RAISED MARINE TERRACES SOUTHEAST
OF LITUYA BAY, ALASKA.

A Thesis
Presented in Partial Fulfillment of the Requirements
for the Degree Master of Science

by
Stephen Jay Derksen, B.S.
The Ohio State University
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Approved by

Richard P. Goldthwait
Adviser
Department of Geology
and Mineralogy
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INTRODUCTION

Along 40 miles of coastline of the Gulf of Alaska between Cape Fairweather and Icy Point in Glacier Bay National Monument (Fig. 1) lie five conspicuous terraces at elevations up to 550 meters. These were described briefly by Mertie (1933), Rossman (1957), and in more detail by Heusser (1960) and Miller (1961). Mertie, Heusser, and Miller assumed their marine origin although only one deposit containing marine shells has been described from a terrace at 46 meters elevation (Rubin and Alexander, 1958). However, fossiliferous marine gravel, sand, and clay is found locally at various elevations up to 185 meters throughout southeastern Alaska (Buddington, 1927). Goldthwait and others (1963) assumed these five terraces were cut by interglacial higher sea levels.

The purpose of this investigation was to verify a marine origin for these features and, if possible, to date the time of their emergence from the sea. This would clarify the history of regional glaciation by bracketing the age of ancient glacial deposits found on several terraces, determine how long unglaciated parts of the terraced area have served as an ice-free refugium
for flora and fauna during glacial maxima, and determine rates of tectonic uplift along this coast. Pollen analysis of peat deposits on unglaciated terrace surfaces would be useful as a stratigraphic tool, and provide a history of regional vegetation and climatic change far older than the known postglacial record of southern and southeastern Alaska and British Columbia (Heusser, 1952, 1954, 1960).

A study area of 57 square kilometers was selected between Lituya Bay and Crillon Lake (Fig. 1) because all five terraces are well-developed in this area and the more recent glacial history Lituya Bay and Crillon Lake has been described (Goldthwait et al., 1963). Field work was carried out during six weeks of the summer of 1973. Logistic difficulties, dense vegetation, few natural exposures of surficial deposits, and inadequate coring apparatus complicated field research. However, significant observations of terrace morphology, stratigraphy, and vegetation were made, and samples were collected for $^{14}C$ dating, pollen analysis, grain-size and heavy mineral analysis, and diatom and foraminifera identification.

Geologic Setting

The terraced area lies in a low foothill belt of folded, faulted, and in part metamorphosed late-Tertiary
Figure 1. Location of the Study Area.
marine sedimentary and volcanic rocks separated from the crystalline rocks of the massive Fairweather Range of the St. Elias Mountains by the active right-lateral Fairweather Fault (Fig. 2). The Fairweather Fault extends northwest from Icy Point to merge with the Chugach-St. Elias Fault System that curves around roughly paralleling the Gulf of Alaska to terminate at the Copper River some 280 miles distant (Plafker, 1967). Displacement along this fault of 6.5 meters horizontally and 1.1 meter vertically in 1958 caused landslides in Lituya Bay that produced giant waves which anihilated trees up to 1700 feet above the Bay (Tocher and Miller, 1959). Older wave-caused trimlines suggest former seismic activity in 1899, 1874, and 1853-54.

The coastline is unusually regular from Icy Point northwest to the Copper River and is marked by only three large indentations: Icy Bay, Yakutat Bay, and Lituya Bay. The Tertiary foothills generally lie below 1100 meters in elevation, but the St. Elias Mountains include fourteen peaks of over 14,000 feet, the highest being Mt. Logan, 6,050 meters. The St. Elias are the highest coastal mountains in the world and heavy precipitation occurs as relatively warm, moist air from the Gulf of Alaska condenses as it rises over this mountain mass from the southwest during most of the year. This rugged area
Figure 2. Geographic location of the Study Area. The several raised terraces are visible in the right side of the photograph, Lituya Bay is on the left, and the Fairweather Range rises in the background. The high peak at center is Mount Grillon, 3932 m, only 17.5 km from the coast.

(Photo by Bradford Washburn, 1934)
Figure 3.

Geology of the Study Area

[Legend and map details not transcribed]
has been intensely glaciated and has an average relief of over 1500 meters.

Bedrock geology of the study area has been described by Mertie (1933), Kennedy and Walton (1946), Miller (1953, 1957, 1958, 1960, 1961), Rossman (1959), and most recently by Plafker (1957, 1970), (Fig. 3).

The crystalline rocks of the Fairweather Range include granite, quartz monzonite, granodiorite, mafic intrusives, schist, gneiss, amphibolite, and marble, all of Mesozoic or earliest Tertiary age. Metamorphic rocks northeast of the Fairweather Fault are moderately to intensely metamorphosed and complexly deformed.

The Tertiary coastal lowland rocks were divided into three formations by Plafker (1967). Nearest the coast is the Yakataga Formation of middle Miocene to early Pleistocene age. It consists of about 5,030 meters of marine mudstone, siltstone, sandstone, and minor conglomerate interbedded with abundant conglomeratic sandy mudstone (tillite ?) characterized by unsorted, striated, and faceted clasts of diverse lithologies. Underlying this formation is the Topsy Formation and Cenotaph Volcanics of mid-Tertiary age.

The Topsy Formation consists of 365 meters of calcareous siltstone and sandstone that intertongues with and partly overlies 380 meters of the Cenotaph Volcanics
which consist of andesitic volcanics interbedded with
tuffaceous siltstone, glauconitic sandstone, pebble-
cobble conglomerate, and minor coal.

Beneath these Tertiary rocks lies a sequence of
complexly deformed, moderately metamorphosed Mesozoic
greenstone and volcanic graywacke with minor argillite,
chert, and limestone. These rocks only occur in the
study area in a thin belt along the southwestern side
of the Fairweather Fault.

Bedrock mapping by Miller (1961) has shown that
the lowland Tertiary rocks have been folded along axes
that more or less parallel the coast, but demonstrate
no obvious relationship between structure and several
terraces (Fig. 3).

Beach sands containing high concentrations of
heavy minerals in their upper part including gold and
platinum have been mined sporadically for gold since
1894.

Description of the Terraced Area

The Study Area

The general appearance of the study area is shown
by Figures 4 and 5. The terraced area is like a giant
staircase up the southwest side of the young coastal
mountains.
Figure 4. Aerial photograph of the terraced area.

(Photo by Eredford Washburn, 1934)
Figure 5. Relationship of terraces and moraines southeast of Lituya Bay. Note the termination of cliff B & C, glacial deposits, and cliffs $A_1$ and $A_2$. (Photo by Bradford Washburn, 1934).
Figure 6. Generalized cross-section of the terraced area just southeast of Lituya Bay.
Figure 7. Uplifted marine platform along the coast near Steelhead Creek.

Figure 8. Bedded sands in the lower margin of terrace A exposed at the mouth of Whale Creek.
The modern sand beach averages about 120 meters in width from the vicinity of the prominent Late-Wisconsin and Neoglacial moraines (Goldthwait, et al., 1963) southeast of Lituya Bay down to Whale Creek where a small patch of moraine marks the greatest expansion of ice from Lituya Bay (Fig. 6). Southeast of Whale Creek the beach narrows to about 60 meters and outcrops of nearly vertical strata of the Yakataga Formation occur along the beach for about seven kilometers. The accordant height of much of the exposed bedrock strata suggests the former surface of an uplifted marine platform (Fig. 7). Southeast of Topsy Creek the bedrock again disappears and a wide sand beach stretches down to the Crillon River.

