25	5	5		INDETERMINATE (TOO RARE)						
15,690	15,780	cuttings	15		65	2	18		INDETERMINATE (TOO RARE)						
16,590	16,680	cuttings			5		10	85	INDETERMINATE (TOO RARE)						
16,680	16,770	cuttings			5		5	90	INDETERMINATE (TOO RARE)						
16,770	16,860	cuttings					10	90	INDETERMINATE (TOO RARE)						
16,860	16,950	cuttings					5	95	INDETERMINATE (TOO RARE)						
16,950	17,040	cuttings					5	95	INDETERMINATE (TOO RARE)						

Table 3. Percent values of major kerogen types and major palynomorph groups in COST well coals based on the present study.

Source: Robertson Research and Exlog HI Pyrolysis Data (HI>150) for North Aleutian COST 1 Well

Depth	Sample Type	HI=S2(100)/TOC (mg HC/g TOC)
8314.0	Sidewall Cores/Robertson Research	366
10832.0	Sidewall Cores/Robertson Research	200
11102.5	Conventional Core 13/RobertsonResearch	151
11224.0	Sidewall Cores/Robertson Research	307
12021.0	Sidewall Cores/Robertson Research	271
12250.8	Exlog/Conventional Core 14	157
12251.2	Conventional Core 14/RobertsonResearch	207
12252.0	Sidewall Cores/Robertson Research	280
12262.4	Conventional Core 14/RobertsonResearch	313
12269.3	Conventional Core 14/RobertsonResearch	270
12510.0	Exlog-Cuttings-Hand Picked brown-black shales	313
12570.0	Exlog-Cuttings-Hand Picked brown-black shales	449
12630.0	Exlog-Cuttings-Hand Picked brown-black shales	376
12630.9	Conventional Core 15/RobertsonResearch	303
12634.8	Conventional Core 15/RobertsonResearch	290
12635.4	Conventional Core 15/RobertsonResearch	274
12635.4	Exlog/Conventional Core 15	323
12644.0	Exlog/Conventional Core 15	153
12820.0	Sidewall Cores/Robertson Research	466
12825.0	Sidewall Cores/Robertson Research	326
13275.0	Sidewall Cores/Robertson Research	179
14167.3	Exlog/Conventional Core 16	389
14167.4	Conventional Core 16/RobertsonResearch	345
14167.7	Conventional Core 16/RobertsonResearch	366
14168.0	Exlog/Conventional Core 16	318
14179.1	Conventional Core 16/RobertsonResearch	365
14179.4	Conventional Core 16/RobertsonResearch	373
14179.4	Exlog/Conventional Core 16	338
14183.8	Conventional Core 16/RobertsonResearch	335
14183.8	Exlog/Conventional Core 16	304
14183.8	Exlog/Conventional Core 16	288
14186.2	Conventional Core 16/RobertsonResearch	620
14186.5	Exlog/Conventional Core 16	355
15364.7	Conventional Core 17/RobertsonResearch	542
16011.8	Exlog/Conventional Core 18	155

Table 4. Sidewall and conventional core samples with a reported HI exceeding 150 by Dow (1983, in Robertson Research, 1983) and Exlog (1983). Most of the samples contain coals.

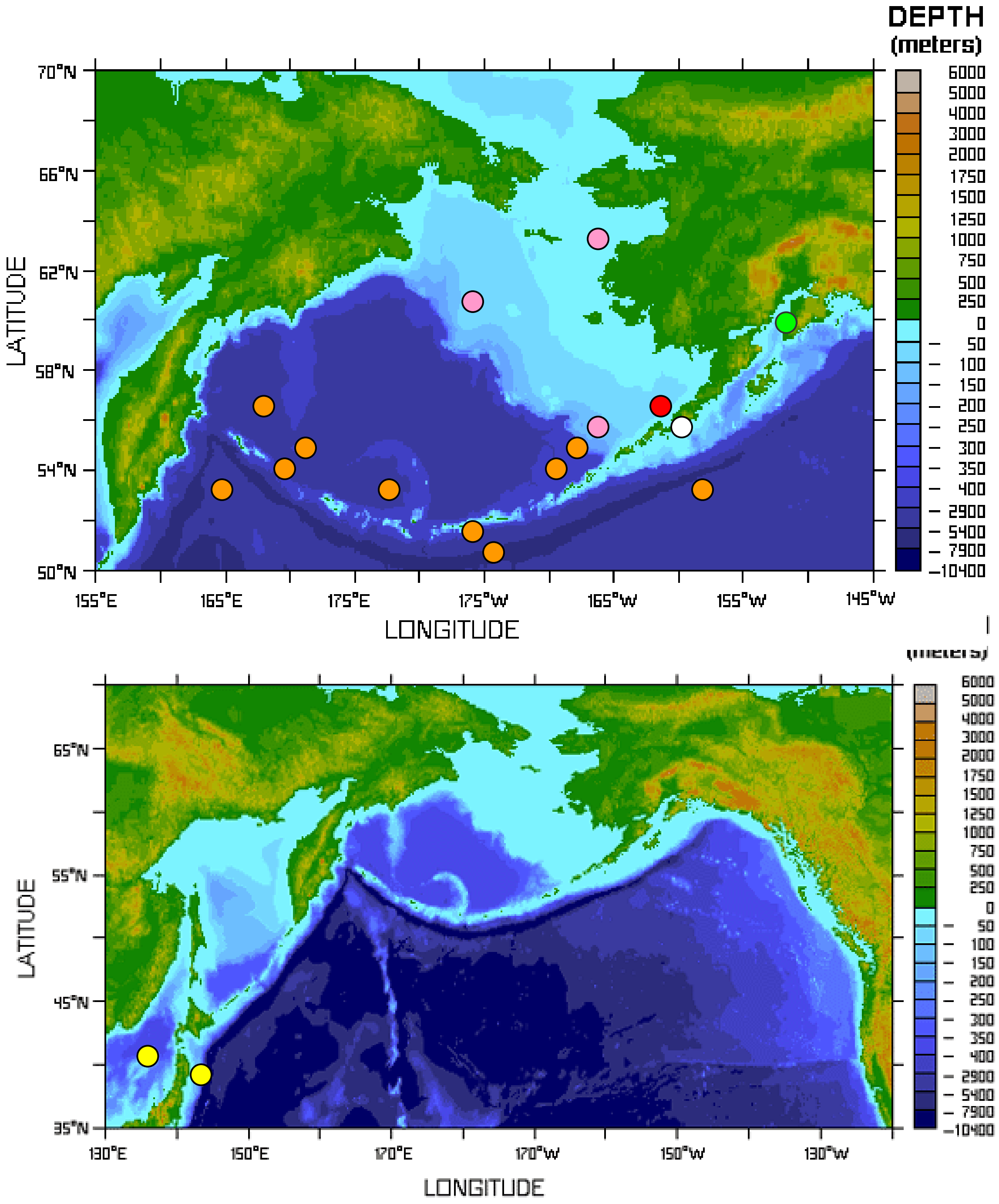


Figure 1. Location map: North Aleutian Shelf COST No.1 well in red, Port Moller in white (Finzel *et al.*, 2009), Cook Inlet in green (Reininck-Smith & Leopold, 2005), DSDP Leg 19 sites in orange (Bujak 1984), Navarin Basin, Norton Sound, St. George Basin COST wells in pink (Matsuoka & Bujak 1987), Sea of Japan (Matsuoka, Bujak & Shimazaki, 1987) and DSDP Leg 57, offshore northeastern Japan (Kurita & Obuse, 2003) in yellow.

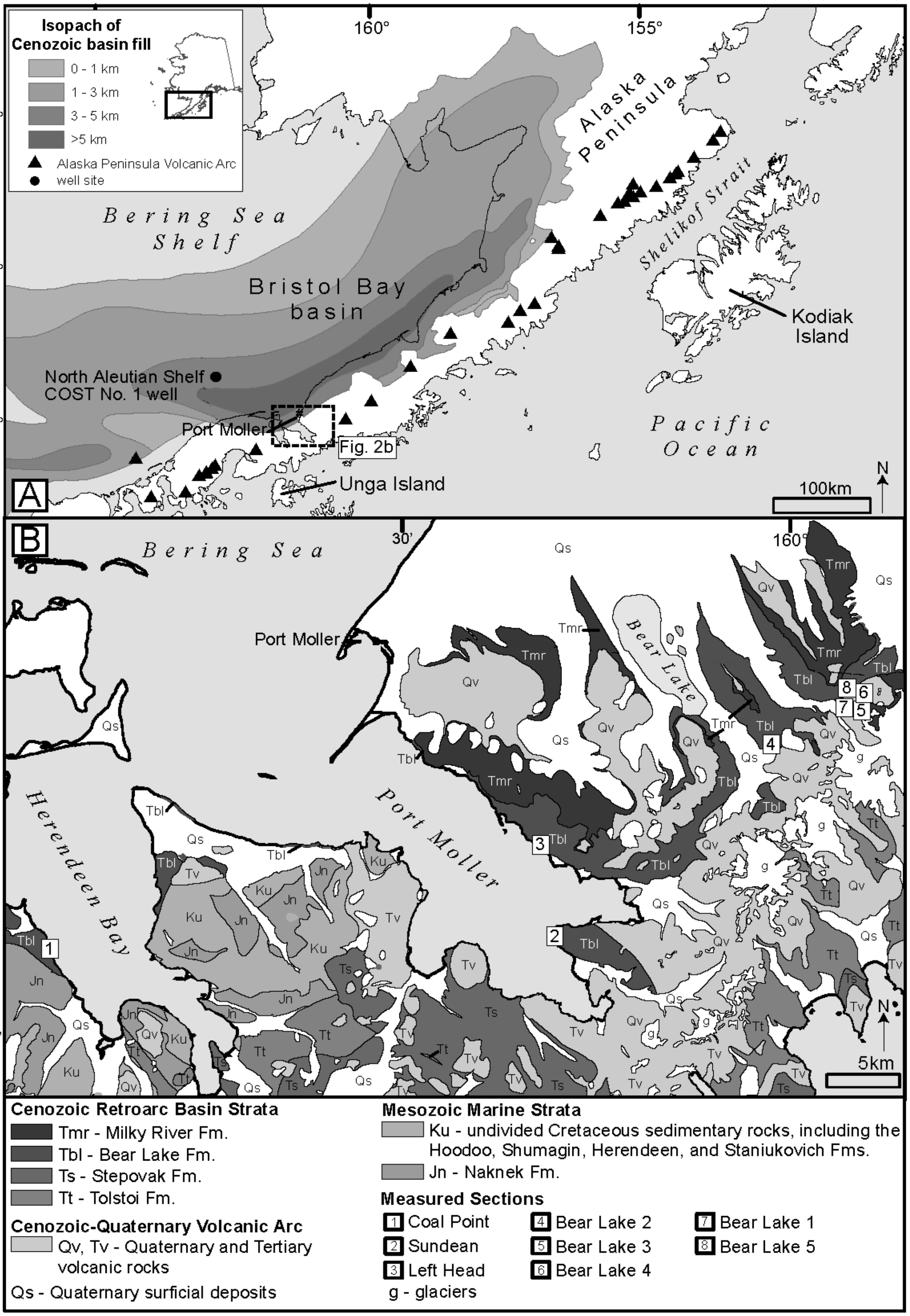
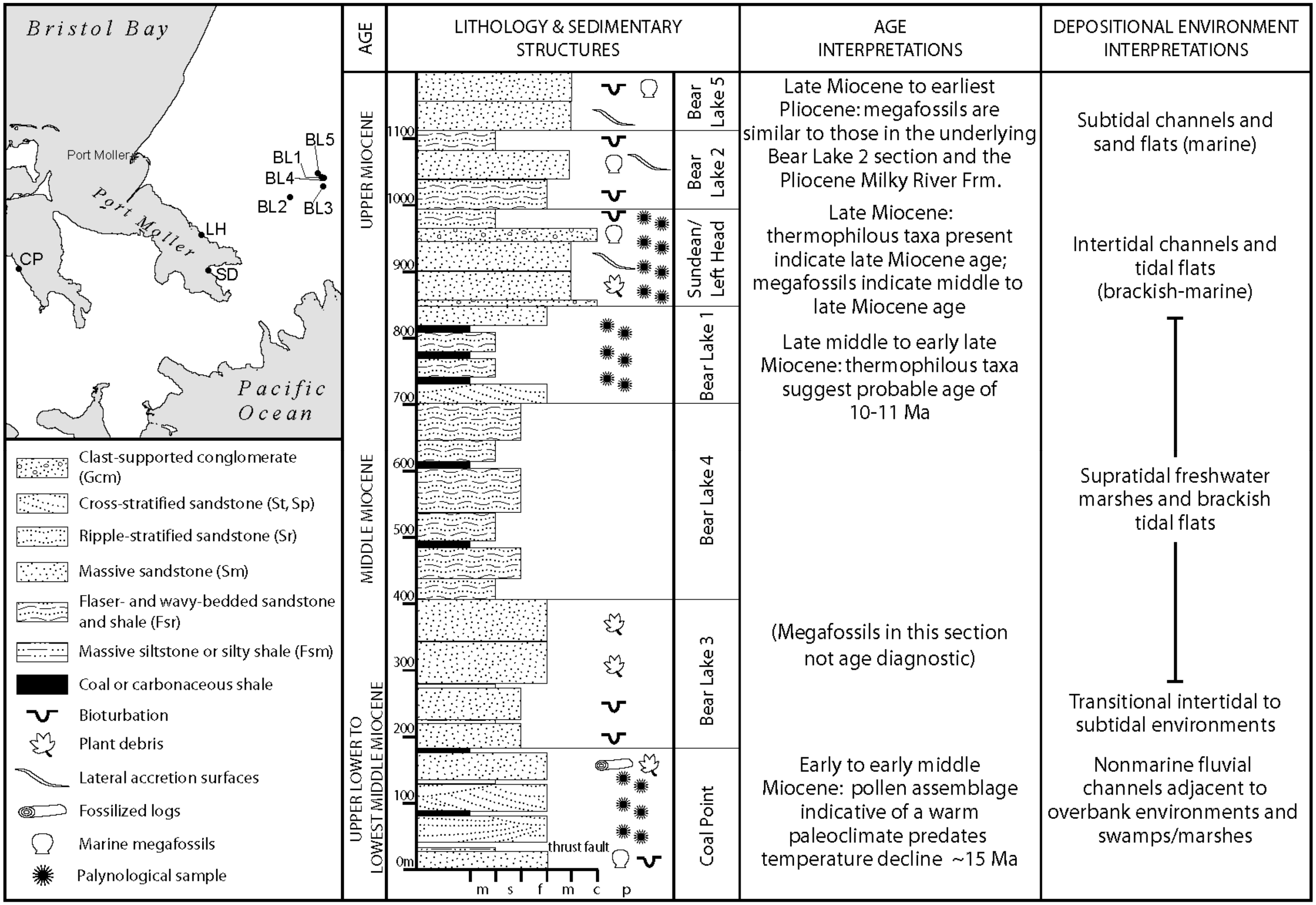


