# Glaciomarine deposits of Miocene through Holocene age in the Yakataga Formation along the Gulf of Alaska margin, Alaska

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ABSTRACT

Perhaps the world's longest and most complete onshore sedimentary record of late Cenozoic glaciation is preserved in the Gulf of Alaska Tertiary province that extends 800 km along the coast of southern Alaska. The Yakataga Formation, with an aggregate outcrop thickness of about 5,000 m, is characterized by variable amounts of distinctive neritic marine tillite-like diamictite and laminated siltstone containing dropstones interpreted as ice-rafted glacial debris. The lithology, sedimentary structures and molluscan fauna of the formation suggest that active tidal glaciers or an ice shelf were present along the landward margin of the basin possibly beginning in early or early middle Miocene time. Dropstone distribution in outcrop sections indicates that glaciers reached tidewater intermittently during the Miocene and were almost continuously present throughout the Pliocene and much of the Pleistocene. Paleomagnetic and nannoplankton dating of the upper 1,181 m of the Yakataga Formation at Middleton Island indicate that this part of the sequence probably was entirely deposited during the Matuyama reversed polarity epoch of the Pleistocene during which the sedimentation rate was of the order of 1 m/1,000 years. Lithologically similar deposits of poorly consolidated sandy mud and pebbly mud continue to accumulate locally near tidal glaciers in the same

## INTRODUCTION

A thick sequence of Miocene through Holocene glaciomarine deposits interbedded with normal marine clastic rocks makes up the Yakataga Formation along the eastern Gulf of Alaska margin (fig. 1). This sequence is

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Figure 1 near here.

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unique in that it contains evidence for the earliest known late Cenozoic glaciation exposed on land in North America. The Yakataga is one of the best exposed and thickest glaciomarine sequences known anywhere, and as a consequence, is of special interest for reconstruction of the late Cenozoic paleoclimate and paleogeography of the Gulf of Alaska margin. Because both the onshore and offshore portions of the Gulf of Alaska are presently areas of high petroleum exploration interest, an understanding of the depositional environment is necessary to interpretation of the thickness, the reservoir and source-rock potential, and the role that this thick sequence has played in generation and migration of hydrocarbons within the Tertiary basin.

We briefly summarize here the major characteristics of the Yakataga Formation and present a tentative interpretation of its age and depositional environment based on the lithology, sedimentary structures, and organic remains. In doing so, we have drawn heavily on comparisons with the modern depositional environment which, we believe, is an excellent analog for conditions that prevailed throughout much of Yakataga time.

Most of the pioneer field work on the Yakataga Formation was done by Don J. Miller as part of his reconnaissance investigations of the Gulf of Alaska Tertiary province. The results of this work have been outlined in a series of maps and reports by Miller and his coworkers;

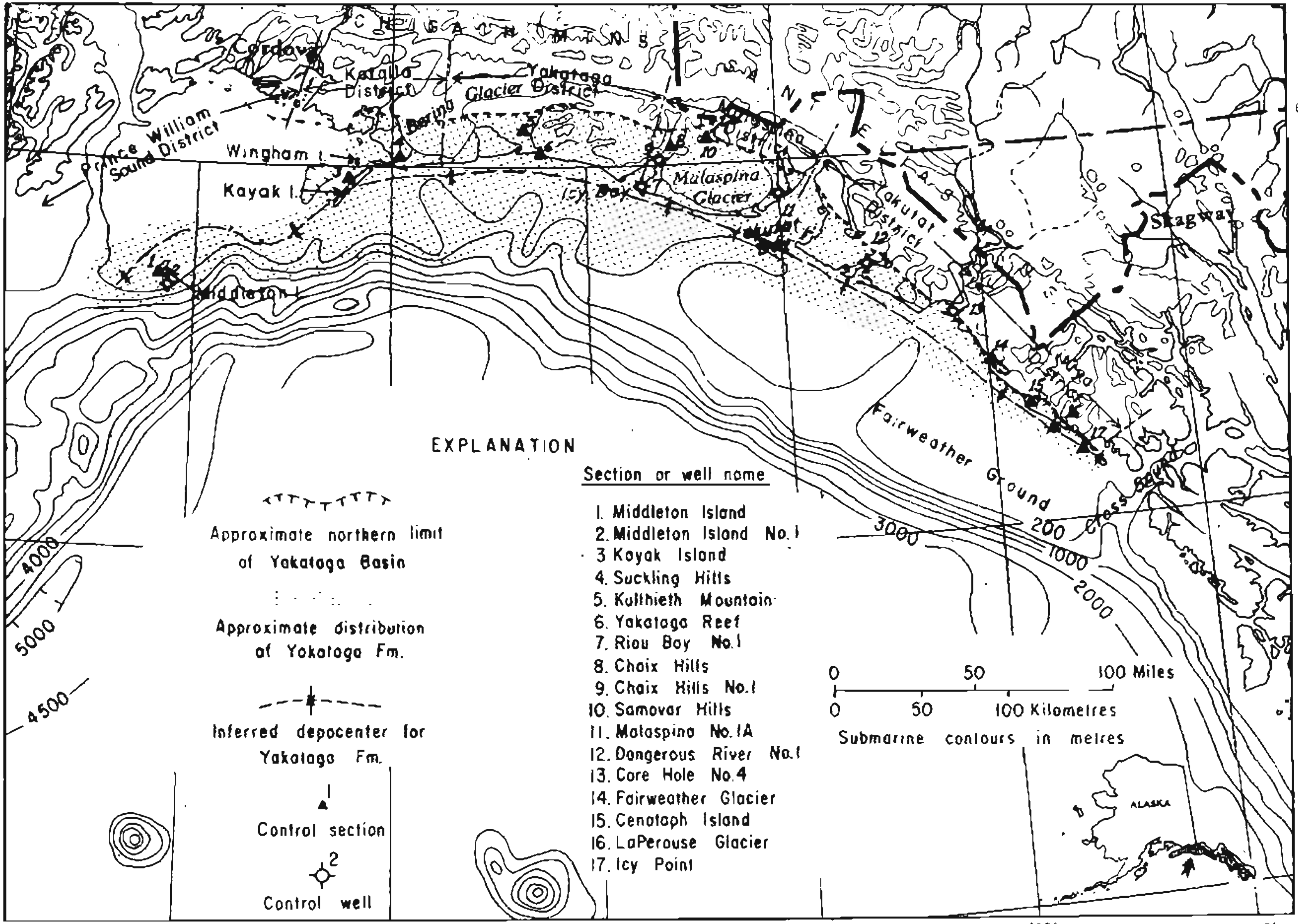


Figure 1. Map showing known and inferred distribution of the Yakataga Formation, and the locations of selected control sections and wells.

preparation of a planned comprehensive report on the geology was interrupted by Miller's death by drowning in Alaska in 1960. This paper is based largely on a stratigraphic reconnaissance of the Yakataga Formation by Plafker in 1963, but incorporates some of Miller's data. Prior to the present study, work on molluscan faunas of the Gulf of Alaska was done largely by F. S. MacNeil, L. G. Hertlein, and Saburo Kanno. For this report, Addicott reviewed the Survey collections, relying heavily on the work of all these earlier workers and on discussions with Scott McCoy (Phillips Petroleum Company) in interpreting the age and depositional environment of the faunas.