The highest modern storm waves reach inland to an elevation of 7.5 meters where a small escarpment and tangle of logs from the destruction of the 1958 waves in Lituya Bay marks the seaward edge of terrace "A" (Fig. 8). This 150-meter-wide terrace slopes gently inland to a low cliff (cliff "A") at 12-14 meters elevation at the base which forms the upper boundary of this lowest terrace. This bench is mantled by more than three meters of unweathered sand and an accumulation of 7 to 10 cm of peat. The vegetation changes rapidly from grass, lupine, and beach pea at 7.5 meters elevation to
arboreal species at about 10.5 meters. Alaska yellow cedar and Sitka spruce form the periphery, but spruce increases in number inland so that near the cliff the sub-climax forest is composed entirely of small-diameter spruce trees and a few hemlock saplings. An old whale skull lies near the cliff (Fig. 9).

Cliff A stands like a nearly vertical wall about 11 meters high where it is cut into bedrock landward of the uplifted marine platform along the coast (Fig. 10). However, both northwest and southeast of the coastal bedrock cliff A is broken into two smaller cliffs, A₁ higher and A₂ lower, with an A₁ sand terrace between (Fig. 6). The A₂ cliff is merely a continuation of cliff A forming the upper margin of the A terrace except that A₂ is cut into sand instead of bedrock (Fig. 11). Near Whale Creek cliff A₂ is about six meters high but decreases to less than one meter to the northwest where A₂ cuts into the large Late Wisconsin and Neoglacial moraine from Lituya Bay.

The A₁ terrace is about 100 meters in maximum width and appears to be composed entirely of bedded gray sand, weathered brown to a depth of about 45 cm. It is overlain by 10 to 30 cm of peat and covered by a young spruce-hemlock forest. Fallen logs are common,
Figure 9. An old whale skull surrounded by spruce forest on Terrace A.
Figure 10. The vertical-standing A cliff with bedrock exposed behind a recent slump.
Figure 11. The low A_2 cliff near Boulder Creek. Note the active soil creep downslope and smaller spruce trees below the cliff.
but still much less abundant than on higher terraces. The terrace is about 15-19 meters elevation at its seaward edge and slopes gently inland to about 15-17 meters at the base of cliff $A_1$. Where cliffs $A_1$ and $A_2$ merge at Whale Creek to form cliff A the terrace almost entirely disappears, but horizontal breaks in the slope of cliff A at several localities marks its presence in the bedrock cliff area as well.

The $A_1$ cliff (Fig. 12) is cut into sand and gravel of marine, fluvial, and glaciofluvial origin according to Miller (1961), and is generally about 8 meters high although it decreases in height toward the prominent moraines near Lituya Bay where it is breached by (Neoglacial ?) outwash.

The next major terrace, B, is about 250 meters wide and slopes gently upward from about 23 meters elevation to about 30.5 meters at the base of cliff B. This cliff is clearly truncated by (Neoglacial ?) outwash from Crillon Lake on the southeast, but terminates on the northwest near Whale Creek against a small moraine that marks the maximum extent of ice from Lituya Bay for all time (Fig. 6). This rock-cut terrace is veneered with sand and gravel deposits overlain by 25 to 90 cm of peat and decaying forest debris (Fig. 13). A mature hemlock-spruce forest covers the bench with a
dense understory of blueberry, high-bush cranberry, gooseberry, devil's club, and skunk cabbage (Fig. 14). Few small patches of open muskeg break the continuity of the dense forest. The cliff that forms the upper margin of the B terrace has about 15 meters of relief near Steelhead Creek, but stands as much as 37 meters high further southeast.

Figure 12. Cliff A₁ about 6 meters high near Boulder Creek. The curved tree trunks indicate active soil creep on this slope.

Above bench B stands the first of the three large high terraces. Terrace C is as much as 1.6 km wide and characterized by an irregular upper margin bounded by a cliff 60 to 65 meters high (Fig. 15) and the presence of numerous small bedrock "islands" and "sea-stacks" dotting
Figure 13. Reddied gravels and sand of marine origin overlying wave-cut bedrock on Terrace B.

Figure 14. An 80 inch-diameter spruce on Terrace B.
Figure 15. The 65 meter-high cliff that forms the upper margin of Terrace C.

Figure 16. Large pit-pond in a muskeg on Terrace C View is south-southwest toward the ocean from the crest of cliff C.
the terrace surface (Fig. 4). The entire terrace is tilted slightly on end; the base of cliff C is about 85 meters elevation at Topsy Creek and slopes downward toward Lituya Bay with a gradient of 3 m/km. An exposure in Steelhead Creek shows laminated sands similar to the modern beach directly overlying steeply-dipping, horizontally-truncated bedrock. The terrace surface is mantled by large, open patches of muskeg consisting of more than three meters of peat. Numerous pit-ponds dot the muskeg. Hemlock-spruce forest surrounds the muskesks where drainage is improved along steeper slopes and stream courses (Fig. 16).

Terrace D is the widest, being about 2.3 km in maximum width. It also is tilted toward Lituya Bay with a gradient of about 18 m/km; the base of cliff D is at an elevation of about 245 meters where the terrace is truncated by the massive moraine around Crillon Lake, but only 170 meters by Lituya Bay where intersected by the large moraine of similar age (Fig. 3). The vegetation is very similar to that of the next lower terrace, C. Sand underlies the peat in places.

The highest terrace, E, slopes away from Lituya Bay at 520 meters elevation to only 400 meters near upper Topsy Creek. The surface of this short terrace segment, only 4.6 km long and 0.6 km wide, is deeply dissected by
several streams (Fig. 4). The vegetation at this elevation, only 90 meters below treeline, is subalpine, mostly small spruce and mountain hemlock forest interspersed with patches of sedge muskeg overlying sand-covered bedrock.

Relationship of the Study Area With Other Terraces:

Using published elevation data from Mertie (1933) and Miller (1961) and unpublished information from B. Washburn (1934), R.P. Goldthwait (1934), and I. Worley (1973) the probable relationships between terraces in the study area and other terraces northwest and southeast of it can be seen to fit a consistent pattern (Fig. 17). Terraces at Icy Point appear to have been uplifted higher and faster than those near the Fairweather Glacier. The higher terraces appear progressively more deformed. The B terrace and cliff are represented between Fairweather Glacier and Lituya Bay by raised beach and lagoonal deposits without the formation of a sharp cliff. The short terrace segment, E, within the study area slopes anomalously to the southeast as compared to northwest-sloping terrace segments at similar elevation northwest of Lituya Bay.
Figure 17. Elevation of the base of cliffs A, B, C, D, and E from Icy Point to the Fairweather Glacier.
Origins of the Terraces

**Structural Hypotheses:**

It might be argued that these stairstep features are a series of structural terraces accentuated by erosion on the more steeply dipping flank to produce the sharp cliff face. However, Miller's bedrock mapping (1953, 1961) supplemented by present field investigations disclosed no evidence of folding of this nature. Furthermore, the step-by-step increase in the maturity of the forest, thickness of peat deposits, weathering of sand, and more subdued morphology of the cliff faces from terrace A upwards implies a sequential increase in terrace age with increasing elevation. Minor changes with elevation in the local ecosystem such as temperature and precipitation are too insignificant to account for the sharp differences in vegetation and weathering profile between the lower benches.

Similarly, faulting may be ruled out. The apparent age differences between terraces, the close parallelism with the modern coastline, consistent relief of cliff faces along 67 kilometers of coast, and the abrupt termination of glacial deposits eliminate faulting as a viable hypothesis. Miller (1953, 1961) found no evidence of a genetic relationship between the terraces and
local faults. The overthrust fault that marks the crest of the anticlinal structure in the Tertiary foothill belt bears no relationship to the development of these terraces (Fig. 3).

