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PALEOCLIMATIC EVIDENCE FOR CENOZOIC MIGRATION OF ALASKAN TERRANES

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Abstract. Chronostratigraphic and paleoclimatic comparisons of microfossils from deep-sea cores, from samples of an exploratory drill hole, and from dredged rock of the Gulf of Alaska with coeval microfossil assemblages on the North American continent provide constraints on the northward migration of the Yakutat block, the Prince William terrane and the Pacific plate during Tertiary time. The comparative paleolatitudes of microfauna and flora provide three main constraints. (1) The Prince William terrane was in its present position with respect to North America (at high latitudes, 50° ± 5°N) by middle Eocene time (40-42 Ma), consistent with models derived from paleomagnetic data. (2) The adjacent Yakutat block was 30° ± 5° south of its present position in early Eocene (50 Ma), 20° ± 5° south in middle Eocene (40-44 Ma), and 15°± 5° south in late Eocene time (37-40 Ma), thus requiring a northward motion of about 30° since 50 Ma. Moreover, the Yakutat block was at least 10° south of the Prince William terrane during Eocene time. These data are consistent with migration of the Yakutat block with the Pacific and Kula plates for at least the last 50 Ma. (3) site 192 on the Pacific plate was at about 15° ± 5°N latitude in the late Cretaceous (68 Ma), at 30° ± 5°N in early Eocene (50 Ma), at 40° ± 5°N in middle Eocene (40-44 Ma), at 45° ± 5°N in late Eocene (37-40 Ma), and north of 50° ± 5°N in latest Eocene to early Oligocene time (34-37 Ma). These paleolatitudes, based on planktonic foraminiferal assemblages, indicate northward drift consistent with the North America-Pacific plate reconstructions from about 68 Ma to 40 Ma (Engebretson, 1982). However, from Cretaceous to early Eocene time, faunal data indicate significantly lower latitudinal positions, and from Oligocene to early Miocene time, significantly higher latitudinal positions. These discrepancies can be explained by the northward expansion of tropical faunas during the globally warm early Tertiary and southward expansion of cold subarctic faunas as a result of global cooling during Oligocene time.

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INTRODUCTION

The reconnaisance nature of sampling in the offshore areas of the Gulf of Alaska, and the sparce diversity of high-latitude microfauna and flora provide scarce material for a biostratigraphic and paleoecologic study of this area. Nevertheless, a review of available data and comparisons with coeval sequences in marine sections of California, Oregon, and Washington as well as deep-sea sections of

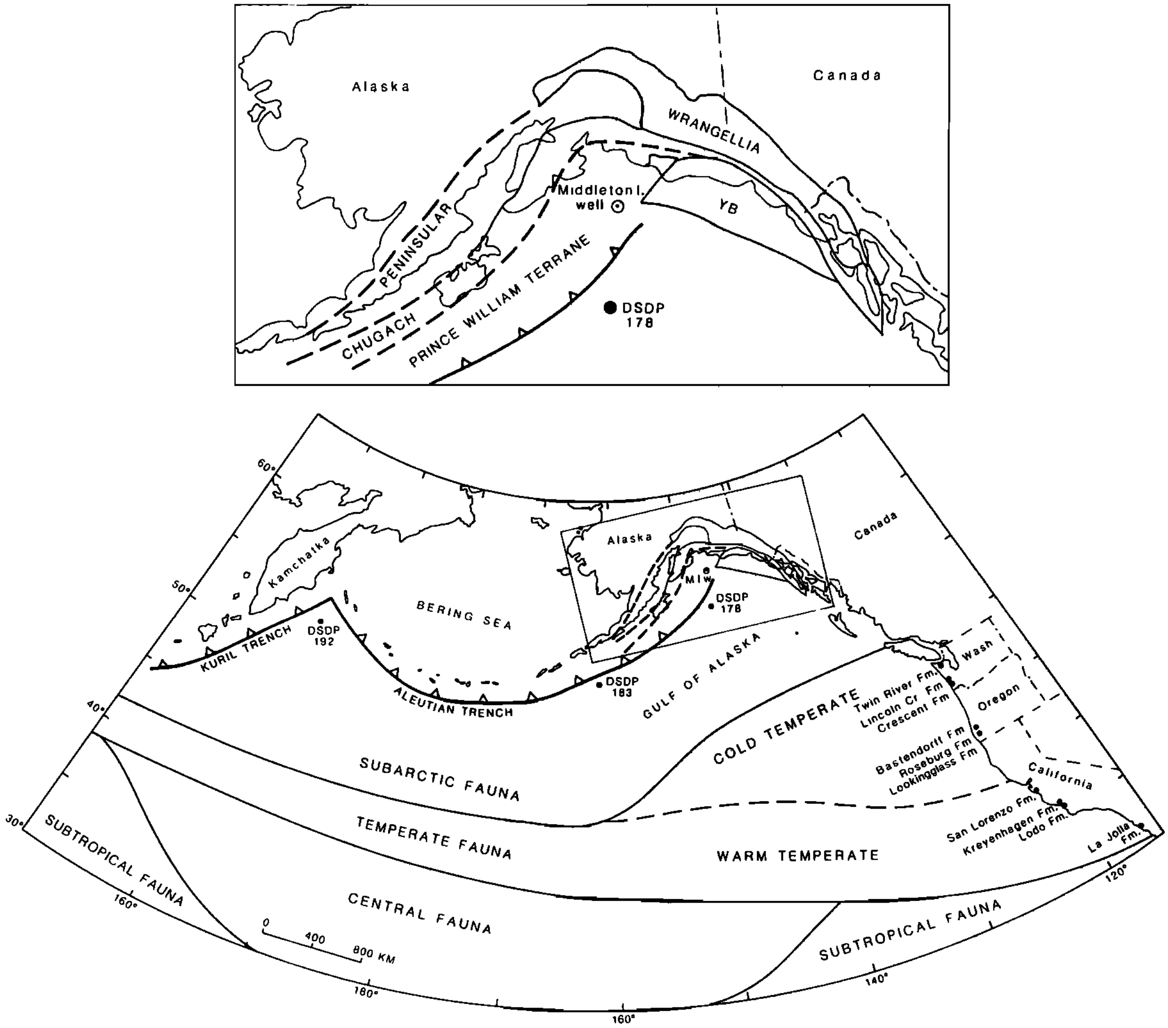

Fig. 1. Location map of sites studied, terrane boundaries after Jones et al. [1981], and geographic distribution of present faunal provinces.

the North Pacific have provided important constraints on the temporal and spatial positions of sediment deposited on allochthonous terranes in the Gulf of Alaska. In this study we summarize a reexamination of the scattered paleontologic data in a number of informal and unpublished reports of the U. S. Geological Survey, the State of Alaska, the Deep Sea Drilling Project, and new data from examination of material sampled in the Middleton Island exploratory well which was released to us by Tenneco Oil Company. From this biostratigraphy there emerges a paleobathymetric and paleoceanographic history of the western Gulf of Alaska.

Recent paleomagnetic information [Plumley et al., 1983] and tectonic models [Engebretson, 1982; Bruns, 1983a] indicate that the last of the terranes that are thought to have formed southern Alaska were moved into their present positions in Cenozoic time (Figure 1). Two terranes with Cenozoic migration histories are the Prince William terrane and Yakutat block [Jones et al., 1981; Rogers, 1977]. The Prince William terrane, which includes the Prince William Sound region and Kodiak Island, does not have well-defined geologic boundaries, but certainly includes the shelf adjacent to the Kodiak group of Islands. The Yakutat block is bounded on the northeast by the Fairweather fault and its continuation into the Chugach-Saint Elias thrust fault system, on the west by the thrust faults paralleling Kayak Island and crossing the adjacent shelf, and on the south by the base of the continental slope. The biostratigraphic and paleoclimatic records presented here set constraints independent of plate tectonic models on the position of these terranes during their Cenozoic northward migration.

This report is in two parts. We discuss the biostratigraphic, paleobathymetric and paleoceanographic data of the Yakutat block, Prince William terrane and the Pacific plate and infer their paleolatitude at the time fossiliferous sediment was deposited on them. The second part concerns the tectonic implications of these faunal and floral analyses, which we compare to the migration history of these terranes and the Pacific plate as proposed in published tectonic models.

Determination of paleolatitude positions is complicated by the fact that both our reference points, the North American plate and the Pacific plate, have moved through time. Our most precise paleopositions are derived from comparisons between coeval faunal assemblages on the Alaskan terranes and on the North American continental margin. However, the North American plate has been displaced southward by about 6° during the last 50 Ma. In the text and Table 1, we refer to paleolatitudes in the present earth coordinate system, referencing either the present latitude of onshore assembledges or the present Pacific faunal zones. In addition, in Table 2 and Figure 4, we correct for the Cenozoic southward drift of North America and give absolute paleolatitudes. Finally, in Figure 5, we show the travel paths of sites with respect to a fixed North American plate.

Our study was based on new materials from the Middleton Island well, on cores and dredge samples off Kodiak Island, and on reviews of original materials from studies of other investigators, principally W. W. Rau. We are grateful to W. W. Rau and for the cooperation of other investigators.