We thank D. M. Hopkins and A. T. Ovenshine for their helpful critical reviews of this paper.

## DISTRIBUTION AND THICKNESS

The Yakataga Formation is part of a thick sequence of Cenozoic strata that makes up the Gulf of Alaska Tertiary basin of the eastern Gulf of Alaska (Plafker, 1967, 1971). The formation is exposed on the mainland coast in an outcrop belt 460 km long and up to 30 km wide that extends from the Suckling Hills in the Katalla district on the west to Icy Point in the Lituya district. It underlies all of Middleton Island and parts of Kayak and Wingham Islands, and probably occurs over much of the intervening continental shelf in the eastern Gulf of Alaska (fig. 1). Being relatively resistant to erosion, it forms some of the highest peaks and steepest and most spectacular scarps in the foothills of the Chugach and Saint Elias Mountains.

There is no single outcrop section or well where the entire thickness of the Yakataga Formation has been penetrated. As shown by figure 2, the

Figure 2 near here.

composite thickness of measured sections of the unit on land is roughly 5,000 m and wells drilled for oil, such as Riou Bay #1, have penetrated 4,300 m of the Yakataga without reaching the base. Preliminary analysis of marine geophysical data suggests that the formation is more than 4,000 m thick on the adjacent continental shelf between Yakutat Bay and Kayak Island. The Yakataga Formation is very thin or missing over the Fairweather Ground on the outer continental shelf off the Lituya district. On the shelf west of Kayak Island, its thickness is highly variable but the section in general appears from the geophysical data to thin markedly and may locally be missing over structural highs.

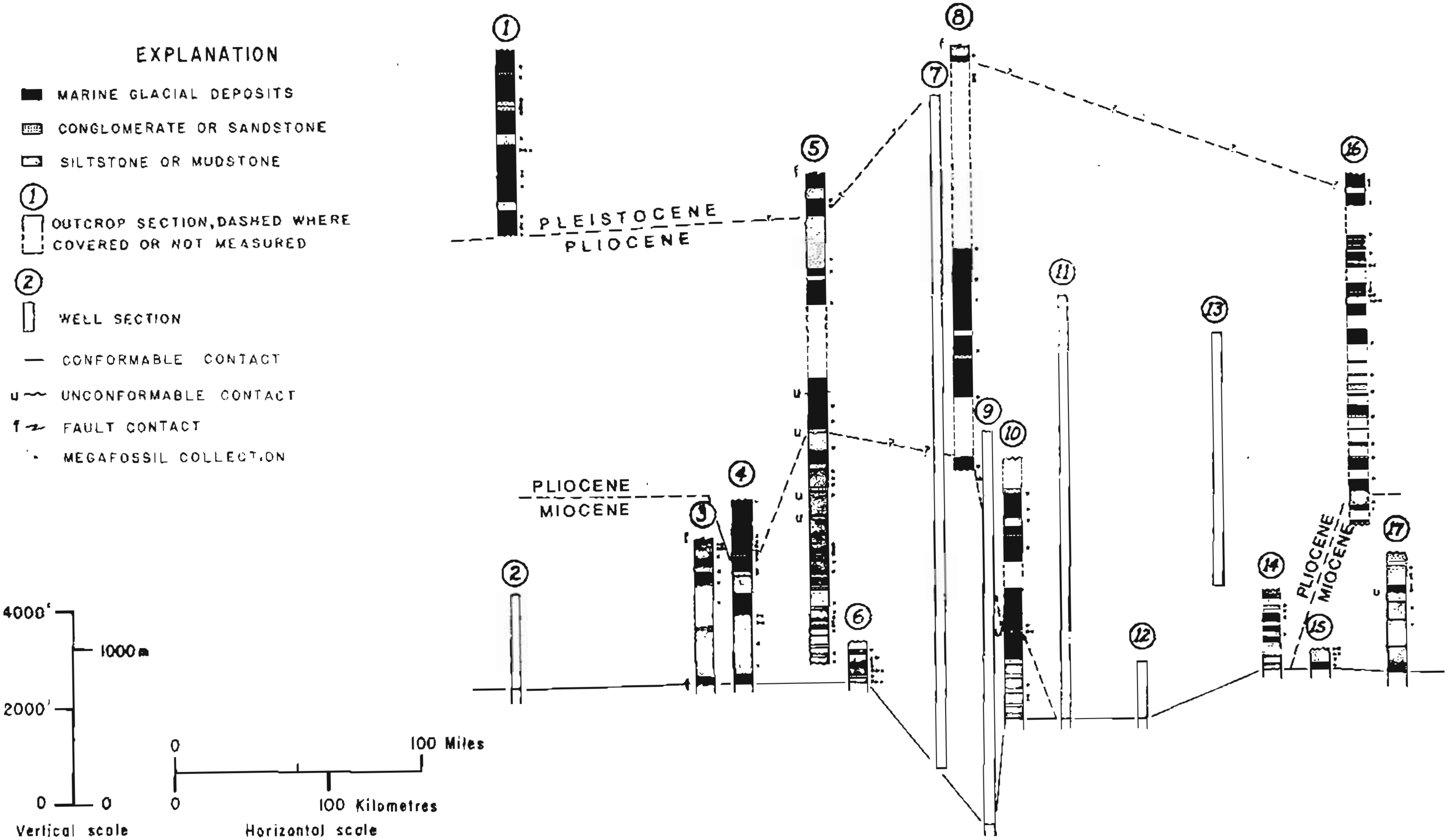


Figure 2. Generalized lithology, thickness, and stratigraphic relations of the Yakataga Formation in selected outcrop sections and wells. Numerals refer to sections and wells shown on Figure 1.

## DEFINITION

The name Yakataga Formation was proposed by Taliaferro (1932, p. 756-759) for a "series of sandstones, dark shales, and conglomerates" including "shale-matrix" conglomerates exceeding 1,500 m in thickness and lying conformably on the Poul Creek Formation in the coastal area of the Yakataga district. He did not designate a specific type locality or a specific geographic feature as the source of the formation name, although he stated that the formation is well exposed at Yakataga Reef (fig. 1) and on both flanks of the "Yakataga" anticline, the coastal anticline now called the Sullivan anticline, to the east of Yakataga Reef. Taliaferro took as the base of his Yakataga Formation "the first thick sandstone encountered above the shales of the Poul Creek formation." The upper limit of the Yakataga Formation was not defined.

Taliaferro's concept of the Yakataga Formation was followed in a series of later reports by Miller (1951, 1957, 1961a, 1961b), although the criteria for placing the basal contact were slightly redefined. More recently, the name Yakataga Formation was extended to lithologically similar strata exposed in the Malaspina district (Miller, 1961c; Plafker and Miller, 1957), in the eastern Katalla district, the Lituya district, and on Middleton Island (Plafker, 1967), and on Kayak and Wingham Islands (Plafker, 1974). In the Malaspina district, the Yakataga Formation includes the distinctive beds originally described as the Pinnacle System by Russell (1891, p. 170-173).

