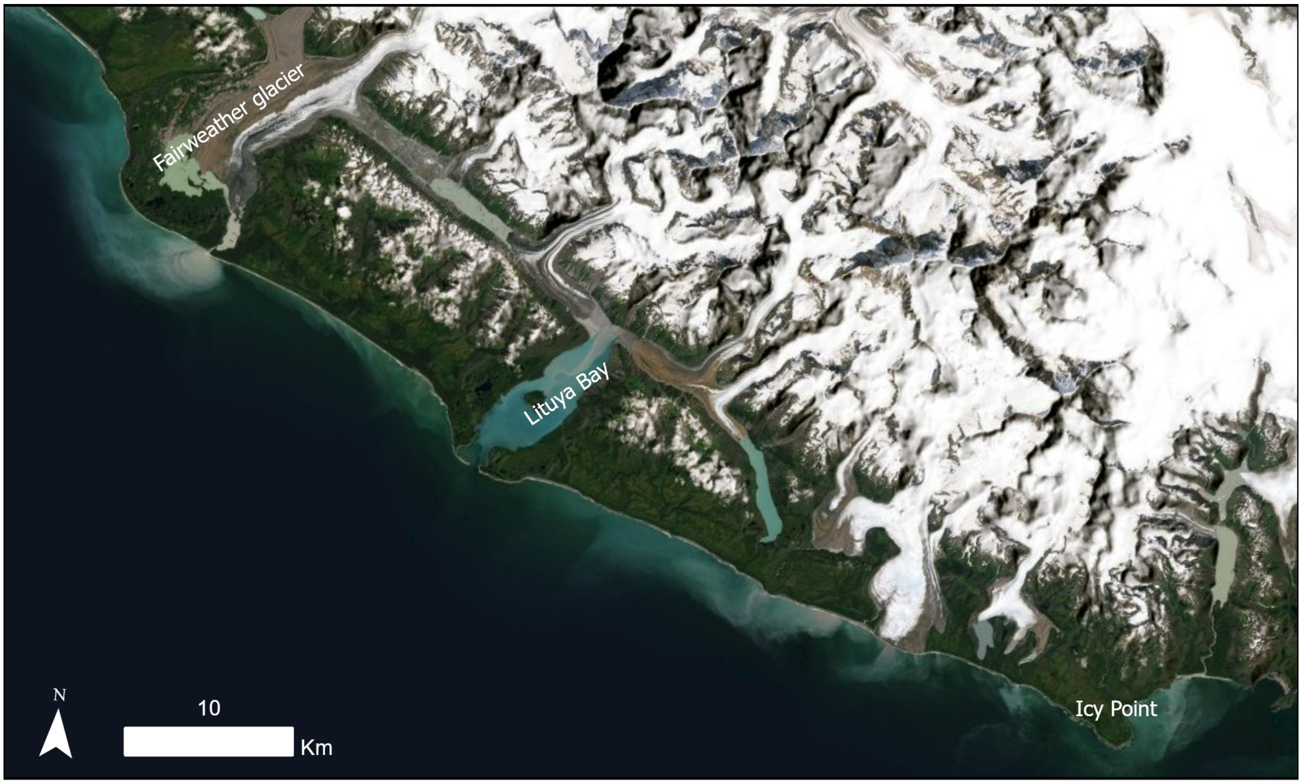
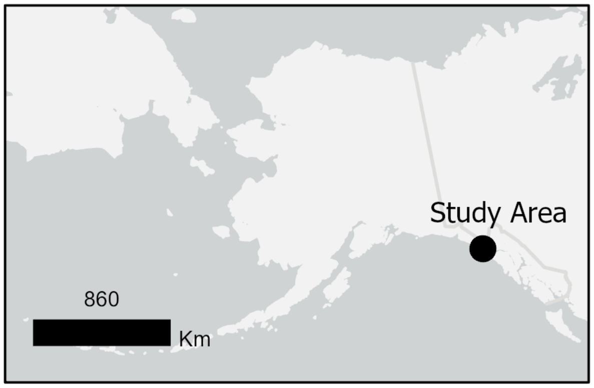
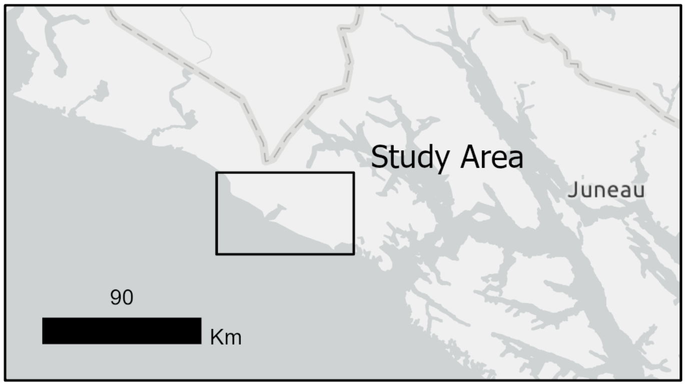
Report of Investigation 2022-4