BIOSTRATIGRAPHIC AND PALEOCEANOGRAPHIC ANALYSES

Samples from the onshore and offshore regions of the Gulf of Alaska have been examined for planktonic and benthonic foraminifers, coccoliths and diatoms to determine their age, and infer the paleoclimatic conditions at the time of deposition. To obtain relative paleolatitudes, faunal assemblages have been correlated with onshore marine sequences of California, Oregon, and Washington. Interpretation of paleolatitudes are also aided by comparison with the present distribution of planktonic faunal provinces (subtropical, temperate, subarctic, Figure 1). These comparisons with present provinces are adjusted for the effects of major paleoclimatic changes. The main effect of globally warmer conditions, for instance, during Cretaceous through middle Eocene time, was a northward shift of the faunal provinces; conversely, during globally cooler conditions of the latest Eocene to Oligocene time the subarctic fauna expanded southward. Therefore at times of climatic extremes, our paleolatitude determinations based on planktonic faunal provinces may be 5°-10° in error. Where comparisons with coeval onshore sequences can be made, the paleolatitudes relative to the North American continent are better constrained. Vedder et al. [1983], Jones et al. [1983] and Beck [1980] show that northward movement of onshore sequences in California, Oregon, and Washington has not been significant during the past 50 m.y.

Vedder et al. [1983] suggest that the Sur-Obispo and Salinian composite terranes, as well as other terranes on which the La Jolla Group, and the Lodo, Kreyenhagen, and San Lorenzo Formations are deposited, were accreted to southern California in latest Paleocene or earliest Eocene time. In the Pacific northwest, paleomagnetic data show that localities including the Crescent, Flourney, and Roseburg Formation of Oregon and the Twin River Group and Lincoln Creek Formation of Washington have not been translated latitudinally since early Eocene time [Beck, 1980].

Microfossil analyses were provided by the authors [G. K. and K. M.] as well as from published sources. Coccoliths examined earlier and for this report were analyzed by Bukry [Plafker et al., 1979, 1980; Poore and Bukry, 1978]. Benthonic foraminifers were examined and reported by Rau [Rau et al., 1977; Rau, 1978; Plafker et al., 1979, 1980] and for this report by K. M. Planktonic foraminifers were reported from three dredge samples by Poore [Poore and Bukry, 1978] and were studied for this report by G. K. Diatoms, originally studied by Koizumi [1973] for sites 192 and 183, and Schrader [1973] for site 178, were re-examined by Harper [1977] and Barron [unpublished data, 1983]. This paper summarizes and combines these earlier studies with the results of our studies to provide a more comprehensive paleoclimatic and paleoceanographic history of the Gulf of Alaska region. Key samples for determinations of age and paleolatitude of the Yakutat block and Prince William terrane are summarized in Table 1. Paleontologic data are summarized in Figure 2 with respect to age, paleodepth and paleoenvironment. The absolute time scale is based on paleomagnetic calibrations of Berggren et al. [1984].

YAKUTAT BLOCK

Early Eocene: 50 Ma

Diverse and well preserved warm water planktonic foraminiferal and coccolith assemblages are present in dredge hauls S5-78-EG-43E, 43F, and Chan-79-41B from the lower continental slope of the Yakutat block (sample locations by Plafker et al. [979, 1980]). These samples contain common cool water Globorotalia pseudoscitula, Globigerina primitiva, G. linaperta, and warm water Globorotalia soldadoensis, Gl. bullbrooki, Gl. aragonensis and Gl. breodermanni. This assemblage is indicative of a subtropical to warm temperate depositional environment of late early Eocene age in planktonic foraminiferal Zone P8 or P9. The presence of Globorotalia bullbrooki, which first appears near the early/middle Eocene boundary, suggests that these samples are probably of Zone P9 age, or about 50 Ma. Similar faunal assemblages, although with more abundant cooler water elements were observed in the Roseburg Formation of Oregon [Miles, 1977; 1981] the Santa Lucia Range of northern California [Poore et al., 1977] and the Lodo Formation of California [Schmidt, 1970] as will be described later. These and additional samples have been examined for coccoliths by Bukry (in the work of Plafker et al. [979, 1980]; Poore and Bukry, [1978]). Their late early Eocene age Discoaster lodoensis Zone (CP11, about 50 Ma) is in close agreement with the age determined from planktonic forminifers in this report. A late early Eocene age is also indicated by benthic foraminiferal assemblages. Benthic species diagnostic of the provincial Ulatisian Stage are present in dredge samples S5,78-EG-43, Chan-79-41B and 43 as indicated by the co-occurrence of Dentalina hexacostata, Lenticulina turbinatus, Loxostomum applinae, Nodosaria latejugata, Planularia truncana, Silicosigmoilina californica, Vaginulinpsis asperuliformis and V. mexicana nudicostata. Hence a late early Eocene age which spans the planktonic foraminifer Zones P8-P9 interval [Poore, 1980, Figure 2] is compatible with the known range of the Ulatisian Stage.

Paleobathymetry

Deposition of benthic assemblages occurred at lower middle bathyal or deeper depths (1500 m or deeper). Assemblages are diverse and composed of lower middle bathyal species such as various species of Stilostomella, Gyroidina and fine grained arenaceous forms with siliceous cement (Spiroplectammina and Karreriella) and Silicosigmoilina californica. The bulk of the assemblages, however, are composed of species with shallower upper depth limits, such as Bulimina consanguinea, Cibicides fortunatus, Loxostomum applinae, Vaginulinopsis asperiformis, V. mexicana nudicostata and large lenticulinids. These specimens indicate transport from outer shelf and upper slope areas.

Paleolatitude

The planktonic forminiferal assemblages of the Yakutat block are similar, although more diverse and abundant, than those reported from coeval sequences of the northern Santa Lucia Range of California (present latitude 36°N) [Poore et al., 1977], the Lodo Formation of Fresno County (present latitude 37°N), California [Schmidt, 1970], and the Roseburg Formation of Oregon (present latitude 42°-45°N) [Miles, 1981]. The presence of the tropical to subtropical species Globorotalia soldadoensis, Gl. aragonensis and Gl. broedermanni along with cool water species in the Gulf of Alaska dredge samples, indicates a subtropical to warm temperate environment, or about 20°-30°N latitude in Eocene time [Keller, 1983a, b]. The comparative relation suggests that the Alaskan samples may have been slightly south of coeval California onshore marine sequences (Table 1). A few Globigerina primitiva were reported from the Roseburg Formation along with numerous other cool water species such as