Erosional Hypotheses:

Differential erosion of different bedrock types might possibly explain terrace formation except that, in this area, the terraces cut across all formation boundaries shown by Miller, and steeply-dipping strata are truncated horizontally outside the formerly glaciated areas of benches B, C, and E. The widespread nearly flat areas on terrace surfaces generally are inconsistent with surfaces produced by differential bedrock erosion. Clearly, some other explanation must be sought.

Glacial limits are well defined in the area by moraine and outwash deposits near Whale Creek and the large moraines around Crillon Lake. Unless very ancient drift has been so completely obliterated that pointed search has failed to spot it, these deposits mark the maximum extent of ice into this region (Goldthwait et al. 1963). This, and the fact that the lowest cliff system cuts across the most recent glacial deposits implies glacial erosion could not be a factor in terrace cutting.

Cryoplanation, on the other hand, might have been
a significant factor, at least in the modification of the highest terrace, E. With the lowering of snowline during glacial periods, periglacial phenomena would occur at lower elevations than at present. Turf-banked terraces were observed on the slopes of Bald Mountain above terrace E (R.P. Goldthwait, pers. comm.). Similar structures on the E terrace may be hidden by a post-glacial covering of peat.

The best explanation for the cutting of all terraces is marine abrasion. A marine origin for these rock-cut platforms along a slowly uplifted coast is suggested by all of the following: (1) the whale skull on the lowest terrace backed by a freshly-eroded cliff, (2) the long geographic extent of terraces parallelizing the present coast, (3) terrace morphology, (4) terrace stratigraphy, (5) the apparent sequential increase in terrace age with elevation, (6) the cross-cutting relationships between terraces, bedrock, and glacial deposits, (7) the "sea stacks" on terrace C, and (8) the presence of numerous terraces up to 185 meters elevation throughout southeastern Alaska containing fossiliferous marine sand, gravel, and clay.

As the sea is not cutting a cliff along this coastline at present the question naturally arises, what factors caused cutting of marine platforms in the past?

Variation in the amount of sediment carried along
the coast due to changes in currents or glacial activity might cause wave-action to alternately erode or form a prograding shoreline. However, an increase in glacial activity would have the effect of increasing sediment load and thus, deposition, and the wide, uniform continental shelf would have little effect on local currents if sea level were lowered.

R. Fairbridge (pers. comm.) has suggested abrading sea-ice could cut a marine platform during glacial periods. However, since sea level was considerably lowered during glacial maxima any terrace and cliff formed by eustatically lower sea level would be drowned and considerably altered by the following eustatic rise. Glacial deposits above these cliffs are unaltered, and furthermore, Fewe and others (1965) have found no evidence of extensive masses of sea-ice ever existing between Cape St. Elias in southern Alaska to Icy Point.

In the classic view of platform cutting (Davis, 1909; Johnson, 1919; Cotton, 1942; Thornbury, 1954) sea level is considered stationary. Bradley (1958) has shown, however, that stationary sea level could only cut a platform to a width of about one-third mile (0.5 km). Wider platforms, Bradley says, could only be cut by the sea rising relative to the land. Terrace C is about three times this width, D is over four times wider, and
even the remnant of E is still slightly wider. Therefore, at least these three terraces were cut by sea level rising faster than the rate of uplift of the land; almost certainly during long interglacial warm periods.

Terrace B was initially wider, but has been truncated relatively soon after its formation by the cutting of the A₁ terrace. Its narrower width possibly suggests a lower, shorter interstadial eustatic rise.

Seacliffs A and A₁ probably represent two recent stands of sea level, followed by uplift of the coast.

"Beach" Sediment Analyses

Mertie (1933) asserted that these rock-cut benches were of marine origin with a veneer of recent non-marine sediments. Bradley (1957) describes similar marine-cut platforms in Southern California with a thick accumulation of beach sediments deposited as the platform rose relative to sea level. The lack of marine macrofossils on the higher terraces suggested grain-size, heavy mineral, and microfossil analyses of terrace sediments to determine if they were indeed of marine origin.

Grain-size Analysis:

Twenty sediment samples collected from pits and exposures in the benched area southeast of the Bay and
two till samples from upper Whale and Boulder Creeks were analyzed for total sand, silt, and clay composition using sieve and hydrometer techniques (A.S.T.M., 1964) with results plotted in Figure 18.

The composite sample from the modern beach foreshore is 99% sand. Samples from terrace A, three from A1, and the sample from C over wave-planed bedrock also consist of more than 95% sand, but generally the amount of silt and clay increases with the height of the bench. Higher amounts of silt and clay may be interpreted either as a weathering product of beach sand or as fluvial and colluvial sediments derived from local sources. The two till samples plot distinctively separate from the other samples.

Histograms of the size fractions 0 to 8 phi (very coarse sand to very fine silt) are more revealing (Fig. 19). The twenty samples may be broadly separated into four distinct groups: well-sorted, moderately-sorted, poorly-sorted, and bimodal.

The seven well-sorted samples all bear a striking resemblance to the modern beach foreshore (Sample 1). These are the same seven samples that consisted of more than 95% sand (Fig. 18).

The moderately-sorted samples indicate a lower energy of deposition except for Sample 15 which is mostly
Figure 18. Percent sand, silt, and clay of sediments from the terraced area southeast of Lituya Bay.
Figure 19. Grain-size analysis of sediments collected from the terraced area southeast of Lituya Bay.
coarse sand. Its finer sizes may be due to the breakdown by weathering of coarse sand grains; it was collected from within the B soil horizon on terrace B. Sample 8, which is predominantly very fine silt and clay overlying well-sorted sands on terrace A₁, may be a swamp or lagoonal deposit. The remaining four samples are suggestive of the quieter environment of the beach backshore.

The poorly-sorted material may be due to weathering or low-energy fluvial or colluvial deposition. Sample 12 is poorly-sorted but forms the finer fraction of a coarse beach gravel on terrace B containing well-rounded wood fragments and granitic pebbles.

The sample from the highest terrace is bimodal, containing mostly very coarse sand and fine silt, which suggests it is a residuum formed by weathering.

In summary, grain-size analysis suggests that sediments on terraces A, A₁, B, and C are beach deposits or could have been derived from beach deposits. The sample from the highest terrace, E, may have been derived from local bedrock.

**Heavy Mineral Analysis:**

Heavy minerals were separated from the coarse to very fine sand fractions of the twenty sand samples using
tetrabromoethane, specific gravity 2.96. Magnetite was then removed from the heavies with a hand magnet and a paramagnetic fraction was separated from the remaining minerals with a Frantz isodynamic magnetic separator using a current of 0.4 Amperes, side inclination of 20°, and forward slope of 30° to remove primarily ilmenite and garnet (after Hess, 1959). Results of these procedures are given in Figure 20. Finally, the composition of both heavy and light mineral fractions was examined using a binocular microscope.

Rossman (1957) found the main heavy minerals in beach deposits within the terraced area to be in decreasing order of abundance: garnet, pyroxene, ilmenite, amphibole, magnetite, staurolite, epidote, rutile, sphene, and zircon. The light material includes quartz, feldspar, mica, calcite, and small rock fragments. These minerals are probably derived in large part from the highly metamorphosed and granitic rocks northeast of the Fairweather Fault transported by large mountain glaciers descending from the Fairweather Range into the coastal area. The pyroxene grains are identical in physical and optical properties to those found in mafic and other intrusive rocks on the inland side of the fault.