Figure 2. (A) Location map of the area studies by Finzel *et al.* (2009), showing the Bristol Bay Basin and North Aleutian Shelf COST No. 1 well. The shaded contours are an isopach map of Cenozoic strata. (B) Geological map showing the location of sections studied by Finzel *et al.* (2009). Figure from Finzel *et al.* (2009, figure 1). AAPG©2010, reprinted by permission of the AAPG whose permission is required for further use.



Late Miocene to earliest Pliocene: megafossils are similar to those in the underlying Bear Lake 2 section and the Pliocene Milky River Frm.

Late Miocene: thermophilous taxa present indicate late Miocene age; megafossils indicate middle to late Miocene age

Late middle to early late Miocene: thermophilous taxa suggest probable age of 10-11 Ma

(Megafossils in this section not age diagnostic)

Early to early middle Miocene: pollen assemblage indicative of a warm paleoclimate predates temperature decline ~15 Ma

Subtidal channels and sand flats (marine)

Intertidal channels and tidal flats (brackish-marine)

Supratidal freshwater marshes and brackish tidal flats

Transitional intertidal to subtidal environments

Nonmarine fluvial channels adjacent to overbank environments and swamps/marshes

Figure 3. Composite stratigraphic section of the Bear Lake Formation in the vicinity of Port Moller, Alaska, showing age, lithology, and palynological and macrofossil data. Stratigraphic locations of the fossil samples are shown on the right of the lithological section. Evidence for interpreted ages is outlined in the third column. Figure from Finzel *et al.* (2009, figure 6). AAPG©2010, reprinted by permission of the AAPG whose permission is required for further use.

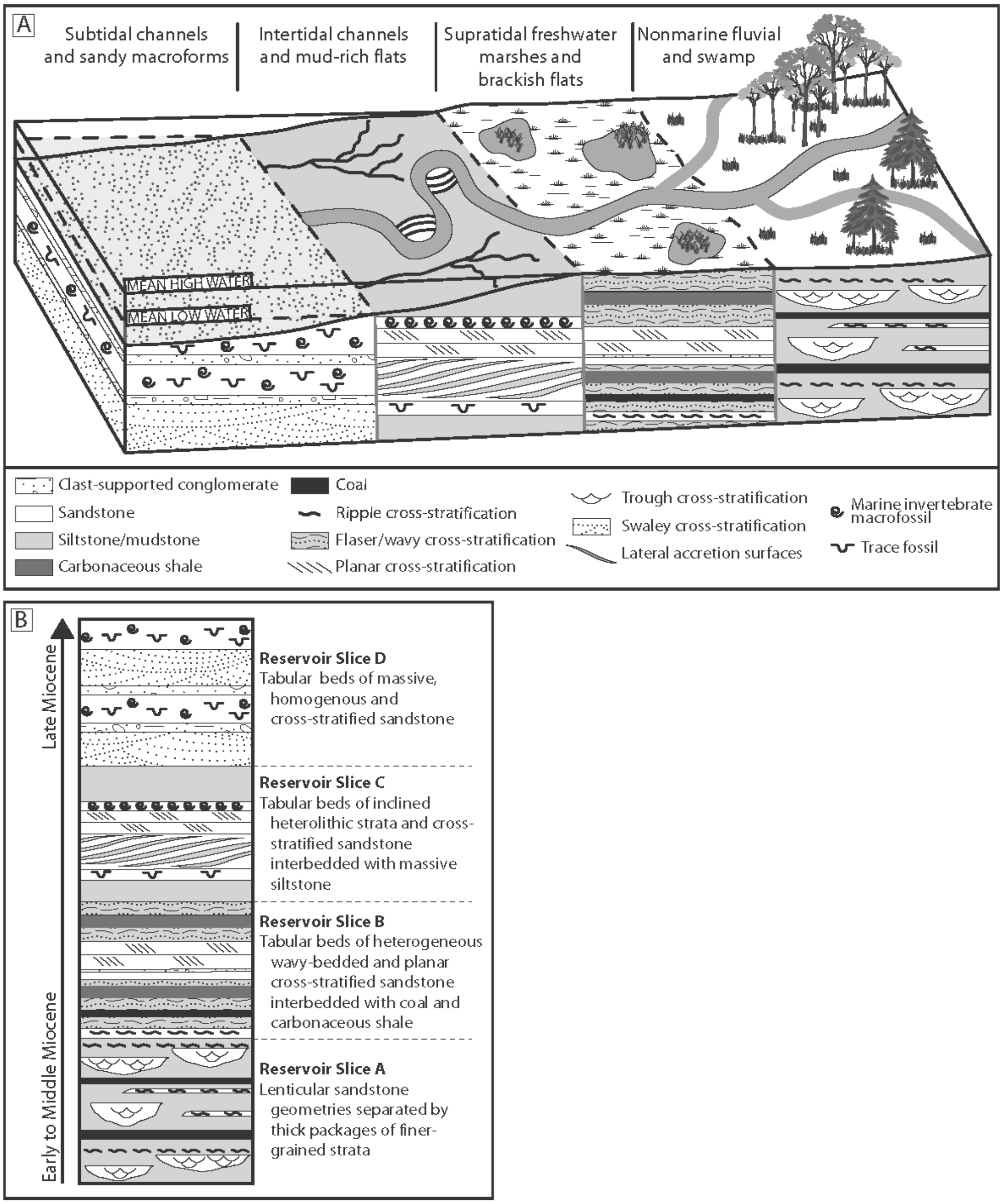


Figure 4. (A) Depositional configuration, interpreted depositional environments, and key sedimentary structures of the Bear Lake Formation at the localities studied by Finzel *et al.* (2009). Angiosperm conifer forests, freshwater fluvial channels, and peat-forming environments are common in the upper, nonmarine parts of the estuarine system. Carbonaceous shale and mud-rich wavy bedding characterize the supratidal parts of the system. Intertidal channels and flats of the middle and lower parts of the estuarine system are represented by flaser bedding, mussel banks, and lateral accretion surfaces. In the subtidal part of the estuary, sand-rich macroforms and conglomeratic storm deposits are typical. (B) The stratigraphic configuration of the Bear Lake Formation shows it to be a product of a transgressive estuarine depositional system at the localities studied by Finzel *et al.* (2009) indicated by the upward change from nonmarine fluvial environments through supratidal and intertidal deposition, culminating if subtidal strata at the top of the section. Reservoir slices highlight how the types of reservoirs change with stratigraphic position in the Bear Lake Formation. (From Finzel *et al.*, 2009, Figure 12). AAPG©2010, reprinted by permission of the AAPG whose permission is required for further use.

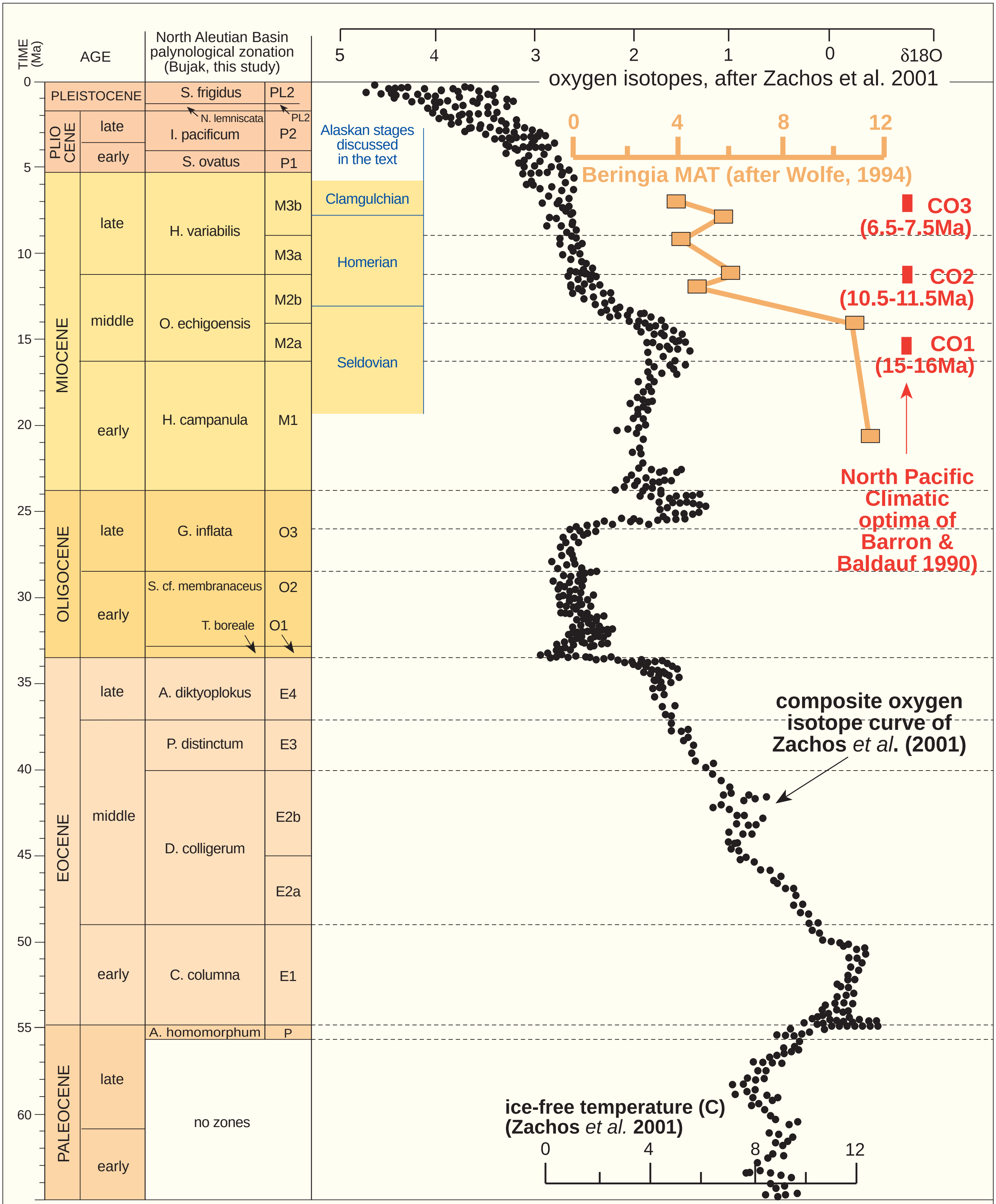


Figure 5. North Pacific-Bering Sea Cenozoic palynological zones, plotted against the composite oxygen isotope curve of Zachos *et al.* (2001), Beringia Mean Annual Tempereratures (MAT) of Wolfe (1994) and climatic optima of Barron & Baldauf (1990).