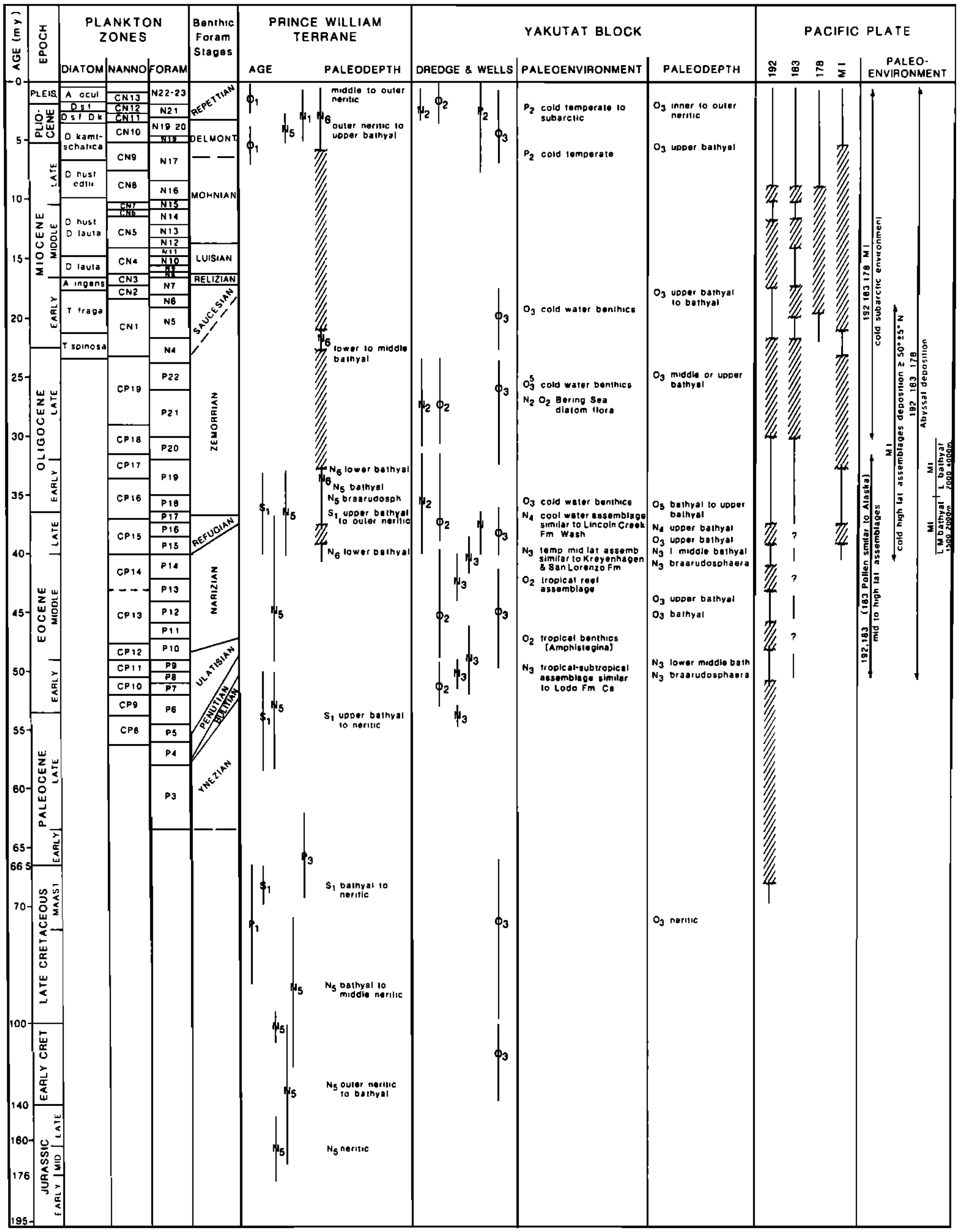

Fig. 2. Biostratigraphy, age ranges, paleodepth and paleoenvironment of samples studies for this report and/or published earlier from the Prince William terrane, Yakutat block, and Pacific plate. Age scale after Berggren et al. [1984], Plankton zones after Barron ([1980], diatoms), Okada and Bukry ([1980], nannofossils), Blow ([1969], foraminifera), and California benthic stages after Poore [1980]. Diagonal lines mark hiatuses. Codes: N, samples studied for this report; N1 (G. Keller, unpublished data, Kodiak shelf, 1983); N2 (J. A. Barron, unpublished data, Eastern Gulf of Alaska, 1983); N3 & N4 (G. Keller, this report, samples of Plafker et al. [1979, 1980]); N5 (K. McDougall, unpublished data, 1983,; Kodiak shelf and Kodiak Island-Lower Cook Inlet outcrop samples); N6 (this report, Middleton Island well); N7 (G. Keller and K. McDougall, unpublished data, Orca Group); O, Open-File Report; O1 (80-1237, McClellan et al. [1981]); O2 (80-1089, Plafker et al. [1980]); O3 (77-747, Rau et al. [1977]); P, published reports; P1 [Tysdal and Plafker, 1978]; P2 [Lattanzi, 1979]; P3 [Byrne, 1982]; S1, State of Alaska Open File Report 114 [Lyle and Morehouse, 1978].

TABLE 1. Summary of Chronostratigraphy, Paleobathymetry, Onshore Correlations and Paleolatitude Determinations Relative to Present Latitude of Onshore Assemblages of Pacific Faunal Zones of Key Samples From the Yakutat Block and Prince William (Middleton Island Well) Terrane.

Age	Zone	Samples	Paleobathymetry	Correlations	Present Latitude
Early Eocene 50 Ma	P8 or P9 CP11 Ulatisian	S5-EG-43E, 43F Chan-79-41B, 43	lower middle bathyal or deeper ≥1500 m downslope transport	Santa Lucia Range, Ca. Lodo Fm. Ca. La Jolla Fm., Ca. Guyabal Fm. and Aragon Fm., Mexico	subtropical to warm temperate 30° ± 5°N
Middle Eocene 44-40 Ma	P13 or P14 CP14b or CP15a Nariaian	S5-78-44E-44F, 44D, Chan-79- 36A, 36C, 41A, 43A 37C	lower middle bathyal or deeper ≥1500-2000 m lower bathyal, abyssal	Kreyenhagen Fm., Ca. San Lorenzo Fm., Ca. Lincoln Creek Fm., Washington	Temperate 40° ± 5°N
Late Eocene 40-36 Ma	P16-P17 P15 L. Narizian Refugian	W-79-45 72-APR-112 70A, 106E, 52A S2-77-E6 Chan-10A, 24B 39F, 39G, 38A	middle bathyal <1500 m (Narizian) upper slope-shelf transport in Refugian	Lincoln Creek Fm. Twin River Fm., Washington Bastendorff Fm., Oregon	cool temperate 45° ± 5°N
Middle Eocene 42-40 Ma	P15 or P14? CP14b or CP15a Narizian	Middleton Is. 3658-3642 m, 3639-3642 m	lower bathyal 2000-4000 m	S5-78-EG-44 Chan-79-36, 37	cold subarctic 50° ± 5°N
Late Eocene 38-36 Ma	P16-P17	3495-3432 m	Lower bathyal 2000-4000 m	W-79-45	cold subarctic 50° ± 5°N

Late Eocene/ Early Oligo. undifferent. 38-34? Ma	P17 or P18-P19 Narizian to Refugian	3347-3207 m, to 2347 m 3246-1329 m	lower bathyal 2000-4000m downslope transport	Lincoln Creek Fm., Washington, DSDP Site 192	cold subarctic north of 50° ± 5°N
Oligocene 32?-36 Ma	Zemorrian	1469-1213 m	lower to middle bathyal >1500 m downslope transport	Lincoln Creek Fm., Washington	present latitude
Early Miocene	Saucesian	1217-890 m	lower to middle bathyl >1500 m		present latitude
Late Miocene to Pleistocene		701-219 m	shelf, neritic		present latitude

Globigerina eocaena, G. subotina, G. varianta, Psuedohastigerina wilcoxensis, and numerous Truncortaloides collactea [Miles, 1981]. These assemblages suggest a cooler environment than in central and southern California (see also Miles [981]). Miles [1981, p. 99] also observed that "planktonic foraminifera of the Umpqua Group (Roseburg, Lookinglass, and Flournoy Formations) are similar to age equivalent faunas from California, but are less diverse and have a more temperate aspect." These cooler aspects of the Oregon assemblages, as compared to the dredge samples from the Yakutat block, suggest that deposition of the latter samples occurred south of the onshore Oregon marine sequences.

Coccolith assemblages of the Discoaster lodoensis Zone (CP11) are diverse and abundant (samples S5-78-EG-43E, 43F and S5-78-EG-45C). They also indicate warm surface water conditions as suggested by the abundance of Discoaster and Sphenolithus and sparse Chiasmolithus [Poore and Bukry, 1978]. However, no direct correlations have been made with onshore marine sequences.

Benthic foraminiferal assemblages also indicate a warm middle to low latitude environment. Benthic assemblages contain many of the same species reported by Mallory [1959] from the Vacaville Shale correlative with the Lodo Formation and other Ulatisian age deposits of the San Joaquin Valley, California, and Hanna's [1926] Rose Canyon Shale Member now abandoned of his La Jolla Formation near San Diego, California. The shelf and upper slope species of the Gulf of Alaska assemblages also resemble those of the subtropical, shallow water early to middle Eocene age assemblages of the Guyabal and Aragon Formations of Mexico (presently at about 21°N latitude) [Nuttal, 1930]. The Alaskan assemblages, however, are slightly less diverse and commonly contain larger, more highly ornamented forms than the California assemblages. These differences may either indicate selective transport and preservation, or a more southern site of deposition than the California assemblages.

Benthic foraminiferal assemblages of early Ulatisian age are also present in the Lookingglass and Roseburg Formations of the Umpqua Group, Oregon [Miles, 1981; Thoms, 1965], and in the Crescent Formation of southwestern Washington [Rau, 1966] and the Olympic Peninsula [Drugg, 1959; Rau, 1964, 1981]. The age of the Washington assemblages are questioned because (1) benthic foraminiferal assemblages of the upper part of the Crescent Formation contain more of the younger (late Ulatisian and Narizian) species, thus suggesting a younger age and (2) the Amphistegina bearing basal part of the Crescent Formation appears to be of Penutian or late Paleocene age.

Rau [1964, 1966] interpreted the age of the Crescent Formation in the northern Olympic Peninsula and Sapsop River area of southwest Washington as Ulatisian based on the "common occurence of Amphistegina californla" and their reported occurrence in the California Coast ranges [Mallory, 1959, p. 77]. However, Mallory [1953] earlier assigned a Penutian age to the Crescent Formation based on a correlation with the "Maburg Reef sandstone" and "basal Spiroglyptus sands" at the Media Agua Creek in California. The most fossiliferous Amphistegina assemblage (20 species) noted by Rau [1964, Table 1; sample f11720] contains Discocyclina psila and D. asteri which are restricted to Penutian or older rocks; the other Amphistegina bearing assemblages contain few species and are not age diagnostic. Therefore the Amphistegina bearing basal part of the Crescent Formation is probably of Penutian age (late Paleocene or as old as 58 Ma) and hence is older than the Yakutat block dredge samples. The shallow, warm water Amphistegina assemblages in the lower part of the Crescent Formation reflect the generally warm global climates of the late Paleocene (Penutian) and could have lived adjacent to a late Paleocene island arc or protected lagoon. In contrast are the cooler deeper water assemblages in the late early Eocene (Ulatisian), upper part of the Crescent Formation.