TECTONIC CONTROLS ON MARINE TERRACE ORIGIN AND CHARACTER IN THE LITUYA BAY AREA, EASTERN GULF OF ALASKA

Travis Hudson, George Plafker, and Meyer Rubin







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State of Alaska
Department of Natural Resources
Division of Geological & Geophysical Surveys

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Cover. Location map of the Lituya Bay area studied in this report.

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TECTONIC CONTROLS ON MARINE TERRACE ORIGIN AND CHARACTER IN THE LITUYA BAY AREA, EASTERN GULF OF ALASKA

Travis Hudson[1], George Plafker[2], and Meyer Rubin[3]

Abstract

Strongly deformed marine terraces differ in their degree of development and preservation along 65 km of the coast between Fairweather Glacier and Icy Point in the Lituya Bay area of the eastern Gulf of Alaska. From Fairweather Glacier to Lituya Bay one prominent terrace flanks the coastal mountain front, and isolated remnants of a lower, younger terrace occur landward of a wide prograded coastal plain. From Lituya Bay to Crillon River a sequence of five well-developed terraces bevel the coastal foothills. From Finger Glacier to Icy Point four terraces and the possible remnants of a fifth occur. The terraces form an arch with an axis of maximum uplift near La Perouse Glacier. The deformation is progressively greater in the older terraces and shoreline angle relief on the highest terrace is 100 m or more.

The terraces are of Pleistocene and Holocene age. The oldest terrace studied is not well dated but the next oldest may have formed during the post-Wisconsin sea level rise. The three Holocene terraces probably formed about 3,500 (3,990–2,960 cal yr BP), 1,000, and 500 years ago. Ongoing uplift and arching of the coastal zone may mark renewal of mid-Pleistocene folding, but Holocene uplift has taken place as discrete events that were probably accompanied by earthquakes. At least five uplift events have taken place between Lituya Bay and Icy Point in the past 3,000 to 4,000 years, which imply an average recurrence interval of ~500 years. Because recurrence of events that uplifted the terraces is distinctly longer than the average earthquake recurrence interval for the nearby Fairweather fault, coastal uplift may occur independently. The Finger Glacier fault displaces the Holocene terraces and may be a developing link between the onshore and offshore segments of the Fairweather fault.

INTRODUCTION

Work on Middleton Island (fig. 1) after the Alaska earthquake of March 27, 1964, revealed that a sequence of marine terraces, originally described by Miller (1953), recorded repeated tectonic uplift during major Holocene earthquakes. Radiocarbon dating of driftwood and peat from five of these terraces established an average uplift rate of 1 cm/yr for about the past 4,300 years and that the interval between major uplifts was 500 to 1,350 years. The results from Middleton Island suggested that other marine terrace sequences in the Gulf of Alaska should be studied to better understand their possible relations to tectonism and deformation in the region.