The base of the Yakataga Formation as defined here is marked by the lowest appearance of "floating" sand grains or coarse angular clasts suggestive of ice-rafting. The contact may also be indicated by one or more of the following: a marked weathering color change across the contact from reddish brown to gray, an upward disappearance of glauconite in the section, an influx of coarse and thick beds of sandstone and conglomerate, and a change from a deeper water temperate fauna to a fauna indicative of shallow and cooler water. The basal contact may be abrupt, or transitional over a narrow interval of 30 m or less as at the Kayak Island, Suckling Hills, and Yakataga Reef sections; it may be in unconformable contact with Eocene or pre-Tertiary rocks such as at the Samovar Hills and Fairweather Glacier sections; or it may be gradational or imprecisely located over an interval of as much as several hundred meters as at the Icy Point section. The uppermost part of the unit exposed on land includes indurated lower Pleistocene strata on Middleton Island. In offshore areas of the basin marine seismic profiling and bottom sampling indicate that the youngest part of the formation includes unlithified Holocene deposits. With more detailed stratigraphic studies, it may be feasible to subdivide the sequence into a number of mappable formations of glaciomarine and normal marine strata and to elevate the Yakataga to group rank.

In the absence of a specific designation of a geographic source name for the Yakataga Formation in the original description by Taliaferro, the Yakataga district is suggested as the most appropriate. The continuous section of about 1,800 m of beds exposed between the contact with the Poul Creek Formation at the head of Poul Creek and the southern margin of the Guyot Glacier north of Munday Peak is here designated as the type section (see Miller, 1957, for location and stratigraphic column). Major representative parts of the formation crop out in continuous sections elsewhere in the Yakataga area at Yakataga Reef, on Kulthieth Mountain, just west of Icy Bay on Carson Creek, and along the southeastern margin of the Guyot

Glacier (figs. 1 and 2). The youngest onshore part of the formation crops out on Middleton Island.

## CORRELATIONS

Possibly coeval strata in the Gulf of Alaska Tertiary province that do not contain definite ice-rafted detritus include the highly conglomeratic and sandy sequence of the central Katalla district that was named the Redwood Formation by Taliaferro (1932), and the upper part of the Topsy Formation in the southeastern Lituya district (Plafker, 1967). In the Kodiak Tertiary province to the west, coeval units include the Pliocene Tugidak Formation of the Trinity Islands area which contains abundant ice-rafted detritus, and the nonglacial marine middle Miocene Narrow Cape Formation, which contains a temperate-water megafauna (Moore, 1969; Addicott, 1969). The Redwood Formation most probably is equivalent in age to the lowest part of the Yakataga Formation but could include beds that are slightly older. The relation of the Topsy, Tugidak, and Narrow Cape Formations to the Yakataga Formation is discussed by Plafker in an earlier publication (1971, fig. 2).

## LITHOLOGIC CHARACTER

The Yakataga Formation is made up of sedimentary rocks, almost entirely clastic, laid down in both marine and glaciomarine environments. The gross lithologic character of the formation in various parts of the region is illustrated by the highly generalized measured sections shown in figure 2, and by table 1, which is derived from these measured sections.

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Table 1 near here.

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Interbedded sandstone, siltstone, and mudstone predominate in the lower part of the formation through an interval ranging in thickness from 1,000 m to 1,500 m in parts of the Katalla, Yakataga, and Malaspina districts. Till-like diamictite (termed "conglomeratic" sandy mudstone by Miller (1953)) is interbedded with sandstone and siltstone in all but the basal part of the formation and is the dominant rock type in much of it, particularly the upper part. Conglomerates with rounded clasts and a matrix of either sand- to granule-size grains or sandy mudstone occur throughout but are prominent at only a few localities. Scattered clasts, most of which are interpreted as dropstones, are present in all lithologic types, but especially in the diamictite and laminated siltstones or mudstones. The only nonclastic rock in the sequence is impure limestone, which occurs as concretions and thin, lenticular beds in the mudstone and siltstone.

### Diamictite

The diamictite of the Yakataga Formation is typically a massive mudstone or sandy mudstone containing angular to rounded clasts ranging in size from granules to huge blocks as much as 5 m long (fig. 3). The

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Figure 3 near here.

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Table 1. Relative percentages of major lithologic types in measured sections of the Yakataga Formation

| SECTION | DIAMICTITE | SILTSTONE AND MUDSTONE | INTERBEDDED SANDSTONE AND SILTSTONE | SANDSTONE | CONGLOMERATE |
|---|---|---|---|---|---|
| Middleton Island | 86 | 1 | 1 | 3 | 9 |
| Kayak Island | 20 | 62 | 7 | 5 | 6 |
| Suckling Hills | 29 | 60 | | 8 | 3 |
| Kulthieth Mountain | 27 | 14 | 26 | 29 | 4 |
| Yakataga Reef | 21 | 40 | -- | 37 | 2 |
| Samovar Hills | 55 | 2 | 23 | 17 | 3 |
| La Perouse Glacier | 66 | 11 | -- | 22 | 1 |
| Icy Point | 4 | 28 | 22 | 46 | -- |

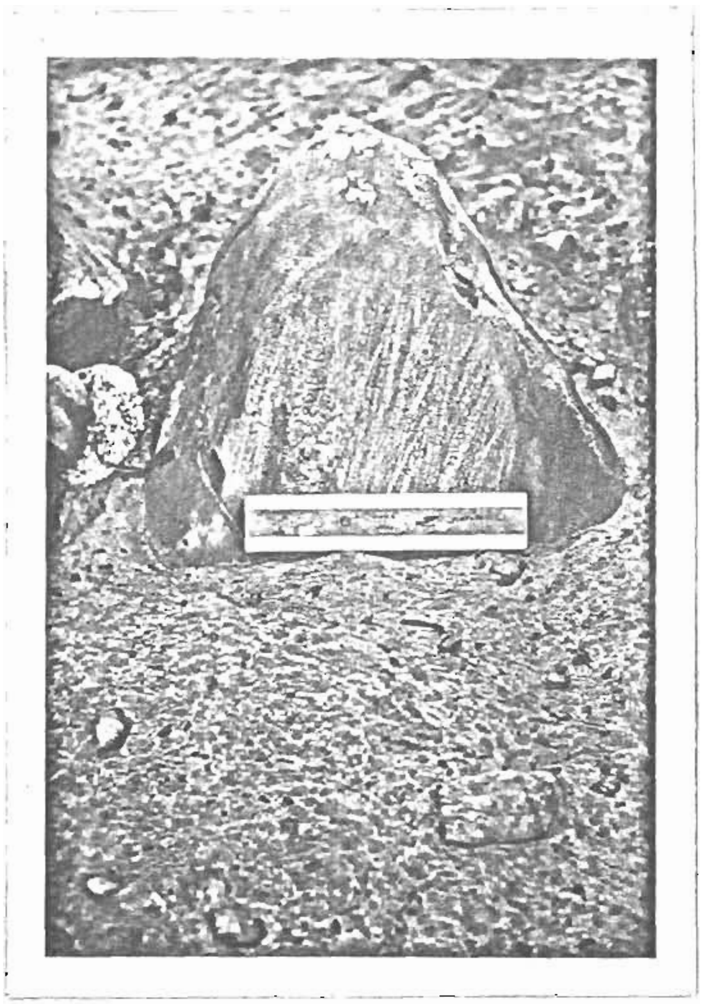

Figure 3.--Diamictite on Middleton Island showing faceted and striated ice-rafted boulder in mudstone matrix. Scale is 17 cm long.

proportion of coarse clasts in the matrix is highly variable but most commonly 5-20 percent. The diamictite is part of a continuous spectrum grading from mudstone to true conglomerate, depending upon the relative abundance and character of the clasts. Coarse clasts are normally randomly distributed throughout the matrix although in places they define a rude stratification within the diamictite. Clasts with preserved glacial striae and (or) glacial facets constitute a few percent of the total, but they occur throughout the formation. The clasts range widely in composition and have been derived from both near and distant source terranes, mostly in the bordering Chugach and Saint Elias Mountains. Commonly their upper surfaces are covered with barnacles, calcareous worm tubes, and other sessile organisms so fortunate as to find solid holdfasts on an otherwise soft mud bottom.