The Ulatisian assemblages, of the upper part of the Crescent Formation, Washington, above the basal Amphistegina bearing sediments, and in the Umpqua Group of Oregon, contain a few species in common with coeval Yakutat block assemblages, such as Nodosaria latejugata and two species of Vaginulinopsis. These common coeval species become increasingly rare in the northern onshore sections and are rare or absent in Alaskan sections except for the Yakutat dredge samples. Missing from the Washington and Oregon onshore assemblages are the large highly ornamented species of the superfamily Nodosareacea. These species usually occupy the tropical and subtropical shelf environments [Murray, 1973; Phleger, 1960; Bandy, 1956] and, if they were indigenous to the region at the time, they should be represented by either in situ or transported specimens. Instead, species of Vaginulinopsis and Nodosaria latejugata represent the large ornamented forms of this superfamily in the onshore sections. In the Yakutat block assemblages, the Vaginulinopsis and Nodosaria species coexist with various ornamented species of Lenticulina, as identified from the more southern formations. The benthic foraminiferal assemblages of the Yakutat block have more affinities to the tropical and subtropical assemblages of southern California and Mexico than to Oregon and Washington and were probably deposited at a latitude south of, or equivalent to, La Jolla, California (present latitude of 33°N).

The late early Eocene (50 Ma) planktonic and benthic organisms indicate that the Yakutat block samples were originally deposited at about 30° ± 5°N relative to onshore assembledges. This compares well with the coeval position of 37°N for the Yakutat block in the model of Bruns [1983a] based on poles determined by Engebretson [1982].

Middle Eocene: 40-44 Ma

Planktonic foraminiferal assemblages of late middle Eocene Zone P13 or P14 (40-44 Ma) are present in dredge hauls S5-78-EG-44E, 44F, 44D, Chan-79-36A, 36C, 37C, 41A, and 43A from the lower slope of the Yakutat block (locations by Plafker et al. [1980]). These planktonic foraminiferal assemblages contain common to abundant Globorotaloides wilsoni and Globigerina linaperta and few to rare Globorotalia cerroazulensis pomeroli, Gl. bullbrooki, Globigerina minima, Catapsydrax pera, C. unicava, and Pseudohastigerina micra. The assemblages are indicative of the temperate mid-latitude environment of the northeast Pacific (Figure 1). The presence of Globorotalia bullbrooki (extinct in Zone P14) and Gl. cerrazulensis pomeroli suggest that these samples are probably of Zone P14 age (40-42 Ma), but it is possible that they may be as old as Zone P13 (42-44 Ma).

Coccoliths examined in these samples (Bukry in Plafker et al. [1979, 1980]; Poore and Bukry [1978]) also yield a late middle Eocene age, compatible with the age determination based on planktonic foraminifers. The most age diagnostic samples, S5-78-EG-44D, 44E and 44F, contain assemblages of the late middle Eocene Discoaster saipanensis Subzone (CP14b, 40-42 Ma), or basal upper Eocene Chiasmolithus oamaruensis Subzone (CP15a, 39-40 Ma, Poore and Bukry [1978], although the assemblages lack index species.

A middle Eocene age is also indicated by benthic foraminifers diagnostic of the Narizian Stage which spans from the base of the middle Eocene into early late Eocene time (Figure 2). Benthic foraminifers are common and diverse in dredge samples S5-78-EG-44D, 44E, 44F, 44 and Chan-79-36A, 36C, 37C, 41A, and 43A. Age diagnostic species include Anomalina garzaensis, Bullimina microcostata, Uvigerina garzaensis and Valvulineria jacksonensis welcomensis. Also present in many of these assemblages are rare occurrences of species suggesting a late Narizian or younger age, such as Boldia hodgei, Globocassidulina globosa, Lenticulina welchi, Plectofrondicularia packardi and Valvulineria tumeyensis. Thus planktonic and benthic assemblages both indicate a late middle Eocene age for these samples.

Paleobathymetry

Benthic foraminiferal assemblages indicate deposition occurred at lower middle bathyal (1500-2000 m) or greater depths. This interpretation is based on the common occurrences of various species of Stilostomella and Gyroidina, Anomalina garzaensis, Bulimina corrugata (rare), Sigmoilina tenuis, Spiroloculina texana, Uvigerina churchi demicostata, and Uvigerina garzaensis. Upper bathyal and upper middle bathyal species (Bulimina microcosta, Lenticulina budensis, L. welchi, Plectofrondicularia packardi and valvulinids) are also common in these assemblages and include species that are commonly found in association with low oxygen assemblages [McDougall, 1980], such as Planularia tolmani, P. markleyana, Lenticulina kreyenhagensis, and aberrant forms of Hoeglundina eocenica and Praeglobobulimina pupoides. These species suggest that deposition occurred below an upper slope oxygen minimum zone.

A different environment is indicated for sample Chan-79-37C, which contains primarily lower bathyal and abyssal species such as abundant Bulimina corrugata B. consanguinea, Uvigerina garzaensis, gyroidinids and the presence of Cibicidoides sp., Anomalinoides sp and Pleurostomella alazaensis. This assemblage suggest either deposition at greater depths (lower bathyal to abyssal), or in an area influenced by a cooler, deep-ocean bottom water mass.

Paleolatitude

Planktonic foraminiferal assemblages in the middle Eocene rocks of the Yakutat block represent a temperate mid-latitude environment similar to coeval assemblages of the Kreyenhagen Formation (presently at 36°N latitude, R. Milam, unpublished data, 1983), the San Lorenzo Formation of northern California (presently at 38°N) [Poore and Brabb, 1977] and the cooler Flournoy Formation of Oregon (presently at 42°-45°N). Abundance of the cool temperature Globorotaloides wilsoni and Globigerina linaperta in the Yakutat terrane samples suggest that the depositional environment of these faunas was just north of the presently onshore coeval marine sequences in California and at about the same latitude as the Flournoy Formation of Oregon (Table 1, Figure 1), or about 20 $\pm$ 5° south of their present position.

Benthic foraminiferal assemblages also indicate a temperate to middle latitude fauna. Assemblages similar to the Yakutat dredge assemblages are common in the Kreyenhagen Formation [Cushman and Hanna, 1927; Jeffries, personal communication, 1984] and include Bulimina microcostata, Lenticulina budensis, L. kreyenhagensis, L. welchi, Planulina markleyana, P. tolmani, Sigmoilina tenuis and Spiroloculina texana. Most of these species are also found in other Narizian assemblages in California [Mallory, 1959] but less commonly in Washington and Oregon assemblages [Rau, 1966; McDougall, 1980]; they are nearly absent in other Alaskan assemblages [Rau et al., 1977]. Narizian age benthic foraminiferal assemblages from the Pacific Northwest are present in the Coaledo Formation (43°30'N present latitude [Roth, 1974]), "Sedimentary rocks of late Eocene age" from the Cowlitz and McIntosh Formations (46°-47°N present latitude; Beck [1943]; Rau [1958, 1966, 1981]; Armentrout et al. [1980]; McDougall [1980]), and the Lyre Formation and lower part of the Twin River Formation (since raised in rank to the Twin River Group by Snavely et al. [1978]) (48°N latitude

[Rau, 1964]). These assemblages, however, contain more upper slope and shelf species than either the Yakutat terrane dredge samples, or the Kreyenhagen Formation. Important, however, in these Pacific Northwest onshore sections is the successive northward decrease in abundance of the species common (listed above) to both the Kreyenhagen and Yakutat dredge samples indicating an apparent increasing temperature gradient from north to south.

Samples Chan-79-36F, 34A, 26A, 26B, and 20H (locations by Plafker et al. [1979]) contain abundant Amphistegina which indicate a tropical to subtropical environment and most likely a shallow reef. Amphistegina californica occurs in California [Mallory, 1959] and Washington land sections as discussed earlier [Rau, 1966] in Ulatisian (P7 to P9) and Penutian sediments respectively. Whereas late Paleocene (Penutian) Amphistegina appear to have ranged as far north as Washington, late middle Eocene to late Eocene occurrences of Amphistegina are limited to more southern areas. The northernmost occurrences of Amphistegina in late middle to late Eocene onshore sequences is noted by Blondeau and Brabb [1983], who identified species of this genus from unnamed sedimentary rocks near San Jose, California (37°N present latitude). The occurrence of Ampistegina in the middle Eocene (44-40 Ma) Yakutat dredge samples therefore suggests that deposition occurred at about the same latitude as rocks now at 40°± 5°N (or 44° ± 5°N absolute paleolatitude, Table 2) or about 20° ± 5° south of the current location. This compares well with the coeval position of 46°-48°N for the Yakutat block predicted by the plate tectonic reconstruction of Bruns [1983a].

Late Eocene: 38-40 Ma, 36-38 Ma

Late Eocene planktonic foraminiferal faunas were found in the Yakutat block dredge sample W-79-45, Cape St. Peter samples 72-APR-112, 72-APR-70A, and Kayak Island samples 72-APR-106E, and 72-APR-52A (locations by Rau et al. [1977]; Plafker et al. [1979]). The Cape St. Peter and Kayak Island samples contain sparse late Eocene assemblages consisting of Globigerina linaperta, G. praebulloides, G. officinalis, Catapsydrax unicava, C. kugleri, Globigerinatheka mexicana barri and G. index. The presence of Globigerinatheka in these samples suggests a Zone P15 age (38-40 Ma), although the zonal index marker is missing. The faunal assemblage suggests a cool temperate mid-latitude environment.

Dredge sample W-79-45 also contains a cool water assemblage consisting of common to abundant Globoratalia opima nana, Catapsydrax unicava and C. pera. The presence of Globigerna utilisindex, which first appears in the latest Eocene (Zones P16-17, Keller [1983a]) and common Gl. opima nana, suggests that this sample is no older than Zone P16-17 (36.3-38 Ma), but may be as young as early Oligocene.