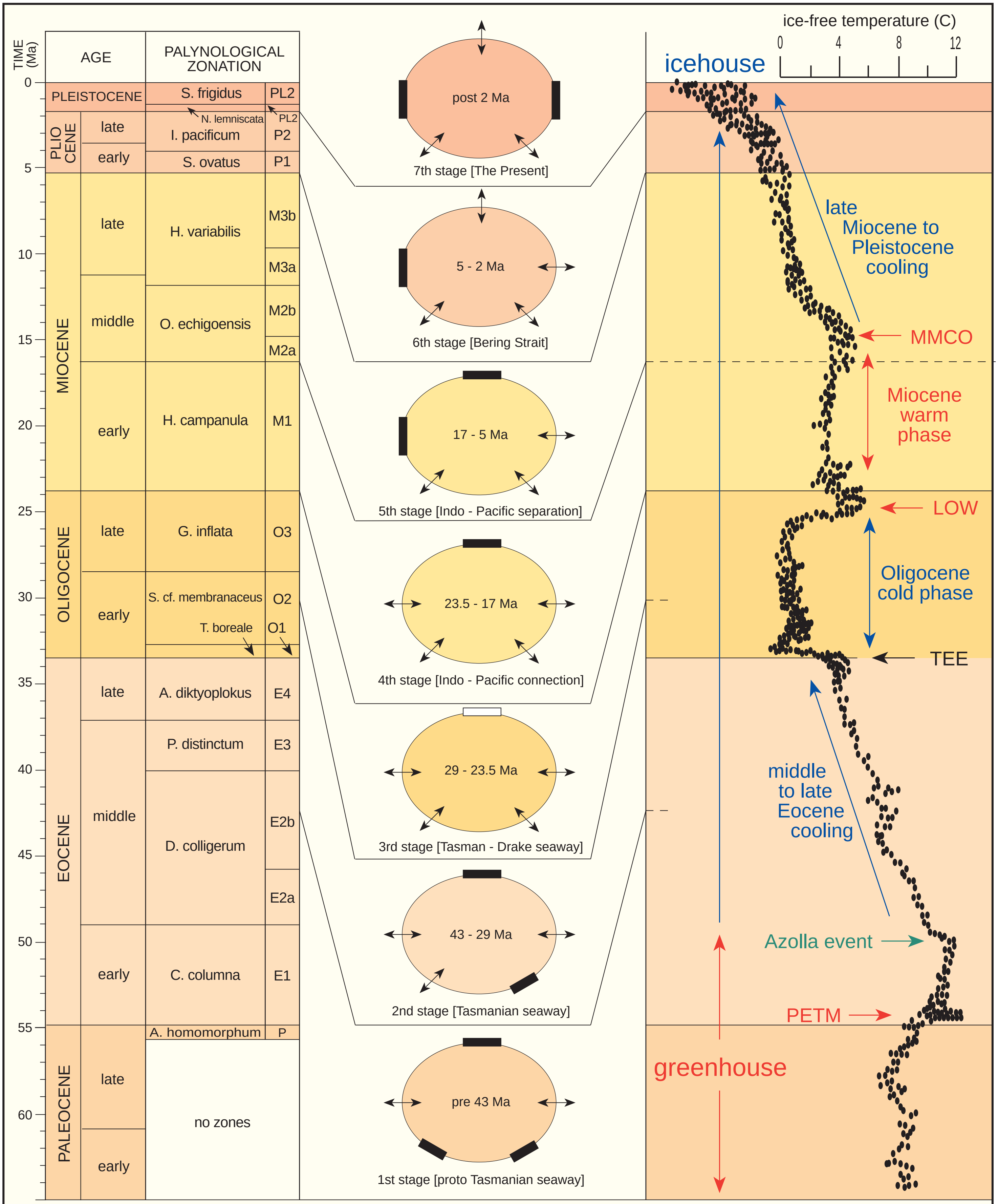


Figure 6. North Pacific-Bering Sea Cenozoic palynological zones (this study), plotted against the succession of Pacific gateways (after Ogasawara, 2002) and the composite oxygen isotope curve of Zachos *et al.* (2001). Major climatic events are shown in red (warm) and blue (cold), plus the Arctic Azolla event in green coincident with the greenhouse to icehouse shift. TEE = Terminal Eocene Event, LOW = Late Oligocene Warming Event, MMCO = middle Miocene climatic optimum (see Figure 7 for key).

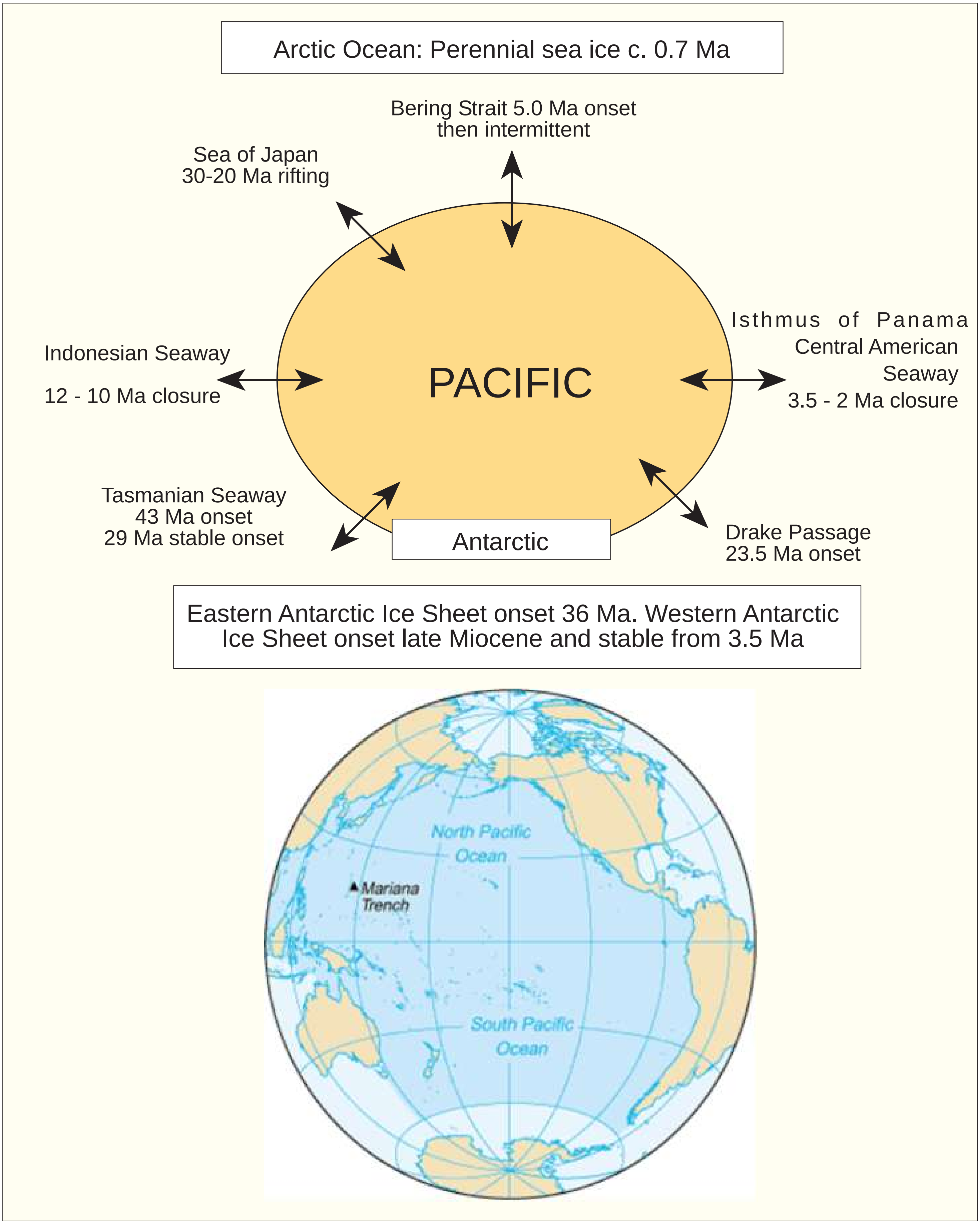


Figure 7. Key to Pacific Cenozoic Cenozoic gateways (after Ogasawara, 2002)

Figure 8. Dinocyst zones erected for Bering Sea / northern North Pacific DSDP Leg 19 by Bujak (1984).

AGE / STAGE			DIATOMS (Koizumi 1973, 1975; Barron 1980)	HIGH LATITUDE SILICOFLAGELLATES & EBRIDIANS (Ling 1973, 1977, 1980)	BERING SEA DINOFLAGELLATES (Bujak 1984) (includes abundance data: x present; **X** common)	? Cannosphaeropsis sp. B of Bujak 1984	?Multispinula minuta	Areosphaeridium diktyoplokus	Beringella fritilla	Brigantedinium spp.	Chiropteridium dispersum	Filisphaera filifera	Gelatia inflata	Halodinium major	Halodinium minor	Hystrichokolpoma cf. cinctum sensu Bujak 1984	Hystrichostrogylon membraniphorum	Impagidinium pacificum	Impagidinium pallidum	Impagidinium velorum	Kallosphaeridium curiosum	Lejeunecysta fallax	Leujeunecysta globosa	Nematosphaeropsis lemniscata	Operculodinium centrocarpum	Phthanoperidinium bennettii	Phthanoperidinium comatum	Quinquecuspis concentricum	Selenopemphix cf. armata sensu Bujak 1984	Selenopemphix nephroides	Selenopemphix sp. A of Bujak 1984	Spiniferites cf. membranaceus sensu Bujak 1984	Spiniferites frigidus	Spiniferites ramosus	Spiniferites ovatus	Tectatodinium pellitum	Trinovantedinium boreale	Tuberculodinium vancampoae	Xandarodinium variabile	BERING SEA DINOFLAGELLATES (Bujak 1984) (includes abundance data: x present; **X** common)	AGE / STAGE	
PLEISTOCENE		Ioanian	D. seminae	D. octangulatus	S. frigidus				x	X				x	X										X			x					x	x						S. frigidus		PLEISTOCENE
			R. curvirostris	D. octanarius			x			X				x	x										x			x						x								
		Calabrian	A. ocuatus	D. subarctios	N. lemniscata					X		X												X	X					x				x					x	N. lemniscata		
PLIOCENE	late	Gelasian			I. pacificum					X		X						X	x	x		X		X	x					x				x		x		x	X	I. pacificum	late	PLIOCENE
										X		X						X	x	x		X		X	x					x				x		x		x	X			
		Piacenzian	D. seminae fossilis	A. rectangulare						X		X						X	x	x		X		X	x					x				x		x		x	X			
										X		X						X	x	x		X		X	x					x				x		x		x	X			
	early	Zanclean		E. antiqua antiqua						X		X						X	x	x		X		X	x					x				x		x		x	X		early	
			D. seminae fossilis - D. kamtschatica		S. ovatus					X		X							x	x		X		X	X					X				x	X			x	X	S. ovatus		
				D. jimlingii						X		X							x	x		X		X	X					X				x	X			x	X			
			D. kamtschatica	D. quniququangellus						X		X							x	x		X		X	X					X				x	X			x	X			
MIOCENE	late	Messinian								X		X							x	x		X		X	X					X				x	X			x	X		late	MIOCENE
			D. hustedtii			x				X		X							x	x		X	x	X	X					X				x	X			x	X			
		Tortonian		Mesoceno-circulua apiculata		x				X		X							x	x		X	x	X	X					X				x	X			x	X			
						x				X		X							x	x		X	x	X	X					X				x	X			x	X			
			D. hustedtii - D. lauta			x				X		X							x	x		X	x	X	X					X				x	X			x	X			
						x				X		X							x	x		X	x	X	X	x	x			X				x	X			x	X			
	middle	Serravallinian		D. schauinslandii	no data (section absent or devoid of dinoflagellates)																																			no data (section absent or devoid of dinoflagellates)	middle	
		Langhian	D. lauta	C. triacantha																																						
				no data (section absent or devoid of silcoflagellates and ebridians)																																						
	early	Burdigalian	A. ingens																																						early	
			no data (section absent or devoid of diatoms)																																							
		Aquitanian																																								
OLIGOCENE	late	Chattian			G. inflata						x		X						X	X				x	x					x				x						G. inflata	late	OLIGOCENE
											x		X						X	X				x	x					x				x								
											x		X						X	X				x	x					x				x								
											x		X						X	X				x	x					x				x								
	early	Rupelian			S. cf. membranaceus								x			x	x		x	x					X					x		X		X						S. cf. membranaceus	early	
													x			x	x		x	x					X					x		X		X								
													x			x	x		x	x					X					x		X		X								
													x			x	x		x	x					X					x		X		X								
													x			x	x		x	x					X					x		X		X								
													X						X	X					X					x				x								
EOCENE	late	Priabonian			T. boreale			x					X						X	X					X					x				x			x			T. boreale	late	EOCENE
								x					X						X	X					X					x				x			x					
					K. curiosum															x	x				x					x				x						K. curiosum		
	middle	Bartonian																		x	x				x					x				x							middle	
		Lutetian																																								
	early	Ypresian																																							early	
PALEOCENE	late	Thanetian																																							late	PALEOCENE

Figure 9. Dinocyst zones erected for the Navarin Basin, Norton Sound and the St. George Basin COST wells by Matsuoka & Bujak (1988).