Rossman described the concentration of heavy minerals in the modern beach sands between Cape Fairweather
Figure 20. Idealized cross-section of terraces southeast of Lituya Bay showing sample locations, percent heavy minerals, percent magnetite, and percent paramagnetic minerals of the sand fraction of the sediment.
Figure 21

Decrease in Heavy Mineral Content With Increasing Terrace Elevation

![Graph showing Terrace Shoreline Elevation vs Percentage Heavy Minerals]
and Dixon Harbor as varying between 5 and 40 percent. Within the study area southeast of Lituya Bay concentrations ranged between 20 to 40 percent for the surface sands extending almost the full length of the beach, approximately 3.8 kilometers. These concentrations occur as layers in the backshore deposits in patches as small as a few square feet to as wide as the full width of the backshore and extend downwards to depths of at least two meters although the layers appear to become thinner and leaner with depth. Cook (1964), analyzing a 250 kgm beach sand sample from a few kilometers northwest of the Bay found 61.4% heavy minerals in the coarse to very fine sand fractions. These figures are in good agreement with the data presented in Figure 20 for the modern beach, and the A and A₁ terraces. Above the A₁ surface, decline in heavy mineral content may be due to low initial concentration in beach deposits, weathering, or the accumulation of local alluvium and colluvium mantling the terrace surfaces (Fig. 21).

Magnetite concentrations in Rossman's samples varied between 0.5 and 10 percent with an average value of about 0.8 percent. Cook's sample was only 0.3 percent magnetite. Similarly, Figure 20 shows magnetite concentrations of about one percent on the modern beach, terrace A, and A₁. Values decrease to 0 and 0.1 percent on B, and
no magnetite was detected from higher terraces. However, the exposure along Steelhead Creek of well-sorted sand with distinct iron-stained laminae overlying the wave-planed bedrock surface of marine platform C contained no detectable magnetite either, which implies sufficient time has passed for the oxidation and removal of ferromagnesium minerals from beach deposits on the higher benches.

The paramagnetic fraction contained not only ilmenite and garnet, but variable amounts of pyroxene (hypersthene), amphibole (hornblende), and traces of limonite, epidote, and staurolite. This fraction shows considerable variation in amount (Fig. 20). Values from the modern beach to A1 range from 2.6 to 57.3 percent. Samples from higher terraces also have variable values, but these show a general decrease with increasing elevation.

Comparing these results with grain-size analysis (Fig. 19) shows that the well-sorted sediments also have the highest percentages of heavy minerals and magnetite, although poor-sorting does not necessarily reflect low heavy mineral content.

In overall mineralogic composition, samples from the modern beach upward through terrace D are generally quite similar regardless of clay content or sorting.
However, the bimodal Sample 20 from a 25 cm thick sand lens containing wood fragments overlying andesite bedrock on the highest bench consists mostly of oblate, subrounded grains of andesite with only 1.3 percent heavy minerals which are distinct in containing abundant angular grains of hornblende, very little garnet and pyroxene, and no ilmenite. This is consistent with a sediment derived entirely from the local bedrock.

In summary, analysis of heavy minerals indicates sediments from the lower four major terraces are beach deposits similar to the modern beach or could have been derived from such beach deposits, but the sand from the highest terrace is of local origin. Total heavy mineral, magnetite, and paramagnetic content decreases with increasing elevation (age) of the terraces.

**Diatoms:**

The twenty "beach" samples were rinsed with water to separate diatoms from the coarser sediment. The material carried away in suspension was dried on a glass slide, baked at 550° C. for eleven minutes to remove other organics, mounted in Hyrax, and examined under a high-powered microscope. Genus identification was made by R. Koch, an algae specialist, of the Department of Botany, Ohio State University.

No marine forms were identified in any of the
samples. The composite sample from the modern beach foreshore contained a few broken bits of diatom tests, but not of sufficient size to make identification possible. Similarly, the six other well-sorted samples contain no more than broken bits with one exception: a sample from bedded sand on the A1 terrace contains the genus *Eunotia* which lives in moist forest floor debris.

The twelve moderately and poorly-sorted samples generally contain several fresh-water forms that thrive in forest floor or peat environments including *Eunotia*, *Nitzschia*, *Pinnularia*, *Cymbella*, *Stauroneis*, and *Cocconeis*. Sample 19 from bedded sand on terrace D exposed in a stream cut contained *Diatoma* indicative of fresh-water stream environments. The sample from the highest terrace contained no recognizable diatoms.

In conclusion, coarse, well-sorted beach sands contain few diatoms. Fresh-water species may reflect fluvial or colluvial sediment deposition or simply contamination from overlying organic deposits.

**Foraminifera:**

No recognizable foraminifera occur in any of the samples with the exception of a very few broken bits in the modern beach. However, the calcium carbonate tests of most foraminifera would rapidly leach from these
porous soils with their high humic acid content in the heavy rainfall of this region.

Pollen Analysis

Introduction:

A palynological study was carried out on peat samples collected from muskegs on terraces C, D, and E with a three-fold purpose: 1) as a stratigraphic tool to date and correlate peat deposits on terrace surfaces by comparison with published data from the same region; 2) to gather information concerning the minimum ages of the several terraces, and 3) to amplify the known vegetational history from glaciated localities near sea level in southeastern Alaska. This study produced data from sites that differ both in elevation (up to 490 meters) and age as part of the terraced area appears to have been ice free since at least Illinoian time, and possibly much longer.

On the advice of Dr. C.J. Heusser of New York University, and Dr. P.A. Colinaux of the Ohio State University, who have both worked on Alaskan pollen, this study was confined to arboreal species as reliable indicators of regional vegetation and thus climatic change. Herbaceous species do provide useful information, but
are less well represented in the pollen record, they include numerous taxa, and they generally indicate only very local conditions at a particular site.

**Arboreal Vegetation of Southeastern Alaska:**

Only six arboreal genera occur in southeast Alaska: pine, spruce, hemlock, cedar, alder, and willow.

Lodgepole pine (Pinus contorta) is near the northern limit of its range at Yakutat Bay, 120 km to the north. It is highly shade intolerant and is only found as a low, gnarled tree on the surface of open muskegs at elevations less than about 180 meters.

Sitka spruce (Picea sitchensis) is a major constituent of the modern forest from tidewater to timber line. In deglaciated areas, spruce forms the subclimax forest replacing alder in succession, but is itself crowded out in time by the highly shade-tolerant western hemlock. H.E. Anderson (in Heusser, 1950) believes that Sitka spruce behaves as an intolerant species in this part of Alaska, and would in time be entirely replaced by hemlock, but is constantly maintained by blowdowns and other disturbances.

Two hemlocks predominate in the climax forest of this region. Western hemlock (Tsuga heterophylla) is by far the more common of the two, especially at lower
elevations. Mountain hemlock (*Tsuga mertensiana*) is a smaller tree, more tolerant of temperature extremes, and forms the major tree of the subalpine ecosystem.

Alaska yellow cedar (*Chamaecyparis nootkatensis*) is found throughout the region, but makes up a very few percent of the forest and was ignored in this study.

Alder (*Alnus*) and willow (*Salix*) are common to disturbed areas in the climax forest and early colonizers of deglaciated terrain. Alder is the more common of the two, but certain species of willow can tolerate the harsher extremes of an alpine environment.

**Sampling, Processing, and Counting Procedure:**

Peat sections from muskegs on three different terraces were sampled by digging pits into the peat and removing samples at 10 cm intervals. If a pit did not penetrate to the bottom of a peat deposit a soil auger was used to probe to greater depths, but suitable samples could not be taken in this manner because of the danger of contamination.