A late Eocene age (Refugian Stage) is also indicated by benthic foraminifers in both dredge and outcrop samples from Kayak Island and Cape St. Peters [Rau et al., 1977]. Additional dredge samples examined from the Yakutat block (S2-77-EG, Chan 10A, 24B, 39F, 39G and 38A, locations by Plafker et al. [1980]) also indicate a late Eocene (late Narizian and Refugian) age. These benthic assemblages are similar to those observed by Rau et al. [1977] in the Cape St. Peters and Kayak Island sections. Benthic foraminifers diagnostic of Narizian age include Cibicides natlandi, Globocassidulina globosa, Uvigerina garzaensis, Valvulineria jacksonensis welcomensis, and Valvulinera tumeyensis, and of Refugian age include Anomalina californiensis, Bulimina sculptilis lacinata, Cibicides elemaensis, C. haydoni, Plectofrondicularia packardi, Quinqueloculina imperialis, Uvigerina atwilli, U. cocoaensis and U. jacksonensis.

Paleobathymetry

Late Narizian and Refugian faunas indicate deposition at middle bathyal depth (<1500 m). Middle bathyal species such as Uvigerina garzaensis appear to decrease in abundance in younger (Refugian) sediments and are replaced by upper slope and outer shelf species. This faunal change suggests either a gradual shallowing, or increased sediment transport from shallower biofacies.

Paleolatitude

The generally cool temperate faunas of the Yakutat block late Eocene assemblages (Zones P15, 38-40 Ma, and probably Zone P16-17, 36.5-38.0 Ma) are similar to those examined from coeval onshore marine sequences in the Bastendorff Formation of

TABLE 2. Comparison of Absolute Paleolatitude Positions Determined From Faunal Data and Plate Tectonic Models for the Yakutat Block, Prince William Terrane, and Pacific Plate.

Age	Yakutat		Prince William		Pacific	
	Faunal	Tectonic	Faunal	Tectonic	Faunal	Tectonic
Late Oligocene to early Miocene 20–30 Ma	north of 50° ± 5°N	50°–53°N	north of 50° ± 5°	present	north of 50° ± 5°	44°–47°N
Late Eocene to Early Oligocene 34–36 Ma	north of 50° ± 5°N	49–50°N	north of 50° ± 5°	present	north of 50° ± 5°	43°N
Late Eocene 36–40 Ma	48° ± 5°N	48°–49°N	50° ± 5°N	present	(192) 45° ± 5°N	42°N
Middle Eocene 40–44 Ma	44° ± 5°N	46°–48°N	50° ± 5°N	present	(192) 40° ± 5°N	40°–42°N
Early Eocene 50 Ma	35° ± 5°N	37°N			(192) 30° ± 5°N	37°N
Paleocene 62 Ma			paleomagnetic, Ghost Rocks Fm. 40° ± 9°N			30°N
Late Cretaceous					(192) 15° ± 5°N	26°N

Onshore correlations corrected for southward drift of North America during the Cenozoic. Data are also plotted in Figure 4.

Oregon (45°N present latitude) [Warren and Newell, 1981] and in the Sapsop and Little River sections of the Lincoln Creek Formation of southwest Washington (G. Keller, unpublished data, 1984). However, the lower species diversity of coeval assemblages from the Lincoln Creek Formation suggests deposition in a cooler environment than those from the Yakutat terrane. The faunal assemblages of the Bastendorff Formation, are very similar to those from the Yakutat block, except that Globorotalia insolita, a species first described from New Zealand, was also reported [Warren and Newell, 1981]. The similarity of these faunal assemblages suggest that the late Eocene to early Oligocene depositional environment of the Yakutat terrane was probably slightly south of the southwestern Washington locality and at a similar paleolatitude to that of the Bastendorff Formation of Oregon, now at 45°N (Table 1, or at 48° ± 5°N absolute paleolatitude, Table 2). The same paleolatitude position 48-49°N, is predicted for the Yakutat block based on the plate tectonic reconstruction by Bruns [1983a] (Table 2).

The late Eocene benthic foraminiferal assemblages of the Yakutat block are most similar to the cold water late Eocene assemblages of the Lincoln Creek Formation [Rau, 1948, 1966; McDougall, 1980], the shallow water facies of the Twin River Formation of Washington [Rau, 1964], and the benthic assemblages of the Eocene to Oligocene Caucasina eocaenica kamchatica Zone of the Kamchatka Peninsula [Serova, 1976]. Benthic assemblages similar to the Twin River Formation of Washington [Rau, 1964], are found in various late Eocene onshore sections around the Gulf of Alaska [Rau et al., 1977] and in the Middleton Island well, but these assemblages are commonly dominated by arenaceous forms characteristic of cooler shelf and slope faunas. Late Eocene assemblages from California [Mallory, 1959] and Japan [Ujiie and Watanabe, 1960] also contain many of the same species as found in rocks of the Yakutat block; however, these more southern assemblages also contain warmer water species not present in Alaska. These faunal comparisons also suggest that the late Eocene to Early Oligocene Yakutat block samples were deposited in an environment similar to samples from southwestern Washington and Oregon, or about 45° ± 5°N present latitude.

PRINCE WILLIAM TERRANE

Middleton Island Well

Microfossil assemblages from the Middleton Island well (59°25'N, present latitude) are generally sparse and poorly preserved in the upper part of the well, however, in the lower part definite age assignments could be made. Sixty-six samples were examined for coccolith and foraminifers. Twenty of these contained coccoliths, but only four samples have diagnostic or diverse assemblages adequate for good age correlations. Planktonic foraminifers are also poorly represented, whereas benthic foraminifers are more common. The Middleton Island well was studies earlier by Rau for benthic foraminifers [Rau et al., 1977], with the few samples available at that time. Correlations for faunal comparisons were achieved between the Middleton Island well and sediments of the Yakutat block described in Plafker et al. [1979, 1980], Rau et al. [1977], and Poore and Bukry [1978]. Samples were reexamined for planktonic foraminifers for this report. Faunal data are summarized in Figure 2 and Table 1.

Late Middle Eocene: 40-42 Ma

The basal sample of the Middleton Island well (3658-3642 m) contains Globigerina linaperta and rare Globigerinatheka semiinvoluta, the index species for the early late Eocene Zone P15 (38.5-40 Ma). Coccolith assemblages of sample 3639-3642 m contain Chiasmolithus grandis and Reticulofenestra umilica that suggest the late middle Eocene Discoaster saipanensis Subzone (CP14b, 40-42 Ma). The overlying sample (3633-3637 m) contains Discoaster barbadiensis that suggests a late Eocene age in agreement with the age determined from planktonic foraminifers. Coccolith stratigraphy therefore indicates that the middle to late Eocene boundary falls between sample 3642 m and 3636 m with a possible hiatus indicated by the absence of C. oamaruensis Subzone (CP15a, 1 m.y.). Therefore, at its greatest depth the Middleton Island well penetrated late middle Eocene, or earliest late Eocene sediment (40-42 Ma).

Benthic foraminifers are rare in the lower part of the Middleton Island well (3658-3258 m), but they also suggest a middle to late Eocene (Narizian Stage) age as indicated by Ammodiscus incertus, Glomospira charoides corona, Karreriella chapatoensis and Pullenia eocenica. Rau et al. [1977] reported a more diverse benthic fauna of questionable Penutian, or Ulatisian Stage (early to middle Eocene). This age call could not be confirmed by our study.

Paleolatitude

The low diversity microfossil assemblages in the Middleton Island well, as compared to coeval assemblages from dredge hauls (S5-78-EG-44 and Chan-79-36, 37) from the continental slope of the Yakutat block indicate that the Middleton Island assemblages were deposited in a significantly cooler water environment and perhaps 10°N of the Yakutat fauna (Table 1).

Late Eocene: 36-38 Ma

Planktonic foraminiferal assemblages in samples between 3495 m and 3432 m consist of Catapsydrax dissimilis, C. unicava, C. pera, Globorotalia opima nana, Gl. carcosellensis, Globigerina linaperta, G. utilisindex, G. angiporoides and G. praebulloides. This assemblage is indicative of the late Eocene Zone P16-17 (36.5-38 Ma) although in the absence of the index species, it could be as young as early Oligocene. Coccolith assemblages are indeterminate late Eocene to early Oligocene. This sample is coeval with the dredge sample W-79-45 from the Yakutat block. The low faunal diversity and absence of warm water species in both the Middleton Island well and the latter sample suggests a similar cool environment indicative of high northern latitudes of about 50 ± 5°N.

Latest Eocene to Early Oligocene: 34?-38 Ma

Middleton Island well samples between 3347 m and 3207 m contain planktonic foraminiferal assemblages indicative of late Eocene (Zone P17) or early Oligocene (Zones P18-19) age. The species present are Globigerina praebulloides, G. angiporoides, G. utilisindex, G. linaperta and Catapsydrax unicava. Coccolith assemblages between 3505-3613 m can, at best, be assigned a late Eocene to early Oligocene age on the basis of Dictyococcites bisectus and D. scrippsae. The presence of D. bisectus and Reticulofenestra umbilica in samples 3237-3240 m and 3230-3234 m signify a probable latest Eocene or early Oligocene age also. This age is in good agreement with age determinations based on planktonic foraminifers.