The matrix of the diamictite is gray, greenish-gray, or olive-gray mudstone or sandy mudstone, essentially a mixture of poorly sorted, fresh, angular, finely ground rock material. It is commonly massive but may be faintly laminated or varve-like on a centimeter scale. Clay-size fragments are abundant, but phyllosilicate clay minerals are virtually absent. Mollusks are moderately abundant, and microfossils may be extremely abundant locally in siltstone laminae. The marine diamictite is generally massive, forming blanket-type units of large extent and uniform thickness, as much as 200 m, but more commonly tens of meters thick (figs. 4 and 5). It also occurs as lenticular units that grade

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Figures 4 and 5 near here.

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laterally or vertically into sandstone, siltstone, or conglomerate.

The diamictite is, at least in large part, of glacial origin. The coarse clasts and a part of the finer grained sediment were transported

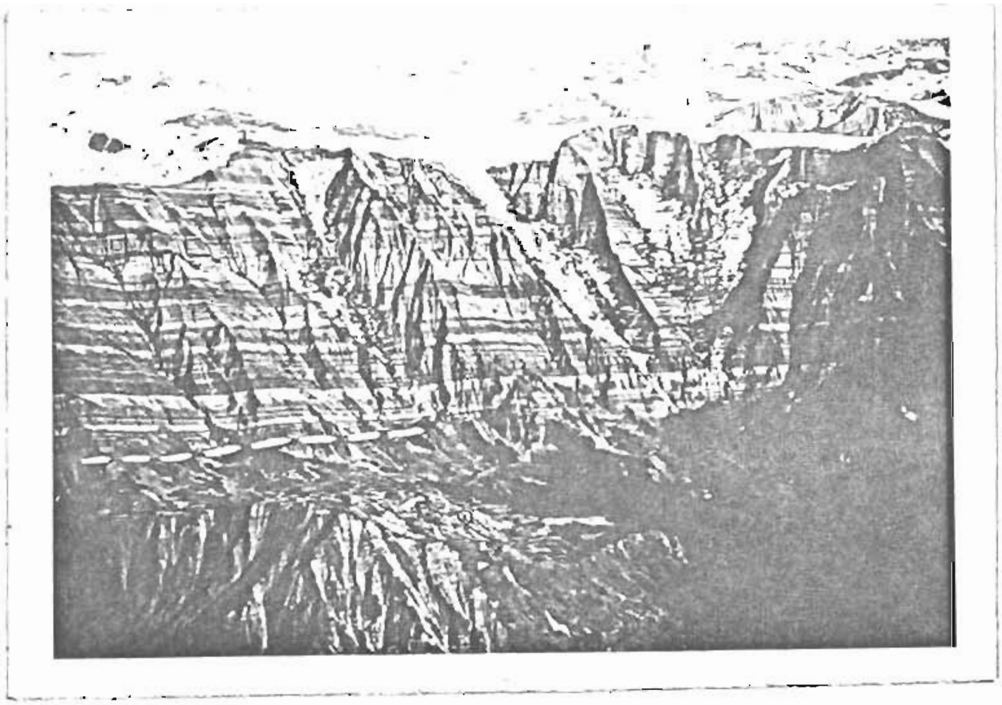

Figure 4.--Basal 1,700 m of Yakataga Formation along Sullivan Ridge, Yakataga district. Dark beds are marine diamictite and siltstone that form massive units to 100 m thick; light beds are mainly sandstone with minor conglomerate. Basal contact (dashed line) with underlying Poul Creek Formation is apparently conformable and gradational over a narrow stratigraphic interval. Photo by Don J. Miller.


Figure 5.--Folded and channelled Pliocene part of Yakataga Formation at Karr Hills. Intraformational unconformities are indicated by dashed line. Photo by Austin Post.

and deposited by floating ice with little or no sorting. Some of the coarse clasts that have fallen to the bottom through the water column have depressed soft laminated bottom muds or have crushed the shells of scallops and similar organisms found in growth position (fig. 6). In

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Figure 6 near here.

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texture and composition, the matrix mudstone is virtually indistinguishable from modern glacial rock flour mud in the nearshore environment of the Gulf of Alaska. The diamictite resembles typical tillite of terrestrial origin in that it consists of unsorted fresh rock and mineral fragments of clay to boulder size; it differs in that it contains marine fossils, it has a higher proportion of rock flour matrix, and it is interbedded with and grades laterally into normal marine deposits.

### Siltstone, Claystone, and Mudstone

Siltstone makes up as much as 63 percent of some sections. It is platy to massive, medium to dark gray on both fresh and weathered surfaces. It forms some massive units, but is more commonly interbedded with size-graded sandstone in units ranging from a few centimeters to a few meters thick. In fresh exposures, apparently massive siltstone beds may show faint varvelike grading on a scale of a few to several centimeters. The siltstone is largely noncalcareous or only slightly calcareous, but contains numerous thin, resistant discontinuous beds and elongate, flat lenses or concretions of gray, impure limestone. Small spheroidal and thicker lenticular concretions were seen at a few localities in the basal part of the Yakataga Formation, but are much less common than in the underlying Poul Creek or Katalla Formations and tend to be more irregular in shape. A significant proportion of the finer grained clastic

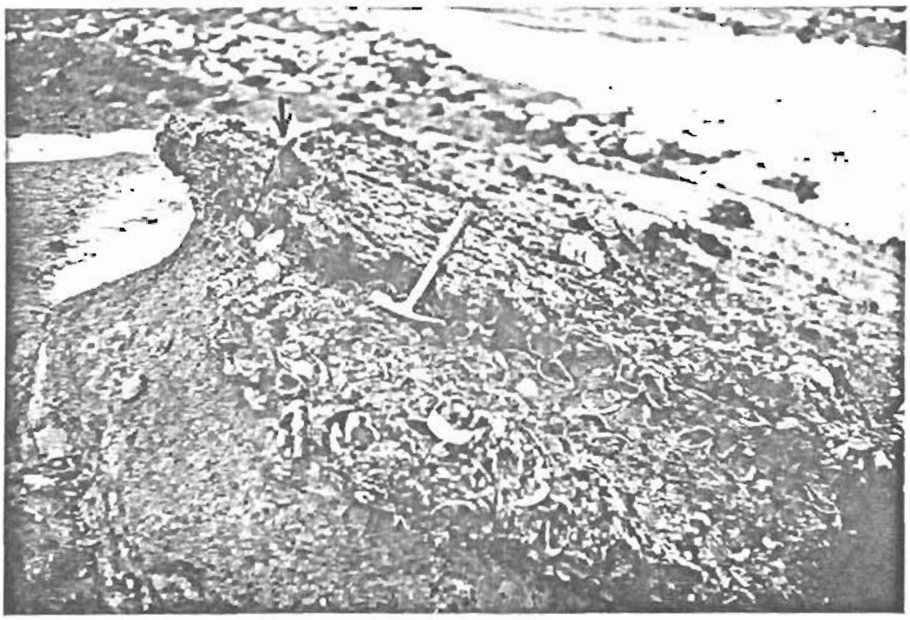

Figure 6.--Calcareous sandstone on Middleton Island containing abundant articulated fossil pectens in growth position. Interbedded with massive diamictite. Arrow indicates ice-rafted cobble embedded in the top of the fossil horizon.