Peat samples were processed chemically to remove most of the organic debris and produce a concentration of pollen grains which was mounted on a glass slide with glycerine. Details of the chemical procedure are given in Appendix I.
Each pollen grain was identified and counted in a systematic traverse of the microscope slide under a magnification of 450 X. Badly crushed or broken grains that could not be identified were ignored in the count. This may have had the effect of increasing the recorded percentage of smaller, less easily damaged alder grains, but would not affect the fluctuations in abundance of species that indicate climatic change. Identifiable parts of pollen grains such as spruce bladders were noted and the totals of each species were adjusted for the number of complete grains represented in the slide.

Analysis of Pollen Data:

Post glacial pollen histories from coastal southern and southeastern Alaska and British Columbia (Heusser, 1952, 1954, 1960) and vegetational studies of recently deglaciated terrain in Glacier Bay (Cooper, 1923; Decker, 1966) show that in glaciated areas the first tree to return is alder, followed by pine, spruce, western hemlock, and finally mountain hemlock to produce the hemlock-spruce forest characteristic of this region. However, in ice-free areas in the coastal mountains all of these species might have survived the approximately 6 C° drop in average yearly temperature during the last major glaciation (Heusser, 1960). Therefore, the mere
presence of spruce and hemlock pollen at the bottom of the peat section does not in itself imply a postglacial origin for the deposit.

An increase in regional precipitation would allow the muskegs to expand at the expense of the surrounding forest (Heusser, 1954). Thus, lodgepole pine which only thrives on open patches of muskeg should show a marked increase during wetter periods. However, pronounced cooling would inhibit its growth as it is already near the northern limit of its range. Spruce and hemlock also thrive in cool, wet conditions, with spruce increasing relative to hemlock during periods of disturbed conditions (increased wind damage, avalanches, landslides, or glacial retreat). The Alder record is also sensitive to conditions that open bare ground for recolonization. At higher elevations the lowering of tree line due to climatic cooling should cause an influx of subalpine or alpine flora into the pollen record such as mountain hemlock and willow.

The three pollen diagrams discussed here were produced from sites within a few miles of each other and, though the sites vary widely in elevation and modern forest composition, have certain features in common which agree with Heusser's work in the same region (1952, 1954, 1960).
Pollen from a muskeg on terrace C was extracted from the top 1.8 meters of an accumulation of more than three meters of soft, mixed bryophyte-sedge peat. The site lies at an elevation of 67 meters approximately 200 meters southwest of one of the large old sea stacks on the surface of terrace C (58°, 35' N; 137°, 32' W). Numerous pit-ponds dot the surface of the muskeg and the spotty arboreal vegetation consists mostly of stunted lodgepole pine, isolated Sitka spruce and western hemlock, and an occasional Alaska yellow cedar (Figure 22). The entire surface of terrace C is covered by similar muskegs interlaced by thick stands of hemlock-spruce forest with a dense understory of heath along steeper slopes and stream-courses. The relative abundance of arboreal species found in the pollen record from this terrace is shown in Figure 23.

Figure 23 probably reveals a relatively short vegetational history. The soft, bryophytic-sedge peat was uniform throughout the section, containing only one horizontal log at one meter depth. Radiocarbon dating of basal peats in this region by Heusser (1960) suggests that two meters of this type of peat can accumulate in as little as 1210 ± 200 years (Grand Plateau Glacier, elevation 9 meters), although a ligneous peat zone at a depth of about two meters northwest of Lituya Bay
Figure 22. Site of pollen samples from muskeg on Terrace C. Note lodgepole pine and sea-stack in the distance.
Figure 23.

**Pollen Percentage Diagram**

**Terrace C**

- Depth (m)
- Pine
- Spruce
- W. Hemlock
- Mtn. Hemlock
- Alder
- Total

- 0
- 0.2
- 0.4
- 0.6
- 0.8
- 1.0
- 1.2
- 1.4
- 1.6
- 1.8

- 186
- 236
- 184
- 211
- 165
- 207
- 165

- Wood
- + = <2%

- BS: Bryophitic-Sedge Peat
Figure 24. Site of the pollen samples from Terrace D. Note similarity of vegetation to Figure 22.
produced a date of 6890 ± 350 years B.P. (elevation 33.5 meters). Two meters of peat from terrace D within the study area of 125 meters elevation was dated at 5780 ± 160 B.P. Therefore, a maximum age of about 6000 years for the 1.8 meters of peat recovered in this section would be reasonable.

The pine curve in Figure 23 decreases from a maximum near the base to a minimum at a depth of 0.4 meters, then increases somewhat to the present which may represent a "real" event or simply a statistical dilution due to an increase in spruce and hemlock. Three lines of evidence, however, suggest that this is a "real" event and does reflect a climatic change. First, pine is a highly prolific producer of pollen compared to spruce or hemlock (P. Colinvaux, pers. comm.). Therefore, if pine production remained constant, it would require a drastic increase in spruce and hemlock to over-shadow pine in the pollen record. Secondly, the ratio of spruce to hemlock increases significantly toward the top of the section suggesting the onset of disturbed conditions, and finally, a similar record is preserved in the upper meter of peat from a nearby site on terrace D.

In conclusion, this pollen stratigraphy probably dates back to the close of the Hypsithermal about 3500 B.P. when a period of increased precipitation caused pine
to flourish (Heusser, 1960). With colder temperatures and/or drier conditions pine again decreased in importance and spruce and hemlock make up the bulk of the record. Treeline fluctuations in the White Mountains of California indicate the onset of cooler, wetter conditions about 3500 B.P. to 2500 B.P. followed by a cool, but drier climate (La Marche, 1973). Western hemlock often shows its greatest abundance in southeastern Alaska at this time (Heusser, 1960). The base of this peat deposit probably dates back into at least Hypsithermal time, and may possibly be much older.

The vegetation on terrace D is very similar to that of the lower terrace (Fig. 24). Large, open patches of muskeg cover the flatter areas with dense stands of spruce-hemlock along stream courses and steeper slopes. A pollen record was derived from 2.0 meters of peat recovered from a 2.6 meter thick deposit of bryophytic-sedge peat overlying a weathered brown sand of probably fluvial deposition (Sample 18, previously discussed). This site lies at an elevation of 125 meters, 58°, 36' N; 137°, 33' W. The results of this investigation are given in Figure 25.

The peat stratigraphy at this site shows a rapid change at one meter depth from a compact, reddish-brown sedge peat below to a darker brown, less-compact,
more bryophytic peat above suggesting the onset of wetter conditions at that time. A radiocarbon date from the lowest recovered peat at 2.0 meters depth gave an age of $5780 \pm 160$ B.P. (CWA-176) which supports the conclusion that this change in peat stratigraphy occurred with the onset of wetter conditions at the close of the Hypsithermal at about 3500 B.P. Another pit on this terrace revealed a similar change in peat stratigraphy at a depth of 0.8 meters.

The pollen data is consistent with this hypothesis. Much as in the profile from terrace C, the pine curve shows an increase with the onset of wetter conditions, a decline, and then recovery to the present. Spruce and hemlock again show a steady increase during this interval, and the small peak in western hemlock at 0.2 meters depth may simply be a reflection of the decrease in pine, or may be a "real" event, occurring with a few grains of willow, suggesting the lowering of treeline during the maximum Neoglacial advance between 1100 and 400 years ago (Goldthwait et al., 1963). Similarly, a major lowering of treeline occurred in the White Mountains of California between about 850 and 450 B.P. (La Marche, 1973). The lower part of the diagram below one meter suggests an Hypsithermal climate similar to the present, but an oxidized zone at 1.5 meters depth may be due to the
Figure 25

Pollen Percentage Diagram
Terrace D

Depth (m)

0

0.2

0.4

0.6

0.8

1.0

1.2

1.4

1.6

1.8

2.0

2.6

5780 ± 160 B.P.