Planktonic microfossils are rare between 3240 and 2347 m, but suggest that this interval is also of late Eocene or early Oligocene age. A Braarudosphaera bloom occurs in sample 2347 m and correlates with Braarudoshpaera blooms noted in other early Oligocene (P18-19) deep sea sequences [Keller, 1983a]. No planktonic microfossils are present between 2347 and 890 m; the latter sample contains latest Oligocene or early Miocene planktonic foraminifers indicative of Zone N4 (Globorotalia pseudokugleri, Globigerinita glutinata, G. uvula).

Benthic foraminifers of late Eocene age are also observed between 3246 and 1329 m. Species diagnostic of the Narizian Stage (Anomalina garzaensis and Spiroplectammina tejonensis) are present at 3246-50 m. Mixed assemblages of Narizian and Refugian Stage species (Cibicides elemaensis and Pullenia salisburyi) are present between 3222 m and 2682 m with Refugian age species more common in the upper part. Similar mixed Narizian and Refugian Stage assemblages were observed in coeval sediments of Washington and Oregon [McDougall, 1980]. In these sections middle and lower bathyal Narizian assemblages co-occur with what appear to be transported upper slope and shelf Refugian age assemblages. The mixed assemblages of the Middleton Island well also appear to be the result of downslope transport. The late Eocene to early Oligocene age (Narizian to Refugian [Poore, 1980]) agrees well with the age determinations based on planktonic microfossils.

Paleobathymetry

Benthic foraminiferal assemblages between 3246 and 2673 m contain many species characteristic of middle to lower bathyal depths [Ingle, 1973] such as the arenaceous forms Spiroplectammina directa, S. tejonenesis, Glomospira charoides corona, Eggerella elongata, and the calcareous forms Cibicides spiropunctatus, Oridorsalis umbonatus and Gyroidina soldanii. Upper slope species (Uvigerina cocoaensis and Praeglobobulimina pupoides) and shelf species (Quinqueloculina weaveri, Sigmomorphina schenki, Cibicides elemaensis) occur most commonly at 3207-3222, 3234-3246 and 2673-2682 m, suggesting an increase in downslope transport at these intervals. These data suggest that during late Eocene to early Oligocene time, deposition occurred in a middle to lower bathyal environment with influx of transported material form a nearby slope and shelf region.

Paleolatitude

The long ranging, low diversity planktonic foraminifers from the late Eocene to early Oligocene Middleton Island well (59°25'N present latitude) are indicative of a cold water environment similar to coeval assemblages of the Lincoln Creek Formation of southwest Washington presently at 47°N latitude. The presence of common Globigerina ouachitaensis (common in subtropical to cool temperate assemblages) in the Lincoln Creek Formation, and near absence of this species in the Middleton Island well, however, indicates cooler assemblages at the latter locations. Hence deposition at the Middleton Island well occurred at a latitude higher than that of the Lincoln Creek Formation. We think the Middleton Island late Eocene sediment was deposited in an environment north of 50° ± 5°N latitude (Table 1).

Coccolith assemblages also indicate a cold water environment as suggested by the abundance of I. recurvus, poorly diversified placoliths, and by the lack of tropical taxa (J. D. Bukry, written communication, 1983). These cold water assemblages are most similar to coeval assemblages from DSDP site 192 in the western North Pacific, and also indicate that deposition occurred in colder waters than assemblages from southwestern Washington.

Oligocene

Benthic species diagnostic of the Oligocene Zemorrian Stage are present between 1469 m and 1213 m (see also Rau et al. [1977]. No planktonic microfossils are present. Benthic assemblages indicate deposition occurred at middle to lower bathyal depths with continued transport from shelf and upper slope regions.

Miocene to Pleistocene

Rare Miocene species occur in sample 1213-1219 m and more commonly in sample 890-902 m. An early Miocene, Saucesian Stage, is indicated by the presence of Anomalina glabrata, Bulimina inflata alligata, and Sphaeroidina variabilis. Planktonic foraminifers in sample 890-902 m also suggest an early Miocene, or very latest Oliogene age. Deposition continued in a lower to middle bathyal environment.

The upper part of the Middleton Island well, 701 m to 219-234 m, is of late Miocene to Pleistocene age (undifferentiated). Thus a hiatus is present between early and late Miocene deposits, a hiatus is also observed in the nearby deep ocean DSDP site 178 (discussed later), and noted by Lagoe [1983] in samples from Cape Yakataga. The presence of shallow water benthic species, including numerous Elphidiums, suggests deposition at shelf depths, or that transport from inner shelf regions occurred.

PACIFIC PLATE

Cored sequences provide sufficient continuity to show the chronostratigraphic and paleoclimatic record, and variations in the sedimentation patterns that result from large-scale changes in oceanographic conditions. Figure 3 illustrates the chronostratigraphic and lithologic records of deep-sea sequences of DSDP sites 192, 183, and 178 which are presently at high North Pacific latitudes, and the Middleton Island well. The Yakutat terrane is not included because no similar cored sequence is available. The DSDP sites are on the Pacific plate and hence, during their northward migration, their relative position on the plate remained constant through time. The relative position of the Middleton island well, located on the Prince William terrane, is less well known. Because of similar biogenic sedimentation records (Figure 3), the sediment at the Middleton Island well was probably deposited within the same general paleoceanographic and paleoclimatic regime as those of the DSDP sites.

Lithology

The Eocene to Oligocene sediment at northwest Pacific site 192 consists of interbedded limestone, claystone, and siltstone (Figure 3). To the east, at site 183 and Middleton Island, there are fewer limestone beds and an increase in claystone, siltstone and sand. A lower Miocene limestone bed is present in all three DSDP sites. Miocene to Pleistocene

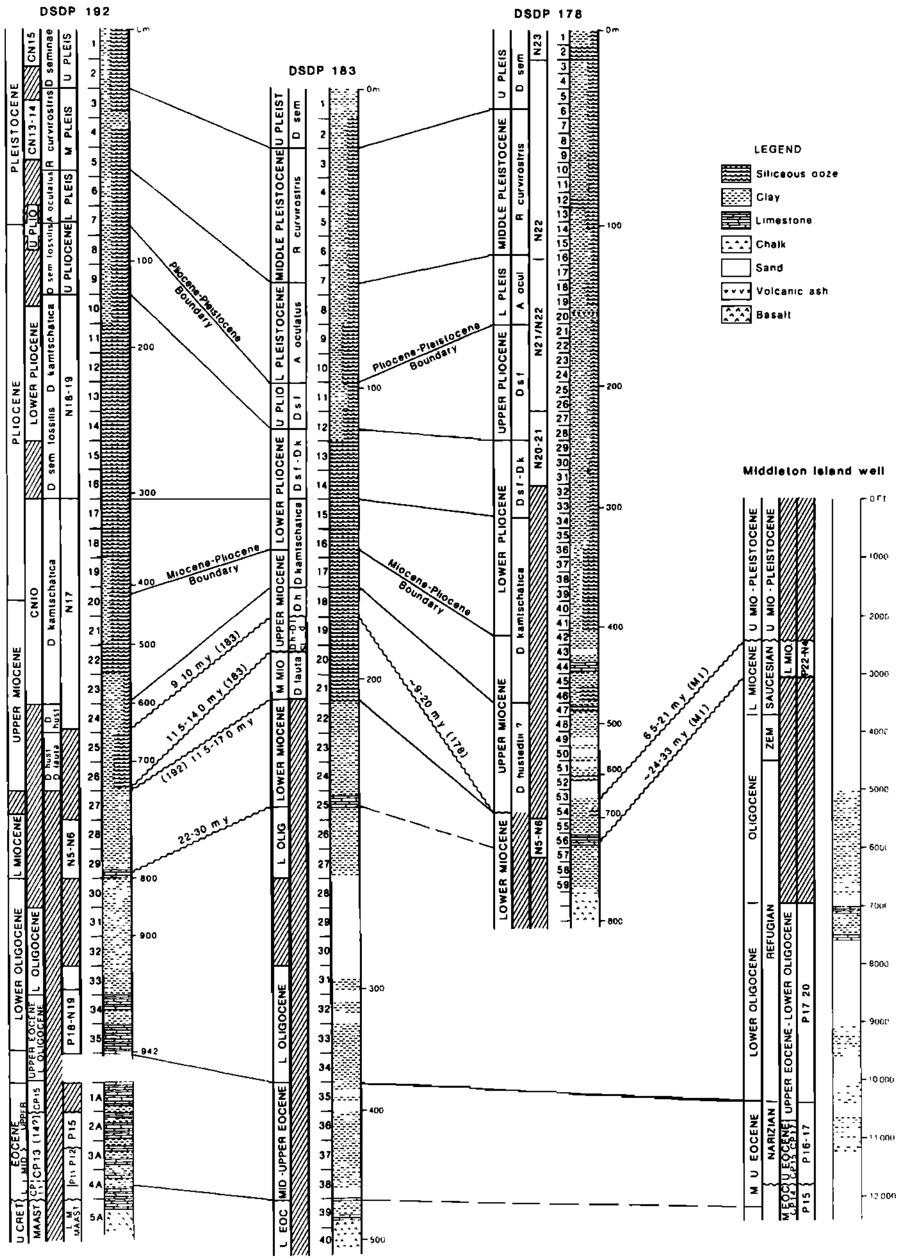

Fig. 3. Biostratigraphic correlation and lithologies of sediments in DSDP sites 192, 183 and 178 and the Middleton Island well. Dashed zigzag lines mark hiatuses. Diagonal lines mark dissolution in sediments. The biostratigraphy at DSDP sites has been previously studied: Nannofossils, Worsley [1973], diatoms for sites 192 and 183 by Koizumi [1973], Harper [1977], and J. A. Barron (unpublished data, 1983), foraminifers by Echols [1973] for sites 192 and 183 and by Keller (this report) and for site 178 by Ingle [1973].

lithologies at sites 192 and 183 are nearly identical with lower Miocene silt and clay, predominantly middle and upper Miocene biogenic silica, and Pliocene and Pleistocene siliceous clay sedimentation (Figure 3). In Pliocene and Pleistocene deposits at site 178, biogenic silica is diluted by clay, silt, sand, and volcanic ash reflecting proximity to Alaska. Coeval sediment in the Middleton Island well is coarser and more terrigenous.