AGE / STAGE			WOLFE STAGE (after Finzel et al. 2009) (ages are approximate)	BRISTOL BAY BASIN LITHOSTRATIGRAPHY (after Finzel et al. 2009) (ages are approximate)	DIATOMS (Koizumi 1973, 1975; Barron 1980)	HIGH LATITUDE SILICOFLAGELLATES & EBRIDIANS (Ling 1973, 1977, 1980)	NAVARIN BASIN, NORTON SOUND & ST GEORGE BASIN (Bujak & Matsuoka 1988)	Filisphaera filifera	Brigantedinium spp.	Impagidinium japonicum	Impagidinium velorum	Filisphaera pilosa	Selenopemphix quanta	Selenopemphix crenata	Xandarodinium variabile	Operculodinium cf. centrocarpum	Hystrichokolpoma rigaudia	Selenopemphix nephroides	Spiniferites aquilonius	Hystrichosphaeropsis variabilis	Algidasphaeridium capillatum	Evittosphaerula sp. A	Reticulatosphaera actinocoronata	Spiniferites frigidua	Tectatodinium minutum	Impagidinium cornutum	Spiniferites coanus	Impagidinium manumii	Spiniferites ellipsoideus	Hystrichosphaeropsis arctica	Tuberculodinium rossignolae	Spiniferites reductus	Operculodinium alsium	Operculodinium wallii	Spiniferites hexatypicus	Spiniferites nortonensis	Achomosphaera spongiosa	Distatodinium paradoxum	Heteraulacacysta campanula	Lingulodinium machaerophorum	Lingulodinium brevispinum	Rottnestia ovata	Spiniferites pseudofurcatus	Tuberculodinium vancampoae	Dapsilidinium pastielsii	Pentadinium laticinctum granulatum	Leujeunecysta convexa	Diphyes cf. colligerum sensu Bujak & Matsuoka 19	Systematophora ancyrea/placacantha	Lejeunecysta fallax	Leujeunecysta granosa	Chiropteridium mespilanum	Trinovantedinium boreale	Hystrichosphaeropsis complanata	Phthanoperidinium bennettii	Lejeunecysta hyalina	Areosphaeridium diktyoplokus	Hystrichokolpoma salacium	AGE / STAGE	
PLEISTOCENE		Ioanian	Clamgulchian	Milky River Fm	D. seminae	D. octangulatus	F. filifera	x																																															**PLEISTOCENE**
					R. curvirostris	D. octanarius		x																																														
		Calabrian			A. ocuatus	D. subarctios		x																																														
PLIOCENE	late	Gelasian					F. pilosa	x	x	x	x	x	x	x	x	x	x	x																																								late	**PLIOCENE**
								x	x	x	x	x	x	x	x	x	x	x																																									
		Piacenzian			D. seminae fossilis	A. rectangulare		x	x	x	x	x	x	x	x	x	x	x																																									
								x	x	x	x	x	x	x	x	x	x	x																																									
	early	Zanclean				E. antiqua antiqua		x	x	x	x	x	x	x	x	x	x	x																																								early	
					D. seminae fossilis - D. kamtschatica			x	x	x	x	x	x	x	x	x	x	x																																									
						D. jimlingii		x	x	x	x	x	x	x	x	x	x	x																																									
				Bear Lake Fm upsection change from fluvial, to tidal, to marine' (Finzel et al 2009)	D. kamtschatica	D. quniququangellus		x	x	x	x	x	x	x	x	x	x	x																																									
MIOCENE	late	Messinian					H. variabilis	x	x	x	x	x		x	x	x	x	x	x	x																																						late	**MIOCENE**
			Homerian		D. hustedtii			x	x	x	x	x		x	x	x	x	x	x	x																																							
		Tortonian				Mesoceno-circulua apiculata		x	x	x	x	x		x	x	x	x	x	x	x																																							
								x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x																													
					D. hustedtii - D. lauta			x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x																					
								x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x																					
	middle	Serravallinian	Seldovian			D. schauinslandii	no data (section absent or devoid of dinoflagellates)																																																				middle	
		Langhian			D. lauta	C. triacantha																																																				
						no data (section absent or devoid of dinoflagellates)																																																					
	early	Burdigalian		Unga Fm	A. ingens		H. campanula		x		x					x	x	x			x		x		x			x	x		x		x	x	x	x	x	x	x																					early	
									x		x					x	x	x			x		x		x			x	x		x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x											
					no data (section absent or devoid of dinoflagellates)				x		x					x	x	x			x		x		x			x	x		x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x											
									x		x					x	x	x			x		x		x			x	x		x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x											
		Aquitanian							x		x					x	x	x			x		x		x			x	x		x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x											
									x		x					x	x	x			x		x		x			x	x		x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x											
									x		x					x	x	x			x		x		x			x	x		x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x											
OLIGOCENE	late	Chattian	Angoonian						x		x					x	x	x						x		x																								x										late	**OLIGOCENE**
											x					x		x						x		x																								x											
				section absent			no data (section absent or devoid of dinoflagellates)																																																				
	early	Rupelian																																																							early	
			unnamed																																																							
							I. velorum				x					x		x					x		x																								x	x	x	x								
				Stepovak Fm interfingering with Meshik volcanics							x					x		x					x		x																								x	x	x	x								
			Kummerian								x					x		x					x		x																								x	x	x	x								
							T. boreale									x		x					x		x																								x				x	x	x	x				
EOCENE	late	Priabonian	Ravenian				A. diktyoplokus									x																																			x				x		x		x	x	late	**EOCENE**
																x																																			x				x		x		x	x		
							no data (section absent or devoid of dinoflagellates)																																																			
	middle	Bartonian		section absent																																																				middle	
		Lutetian																																																							
			Fultonian																																																							
				Tolstoy Fm																																																					
			Franklinian																																																							
	early	Ypresian																																																						early	
PALEOCENE	late	Thanetian	unnamed																																																					late	**PALEOCENE**

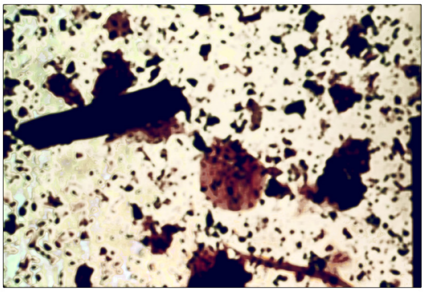
Figure 10. Composite North Pacific - Bering Sea palynological zonation of Bujak (this study).

REGIONAL NORTH PACIFIC - BERING SEA PALYNOLOGICAL ZONATION (THIS STUDY)
Key to symbols: x present; **X** abundant; black x indicates range in the Bering Sea - Aleutian area; taxa shown in red present in the Japanese area but not in the Bering Sea - Aleutian area; red x indicates extended range in Japanese area due to warmer waters. Species and their zonal highest occurrences (e.g., Beringella fritilla / PL2) are listed in order of their highest occurrences in the Bering Sea - Aleutian area.

Figure 11. Regional North Pacific – Bering Sea palynological zonation of Bujak (this study) plotted against other relevant microfossil schemes and Alaskan stages.

AGE / STAGE			COMPOSITE NORTH PACIFIC - BERING SEA DINOFLAGELLATE ZONATION (THIS STUDY)		WOLFE STAGE (after Finzel et al. 2009) (ages are approximate)	BRISTOL BAY BASIN LITHOSTRATIGRAPHY (after Finzel et al. 2009) (ages are approximate)	DIATOMS (Koizumi 1973, 1975; Barron 1980)	HIGH LATITUDE SILICOFLAGELLATES & EBRIDIANS (Ling 1973, 1977, 1980)	BERING SEA DINOFLAGELLATES (Bujak 1984)	NAVARIN BASIN, NORTON SOUND & ST GEORGE BASIN (Bujak & Matsuoka 1988)	JAPAN (Kazumi et al. 1984 on shore and Kurita & Obuse 2003 ODPHole 1151A)	MID TO HIGH LATITUDE ATLANTIC REGION	AGE / STAGE	
PLEISTOCENE		Ioanian	**S. frigidus**	**PL2**	Clamgulchian	Milky River Fm	D. seminae	D. octangulatus	S. frigidus	F. filifera	not applicable to the North Aleutian Basin in the Late Miocene-Pleistocene	not applicable to the North Aleutian Basin in the Oligocene-Neogene		**PLEISTOCENE**
							R. curvirostris	D. octanarius						
		Calabrian	**N. lemniscata**	**PL1**			A. ocuatus	D. subarctios	N. lemniscata					
PLIOCENE	late	Gelasian	**I. pacificum**	**P2**					I. pacificum	F. pilosa			late	**PLIOCENE**
		Piacenzian					D. seminae fossilis	A. rectangulare						
	early	Zanclean						E. antiqua antiqua					early	
			S. ovatus	**P1**			D. seminae fossilis - D. kamtschatica		S. ovatus					
								D. jimlingii						
						Bear Lake Fm upsection change from fluvial, to tidal, to marine' (Finzel et al 2009)	D. kamtschatica	D. quniququangellus						
MIOCENE	late	Messinian	**H. variabilis**	**M3b**						H. variabilis			late	**MIOCENE**
					Homerian		D. hustedtii							
		Tortonian						Mesoceno-circulua apiculata						
				M3a										
							D. hustedtii - D. lauta							
	middle	Serravallinian			Seldovian			D. schauinslandii	no data (section absent or devoid of dinoflagellates)	no data (section absent or devoid of dinoflagellates)			middle	
			O. echigoense	**M2b**							O. echigoense			
		Langhian		**M2a**			D. lauta	C. triacantha			D. latiusculum			
								no data (section absent or devoid of dinoflagellates)						
	early	Burdigalian	**H. campanula**	**M1**		Unga Fm	A. ingens			H. campanula	no data (section absent or devoid of dinoflagellates)		early	
							no data (section absent or devoid of dinoflagellates)							
		Aquitanian												
OLIGOCENE	late	Chattian	**G. inflata**	**O3**	Angoonian				G. inflata				late	**OLIGOCENE**
						section absent				no data (section absent or devoid of dinoflagellates)				
	early	Rupelian	**S. cf. membranaceus**	**O2**					S. cf. membranaceus				early	
					unnamed									
										I. velorum				
						Stepovak Fm interfingering with Meshik volcanics								
					Kummerian									
			T. boreale	**O1**						T. boreale *				
EOCENE	late	Priabonian	**A. diktyoplokus**	**E4**	Ravenian				T. boreale *	A. diktyoplokus		A. diktyoplokus	late	**EOCENE**
									K. curiosum **	no data (section absent or devoid of dinoflagellates)				
	middle	Bartonian	**P. distinctum**	**E3**		section absent						P. distinctum	middle	
									no data (section absent or devoid of dinoflagellates)					
		Lutetian	**D. colligerum**	**E2**								D. colligerum		
									* see report text for explanation of the T. boreale Zone nomenclature and age assignment					
					Fultonian									
						Tolstoy Fm								
					Franklinian				** Kallosphaeridium curiosum Zone poorly constrained and assigned an undifferentiated 'middle to late Eocene age' by Bujak (1984)					
	early	Ypresian	**C. columna**	**E1**								C. columna	early	
PALEOCENE	late	Thanetian	**A. homomorphum**	**P**	unnamed							A. homomorphum	late	**PALEOCENE**