Bryophytic-Sedge Peat
Fibrous Peat

Wood
Sand

+ = <2%

Pine
Spruce
W. Hemlock
Mtn. Hemlock
Alder
Willow
Total

203

208

218

200

200

202

167

144

0

200

208
drying of the muskeg during a period of drought.

A muskeg on the highest terrace, E, at an elevation of 485 meters (58°, 37' N; 137°, 32' W) produced a pollen diagram somewhat different from those at lower elevations (Fig. 26). The modern subalpine vegetation at this often fog-shrouded site is quite distinct from the lower terraces. The muskeg is almost entirely composed of sedge, and the numerous pit-ponds characteristic of muskegs at lower elevations are all but absent. Few isolated trees occur on the muskeg, but surrounding the patches of open muskeg are stands of mostly mountain hemlock with minor amounts of spruce and western hemlock (Fig. 27). No pine was observed on this terrace. Modern tree line occurs some 90 meters higher at about 580 meters elevation.

Figure 27. Open sedge muskeg on Terrace E surrounded by spruce-mountain hemlock forest.
Pollen Percentage Diagram
Terrace E

- Sedge Peat
- Fibrous Peat
- Wood
- Sand
- Bedrock

+ = <2%
The upper 30 cm of the dense sedge peat at this site is totally lacking in logs and bits of wood common down to the base of the peat section at a depth of 1.1 meters. Again, this may reflect expansion of the muskeg due to greater precipitation. Below this peat is a 23 cm thickness of sand containing wood fragments of local origin (Sample 20, previously discussed). Below this sand is reddish-brown, weathered andesitic bedrock.

The pollen record shown in Figure 26 is mostly a story of mountain hemlock. Abundant at the bottom of the profile, it declines noticeably at a depth of 0.5 meters at the same point where willow begins to show a trace in the record suggesting cooler temperatures and a lowering of treeline. However, Heusser (1960) finds sporadic occurrences of willow throughout his profiles taken from sites near sea level. Above 20 cm mountain hemlock increases to the present. The slight increase of spruce and western hemlock as mountain hemlock declines is probably a statistical effect, but the relative increase in spruce to western hemlock again suggests the disturbed conditions of Neoglacial time. As no pine was observed at this elevation, the pine pollen constituent is blown in from muskegs at lower elevations. The minor pine peak at 20 cm may correlate with similar increases in the record of terraces C and D as muskegs
enlarged following the close of the Hypsithermal.

In summary, this pollen sequence suggests the longest history of the three sites despite its shallow depth. This record probably extends back into Hypsithermal, and possibly even Postglacial time. An identical 1.2 meter sequence of peat from a terrace at the same elevation a few kilometers northwest of Lituya Bay overlying brownish clay containing numerous pebbles gave a date of 8,205 ± 135 B.P. at the base of the peat (I. Worley, unpub. Nat. Park Service Report, 1972).

**Significance of the Results:**

First, examination of exclusively arboreal pollen does seem to mirror a climatic change in this region as deduced from glacial history (Lawrence, 1950; 1953; 1958; Goldthwait, 1960; Bengston, 1962; Goldthwait et. al., 1963) and more extensive pollen data (Heusser, 1960).

Second, of the three sites discussed, none yielded a pollen record suggesting an age greater than Hypsithermal, or at most late Postglacial. Grain-size and heavy mineral analyses suggest that the basal sands beneath the peat are of fluvial origin on D and residual origin on E. Northwest of Lituya Bay Dr. I. Worley found ancient peat (32,800 ± 1650 B.P.) underlying the pebbly-clay at the base of his 8200 year old peat sequence.
Together, this suggests that the Wisconsin glaciation caused considerable erosional activity even in the ice-free portions of the terraced area which may have extended into Postglacial time. This conclusion has one main implication, the use of radiocarbon dates of basal peat to infer the age of these marine-cut benches by several investigators (Heusser, 1960; Worley, unpub. Nat. Park Service Report, 1972) may be highly unreliable.

Age of Marine Terrace Cutting

Pleistocene Marine Transgressions in Alaska

If the terraces were cut by eustatically-rising sea level their age might be determined if the eustatic history of sea level was well-known. As many as seven, and possibly nine marine transgressions have been described in Alaska from marine deposits and erosional features of Pleistocene and Recent age (Hopkins, et. al., 1965, 1972; Hopkins, 1967, 1973; Karlstrom, 1968; McCulloch, 1967). The most recent summation of abundant data from western Alaska and the Siberian coast is correlated with marine terraces on Barbados and Caribbean sea-floor cores by Hopkins (1973). This suggests that eustatic fluctuations have caused sea level to rise rapidly at least seven times over the past 250,000 years (Fig. 28).

Hopkins' Krusensternian Transgression (1967) is based on a series of beach ridges at Cape Krusenstern
and upon several of Heusser's (1960) basal peat radiocarbon dates from terraces along the Gulf of Alaska. The Krusensternian is due to the most recent post-Wisconsin eustatic rise and encompasses the time span between about 5,000 and 11,000 years B.P. according to Hopkins.

A series of beach ridges at Point Barrow and a submerged delta off Nome provide evidence of a middle Wisconsin warming that again raised the sea, but not as high as modern sea level. Organic materials picked from Barrow beach deposits gave radiocarbon dates between 25,000 and 40,000 B.P. (Hopkins, 1973). Stratigraphic relations indicate the delta off Nome was deposited at about this same time. Marine deposits from a raised beach at Cape Blanco, Oregon were dated at 35,000 ± 2000 B.P. (Richards and Thurber, 1968) and sea level curves by Shepard (1963), Curay (1965), Milliman and Emory (1968), and Guilcher (1969) all indicate a middle-Wisconsin rise between about 27,000 and 35,000 B.P. However, recent work by R.K. Mathews (1974) suggests older dates of 42,000 and 60,000 B.P. for these eustatic highs.

The Pelukian Transgression, named for a well-defined wave-cut scarp and marine terrace along the Bering Sea,
is found over most of the unglaciated area of the Seward Peninsula and eastern Siberia, and appears to be a com-
 pound event.

The younger event has been radiocarbon dated at about 100,000 B.P. (Hopkins, 1967) which would cor-
 respond with the marine terrace Barbados II (Hopkins, 1973), sea level curves of Fairbridge (1960), Guilcher (1969),
 and Mathews (1974), and the age of a widespread marine terrace in California (Bradley and Addicott, 1968).
 However, Hopkins states (1973) that it may also cor-
 respond to Barbados I at about 80,000 B.P. Hollin (1971,
 1972) and Mathews (1974) also discuss evidence of a
 high sea level rise at about 85,000 B.P.

Pelukian I probably dates from about 120,000 B.P.
 based on its relationship with glacial moraines of the
 penultimate (Illinoian) glaciation in Alaska and cor-
 relation with the Barbados III terrace (Hopkins, 1973),
 as well as dated marine terraces in southern California
 (Fanale and Schaeffer, 1965) and Hawaii (Ku et. al., 1974).

The age of older transgressions and their rela-
 tion to eustatic fluctuations is less well known. Hopkins' (1973) Kotzebuan Transgression is based on Th / 
 U shell dates of 170,000 ± 17,000 and 175,000 ±
 16,000 years B.P. Potassium-argon dates on post-Kot-
 zebuan basalts only show that it is older than 120,000
years. Einahnuhtan Transgression beds are older than Kotzebuan and younger than 320,000 ± 70,000 year old basalts. Hopkins (1967) describes two even older transgressions, the Anvilian, between 0.7 and 1.9 x 10^6 years B.P., and the Beringian, about 2.2 x 10^6 years old.