rocks of the Yakataga Formation are properly classed as claystone and mudstone. They grade into the typical siltstone and differ from it only by containing a larger proportion of clay-size grains. X-Ray diffraction and petrographic studies of the fine-grained rocks indicate that phyllosilicate clay minerals are rare in the clay-size fraction and that it typically consists solely of extremely finely ground rock and mineral detritus.

## Sandstone

Sandstone content of the formation ranges from more than 46 percent in sections on the mainland near the northern margin of the basin to as little as 3 percent on Middleton Island near the edge of the continental shelf. The sandstone is chiefly of two types: thin-bedded, partly banded, very fine grained sandstone in units ranging from a fraction of a centimeter to about a meter thick and interbedded with siltstone; slabby to massive, fine- to coarse-grained sandstone in units ranging in thickness from several centimeters to a few hundred meters. Both types of sandstone are light gray, greenish gray, or brown, and generally show little color change on weathering. Quartz, feldspar, and fragments of igneous, metamorphic, and sedimentary rocks are the principal constituents of both types of sandstone; the thin-bedded sandstone is ordinarily micaceous and may be carbonaceous. Grain counts by Gary R. Winkler of 13 sandstone samples taken throughout the formation indicate that they are predominantly lithofeldspathic in composition. Average modes of quartz, feldspar, and lithic constituents are $Q_{36}\ F_{41}\ L_{23}$ with a range of $Q_{30-48}\ F_{24-53}\ L_{12-33}$. Most of the sandstone is poorly sorted, very hard, and has low to moderate porosity and very low to low permeability. In the noncalcareous sandstone beds the degree of induration, in general, decreases upward. Some of the massive to slabby sandstone in the upper part of the formation is somewhat more friable, better sorted, and more porous, but permeabilities of tested samples are generally low. The thin-bedded sandstone commonly shows well developed symmetrical ripple marks. The more massive sandstone beds are notably lenticular, mainly because they grade laterally into siltstone or mudstone, but locally because they fill channels cut into underlying beds. Well rounded pebbles typically occur as lenses at the base or within these massive sandstone beds or may be scattered randomly throughout the sandstone. Many of the thin lenticular beds of conglomerate consisting of poorly sorted and rounded clasts are interpreted as lag deposits formed by winnowing of the diamictite matrix in higher bottom energy environments. Flame structures, flute casts, and related sole features are uncommon but are found locally, particularly in the Kayak Island section.

Interbedded sandstone and siltstone

A characteristic feature of parts of the Yakataga Formation is a rhythmic alternation of thin graded beds of light-gray to brown very fine grained sandstone or sandy siltstone with darker colored siltstone or claystone. Individual beds range in thickness from a centimeter to tens of centimeters, and the units showing rhythmic alternations of these beds are a meter to a few hundred meters thick. Scattered pebble to boulder size clasts interpreted as dropstones may be present in varying amounts. The coarser beds frequently show ripple marks and cross-bedding, and their upper contacts with the finer grained darker beds at most places are sharper and more distinct than their lower contacts. Current ripples and micro-crosslamination suggestive of deposition in a turbidity current environment occur locally, particularly on Kayak Island. Contorted bedding, small-scale faulting, abrupt pinching out, and other sedimentary structures resulting from penecontemporaneous deformation are locally common.

## Conglomerate

Conglomerate consisting of pebbles and cobbles in a matrix of sandstone or sandy mudstone is present in varying amounts, ranging from less than 1 percent of the section at Icy Point to about 9 percent of the Middleton Island section (table 1). The conglomerate, as much as 80 m thick, occurs as lenticular beds, as lenses and basal layers in sandstone, and as thin beds interstratified with sandstone. At a few localities in the upper part of the formation, conglomerate and associated sandstone form steep foreset beds suggestive of deposition by running water, either around ice margins or in subglacial channels. Some of the conglomerate beds occur at intraformational unconformities. Clasts are mostly well rounded to subrounded, but scattered blocks and pods of more angular material are common and some beds are made up largely of rudely sorted and rounded material. The conglomerate may include irregular lenses of diamictite or it may grade into diamictite both laterally and vertically. Large bulbous flute casts were found at the base of a massive pebble-cobble conglomerate at Kayak Island, but such sole markings are generally absent.

## STRATIGRAPHIC RELATIONS

The contact between the lower part of the Yakataga Formation and the underlying middle Tertiary Poul Creek and Katalla Formations in the Yakataga and Katalla districts is conformable at most places where it is well exposed. However, on structural highs in the Yakataga district the contact is locally marked by an unconformity of as much as 15°. The dominant gray-weathering tone of the Yakataga Formation is especially evident at its contact with the underlying middle Tertiary units (fig. 4). The upward change of weathering tone from reddish brown to gray marks this contact throughout the Yakataga district and the Suckling Hills of the Katalla district. In the Malaspina district, thick conglomerates in the upper Yakataga Formation also weather pale reddish brown.

A regional unconformity is present at a stratigraphic position that is within 1,500 m of the base of the formation in the Yakataga-Malaspina areas. In the Karr Hills, at the boundary between the Yakataga and Malaspina districts, Pliocene Yakataga beds dipping from 45° to 90° (along the north flank of the Yakataga anticline) are overlain with marked angular contact by higher Yakataga beds dipping 30° or less (fig. 5). Excellent exposures of this same unconformity on the south flank of the Yakataga anticline in the Guyot Hills show a lesser angular discordance of 45° to 50°.

In the Samovar Hills of the Malaspina district the upper part of the Yakataga overlaps the upper unit of the early Tertiary Kulthieth Formation and the pre-Tertiary Yakutat Group. At the contact, the Kulthieth is approximately accordant in strike with the overlying Yakataga but dips 5° to 15° more steeply. The unconformity between the Yakataga Formation and Yakutat Group in the eastern part of the Samovar Hills is more marked, the discordance in bedding at places approaching 90° in both strike and dip. In the subsurface of parts of the Yakutat district and in the northwestern part of the Lituya district the Yakataga Formation unconformably overlies pre-Tertiary rocks, whereas in the southeastern part of the Lituya district it is apparently conformable with the middle Tertiary Topsy and Cenotaph Formations.