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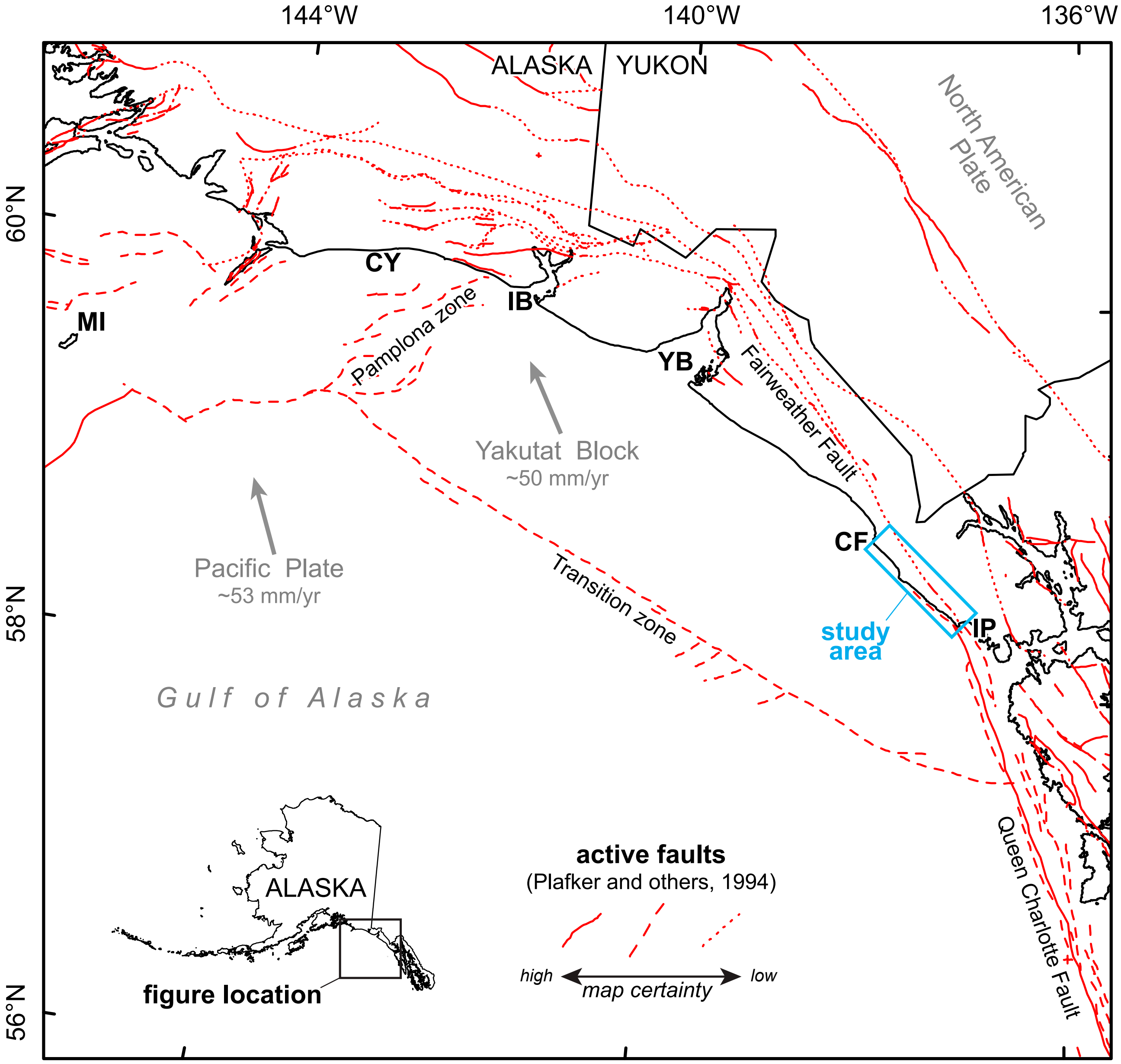

Figure 1. Map of Gulf of Alaska region showing tectonic setting and location of the Lituya Bay area. Areas referenced in the text include Middleton Island (MI), Yakutat Bay (YB), Cape Fairweather (CF), Icy Point (IP), Icy Bay (IB), and Cape Yakataga (CY).