**Rates of Terrace Uplift:**

How do the benches in the study area fit into this sea level chronology? The lowest terrace, A, is apparently extremely young. This can be deduced from: 1) Its forest cover composed almost entirely of small-diameter spruce trees, 2) the absence of windfall logs, 3) a thin, 5 to 7 cm cover of peaty organics over unweathered sand, 4) the freshness of a whale skull found on this surface, 5) nearly vertical profile of seafloor A, 6) the recently-uplifted marine platform between Whale and Topsy Creeks, and 7) cross-cutting relationship between seafloor A and outwash deposits of probable Neoglacial age at Boulder Creek and the Crillon River. The largest spruce found on this bench was ring-dated at 220 years old which indicates a rate of uplift of 1.5 meters/century above the highest reach of storm waves. This is in good agreement with Hicks' and Shornos' (1965) data of 0.59 to 0.75 inches/year (1.5 to 1.9 meters/century) for recent uplift in this area, but is about half the
rate calculated in 1961 by Goldthwait by comparing a 1786 chart of Lituya Bay by the French explorer, La Perouse, with the modern U.S. Coast and Geodetic Survey chart. Using the lower rate, the 12 to 14 meter-high base of seaciff A was completed about 400 years ago.

The greater age of the next higher A₁ terrace is indicated by a more mature spruce-hemlock forest, greater abundance of larger fallen logs, and a 10 to 30 cm thick cover of peaty organic debris over 45 cm of weathered sand. This A₁ seaciff is cut into interbedded sand and gravel of glaciofluvial and fluvial origin (Miller, 1961) which was deposited on the surface of the B terrace.

A muskeg on the outwash surface is radiocarbon dated at 2790 ± 250 B.P. (Heusser, 1960) which Heusser mistakenly believed dated the B terrace, but probably only dates the onset of Neoglacialiation about 2735 B.P. (Goldthwait, 1960). The A₁ terrace is covered near the Late Wisconsin-Neoglacial moraine boundary by what is probably late Neoglacial outwash (from 1100 to 400 years old, Goldthwait, et al., 1963). Thus, the time of cutting of A₁ is bracketed between 2790 and 1100 years ago.

The base of seaciff B averages 100 feet above the sea in the vicinity of Steelhead Creek. This cliff is clearly truncated by Neoglacial (?) outwash from Crillon Lake, but the bench terminates to the northwest
against the small moraine marking the maximum extent of ice from Lituya Bay (Fig. 6). Ice probably stood against this moraine before the cutting of seacliff B since this maximum glaciation was probably accompanied by a greatly reduced sea level, and the seacliff sharply terminates the moraine deposit indicating cutting by a post-glacial rise of the sea. No large cliff was produced northwest of this moraine because older marine, fluvial and fluvioglacial deposits in this area would not likely be cut into a steep, resistant escarpment but would form a sloping beach like the present one.

A youthful age for terrace B is suggested by: 1) the less than one meter of organic debris overlying weathered sand, 2) the immature development of muskeg, 3) high ratio of spruce to hemlock, and 4) two radiocarbon dates; one of 5890 ± 350 B.P. from basal peat at an elevation of 33.5 meters a few kilometers northwest of the Bay (Heusser, 1960), and one of only 3250 ± 200 from wood associated with marine shells at 46 meters elevation 25 km southeast of the Bay (Rubin and Alexander, 1958). However, other lines of evidence suggest it is much older. Therefore, two hypotheses regarding the long-term rate of tectonic uplift of this coastline are discussed (Fig. 20). Both assume rates of uplift relative to the height of the highest storm waves on the
modern beach, 7.5 meters above sea level.

The first hypothesis suggests a high rate of uplift through time, increasing toward the present. Numerous strong earthquakes throughout this region support its present tectonic activity. Blackwelder (1907) concluded that the Gulf of Alaska coastal plain has been uplifted approximately 30.5 meters in post-glacial time. Part of the shoreline of Yakutat Bay was uplifted 14.3 meters by the earthquakes of September, 1899 (Tarr and Martin, 1906). On the basis of eight radiocarbon dates of mostly basal peat on marine terraces scattered from Katalla to southeast of Lituya Bay, Heusser (1960) has calculated rates of postglacial uplift of from 0.3 to 4.6 meters/century. The inferred regional structural interpretation (Plafker, 1967) was influenced somewhat by the "rapid, step-like uplift of the Lituya District coast which is consistent with active movement on an offshore overthrust fault" (Plafker, pers. comm., 1974).

Terraces A and A₁, according to this interpretation, are related mostly to tectonic activity in Holocene time. Terrace B was cut during Hopkins' Krusensternian, the post-Wisconsin eustatic rise in sea level. The C terrace might have been cut by the eustatic rise of mid-Wisconsin time, and the D terrace by a Polukian II sea level either 80,000 or 105,000 years ago. This
Figure 29.

Postulated Rates of Tectonic Uplift of Terrace Shorelines at Steelhead Creek
implies a long-term rate of uplift of 0.8 meters/century at Steelhead Creek. If the highest E terrace is indeed of marine origin, it is probably older than Kotzebuan unless the rate of uplift greatly increased during Illinoian time.

The second hypothesis suggests a constant rate of uplift one-half as great, 0.1 meter/century. This suggests both A and A₁ were cut during the Krusensternian, B during the mid-Wisconsin, C during the Pelukian (Sangamon), D during the Kotzebuan (Yarmouth), and E in some much older transgression, possibly Anvilian. The straight line fit of terrace shoreline elevations at Steelhead Creek with Hopkins' sea level curve for western Alaska shown in Figure 29 is compelling. However, uncertainties in both the age and height of these transgressions above or below modern sea level make this correlation merely tentative.

In Lituya Bay, radiocarbon dates of buried stumps at two localities of 7400 ± 200 B.P., 8925 ± 250 B.P., and 9150 ± 275 B.P. (Goldthwait et al., 1963) favor this second hypothesis. Heusser's date of 6890 ± 350 of basal peat at 33.5 meters elevation northwest of the Bay was used to date the B terrace (Heusser, 1950). However, if B was this young, Goldthwait's stumps would have to have been isostatically depressed by Neoglacial
ice in Lituya Bay by at least 33 meters, and probably considerably more, to account for the low elevation of these older dates. This much local isostatic depression seems unlikely for the 6.7 km wide glacier that filled Lituya Bay in Neoglacial time given the average 58 km radius of relative stiffness of the earth's continental crust in response to loading (Brotchie and Silverster, 1969).

The degree of cavernous weathering of granodiorite boulders derived from the outermost moraine southeast of Lituya Bay (Figs. 30 and 31) which is truncated by the B terrace indicates considerably greater age than any rock derived from the large, radiocarbon dated Late-Wisconsin and Neoglacial "Soloman's Railroad" moraines about the mouth of Lituya Bay. This supports a Mid-Wisconsin age for the cutting of the B bench and sea-cliff.

Furthermore, the bulk of the large "Soloman's Railroad" moraine that rings Lituya Bay is of Late-Wisconsin age (Goldthwait et. al., 1963), and this moraine was clearly deposited after the cutting of terrace B (Fig. 5).

In conclusion, the weight of present evidence suggests the emergence of A and A₁ above the sea is a recent compound event as suggested by Hypothesis I, but the
Figure 30. A cavernously weathered boulder on Terrace A at Whale Creek.

Figure 31. A cavernously weathered boulder on the uplifted marine platform near Whale Creek.
larger, higher terraces are far older, and imply the slower rate of uplift suggested by Hypothesis II. These conclusions are summarized in Table I.