PLATE 1



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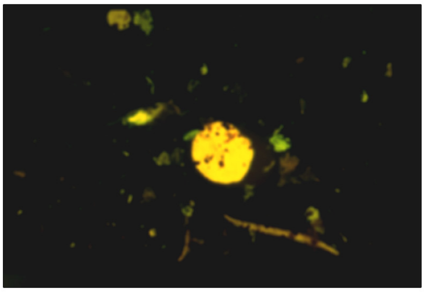

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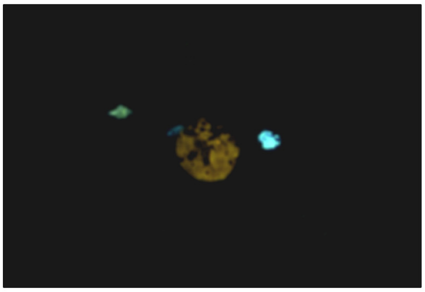

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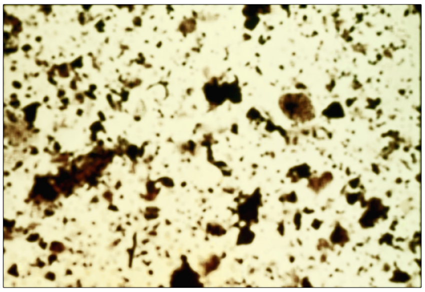

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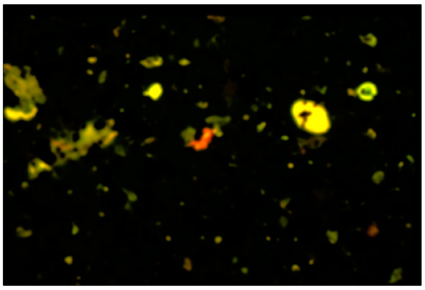

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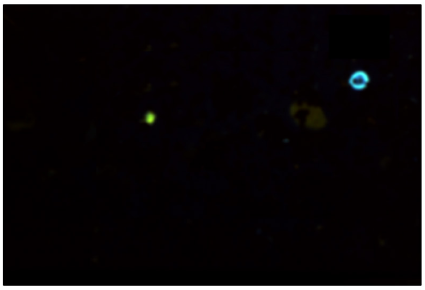

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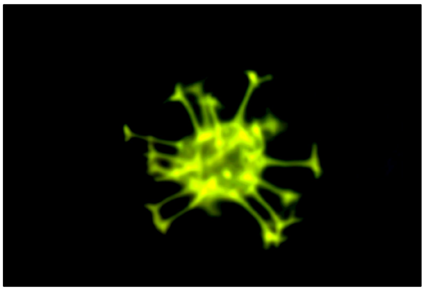

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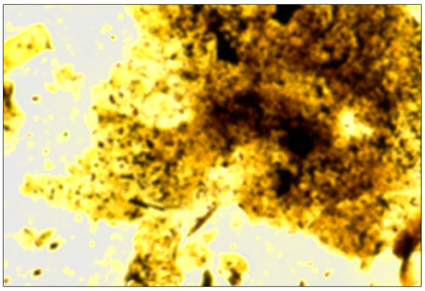

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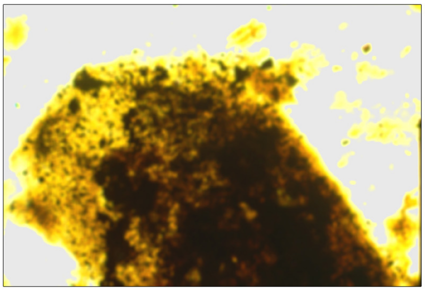
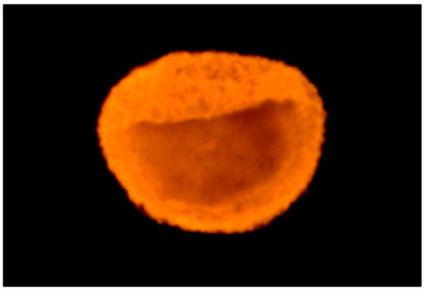


10

Link To
Plate Caption



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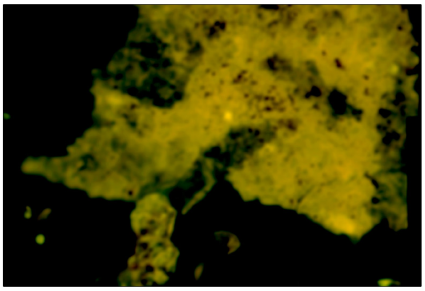

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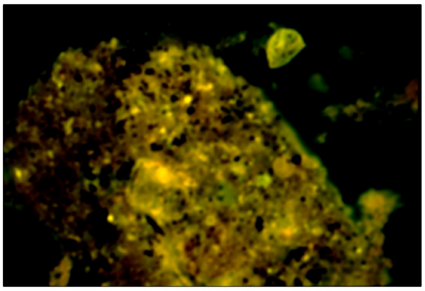


12

APPENDIX A

Stratigraphic Charts 1 and 2

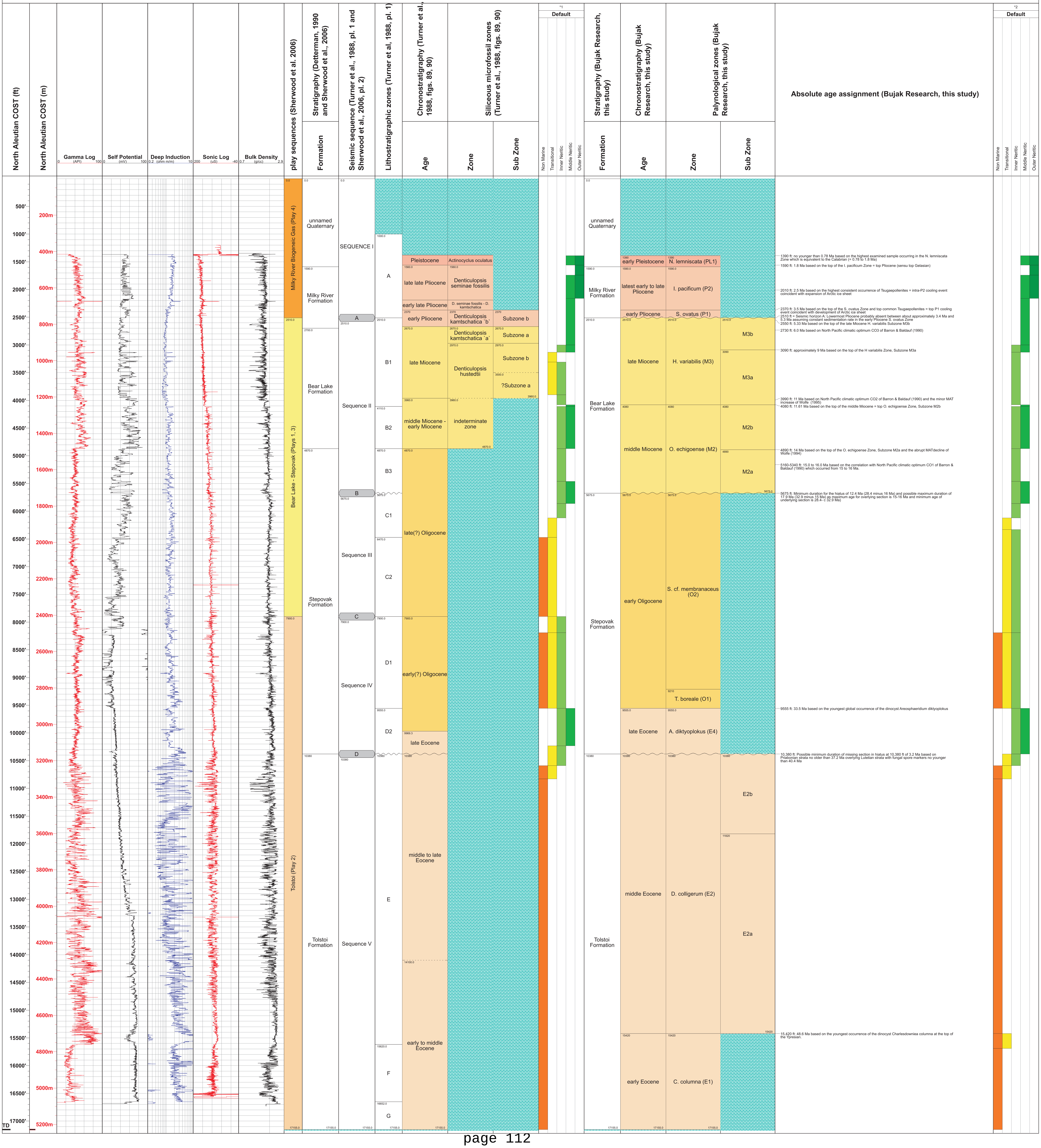
Well Name : North Aleutian COST 1

Interval Various
Scale : 1:10000
Chart date: 18 December 2009

North Aleutian Shelf COST 1 well
Stratigraphic Chart 1
Bujak Research International Ltd

Bujak and Associates
UK

Text Keys
*1 Palaeoenvironment (Turner et al., 1988, pl. 1, fig. 90)
*2 Palaeoenvironment (Bujak Research, this study)



1390 ft: no younger than 0.78 Ma based on the highest examined sample occurring in the N. lemniscata Zone which is equivalent to the Calabrian (= 0.78 to 1.8 Ma)

1590 ft: 1.8 Ma based on the top of the I. pacificum Zone = top Pliocene (sensu top Gelasian)

2010 ft: 2.5 Ma based on the highest consistent occurrence of Tsugaepollenites = intra-P2 cooling event coincident with expansion of Arctic ice sheet

2370 ft: 3.5 Ma based on the top of the S. ovatus Zone and top common Tsugaepollenites = top P1 cooling event coincident with development of Arctic ice sheet

2510 ft = Seismic horizon A: Lowermost Pliocene probably absent between about approximately 3.4 Ma and 5.3 Ma assuming constant sedimentation rate in the early Pliocene S. ovatus Zone

2550 ft: 5.33 Ma based on the top of the late Miocene H. variabilis Subzone M3b

2730 ft: 6.0 Ma based on North Pacific climatic optimum CO3 of Barron & Baldauf (1990)

3090 ft: approximately 9 Ma based on the top of the H variabilis Zone, Subzone M3a

3990 ft: 11 Ma based on North Pacific climatic optimum CO2 of Barron & Baldauf (1990) and the minor MAT increase of Wolfe (1995)

4080 ft: 11.61 Ma based on the top of the middle Miocene = top O. echigoense Zone, Subzone M2b

4890 ft: 14 Ma based on the top of the O. echigoense Zone, Subzone M2a and the abrupt MATdecline of Wolfe (1994)

5160-5340 ft: 15.0 to 16.0 Ma based on the correlation with North Pacific climatic optimum CO1 of Barron & Baldauf (1990) which occurred from 15 to 16 Ma.