The lithologies drilled at the DSDP sites indicate sedimentation in an open oceanic environment during early to late Eocene time, in agreement with the depositional settings implied by faunal compositions and plate tectonic reconstructions.

Upper Cretaceous

The oldest sediment overlying basement at site 192 (hole A), is of Maastrichtian age (70-68 Ma). Coccolith assemblages indicate a tropical to subtropical environment; however, absence of siliceous microfossils suggests that deposition occurred north of the high productivity equatorial region [Worsley, 1973]. This would indicate a latitude of about 15° ± 5°N based on the distribution of Pacific ocean water masses. However, during the warmer climatic conditions of the late Cretaceous the equatorial water mass would have expanded into higher latitudes. Hence this position is not in good agreement with the predicted position of about 26°N latitude based on plate tectonic reconstructions of Engebretson [1982, Table 2].

Microfossils were also recovered from the Ghost Rocks Formation of the Kodiak Islands which was considered to be late Cretaceous and Paleocene by Byrne [1982]. Based on paleomagnetic data, Plumley et al. [1982] infer a Paleocene (62 Ma) paleolatitude of the Kodiak Islands of about 40° ± 9°N latitude, about 25° ± 9° south of the expected paleolatitude if the Kodiak Islands had been in their current position. No sediment of Paleocene age was recovered in the North Pacific DSDP sites. At site 192 a hiatus marks the position of uppermost Cretaceous, the Paleocene, and part of the early Eocene (68-51 Ma), and at site 183 lower Eocene sediments rest on basement basalt (Figure 3).

Eocene

Eocene sedimentation is disrupted by hiatuses at the early-middle Eocene boundary (49-46 Ma), middle-late Eocene boundary (43-41 Ma), and during the late Eocene (39-37.5 Ma, Figures 2, 3). Early Eocene (51-49 Ma) coccolith assemblages at site 192 suggest that deposition occurred in the low productivity central water mass [Worsley, 1973, Figure 1] or at about 30° ± 5°N latitude and hence, at a similar latitude as coeval assemblages of the Yakutat terrane. Plate tectonic reconstructions place site 192 and the Yakutat block at about 37°N latitude in early Eocene time (Table 2); thus there is good agreement with the latitudinal limits determined from faunal evidence.

Middle Eocene sediments at site 192 indicate deposition within the central to temperate water masses, or at about 40° ± 5°N latitude, as compared to about 40°-42°N latitude determined by plate reconstructions (Table 2). Late Eocene assemblages (36-40 Ma) are indicative of a cold subarctic environment, or about 45° ± 5°N latitude. Plate tectonic reconstruction suggests a similar position of about 42°N (Table 2).

Cold subarctic assemblages are also present in the upper Eocene sediment of site 183, although preservation of microfossils is poor. Wolfe [1977] reports pollen assemblages dominated by conifers, similar to coeval assemblages from the Alaskan mainland, and cooler than coeval assemblages from Washington and Oregon. It was also observed earlier that foraminifers from the Middleton Island well indicated a position north of the Lincoln Creek Formation of Washington (i.e., north of 50°N latitude).

Thus late Eocene to early Oligocene assemblages (34-36 Ma) from the Pacific (site 192), Prince William terrane (Middleton Island well), and the Yakutat block contain assemblages from the subarctic faunal province, or at about 50° ± 5°N present latitude. In contrast, plate tectonic reconstructions indicates that the late Eocene to early Oligocene position of sites 192 and 183 was about 7° to 8° further south. This discrepancy may be explained by a southward expansion of the subarctic fauna in the latest Eocene to Oligocene due to initiation of polar glaciation [Keller, 1983a, b; Keigwin and Keller, 1984]. Therefore the effect on faunal paleolatitude determinations would be a bias toward cooler, that is, higher latitudes at this time.

Oligocene

Microfossil preservation in Oligocene sediment is poor and a hiatus appears to represent the late Oligocene (30-20 Ma, Figure 2). In addition, late Eocene to early Oligocene assemblages are commonly indistinguishable and indicate cold subarctic conditions. This circumstance suggests that by Oligocene time deposition at the North Pacific DSDP sites, the Prince William, and the Yakutat block occurred in cold water north of Washington, or north of 50° ± 5°N present latitude.

Miocene to Pleistocene

Early Miocene sediment (23-20 Ma) is present at all North Pacific DSDP sites and the Middleton Island well (Figure 2). Early Miocene assemblages are found in a limestone layer at sites 192, 183, and 178 and sediment enriched in carbonate at the Middleton Island well. Hiatuses are present throughout the Miocene sequences at sites 192 and 183; in the late Miocene (10-9 Ma), middle Miocene (14-11.5 Ma), and early Miocene (20-15 Ma). At site 178 and Middleton Island well, hiatuses removed sediment between 9-20 Ma and 6.5-20 Ma respectively.

Biostratigraphic control in the late Miocene to Pleistocene sequences is excellent, except for the Middleton island well where correlation is more tenuous due to poor preservation of microfossils. Faunal and floral assemblages are typical of subarctic to arctic environments.

TECTONIC IMPLICATIONS

Recent geological and geophysical studies around the Gulf of Alaska indicate a Tertiary northward drift of major crustal fragments that are now lodged in the margin of the Alaskan continent [Stone and Parker, 1979; Plumley et al., 1982; Stone et al., 1982; Plafker, 1983; Bruns, 1983a; Moore et al., 1983]. All movement histories agree on northward drift, but each is somewhat different.

Terrane Migration

The concept that terranes around the Gulf of Alaska have been migrating northward during the Cenozoic has been addressed in paleomagnetic studies and plate tectonic reconstructions [Stone et al., 1982; Plumley et al., 1982, 1983; Moore et al., 1983; Bruns, 1983a]. Positions from paleomagnetic studies and positions based on plate tectonic reconstructions by Engebretson [1982] are illustrated in Figures 4 and 5 along with the positions determined from our faunal data.

Paleomagnetic data from the Prince William terrane [Plumley et al., 1982, 1983; Moore et al., 1983] show that early Paleocene volcanics (about 62 Ma) of the Ghost Rocks Formation of Kodiak Island were emplaced at 25° ± 9° south of its present position (Figures 4 and 5). We assume that the Ghost Rocks Formation and the Middleton Island well were on the same terrane during northward migration. Our paleontologic data indicate that the Middleton Island middle Eocene sediment (Zone P14, 40-42 Ma) was deposited at high latitude (50 ± 5) and could have been about 8° ± 5° south of its current location. Paleontologic data are consistent with these models calling for northward movement of the Prince William terrane but do not aid in differentiating between these models.

Immediately adjacent to Middleton Island is the Yakutat block. The paleontological data require that the Yakutat block had a different movement history from that of the Prince William terrane. The planktonic foraminiferal fauna from dredged late early Eocene (50 Ma, Zone P8-P9) rocks of the Yakutat block are similar to fauna from coeval sequences of California at 36°N present latitude. Middle Eocene fauna (40-42 Ma, Zone P14) from the Yakutat terrane are most similar to coeval sequences of northern California at 40°N present latitude. Late Eocene fauna dated at 38-40 Ma (Zone P15) and 36.5-38.0 Ma (Zone P16-P17) are most similar to the cool subarctic assemblages of southwest Washington (about 45°N present latitude, Table 1). Finally, Oligocene fauna dated at about 34 Ma suggest a high latitude depositional environment of about 50° ± 5°N. Thus the fauna show that the Yakutat block was at least 10° south of the Prince William terrane during middle Eocene time, and reached a similar latitude no earlier than middle Oligocene time.