This study focuses on the well-developed marine terrace sequence in the Lituya Bay area of the eastern Gulf of Alaska (fig. 1). Mertie (1933) was the first to describe the terraces and he suggested that mapping the terraces would distinguish differences between the terrace sequence north and south of Lituya Bay, examine the structural nature of Lituya Bay itself, and investigate the possible relations between tectonism and glacial history in the area. Heusser (1960) reported results of C-14 and pollen studies of several peat sections and discussed some of their implications for sea level changes and tectonism in the area. Miller's (1961) geologic map of the area delineated shoreline angles and elevations of several terraces. Goldthwait and others (1963) identified historical movements of Crillon Glacier and presented some considerations of its older history based on field relations and C-14 data in the Lituya Bay and Crillon Lake areas (fig. 2). These workers considered the Lituya Bay area a glacial refugium in

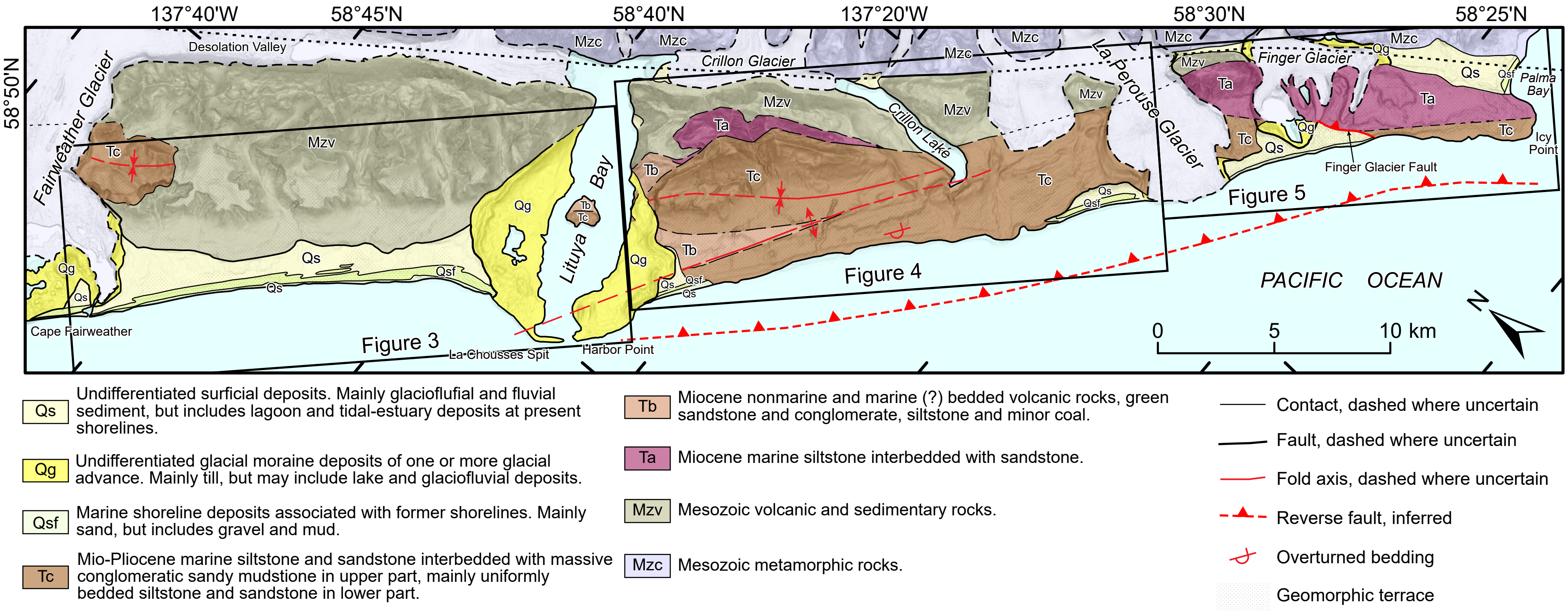

Figure 2. Geologic map of the coastal area near Lituya Bay. Modified from Miller (1961), Plafker (1967), and Plafker and Hudson (unpub. data).

which the marine terraces developed as a result of high sea-level stands during Pleistocene interglacial periods. Derksen (1974, 1975) mapped the terraces southeast of Lituya Bay, studied sediment and pollen samples from the terrace surfaces, and recognized that the lower two terraces were Holocene and probably related to tectonic uplift in some way. Soil and forest development on the terraces were studied by Ugolini and Mann (1979). Mann (1983, 1986) and Mann and Ugolini (1985) studied the Quaternary history of the area and clarified several relationships between the terraces and C-14 dated glacial deposits. Mann (1983) mapped and described the marine terraces (especially between Lituya Bay and the Crillon Lake area), sampled and dated basal peats developed on some of their surfaces, and developed constraints on their ages. He included a locally preserved high (or "E") terrace, the oldest in the Lituya Bay area, in his studies; we show where this surface is preserved (figs. 3 and 4) but we did not include it in our study. Preliminary results and implications of our C-14 dating and mapping of the terraces were outlined by Hudson and others (1976, 1979).