5675 ft: Minimum duration for the hiatus of 12.4 Ma (28.4 minus 16 Ma) and possible maximum duration of 17.9 Ma (32.9 minus 15 Ma) as maximum age for overlying section is 15-16 Ma and minimum age of underlying section is 28.4- c 32.9 Ma)

9555 ft: 33.5 Ma based on the youngest global occurrence of the dinocyst Areosphaeridium diktyoplokus

10,380 ft: Possible minimum duration of missing section in hiatus at 10,380 ft of 3.2 Ma based on Priabonian strata no older than 37.2 Ma overlying Lutetian strata with fungal spore markers no younger than 40.4 Ma

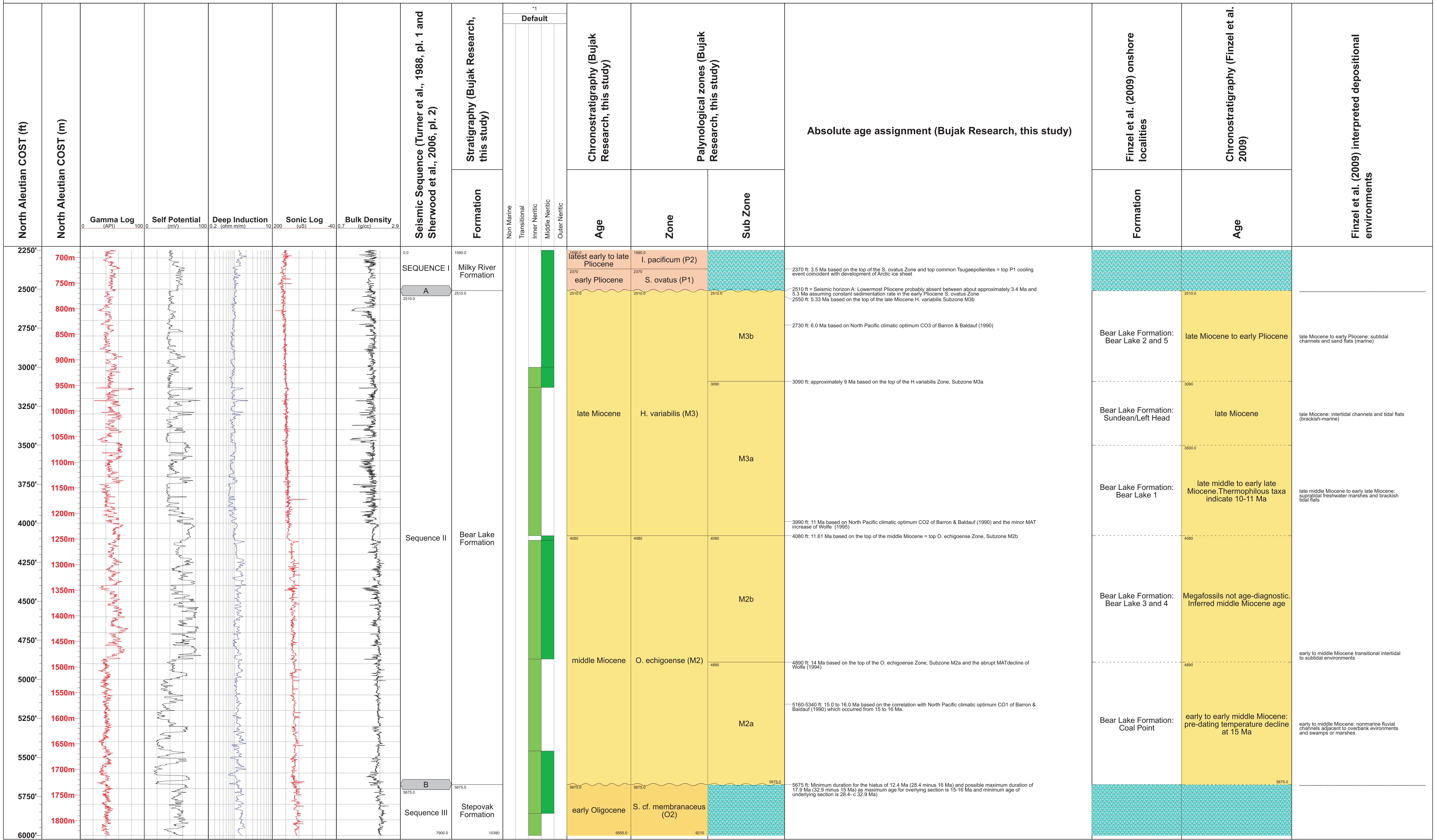
15,420 ft: 48.6 Ma based on the youngest occurrence of the dinocyst Charlesdowniea columna at the top of the Ypresian.

Well Name : North Aleutian COST 1

Bujak and Associates UK

Interval Various | North Aleutian Shelf COST 1 well
Scale : 1:5000 | Stratigraphic Chart 2
Chart date: 18 December 2009 | Bujak Research International Ltd
Bear Lake Formation: correlation with onshore data of Finzel et al. (2009)

Text Keys
*1 Palaeoenvironment (Bujak Research, this study)



Seismic Sequence (Turner et al., 1988, pl. 1 and Sherwood et al., 2006, pl. 2)	Stratigraphy (Bujak Research, this study): Formation	Chronostratigraphy (Bujak Research, this study): Age	Palynological zones (Bujak Research, this study): Zone	Palynological zones: Sub Zone	Finzel et al. (2009) onshore localities: Formation	Chronostratigraphy (Finzel et al. 2009): Age	Finzel et al. (2009) interpreted depositional environments
0.0 SEQUENCE I	1590.0 Milky River Formation	1590.0 latest early to late Pliocene	1590.0 I. pacificum (P2)				
		2370 early Pliocene	2370 S. ovatus (P1)				
2510.0 Sequence II	2510.0 Bear Lake Formation	2510.0 late Miocene	2510.0 H. variabilis (M3)	2510.0 M3b	Bear Lake Formation: Bear Lake 2 and 5	2510.0 late Miocene to early Pliocene	late Miocene to early Pliocene: subtidal channels and sand flats (marine)
				3090 M3a	Bear Lake Formation: Sundean/Left Head	3090 late Miocene	late Miocene: intertidal channels and tidal flats (brackish-marine)
					Bear Lake Formation: Bear Lake 1	3500.0 late middle to early late Miocene.Thermophilous taxa indicate 10-11 Ma	late middle Miocene to early late Miocene: supratidal freshwater marshes and brackish tidal flats
		4080 middle Miocene	4080 O. echigoense (M2)	4080 M2b	Bear Lake Formation: Bear Lake 3 and 4	4080 Megafossils not age-diagnostic. Inferred middle Miocene age	early to middle Miocene transitional intertidal to subtidal environments
				4890 M2a	Bear Lake Formation: Coal Point	4890 early to early middle Miocene: pre-dating temperature decline at 15 Ma	early to middle Miocene: nonmarine fluvial channels adjacent to overbank evironments and swamps or marshes
5675.0 Sequence III	5675.0 Stepovak Formation	5675.0 early Oligocene	5675.0 S. cf. membranaceus (O2)	5675.0		5675.0	
7900.0	10380	9555.0		9210			

Absolute age assignment (Bujak Research, this study)

2370 ft: 3.5 Ma based on the top of the S. ovatus Zone and top common Tsugaepollenites = top P1 cooling event coincident with development of Arctic ice sheet

2510 ft = Seismic horizon A: Lowermost Pliocene probably absent between about approximately 3.4 Ma and 5.3 Ma assuming constant sedimentation rate in the early Pliocene S. ovatus Zone

2550 ft: 5.33 Ma based on the top of the late Miocene H. variabilis Subzone M3b

2730 ft: 6.0 Ma based on North Pacific climatic optimum CO3 of Barron & Baldauf (1990)

3090 ft: approximately 9 Ma based on the top of the H variabilis Zone, Subzone M3a

3990 ft: 11 Ma based on North Pacific climatic optimum CO2 of Barron & Baldauf (1990) and the minor MAT increase of Wolfe (1995)

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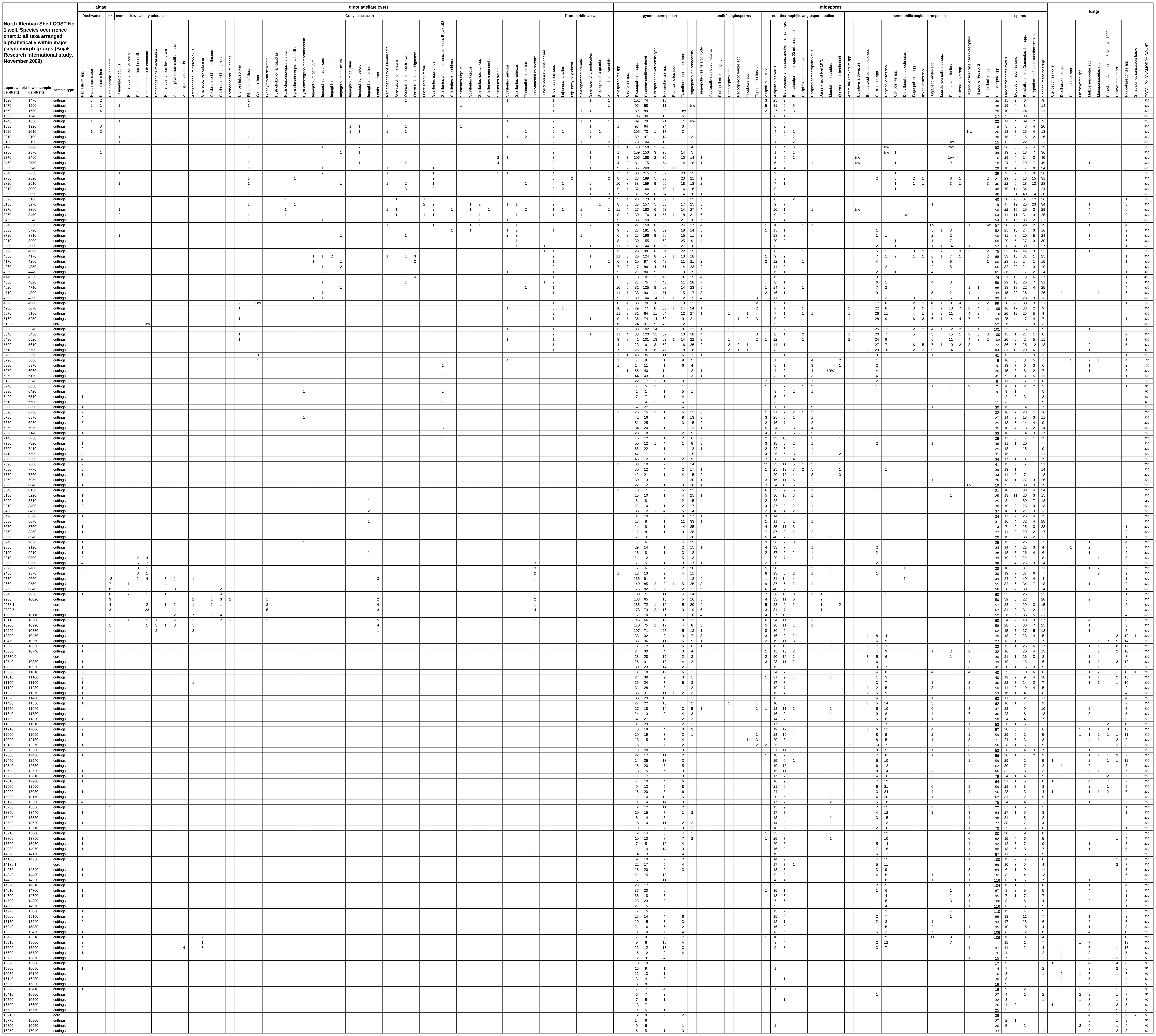
5675 ft: Minimum duration for the hiatus of 12.4 Ma (28.4 minus 16 Ma) and possible maximum duration of 17.9 Ma (32.9 minus 15 Ma) as maximum age for overlying section is 15-16 Ma and minimum age of underlying section is 28.4- c 32.9 Ma)

APPENDIX B

Species Occurrence Charts 1, 2, and 3

North Aleutian Shelf COST No. 1 well. Species occurrence chart 1: all taxa arranged alphabetically within major palynomorph groups (Bujak Research International study, November 2009)



algae

freshwater: Pediastrum spp.; Halodinium major; Halodinium minor

br: Paralecaniella indentata

mar: Tasmanites globulus

dinoflagellate cysts

low-salinity tolerant: Phthanoperidinium amoenum; Phthanoperidinium bennetii; Phthanoperidinium comatum; Phthanoperidinium echinatum; Phthanoperidinium levimurum

Gonyaulacacean: Adnatosphaeridium multispinosum; Areoligera senonensis; Areosphaeridium diktyoplokus; Charledowniea columna; Cordosphaeridium exilimurum; Cordosphaeridium gracile; Cordosphaeridium inodes; Diphyes latiusculum; Filisphaera filifera; Gelatia inflata; Glaphyrocysta semitecta; Hystrichokolpoma rigaudiae; Hystrichosphaeropsis arctica; Hystrichosphaeropsis variabilis; Hystrichostrogylon membraniphorum; Impagidinium cornutum; Impagidinium japonicum; Impagidinium manumii; Impagidinium pacificum; Impagidinium pallidum; Impagidinium velorum; Impagidinium velorum; Lentinia serrata; Nematosphaeropsis lemniscata; Operculodinium alsium; Operculodinium centrocarpum; Operculodinium echigoense; Operculodinium wallii; Spiniferites aquilonius; Spiniferites cf. membranaceus sensu Bujak 1984; Spiniferites ellipsoideus; Spiniferites frigidus; Spiniferites frigidus; Spiniferites hexatypicus; Spiniferites nortonensis; Spiniferites ovatus; Spiniferites ramosus; Spiniferites reductus; Tectatodinium pellitum; Trinovantedinium boreale; Tuberculodinium rossignoliae