Recent geological and geophysical studies of the Yakutat block indicate that it is currently colliding with, and accreting to, southern Alaska [Plafker, 1983; von Huene et al., 1979; Bruns, 1979, 1983a, b; Perez and Jacob, 1980; Lahr and Plafker, 1980; Bruns and Schwab, 1983] and that it has moved with the Pacific plate for at least Pliocene and Quaternary time [Schwab et al., 1980; Bruns, 1983a, b]. A plate tectonic model for the movement history of the Yakutat terrane further suggests that the terrane has moved with the Pacific and Kula plates throughout the

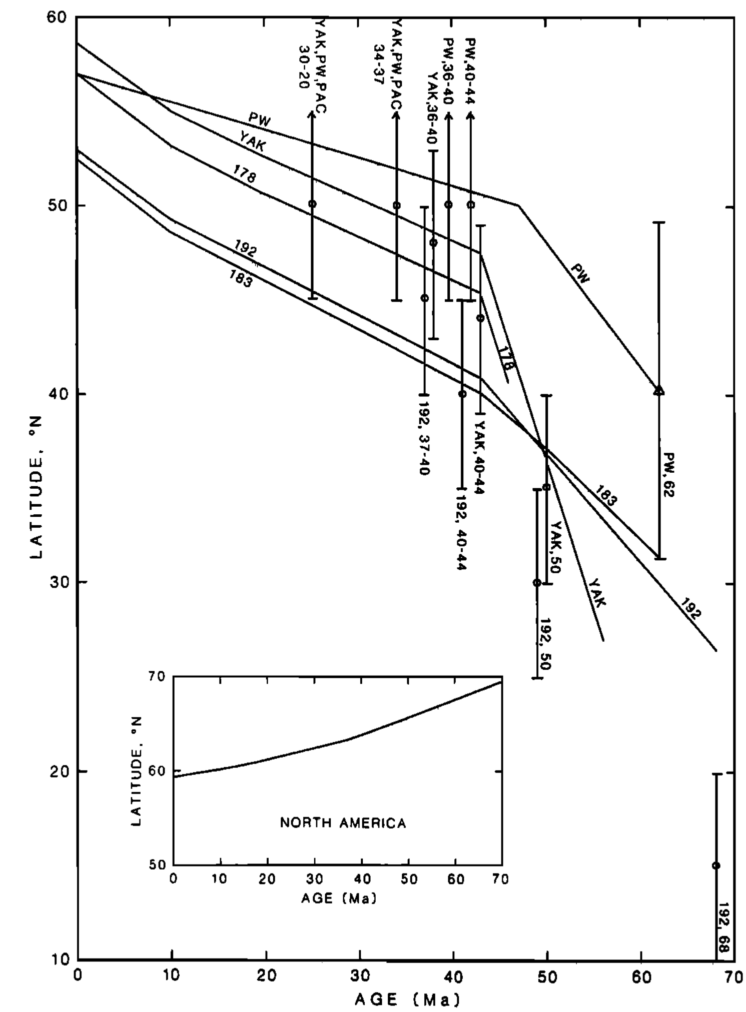

Fig. 4. Plot of absolute paleolatitude versus age of sites studies in this report. All paleolatitudes have been adjusted for motion of Pacific and North America plates based on the movement of these plates relative to the fixed hot spot reference of Engebretson [1982]. Travel paths relative to a fixed North America reference frame are shown in Figure 5. Circles with error bars indicate best estimate of paleolatitude positions determined from faunal data. Triangle with error bar marks paleomagnetic data of Plumley et al. [1982, 1983]. Labeled lines indicate latitude positions of indicated terranes and DSDP sites according to plate tectonic reconstructions of Engebretson [1982], Moore et al. [1983], and Bruns [1983a]. Inset shows southward drift of North America plate during last 70 Ma. Total closure between northward moving terranes and North America plate can be determined by subtracting paleolatitudes of equivalent ages.

Cenozoic (Figure 5; Bruns [1983a]). A comparison of the modeled terrane path and the paleontological data (Figures 4 and 5) shows excellent agreement between the predicted position of the Yakutat block and the Eocene and Oligocene positions indicated by this study. Thus within the limits of uncertainty in the latitude determinations, the paleontological data and terrane path reconstruction are consistent.

The largest northward migrating element of the Gulf of Alaska is the Pacific plate, part of which was the Kula plate prior to the demise of the Pacific-Kula spreading center. In this paper we have

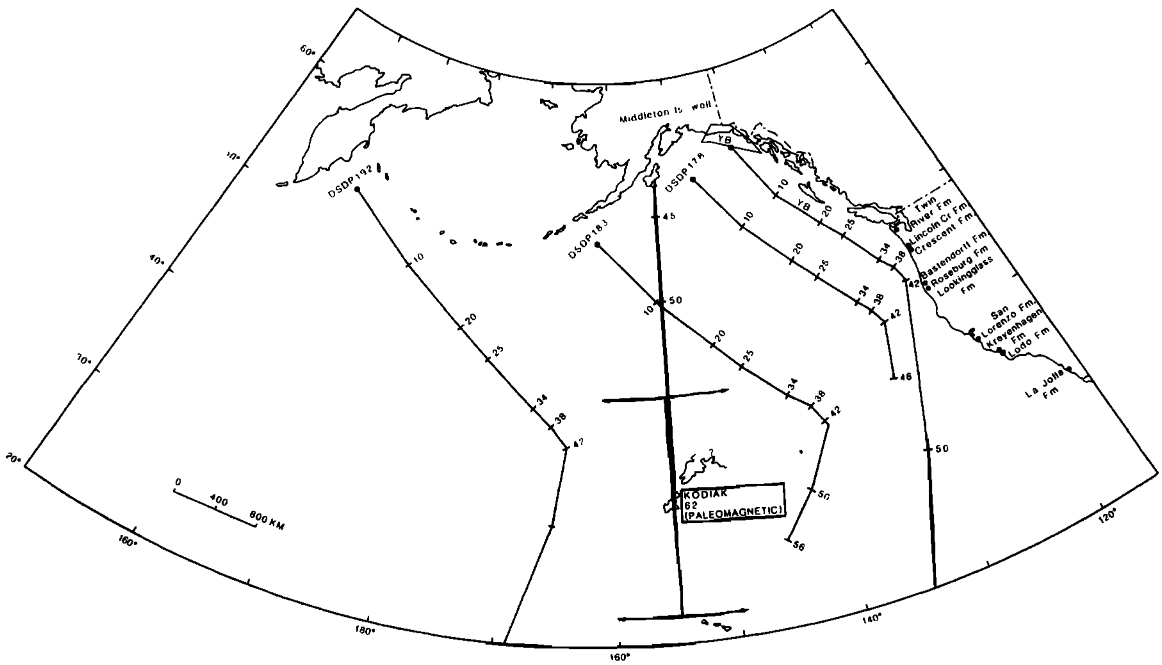

Fig. 5. Backtrack positions of sample localities described in this paper (relative to a North America plate fixed in its current position). Heavy solid lines show movement paths according to Pacific-North America poles of Engebretson [1982], and models for Prince William terrane of Moore et al. [1983] and for the Yakutat block of Bruns [1983a]. Numbers along lines indicate positions in million years. Latitude position of Kodiak Island at 62 Ma based on paleomagnetic data of Plumley et al. [1982, 1983].

accepted Engebretson's [1982] premise that the Pacific-Kula spreading center died at aboaut 43 Ma which is coeval with the bend in the Hawaii-Emperor seamount chain. The paleontologically deduced path of DSDP site 192 indicates northward drift consistent with the North America-Pacific plate hot spot based reconstructions of Engebretson [1982]. From 50 Ma to about 40 Ma, and for late Miocene and younger time, faunal data are in excellent agreement with the Pacific plate reconstruction, and indicate northward motion of about 40° (Figure 5). However, for Oligocene to early Miocene time, the paleolatitude determined from the faunal data at all the DSDP sites is significantly higher and for the late Cretaceous (DSDP site 192) it is about 10° lower than the plate modeled location (Figure 5, Table 2). Because the total northward motion of the Pacific plate is confirmed by the faunal data, this discrepancy must primarily reflect a change in oceanographic conditions during late Cretaceous Oligocene and early Miocene time, and may also be partly due to errors in plate reconstruction models [Molnar and Atwater, 1973; Stock and Molnar, 1983]. As pointed out earlier, the late Cretaceous was a time of global warming, whereas the Oligocene was a time of global cooling causing an expansion of tropical fauna in the late Cretaceous and a southward expansion of the subarctic fauna in the Oligocene. The 10° latitude discrepancy between predicted faunal and plate tectonic positions suggests that the late Cretaceous tropical-subtropical fauna extended to about 25°N and that the Oligocene cold subarctic fauna and flora extended to at least 40°N latitude. Recent faunal and isotope studies [Keller, 1983b; Keigwin and Keller, 1984] have shown that major polar glaciation existed in Oligocene time, hence expansion of the subarctic fauna south to 40°N is an expected consequence.

In summary, paleolatitudes determined from microfaunas and floras in the Gulf of Alaska coastal and offshore areas provide three main tectonic constraints: (1) The

Prince William terrane was at a high northerly latitude near its present position by 40-42 Ma. This observation is consistent with paleomagnetic data from Kodiak Island [Plumley et al., 1983], provided the Prince William terrane traveled northward with the fast moving Kula plate from 62-45 Ma, and was incorporated into Alaska by about 45 Ma. (2) Data from the Yakutat terrane require northward motion of about 30° since 50 Ma, and also require that the Yakutat block was at least 10° south of the Prince William terrane throughout late Eocene time. These data are consistent with motion of the Yakutat block with the Pacific and Kula plates during at least the past 50 Ma, as suggested by Bruns [1983a]. (3) Data from the Pacific plate require about 40° of northward motion and are consistent with the plate tectonic reconstruction of Engebretson [1982] for Pacific plate motion based on hot spot tracks.

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