This report presents map relations of the terraces from Cape Fairweather to Icy Point, outlines the morphological character of individual terraces, identifies the relation of the terraces to glacial and other surficial deposits, and discusses the age relations of the terraces in the context of field relations and new, as well as previously reported, C-14 data. The primary focus is on the Holocene terraces and the implications that they have for the tectonic and seismic history of the area.

PROCEDURES

Our studies were primarily aimed at determining the distribution, morphologic character, and age of the Lituya Bay terraces. Fieldwork, completed in 1975 (peat coring) and 1978, was facilitated by use of helicopter and included foot traverses across the terrace sequences and measurements of topographic profiles and spot elevations with surveying altimeters calibrated to sea-level at the beginning and end of each traverse. The field observations were combined with the study of 1:20,000-scale aerial photographs to produce maps of the terraces showing their distribution and relation to other geomorphic features. Initially we mapped the terraces on 1:63,360 topographic data (U.S. Geological Survey, 2016).

Our efforts to determine the ages of the terraces mostly involved C-14 dating of basal peat accumulations on them. The peat accumulations were sampled with a modified Livingston corer. Cores were recovered in about 1 m lengths and extruded in the field. Total length of core taken was determined by the resistance of sediment; penetration was to a depth where resistance exceeded the weight of two people. Most cores bottomed in sterile sediment, some in gravel, and a few in wood. The interval of core dated was the lowest 8 cm of organic material at the bottom of the core. If a rerun second sample was analyzed, the material came from the next highest 8 cm or of a split of the original sample where available.

Material dated consisted of peat and wood as indicated in table 1. In a few cases, the peat was diluted with sufficient mineral matter to be considered an organic-rich sediment. Pretreatment of samples of peat and organic sediment consisted of boiling in acid, a quick heating in alkali solution, and a hot acid wash; each separated by distilled water rinses. Some samples were given only the acid pretreatment. Wood samples were given full pretreatment of acid, alkali, and acid. The C-14 dates listed in table 1 were originally based on the Libby half-life (5568 ± 30 yr.), referenced to the year A.D. 1950. The dates were not corrected for fractionation by a C-13 measurement. The errors reported in table 1 include the one-sigma statistical counting errors and an error multiplier of three (except in the three determinations where the error is listed as less than 100 years). Calibrated ages shown in table 1 are calculated using OxCal (version 4.2.4, Ramsey [2009]; 95 percent probability distribution at 2σ) with the IntCal13 dataset of Reimer and others (2013) and are reported in solar years to the nearest decade.

SETTING

The coastal setting of the eastern Gulf of Alaska is remarkable in that the very high and rugged St. Elias Mountains and Fairweather Range rise to elevations commonly greater than 3,000 m and as high as 5,489 m (Mt. St. Elias) only short distances (10–25 km) inland from tidewater. These mountains have extensive areas of ice cover and glaciers emanating from them descend to near or at sea level in many places. A prograded coastal plain commonly separates the mountains from the present shoreline from Icy Point north to Icy Bay (fig. 1). This emergent part of the Gulf of Alaska coast contrasts with the fjord-indented character of adjacent regions to the south and west, which have been considered to be submergent (Twenhofel, 1952). Marine terrace sequences are present in two areas along the emergent part of the Gulf of Alaska coast—between Icy Bay and Cape Yakataga, and in the Lituya Bay area. Here we describe the terraces of the Lituya Bay area, between Cape Fairweather and Icy Point (fig. 1).

The emergent coast of the eastern Gulf of Alaska is developed on the Yakutat block, a crustal element bounded to the east by the active Fairweather fault and to the north by the Pamplona zone of active faults and folds (fig. 1). The Fairweather fault is now taking up most of the transform motion (~5 cm/yr) between the Pacific and North American plates in this region (Plafker and others, 1978; Elliott and others, 2010).