<table>
<thead>
<tr>
<th>Shoreline</th>
<th>Elevation at Steelhead Creek (feet)</th>
<th>Age of Emergence (years B.P.)</th>
<th>Marine Transgression (after Hopkins, 1973)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>40 - 45</td>
<td>400</td>
<td>-</td>
</tr>
<tr>
<td>A₁</td>
<td>50 - 55</td>
<td>400 - 2790</td>
<td>Krusensternian?</td>
</tr>
<tr>
<td>B</td>
<td>100</td>
<td>2.7-3.5x10⁴</td>
<td>Mid-Wisconsin</td>
</tr>
<tr>
<td>C</td>
<td>250</td>
<td>8.0-10.5x10⁴</td>
<td>Pelukian</td>
</tr>
<tr>
<td>D</td>
<td>480</td>
<td>17.5x10⁴</td>
<td>Kotzebuan</td>
</tr>
<tr>
<td>E</td>
<td>1700</td>
<td>?</td>
<td>Pre-Kotzebuan</td>
</tr>
</tbody>
</table>

Table I. Estimated Age of the Marine Terraces.

The emergence of terraces A and A₁ is interpreted as a minor event related to uplift and eustatic fluctuations over the past 3000 years, although A₁ may have begun to form during the post-Wisconsin rise in sea level. The narrow terrace B was probably cut during a Mid-Wisconsin interstadial some 27,000 to 35,000 years ago. Wide terrace C dates from Sangamon time, probably the Pelukian II Transgression; D from the Yarmouth Interglacial (Kotzebuan Transgression); and E from some still much older period, possibly the Anvillian.
Relationship Between Marine Terraces and Glacial History

If the conclusions regarding the ages of the marine terraces are correct, a more extensive interpretation of the glacial history of this region can be formulated. The lack of glacial deposits on the highest bench, E, indicates part of this area has served as an ice-free refugium since pre-Kotzebuan time (more than 170,000 years). The outer glacial moraine on the surface of D which is truncated by the Pelukian seaciff C (Figs. 3 and 6) must be of Illinoian age. These are the only glacial deposits known to be of Illinoian age in southeastern Alaska.

The most extensive glaciation in Lituya Bay occurred in Early-Wisconsin time rather than Illinoian which is somewhat anomalous compared to the rest of Alaska (Pewe, 1965). However, the difference between the lateral extent of Illinoian and Early-Wisconsin moraines is small, about 1.2 km (Fig. 3). The Illinoian moraine is a much larger deposit and much of its former extent was probably destroyed by the cutting of terrace C. The Early-Wisconsin glaciation left a small moraine on both benches C and D which was later truncated by seaciff B at Whale Creek during Mid-Wisconsin time.

The immature development of open patches of muskag
on flat portions of terrace B at only 15 meters lower elevation than large muskegs on terrace C indicates more than about 27,000 years are necessary for this forest climax (Zach, 1950) to form.

Late-Wisconsin glaciation in Lituya Bay deposited the large moraines about the periphery of the Bay and sent more outwash down Boulder Creek which helped obscure any development of seacliff B northwest of the small Early-Wisconsin moraine. This glacial advance occurred before 11,000 B.P., probably about 14,000 years ago. (McKenzie and Goldthwait, 1971).

In Neoglacial time, 1800 to 400 B.P., ice again advanced to and overtopped the Late-Wisconsin moraine in places and deposited more outwash after terrace A₁ had formed. Finally, the youngest terrace, the A₁ - A₂ system was completed about 400 years ago which truncates even the youngest glaciofluvial deposits. The coincidence of the completion of this small terrace with the close of extensive Neoglacialiation in the St. Elias Mountains may reflect some marginal component of isostatic rebound of Glacier Bay, 54 km to the northeast. This is consistent with a regional pattern of uplift centered about Glacier Bay deduced from tidal gauge records over the past 80 years (Pierce, 1961; Hicks and Shofnos, 1965). According to Andrews (1974), the rigidity of the
crust is such that the isostatically depressed region extends to distances of 100 to 300 km beyond the ice margin for continental ice sheets. Brotchie and Silvester's (1969) continental value of 58 km of relative stiffness of the earth's crust in response to loading suggests the smaller depression of Glacier Bay would have some effect along this coastline as suggested by Hicks' and Shofnos' data. Thus, the estimated present rate of uplift for this A terrace, 1.5 meters/century, may represent a tectonic rate of 0.1 meter/century plus an isostatic component of about 1.4 meters/century.
APPENDIX I

Laboratory Methods for Preparation of Fossil Pollen

1. Take subsample of measured volume (4 cc. for organic sediments, more for coarse and/or relatively inorganic sediments. Place in 15 ml. size glass centrifuge tube (graduated).

2. Add 5% NaOH (about 5 ml.) to centrifuge tube, mix well, place in rack of tubes in boiling water bath for about 30 minutes.

3. Centrifuge, pour off NaOH.


5. Wash with glacial acetic acid, centrifuge, pour off (Remove water).

6. Repeat step 5.

7. Add acetolysis mixture. Leave stirring rods in tubes, place rack in boiling water bath until mixture turns dark brown and syrupy.

8. Remove from water bath, let cool for a few minutes, then centrifuge well, and pour off very carefully (Acetolysis mixture reacts violently with water).

9. Wash with glacial acetic acid, centrifuge, pour off.


11. Wash in distilled water, centrifuge, pour off.

12. Repeat step 11.

13. Wash with acetone, centrifuge, and pour off.

14. Repeat step 13 twice.

15. Add 3 ml. bromoform-acetone mixture, stir well, centrifuge.

16. Pour off into tube B.
17. Repeat steps 15 and 16.

18. Stir contents of tube B, adjust volume of all tubes to 6 ml, centrifuge.

19. Pour off into tube C containing 9.5 ml acetone. Discard tube B.

20. Centrifuge tube C well, pour off liquid into bottle to save for reclaiming costly bromoform by filtration.

21. Wash contents of tube C with acetone 2-3 times (removes bromoform)

22. Wash with water. After last centrifuging, pour off water carefully, drain tube on paper towel to remove most of water.

23. Make slides.

*technique revised by Dr. P. Colinaux, Ohio State University.*

Additional procedure to remove inorganic particles:

1. If there is a great deal of inorganic material in sample, proceed through NaOH treatment and acetylation. Rinse with glacial acetic acid twice, once with distilled water.

2. Transfer material to polypropylene tube.

3. Slowly add HCl. If carbonates may be present, start with dilute HCl, stirring until foaming stops, then add concentrated HCl. Otherwise, use concentrated HCl only. Centrifuge and pour off.

4. Add HF, stir, place in boiling water bath for 1 hour. **Note:** This step and steps 5 and 6 must be done under a fume hood. Wear lab apron, rubber gloves, and safety glasses or face shield. Avoid any contact with HF. Do not breathe fumes.

5. Remove from water bath, fill tubes with 7% HCl, centrifuge, pour off.
6. Rinse with distilled water, wash back into original glass tube.

7. If material is sufficiently clean, mount on slide. If not, proceed with bromoform separation.

Making fossil pollen slides:

1. With disposable pipet, pick up drop of water in bottom of centrifuge tube containing pollen and place on a clean microscope slide. If pollen is very abundant, divide it between several slides.

2. Let water evaporate, but do not allow pollen to completely dry out. A desk lamp helps speed up evaporation.

3. Add one drop of glycerine lightly stained with safranin, on pollen residue on slide.

4. Stir carefully with a clean dissecting needle.

5. Drop clean cover glass on glycerine drop. Let stand until glycerine spreads to fill entire area under cover slip.

6. Label slide as to locality, code #, depth of sampling interval, etc.

7. Store in flat (horizontal) trays, or in a standard slide box, kept in vertical position.
REFERENCES