Protoperidiniacean: Brigantedinium spp.; Lejeunecysta fallax; Lejeunecysta globosa; Selenopemphix crenata; Selenopemphix nephroides; Selenopemphix quanta; Xandarodinium variabile

miospores

gymnosperm pollen: Abiespollenites spp.; Cedripites spp.; Piceaepollenites spp.; Pinaceae undifferentiated; Pinuspollenites koraiensis-type; Pinuspollenites spp.; Podocarpidites spp.; Taxodiaceaepollenites spp.; Tsugaepollenites canadensis; Tsugaepollenites heterophlycta

undiff. angiosperms: Aquilapollenites quadrilobatus; Pistillipollenites mcgregorii; Retitricolpites spp.; Reticolporopollenites spp.; Tricolpites spp.; Triporopollenites spp.

non-thermophilic angiosperm pollen: Alnipollenites trina; Alnipollenites verus; Betulaceoipollenites spp. greater than 20 micron; Betulaceoipollenites spp. 20 microns or less; Ericipites antecursorioides; Ericipites compactipolleniatus; Jusseia sp. of Piel 1971; Momipites coryloides; Quercoidites microhenrici

thermophilic angiosperm pollen: Artemisia-Taraxacum spp.; Boisduvalia clavatites; Bombacacidites bombacoides; Carpinipites spp.; Caryapollenites spp.; Compositae spp.; Diervillapollenites echinatus; Faguspollenites spp.; Ilexpollenites spp.; Juglanspollenites spp.; Liquidambarpollenites spp.; Pterocaryapollenites spp.; Salixpollenites spp.; Tiliaepollenites crassipites / vescipites; Tiliaepollenites sp. S; Ulmipollenites spp.

spores: Deltoidospora spp.; Laevigatosporites ovatus; Lycopodiumsporites spp.; Baculatisporites / Osmundacidites spp.; Polypodiaceae / Dennstaedtiaceae spp.; Sphagnumsporites spp.

fungi: Ctenosporites wolfei; Dicellaesporites spp.; Diporisporites spp.; Microthyrites spp.; Multicellaesporites spp.; Monoporisporites spp.; Pesavis sp. A, Ioannides & McIntyre 1980; Pesavis tagluensis; Pluricellaesporites spp.; Striadiporites sanctaebarbarae

TOTAL PALYNOMORPH COUNT

upper sample depth (ft)	lower sample depth (ft)	sample type	Pediastrum spp.
1390	1470	cuttings	
1470	1560	cuttings	
1560	1650	cuttings	
1650	1740	cuttings	
1740	1830	cuttings	
1830	1920	cuttings	
1920	2010	cuttings	
2010	2100	cuttings	
2100	2190	cuttings	
2190	2280	cuttings	
2280	2370	cuttings	
2370	2460	cuttings	
2460	2550	cuttings	
2550	2640	cuttings	
2640	2730	cuttings	
2730	2820	cuttings	
2820	2910	cuttings	
2910	3000	cuttings	
3000	3090	cuttings	
3090	3180	cuttings	
3180	3270	cuttings	
3270	3360	cuttings	
3360	3450	cuttings	
3450	3540	cuttings	
3540	3630	cuttings	
3630	3720	cuttings	
3720	3810	cuttings	
3810	3900	cuttings	
3900	3990	cuttings	
3990	4080	cuttings	
4080	4170	cuttings	
4170	4260	cuttings	
4260	4350	cuttings	
4350	4440	cuttings	
4440	4530	cuttings	
4530	4620	cuttings	
4620	4710	cuttings	
4710	4800	cuttings	
4800	4890	cuttings	
4890	4980	cuttings	
4980	5070	cuttings	
5070	5160	cuttings	
5160	5250	cuttings	
5195.3		core	
5250	5340	cuttings	
5340	5430	cuttings	
5430	5520	cuttings	
5520	5610	cuttings	
5610	5700	cuttings	
5700	5790	cuttings	
5790	5880	cuttings	
5880	5970	cuttings	
5970	6060	cuttings	
6060	6150	cuttings	
6150	6240	cuttings	
6240	6330	cuttings	
6330	6420	cuttings	
6420	6510	cuttings	1
6510	6600	cuttings	
6600	6690	cuttings	1
6690	6780	cuttings	2
6780	6870	cuttings	4
6870	6960	cuttings	3
6960	7050	cuttings	2
7050	7140	cuttings	1
7140	7230	cuttings	
7230	7320	cuttings	1
7320	7410	cuttings	2
7410	7500	cuttings	3
7500	7590	cuttings	4
7590	7680	cuttings	2
7680	7770	cuttings	3
7770	7860	cuttings	1
7860	7950	cuttings	
7950	8040	cuttings	1
8040	8130	cuttings	
8130	8220	cuttings	1
8220	8310	cuttings	1
8310	8400	cuttings	2
8400	8490	cuttings	3
8490	8580	cuttings	1
8580	8670	cuttings	
8670	8760	cuttings	1
8760	8850	cuttings	1
8850	8940	cuttings	2
8940	9030	cuttings	1
9030	9120	cuttings	1
9120	9210	cuttings	1
9210	9300	cuttings	2
9300	9390	cuttings	4
9390	9480	cuttings	3
9480	9570	cuttings	
9570	9660	cuttings	
9660	9750	cuttings	
9750	9840	cuttings	
9840	9930	cuttings	1
9930	10020	cuttings	
9978.1		core	
9982.5		core	
10020	10110	cuttings	
10110	10200	cuttings	
10200	10290	cuttings	
10290	10380	cuttings	
10380	10470	cuttings	
10470	10560	cuttings	
10560	10650	cuttings	1
10650	10740	cuttings	1
10730.0		core	
10740	10830	cuttings	1
10830	10920	cuttings	1
10920	11010	cuttings	2
11010	11100	cuttings	3
11100	11190	cuttings	1
11190	11280	cuttings	1
11280	11370	cuttings	1
11370	11460	cuttings	1
11460	11550	cuttings	1
11550	11640	cuttings	
11640	11730	cuttings	
11730	11820	cuttings	1
11820	11910	cuttings	
11910	12000	cuttings	2
12000	12090	cuttings	1
12090	12180	cuttings	
12180	12270	cuttings	1
12270	12360	cuttings	
12360	12450	cuttings	1
12450	12540	cuttings	
12540	12630	cuttings	
12630	12720	cuttings	1
12720	12810	cuttings	1
12810	12900	cuttings	1
12900	12990	cuttings	
12990	13080	cuttings	1
13080	13170	cuttings	2
13170	13260	cuttings	4
13260	13350	cuttings	3
13350	13440	cuttings	1
13440	13530	cuttings	
13530	13620	cuttings	1
13620	13710	cuttings	2
13710	13800	cuttings	
13800	13890	cuttings	1
13890	13980	cuttings	1
13980	14070	cuttings	1
14070	14160	cuttings	
14160	14250	cuttings	
14186.1		core	
14250	14340	cuttings	1
14340	14430	cuttings	1
14430	14520	cuttings	
14520	14610	cuttings	
14610	14700	cuttings	1
14700	14790	cuttings	1
14790	14880	cuttings	
14880	14970	cuttings	2
14970	15060	cuttings	1
15060	15150	cuttings	3
15150	15240	cuttings	2
15240	15330	cuttings	
15330	15420	cuttings	1
15420	15510	cuttings	1
15510	15600	cuttings	3
15600	15690	cuttings	2
15690	15780	cuttings	1
15780	15870	cuttings	
15870	15960	cuttings	
15960	16050	cuttings	1
16050	16140	cuttings	
16140	16230	cuttings	
16230	16320	cuttings	
16320	16410	cuttings	1
16410	16500	cuttings	
16500	16590	cuttings	
16590	16680	cuttings	
16680	16770	cuttings	
16715.0		core	
16770	16860	cuttings	
16860	16950	cuttings	
16950	17040	cuttings	

North Aleutian Shelf COST No. 1 well. Species occurrence chart 2: palynological zonal markers arranged by highest occurrence (Bujak Research International study, November 2009)