# PALEONTOLOGY

## Fossils

Remains of marine invertebrates have been found throughout the Yakataga Formation associated with all lithologic types except the limestone. The fossils are chiefly mollusks, with pelecypods (84 species) exceeding gastropods (45 species) in both number of individuals and variety of species. Bivalves are commonly found articulated and in growth position and there are extensive layers rich in fossil clams, scallops, gastropods, barnacles, echinoids, Foraminifera, and ostracods (fig. 6). Barnacles and worm tubes are frequently found attached to shells of large mollusks or to coarse rock fragments. Brachiopods (3 species) were collected at several localities. Echinoids (4 species), including sea urchins and sand dollars, are locally abundant. Scattered marine mammal bones occur throughout the formation and unidentified fish bones and fish scales have been found. Pieces of wood and poorly preserved leaves are sparsely distributed in the sequence. Resedimented broken fossils are abundant in the sandstone, conglomerate, and diamictite beds..

## Previous work

The molluscan fauna collected from the Yakataga Formation, though abundant and moderately varied, includes relatively few identifiable species that indicate its age any closer than late Tertiary. This is due partly to the state of preservation, but mainly to the fact that the collections are largely of a provincial cold-water fauna that contains few species that can be compared with better known faunas in late Tertiary formations farther south on the Pacific coast. Dall regarded the earliest collections from beds now included in the Yakataga Formation in the Malaspina district as probably Pliocene (Russell, 1891, p. 170-172, and

1893, p. 25; Dall and Harris, 1892, p. 259), and those from the Yakataga district as Miocene to Pleistocene (Maddren, 1914, p. 127-130). He identified the fossil shells collected by Russell in the Malaspina district with living species. This, plus their association with glacial deposits, led Brooks (1906, p. 227, 272) to the erroneous conclusion that the beds containing them were, in fact, Pleistocene. Brooks' error led to the oft-repeated citation of the Pinnacle Pass locality as evidence of Holocene uplift of at least 1,500 m in the St. Elias Mountains.

The collections made by Taliaferro (1932) from the lower part of the Yakataga Formation in the Yakataga district were regarded by Clark (1932, p. 799-801) as late Oligocene, but his determination was based almost entirely on species occurring only in the underlying Poul Creek Formation.

In the Lituya district, a collection made from the basal part of the Yakataga Formation on Cenotaph Island (fig. 1, no. 15) by the Wrights was first determined by Dall (in Buddington and Chapin, 1929, p. 269-270) as probably Pliocene; he later concluded (in Mertie, 1931, p. 129-131) that the fauna was in part of Miocene age and correlative with the fauna of the Astoria Formation of coastal Oregon. L. G. Hertlein examined nearly all of the mollusks and echinoids collected from the Yakataga Formation in the Lituya district during the late 1940's and the 1950's, and F. S. MacNeil made a preliminary study of all the mollusks from the Yakataga Formation in the Geological Survey collections as of 1964. Kanno (1971) described the Tertiary molluscan fauna from the Yakataga district and adjacent areas based on material collected by him during 1968 and on the Geological Survey collections.

Foraminifera are widespread and locally abundant; they have been recovered from about one-third to one-half of the surface samples of siltstone and mudstone that were disaggregated and sieved. Preservation is generally good to excellent in the Pliocene and Pleistocene parts of the formation, progressively poorer with depth in the section. Benthonic species dominate the faunas with Globigerina pachyderma the major planktonic form throughout the section. Because most of the foraminiferal faunal changes represent facies changes and the majority of species identified are living forms, the value of Foraminifera for age zonation of the Yakataga Formation is limited. Nevertheless, at least three broad foraminiferal zones have been recognized by Ruth Todd (written commun., 4/26/72), and restudy by Weldon Rau of the material now in progress should permit refinement of the zonation.

Nannoplankton are sparse throughout the formation; the only short-ranging species found is the Pleistocene form Gephyrocapsa caribbeanica Boudreaux and Hay from the Middleton Island section (David Bukry, written commun., 11/13/72).

Siliceous micro-organisms are sparse in the Yakataga Formation and most are long-ranging forms with little or no age significance. The diatom Thalassiosira oestruppi and the silicoflagellate Distephanus polyactis from the Middleton Island section indicate a late Pliocene or Pleistocene age (J. A. Barron, written commun., 10/23/74, and H. J. Shrader, written commun., 2/6/72).

## Age

Molluscan faunas from the Yakataga Formation range in age from early Miocene to early Pleistocene. Early Miocene assemblages, however, are known only from Kayak Island where *Acila gettysburgensis* (Reagan) occurs at a few localities on both the northeast and northwest coasts. Evaluation of stratigraphic occurrences of this bivalve in the conterminous Pacific Coast States by Addicott shows that its biozone is coeval with the "Blakeley" Stage (Weaver and others, 1944) of western Washington and that it does not range above the provincial early Miocene.

In mainland sections, the basal part of the Yakataga Formation is of provincial middle Miocene age. Some of the most compelling evidence for this age assignment is the conformable and gradational relation between the Yakataga and the underlying Poul Creek Formation apparent in certain onshore sections such as on Yakataga Reef where the basal part of the Yakataga is very fossiliferous (Kanno, 1971). The fauna of the upper part of the Poul Creek is of early Miocene age; it can be readily correlated with lower Miocene formations of western Washington on the basis of many species in common, including the zonal index "*Echinophoria*" *apta* Tegland. The uppermost part of the Poul Creek Formation may be somewhat younger than the *Echinophoria apta* zone but is still of provincial early Miocene age according to recent analysis of the early Miocene of western Washington (Addicott, 1975).

There is a sharp faunal break across the Poul Creek-Yakataga contact marked by a two-fold drop in species diversity and, at the same time, replacement of molluscan taxa of temperate aspect by cold water, high latitude species, an unusually large number of which are still living. These changes are attributed to the initiation of glaciation along the margin of the marine basin during the middle Miocene and concomitant chilling of the nearshore, shallow water marine environment. This cooling intensified faunal differences between the Gulf of Alaska area and western Washington (lat 47°-48° N.) where middle Miocene faunas are characterized by many subtropical genera. Whereas correlation of early Miocene faunas between these areas and, for that matter, northern Japan (Kanno, 1971) are clear-cut, middle Miocene faunas are of strongly contrasting temperature facies and contain almost no species in common. Nevertheless, several lines of faunal evidence point to a middle Miocene age for the lower part of the Yakataga Formation on the mainland. Two species in the Yakataga Formation, Macoma arctata (Conrad) and Molopophorus matthewi Etherington, are restricted to, or do not range above, the middle Miocene of Oregon and Washington. Other species suggest correlation with middle Miocene formations of Hokkaido, northern Japan (Kanno, 1971). Other molluscan taxa that appear at or near the base of the Yakataga Formation are suggestive of a middle Miocene age based upon phylogenetic position or widespread appearance during the middle Miocene around the North Pacific margin. These include the bivalves Patinopecten spp., Swiftopecten swifti (Bernardi) (Masuda, 1972), Siliqua, Mya truncata Linné, Mya cuneiformis (Bohm) and the gastropods Neptunea spp. and Turritella hamiltonensis Clark (Kanno, 1971).

A left-coiling cold water planktonic foraminifer collected from close to the base of the Yakataga Reef section and the Kulthieth Mountain section, Globigerina pachyderma (Ehrenberg) suggested to Bandy and others (1969) that all but the lowest 30 to 50 meters of these sections is of late Miocene age. As details of their microfaunal study have not been published, it is not possible to evaluate their conclusion.