The marine terraces are cut into upper Tertiary bedded rocks of Miocene to Pleistocene age (fig. 2) and include the Cenotaph Volcanics, the Topsy Formation, and the Yakataga Formation (Plafker, 1967, 1971a, 1971b). The Cenotaph Volcanics include nearshore marine and nonmarine basaltic tuffs, flows, and breccias and overlying tuffaceous siltstone, glauconitic sandstone, and glauconitic conglomerate that appear to grade into and interfinger with the marine siltstone and sandstone of the Topsy Formation of late early Miocene to early middle Miocene (Newportian) age (Marincovich, 1980). The Yakataga Formation (Plafker, 1967, 1971a, 1971b; Plafker and Addicott, 1976) is a thick and widespread marine sedimentary unit, of early Miocene to Holocene age, that is characterized by the presence of conglomeratic sandy mudstone which contains unsorted ice-transported clasts of diverse lithologies. As exposed in the Lituya Bay area, the Yakataga Formation includes a 2.5-km-thick section at La Perouse Glacier that ranges in age from late Miocene to early Pleistocene.

The Miocene to Pleistocene bedded rocks are strongly deformed in the Lituya Bay area. Between Lituya Bay and La Perouse Glacier they are folded into a shallow syncline and a highly asymmetric, faulted anticline. The axis of the bedrock folding from Lituya Bay to La Perouse Glacier is subparallel to the coast (fig. 2). From La Perouse Glacier to Icy Point, beds are tilted to form a seaward-facing homocline that is nearly vertical to slightly overturned. The bedrock structure, characterized by distinct overturned fold asymmetry and associated axial faulting, postdates deposition of lower Pleistocene rocks of the Yakataga Formation.

LITUYA BAY TERRACES

Two types of geomorphic features are most prominent along the 65 km coastline between Cape Fairweather and Icy Point: (1) the marine terraces that in places are strikingly developed in a series of steps inland to the mountain front; and (2) youthful terminal moraine complexes that emanate from major breaks in the mountain front and interrupt the terrace sequence at Fairweather Glacier, Lituya Bay, Crillon Lake, La Perouse Glacier, and Finger Glacier. Glaciers presently abut the terminal moraines at Fairweather Glacier and the lateral moraines at Finger Glacier. La Perouse Glacier, in contrast to many glaciers that extend to tidewater in northern hemisphere fjords, fronts directly on the open ocean.

The terrace sequence is divisable into three geomorphically distinct segments: (1) a northern segment, from Fairweather Glacier south to Lituya

Bay, has a single terrace adjacent to the coastal mountain front that is separated from the present shoreline by isolated remnants of a younger terrace and a prograded coastal plain (fig. 3); (2) a central segment, from Lituya Bay south to La Perouse Glacier, has a well-developed sequence of five terraces seaward of the mountain front (fig. 4); and (3) a southern segment, from La Perouse Glacier south to Icy Point, has complicated relations near La Perouse and Finger Glaciers, possible remnants of a high terrace, and a sequence of four well-defined terraces at Icy Point (fig. 5). The terraces at Icy Point are separated from the inland mountain front by a large outwash-filled river valley that is developed along the Fairweather fault and headed against the terminal moraine complex of Finger Glacier. The general geomorphology of the three segments are described separately below.

Northern Segment

The terrace and coastal plain of the northern segment is 2.4 to 3.4 km wide between the terminal moraine complexes of Fairweather Glacier and Lituya Bay (fig. 3). The 0.8-to-1.6-km-wide terrace (Terrace I, fig. 3), is bounded inland by a distinct slope break at an elevation of about 150 m that