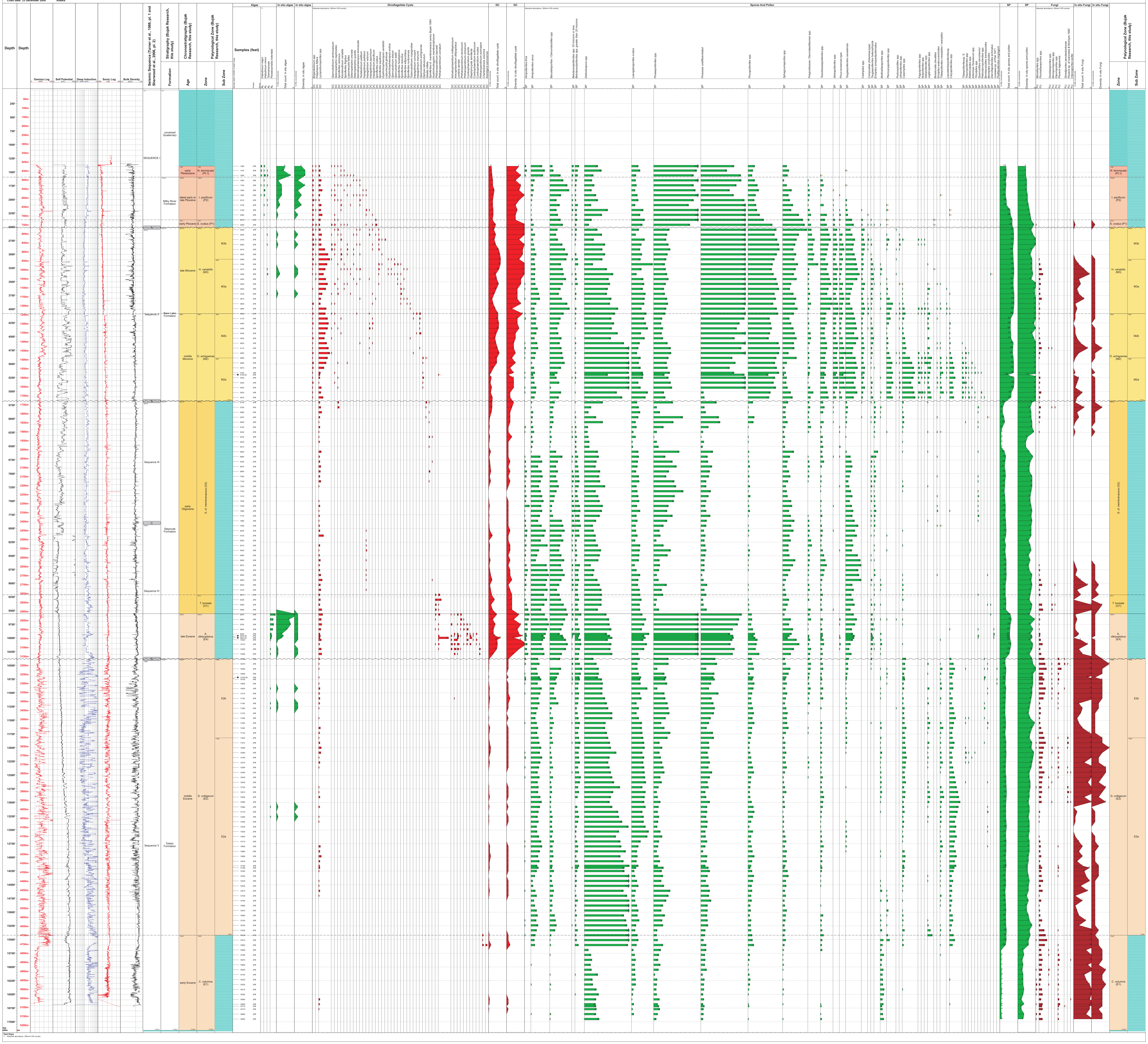
						Lithostratigraphy	Seismic horizons / sequences	Brigantedinium spp.	Filisphaera filifera	Halodinium major	Halodinium minor	Operculodinium centrocarpum	Selenopemphix nephroides	Spiniferites ramosus	Xandarodinium variabile	Spiniferites frigidus	Lejeunecysta fallax	Selenopemphix crenata	Selenopemphix quanta	Tectatodinium pellitum	Nematosphaeropsis lemniscata	Impagidinium pallidum	Impagidinium velorum	Impagidinium japonicum	Impagidinium pacificum	Spiniferites ovatus	Spiniferites aquilonius	Hystrichosphaeropsis variabilis	Leujeunecysta globosa	Hystrichosphaeropsis arctica	Operculodinium alsium	Operculodinium wallii	Spiniferites frigidus	Spiniferites hexatypicus	Spiniferites reductus	Spiniferites ellipsoideus	Spiniferites nortonensis	Tuberculodinium rossignolae	Impagidinium cornutum	Impagidinium manumii	Operculodinium echigoense	Diphyes latiusculum	Gelatia inflata	Spiniferites cf. membranaceus sensu Bujak 1984	Hystrichostrogylon membraniphorum	Impagidinium velorum	Phthanoperidinium bennetii	Phthanoperidinium comatum	Trinovantedinium boreale	Adnatosphaeridium miltispinosum	Areosphaeridium diktyoplokus	Lentinia serrata	Phthanoperidinium levimurum	Cordosphaeridium gracile	Glaphyrocysta semitecta	Cordosphaeridium exilimurum	Cordosphaeridium inodes	Pesavis tagluensis	Striadiporites sanctaebarbarae	Pesavis sp. A, Ioannides & McIntyre 1980	Pistillipollenites mcgregorii	Ctenosporites wolfei	Charledowneia edwardsii	Areoligera senonensis
fossil type: a algae; d dinocysts; f fungi; p pollen; s spores								d	d	a	a	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	f	f	f	p	f	d	d
sample depth (ft)		type	age	zone		zonal tops of marker species		PL2	PL2	PL2	PL2	PL2	PL1	PL2	PL1	PL2	P2	P2	P2	P2	PL1	P2	P2	P2	P2	P1	M3b	M3b	M3b	M3a	M3a	M3a	M3a	M3a	M3a	M3a	M3a	M3a	M3a	M3a	M2b	M2a	O3	O2	O2	O2	O1	O1	O1	E4	E4	E4	E4	E4	E4	E4	E4	E3	E2b	E2a	E2b	E2a	E1	E1
1390	1470	cuttings	PLEISTOCENE	N. LEMNISCATA (PL1)	PL1	UNNAMED QUATERNARY	I	1	1	3	2	1	1	1	1																																																					
1470	1560	cuttings						2	1	2	1				1	1																																																				
1590	log / seismic pick																																																																	
1560	1650	cuttings	EARLY TO LATE PLIOCENE top adjusted to break at 1590 ft	I. PACIFICUM (P2) top adjusted to break at 1590 ft	P2			1		2	4		1		1	1	1	1	1	3																																																	
1650	1740	cuttings						3			1								1	4	1																																															
1740	1830	cuttings						2		1	1		1	1	1		1	1		7																																																
1830	1920	cuttings						3			3	1	1			1				5		1	1																																													
1920	2010	cuttings						2		1	2	1	2				1		1	3	1	1	1																																													
2010	2100	cuttings						4	1				1	1	1					2																																																
2100	2190	cuttings						2			1				2			1		1																																																
2190	2280	cuttings						3	1						1								2	1																																												
2280	2370	cuttings						2			1		1							1			1		1																																											
2370	2460	cuttings	EARLY PLIOCENE	S. OVATUS (P1)	P1			3					1	1												2																																										
2460	2550	cuttings						2	2			2	2		1	1	1						1		1	4																																										
2510	log / seismic pick		LATE MIOCENE top adjusted to break at 2510 ft	H. VARIABILIS (M3) top adjusted to break at 2510 ft	M3b	BEAR LAKE	A																																																																
2550	2640	cuttings					II	2	1				1	2						1	1			1	1		1																																									
2640	2730	cuttings						4				1		1	1				1		1			2		1	1																																									
2730	2820	cuttings						3	1						2												2	1	2																																								
2820	2910	cuttings						4	1			2	2				1			1	1				1		1																																									
2910	3000	cuttings						3				3	1		1		2		1						1		2																																									
3000	3090	cuttings						2	1				1		3		1		1	1								1																																								
3090	3180	cuttings			M3a			3				1			2															1	1	1																																				
3180	3270	cuttings						2	1					1					1								2	1				2	1	2	1																															
3270	3360	cuttings						1							1		1	1		2	1						2			1	1		1			1	1																													
3360	3450	cuttings						1	1									1									1			1	1	1		1	1																															
3450	3540	cuttings							1					1					1	1				1										1		1																														
3540	3630	cuttings											2				1				1						1						1	1	1																															
3630	3720	cuttings						1						1																			1		2	1																														
3720	3810	cuttings										1		2				1							1										3																															
3810	3900	cuttings																		1						1									1	1	1																													
3900	3990	cuttings						3				1	1												1										1		1	1																												
3990	4080	cuttings						1																														1																												
4080	4170	cuttings	MIDDLE MIOCENE	O. ECHIGOENSE (M2)	M2b			2				1	1								1			1															1	2	3																									
4170	4260	cuttings						1							1										1														1		2																									
5195.3		core																																													1rw																
4260	4350	cuttings						2					1											1	2																1																									
4350	4440	cuttings						1				1		1										3	1																1																									
4440	4530	cuttings						1							1																									1	4																									
4530	4620	cuttings						2				1												1														1																												
4620	4710	cuttings						1												1					1																																							
4710	4800	cuttings						1																1																	1																									
4800	4890	cuttings						2				1												1															1																											
4890	4980	cuttings			M2a			1																																		2	1rw																						
4980	5070	cuttings						3									1																									1																							
5070	5160	cuttings						2																																																										
5160	5250	cuttings						1					1																													1																							
5250	5340	cuttings						1																																		3																							
5340	5430	cuttings						2					1																													1																							
5430	5520	cuttings						1																																		1																							
5520	5610	cuttings						1																																																										
5610	5700	cuttings						1																																																										
5675	log / seismic pick		EARLY OLIGOCENE top adjusted to break at 5675 ft	S . CF. MEMBRANACEUS (O3) top adjusted to break at 5675 ft	O2	STEPOVAK	B																																																												
5700	5790	cuttings					III																																				3	1																					
5790	5880	cuttings																																									1																						
5880	5970	cuttings																																										1																					
5970	6060	cuttings																																									1																						
6060	6150	cuttings																																																																	
6150	6240	cuttings																																																																	
6240	6330	cuttings																																																																
6330	6420	cuttings																																										2	1																				
6420	6510	cuttings																																																																
6510	6600	cuttings																																										1																					
6600	6690	cuttings																																																																
6690	6780	cuttings																																																																
6780	6870	cuttings																																											1																				
6870	6960	cuttings																																																																
6960	7050	cuttings																																										3																					
7050	7140	cuttings																																																																
7140	7230	cuttings																																										1																					
7230	7320	cuttings																																																															
7320	7410	cuttings																																																																
7410	7500	cuttings																																																																
7500	7590	cuttings																																																																
7590	7680	cuttings																																																																
7680	7770	cuttings																																																																
7770	7860	cuttings																																																																
7860	7950	cuttings																																																																
7900	log / seismic pick						C																																																											
7950	8040	cuttings					IV																																																											
8040	8130	cuttings																																												1																			
8130	8220	cuttings																																																																
8220	8310	cuttings																																												1																			
8310	8400	cuttings																																												1																			
8400	8490	cuttings																																												2																			
8490	8580	cuttings																																																																
8580	8670	cuttings																																												1																			
8670	8760	cuttings																																																															
8760	8850	cuttings																																												1																			
8850	8940	cuttings																																												1																			
8940	9030	cuttings																																											1	1																			
9030	9120	cuttings																																																																
9120	9210	cuttings																																												1																			
9210	9300	cuttings		T. BOREALE (O1)	O1																																										2	4	11															
9300	9390	cuttings																																													6	7																
9390	9480	cuttings																																													3	1	8															
9480	9570	cuttings																																													3	1																
9570	9660	cuttings	LATE EOCENE	A. DIKTYOPLOKUS (E4)	E4																																										2	4	3	1	1	3	3											
9660	9750	cuttings																																													1						4											
9750	9840	cuttings																																														1	1	3		1	2	2	1									
9840	9930	cuttings																																													1	1					1	4										
9930	10020	cuttings																																															2		2	2		3	1	1	2							
9978.1		core																																														2	1	2	1	4	1	1	3	1								
9982.5		core																																														23	4			3			5									
10,020	10,110	cuttings																																														1		2	7	1		4		1	2							
10,110	10,200	cuttings																																													1	2	1	4	3	5		2	3		1							
10,200	10,290	cuttings																																														1		3	5	4	1											
10,290	10,380	cuttings																																																	3	1												
10,380	log / seismic pick		MIDDLE EOCENE	D. COLLIGERUM (E2)	E2b	TOLSTOI	D																																																												
10,380	10,470	cuttings					V																																																			3	1					
10,470	10,560	cuttings																																																								5	2	?				
10,560	10,650	cuttings																																																								8			1			
10,650	10,740	cuttings																																																								2						
10,730.0		core																																																																
10,740	10,830	cuttings																																																								3			1			
10,830	10,920	cuttings																																																								1			1			
10,920	11,010	cuttings																																																									1					
11,010	11,100	cuttings																																																															
11,100	11,190	cuttings																																																	1													
11,190	11,280	cuttings																																																																
11,280	11,370	cuttings																																																																
11,370	11,460	cuttings																																																																
11,460	11,550	cuttings																																																																
11,550	11,640	cuttings																																																																
11,640	11,730	cuttings																																																																
11,730	11,820	cuttings																																																																
11,820	11,910	cuttings			E2a																																																							2				
11,910	12,000	cuttings																																																										3				
12,000	12,090	cuttings																																																										1				
12,090	12,180	cuttings																																																																
12,180	12,270	cuttings																																																																
12,270	12,360	cuttings																																																																
12,360	12,450	cuttings																																																										1				
12,450	12,540	cuttings																																																										1		1		
12,540	12,630	cuttings																																																															
12,630	12,720	cuttings																																																																
12,720	12,810	cuttings																																																										2				
12,810	12,900	cuttings																																																										4		1		
12,900	12,990	cuttings																																																										1				
12,990	13,080	cuttings																																																										2		1		
13,080	13,170	cuttings																																																																
13,170	13,260	cuttings																																																																
13,260	13,350	cuttings																																																																
13,350	13,440	cuttings																																																																
13,440	13,530	cuttings																																																																
13,530	13,620	cuttings																																																																
13,620	13,710	cuttings																																																																
13,710	13,800	cuttings																																																																
13,800	13,890	cuttings																																																																
13,890	13,980	cuttings																																																																
13,980	14,070	cuttings																																																																
14,070	14,160	cuttings																																																																
14,160	14,250	cuttings																																																																
14,186.1		core																																																																
14,250	14,340	cuttings																																																																
14,340	14,430	cuttings																																																																
14,430	14,520	cuttings																																																																
14,520	14,610	cuttings																																																																
14,610	14,700	cuttings																																																																
14,700	14,790	cuttings																																																																
14,790	14,880	cuttings																																																																
14,880	14,970	cuttings																																																																
14,970	15,060	cuttings																																																																
15,060	15,150	cuttings																																																																
15,150	15,240	cuttings																																																																
15,240	15,330	cuttings																																																																
15,330	15,420	cuttings																																																																
15,420	15,510	cuttings	EARLY EOCENE	C. COLUMNA (E1)	E1																																																										2	
15,510	15,600	cuttings																																																													1	
15,600	15,690	cuttings																																																													3	2
15,690	15,780	cuttings																																																																
15,780	15,870	cuttings																																																																
15,870	15,960	cuttings																																																													1		
15,960	16,050	cuttings																																																																
16,050	16,140	cuttings																																																																
16,140	16,230	cuttings																																																																
16,230	16,320	cuttings																																																																
16,320	16,410	cuttings																																																																
16,410	16,500	cuttings																																																																
16,500	16,590	cuttings																																																																
16,590	16,680	cuttings																																																													1		
16,680	16,770	cuttings																																																																
16,715.0		core																																																										?					
16,770	16,860	cuttings																																																																
16,860	16,950	cuttings																																																																
16,950	17,040	cuttings																																																																
17,155.0	TD																																																																	

Well Name : North Aleutian COST 1

Interval Various
Scale : 1:5000
Chart date: 23 December 2009

Species occurrence chart 3
prepared by Bujak Research International
Alaska

Bujak and Associates
UK



Text Keys
* : Absolute abundance (50mm=100 counts)