On Kayak and Wingham Islands, Rau (in Plafker, 1974) found Foraminifera about 1,000 m above the base that are typical of the lower or middle Miocene Saucesian or Relizian Stages of Washington. Rau's preliminary data, together with the megafaunal evidence, strongly suggests a greater age for the lower Yakataga than that postulated by Bandy and others (1969).

Determination of series-epoch boundaries, and subdivisions thereof, above the base of the Yakataga Formation is exceptionally difficult owing to the high degree of faunal provincialism coupled with the tendency for late Cenozoic cold water mollusks to be unusually long ranging. On the other hand, the stratigraphic distribution of mollusks in the Yakataga (see MacNeil in Miller, 1957, 1971) permits the establishment of biostratigraphic units useful in correlation within the Gulf of Alaska Tertiary province (Plafker, 1971). Unfortunately, almost none of the stratigraphically restricted species range outside of this province and they cannot be used in interprovincial correlation.

The Miocene-Pliocene boundary is placed between about 1,800 and 2,100 m above the base of the section exposed at Kulthieth Mountain. The stratigraphically higher part of the Kulthieth Mountain section includes low diversity assemblages composed chiefly of modern species. Miocene assemblages contain many extinct species. The pectinid Chlamys (Leochlamys) tugidakensis MacNeil, a characteristic Pliocene and early Pleistocene species, appears in this part of the Kulthieth section. This species is especially characteristic of the Pliocene section of Tugidak Island and the Pleistocene section at Middleton Island.

Mollusks and foraminifers (P. B. Smith, written commun., 1963) from exposures of the Yakataga Formation on Middleton Island are almost entirely living species. The sequence contains an abundant Foraminifera and Ostracoda microfauna; Loeblich and Sohn (in Miller, 1953) suggest a Pleistocene age, although most of the species identified are living in Arctic waters today. Unpublished paleomagnetic studies by E. Mankinen and R. Doell and nannofossil studies by D. Bukry suggest that the entire stratigraphic section exposed on Middleton Island may be of early Pleistocene age. There is nothing within the molluscan and foraminiferal assemblages to contravene either a Pliocene or Pleistocene age.

## Paleoecology

With the exception of lowermost sublittoral to bathyal assemblages of early Miocene age from Kayak Island, molluscan data from the Yakataga Formation reflect shallow water, inner to middle sublittoral depositional environments. Utilizing the modern depth distribution of component molluscan genera and homologous species in the eastern North Pacific as a template, fossil assemblages from the Yakataga Formation appear to have lived in depths less than about 100 m. Most of them seem to indicate depths of about 20 to 60 m; locally shallower depths are indicated.

A definite slight shallowing across the Poul Creek-Yakataga Formation contact is indicated at Yakataga Reef. Mollusks from the upper 200 m of the Poul Creek suggest inner to middle sublittoral depths--about 60 to 100 m. Upper Poul Creek genera that do not range into shallower water include the ornate gastropods *Musashia* and *Ancistrolepis*. Although most of the genera from the basal 200 m of the Yakataga Formation at Yakataga Reef today range from a few meters through the sublittoral zone to depths of 200 m or greater, several are characteristic of inner sublittoral depths and indicate deposition, for this part of the formation, in the range of about 25 to 50 m. Shallow-water genera that are of common occurrence in the Yakataga include *Mya*, *Chione* (*Securella*), *Clinocardium* and *Pododesmus*.

At Kulthieth Mountain, about 20 km northwest of Yakataga Reef, the lower 600 m of the Yakataga include similar, low diversity molluscan assemblages of middle Miocene age that are indicative of comparable water depths. Significant shallowing seems to have occurred near the top of the Miocene part of the Kulthieth Mountain section about 1,000 to 1,200 m above the base. Assemblages from this part of the section include the bivalves

Chione (Securella), Spisula, and Swiftopecten and large sand dollar echinoids. In the stratigraphically highest part of the section on the north side of Kulthieth Mountain, additional very shallow water taxa such as barnacles and the intertidal to high subtidal gastropod Nucella lamellosa (Gmelin) appear in the uppermost 500 to 600 m. This suggests at least local shallowing during the Pliocene.

The lower Pleistocene part of the Yakataga Formation on Middleton Island represents deeper water conditions than the Pliocene section at Kulthieth Mountain. The lowermost 100 m includes moderately diverse assemblages representing depths of about 20 to 60 m. Shallow-water indicators include Mytilus, Balanus, and the distinctive pectinid Chlamys (Leochlamys) which is closely related to C. nipponensis Kuroda, a species that lives in 18 to 36 m off Japan (Kira, 1962).

Assemblages between 350 to 950 m above the base of the Middleton Island section are of greater diversity, containing, in addition to the two shallow water bivalves that appear in the lower part of the section, Mya truncata Linné, Pododesmus, Hiatella, and Nucella lima (Gmelin), which suggest continued shallow water conditions and depths of 15 to 20 m or possibly deeper. Slight deepening occurred during deposition of the stratigraphically highest beds on Middleton Island, beginning at a point about 1,150 m above the base of the exposed section. The appearance of Aforia circinata (Dall) suggests deepening to about 50 to 75 m or more.

The most striking paleoenvironmental difference between the Poul Creek and Katalla Formations and the Yakataga Formation is the abrupt upward change from temperate to cold water conditions at the base of the Yakataga. This abrupt chilling is marked by a sharp decline in taxonomic diversity and the appearance of cold water assemblages of distinctly modern aspect. Relatively few mollusks range from the Poul Creek into the basal part of the Yakataga Formation. Comparable, if not stronger, contrasts in temperature facies across this boundary in mainland sections are postulated by Bandy and others (1969) on the basis of planktonic foraminifers. This abrupt chilling of the shallow water, nearshore marine environment during the middle Miocene stands as a local anomaly in the paleoclimatic history of the Pacific. The middle Miocene of the Pacific Ocean basin was a period of climatic amelioration based upon data from various biologic groups (Addicott, 1969, 1974) as well as oxygen isotope data (Devereux, 1967). There is also evidence of climatic warming in terrestrial biotas (Dorf, 1955; Wolfe and Hopkins, 1967). The anomalous Neogene glaciation in the Gulf of Alaska appears to have had profound effects on the shallow water marine biota along the northern margin of the Gulf of Alaska. The localized extent of this chilling of the marine environment is pointed up by the occurrence of predictably warm water assemblages of middle Miocene age at Narrow Cape on Kodiak Island, along the southwestern margin of the Gulf of Alaska (Addicott, 1969).

## SPECULATIONS ON DEPOSITIONAL ENVIRONMENT

Formulation of a reasonable depositional model for the Yakataga Formation is constrained by its occurrence on land in a narrow, linear outcrop belt that is nearly parallel to the paleoshoreline and by the severe tectonic deformation involving large-scale dislocations within the Yakataga geosyncline that occurred throughout the late Cenozoic. There is at the present time little north-south facies control although future deep drilling on the Continental Shelf is expected to shed light on facies changes perpendicular to the coastline. Nevertheless, the data do permit reconstruction of a generalized model that can account for most of the characteristics of this unique formation.

The Yakataga Formation is largely, of not entirely, of marine origin and was deposited in a linear complex shelf basin in which water was mostly less than 100 m deep. The lithology of the clasts, the limited paleocurrent data, and the facies variations all suggest a general northerly source terrane. Sediment thickness and facies distribution suggest deposition on a very uneven primary sedimentary surface that may have been in part formed by growth structures within the basin and in part by great variations in sedimentation rates in the vicinity of tidal glaciers. The scarcity of beach deposits within the formation and the absence of continental equivalents along the northern margin of the basin (except for one small occurrence in a fault sliver in the eastern Malaspina district) suggest that the coast was generally steep and (or) ice-fronted during much of Yakataga time.

The distribution of ice-rafted detritus in the section indicates that glacial ice initially reached tidewater in the vicinity of the present Bering Glacier some time during the early Miocene. The conglomeratic

Redwood Formation in the central Katalla district may represent coarse deposits of beach-worked fluvioglacial outwash that were deposited in a nearshore environment as the glacier fronts approached the coast. Similar beach-worked deposits were funnelled offshore into a moderately deep shelf basin to form much of the coarse basal part of the Yakataga Formation on Kayak and Wingham Islands. This occurred at about the time that the glaciers reached tidewater and icebergs began rafting occasional dropstones into this basin. Clast lithology in the basal Yakataga strata suggests that the sediment source was the Paleozoic metamorphic terrane with its associated potassium feldspar-rich granitic and syenitic rocks in the northeastern Chugach Mountains. If this terrane was indeed the source, the crest of the ancestral Chugach Mountains was considerably farther north than it is today.

By middle Miocene time glaciers in the vicinity of the Malaspina reached tidewater, followed in the late middle and late Miocene by onset of sporadic ice-rafting in the Lituya district. Thus, dropstone distribution suggest that the onset of ice-rafting progressed, in general, from west to east along the Gulf of Alaska mainland coast.

During Miocene time, glaciers contributed small to moderate amounts of the coarser detritus that reached the shelf basin, but the amount of ice-rafting was highly variable in space and time, depending upon proximity to tidewater glaciers and the prevailing directions of longshore currents. By early Pliocene time, this glacial fraction was significantly augmented in the entire Yakataga basin and intermittent ice-rafting continued at an ever-increasing scale, culminating during the Pleistocene. Ice-rafting continues to the present time in parts of the region, but at a considerably reduced rate.

It is suggested that the highly conglomeratic diamictites and the massive conglomerates and sandstones were deposited largely as thick, steep-sided submarine aprons at or near tidal glacier fronts and that the finer deposits of claystone, siltstone, mudstone, and rhythmically interbedded sandstone-siltstone pairs tended to fill the topographic lows between and seaward of the submarine aprons. Soft-sediment deformation occurred on the steeper slopes, particularly on the flanks of growing anticlinal highs. Periodic slumps from these slopes, triggered in part by earthquakes, could have resulted in deposition of local submarine landslide deposits and widespread turbidites in the deeper parts of the basin, such as those now exposed at Kayak Island. Most of the rhythmically bedded varvelike pairs, however, contain shallow water faunas that do not seem to be displaced. These thin bedded rhythmically alternating silt and very fine sand beds suggest deposition as seasonal or annual layers.

The occurrence of numerous channels, local unconformities, and diamictite and conglomerate within the Pliocene part of the sequence in the Yakataga and Malaspina districts suggest that grounded glaciers periodically migrated across the area between the present coast and the base of the high mountains (fig. 6). During parts of the Pleistocene, they extended all the way across the shelf at least as far as Middleton Island. The general absence of striated pavements is attributed to the fact that these piedmont and tidal glaciers, unlike continental glaciers, were moving across a soft, water-saturated bottom in which grooves are not likely to be preserved. Grooved pavements, believed to have been made by a grounded ice shelf, were found only on the northeastern end of Middleton Island and in the Suckling Hills. The consistent northeast-southwest orientation of grooves at Middleton Island, which are exposed on several bedding planes, is suggestive of scour by an ice sheet rather than grounded bergs. This interpretation is supported by the occurrence of a coarse, rudely sorted and cross-bedded marine channel fill that is believed to be an ice-contact deposit in the upper part of the Middleton Island section.

At their maximum advances during the Pleistocene, the glaciers undoubtedly coalesced to form a near-continuous ice front along the mainland coast that probably extended across the present Continental Shelf. In deeper water off the edge of the Continental Shelf, it may have formed a narrow floating ice shelf from which large ice floes calved directly into the open ocean. However, the shallow-water fauna in the Yakataga Formation and the abundance of marine fossils throughout the sequence suggest that there was no floating ice shelf over the Yakataga basin, except perhaps during the late Pleistocene, for which there is no known onshore stratigraphic record.

Part of the younger history of sedimentation may be deduced from the cores of Deep Sea Drilling Project (DSDP) holes drilled in and near the Aleutian Trench off Kodiak Island and from a series of piston cores taken by the Lamont group over the deep floor of the North Pacific Ocean. The DSDP data indicate that ice-rafting can be recognized at Site 178, located on the outer wall of the Aleutian Trench off Kodiak Island, beginning in the middle Pliocene but that an influx of terrigenous sediments apparently began in early or middle Miocene time (von Huene and Kulm, 1973, p. 966). The piston core studies from further south show that minor ice-rafting began at least as early as the late Pliocene (2.4 m.y.b.p.), but that large-scale ice-rafting occurred mainly within the Pleistocene, beginning about 1.2 m.y.b.p. (Kent and others, 1971). The southernmost extent of ice-rafted detritus in the northeast Pacific Ocean as plotted by Conolly and Ewing (1970) is about latitude 45° South, some 1,500 km south of the Alaskan coast.

In summary, the marine glacial deposits of the Yakataga Formation record a unique depositional environment in the late Cenozoic that continues to the present time. Tidewater glaciers persist along the Gulf of Alaska coast today as a result of the combined effects of the high elevations of the mountain chain along the mainland coast and the heavy precipitation in these mountains from the prevailing northerly winds that pick up moisture as they blow across the relatively warm Japan counter-current. Uplift of the coastal mountains reflects the interactions that have occurred during late Cenozoic time along the interface between the North American continent and the Pacific Ocean basin. As a consequence of these movements, the western part of the Gulf of Alaska adjacent to the Aleutian Trench is essentially a zone of compressive deformation along which the Pacific Plate is underthrusting the continental margin, the easternmost part of the Gulf of Alaska is a zone of shear in which the oceanic plate is moving laterally past the continent along the Queen Charlotte and related strike-slip faults, and the central part of the region is a zone of combined compression and shear due to oblique underthrusting (Plafker, 1969). Evidence for abrupt shoaling of the basin in early Yakataga time and the occurrence of ice-rafted detritus in the Yakataga Formation indicate that this late Cenozoic orogenic episode may have begun roughly 20 m.y. ago and that it probably progressed from west to east along the mainland coastal belt through the Miocene. During this orogeny the Pacific Border Ranges were markedly uplifted, and in places were thrust relatively seaward along a system of major faults. Local multiple angular unconformities record deformation in the depositional basin during Yakataga time.

Continuing active deformation is indicated by tilting, faulting, and uplift of marine rocks as young as early Pleistocene on Middleton Island, by active seismicity and earthquake-related deformation, and by the great topographic relief along the northern margin of the basin.

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