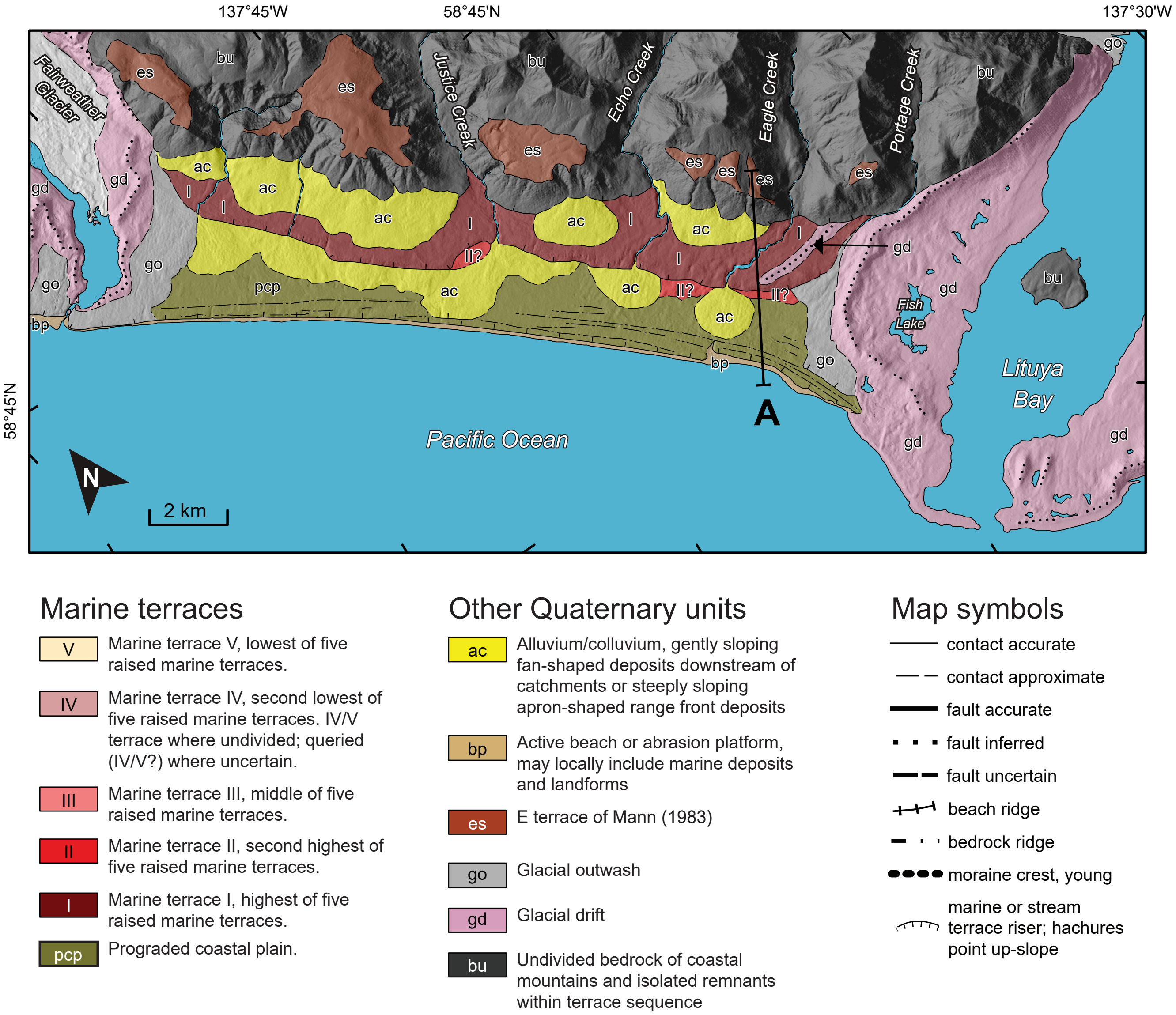

Figure 3. Map of surficial relations on the northern segment of the terrace sequence, between Fairweather Glacier and Lituya Bay. Topographic profile A is shown in figure 6.

marks the transition from the terrace surface to the steep slopes of the coastal mountains. This slope break is elevationally over the shoreline angle for this terrace, which is buried throughout its length by alluvial and colluvial aprons that are well developed along the mountain front. The terrace is deeply incised by the drainages that cross it. These are characteristically narrow, steep-walled canyons cut in bedrock. The terrace itself is level to broadly undulating with many small swales. This surface irregularly gains elevation toward the mountains and in some places, as at Justice Creek, continues up some valleys for short distances past the mountain front. A subdued morainal ridge near Lituya Bay (unit gd, marked by bold dots) is an older lateral moraine deposited on the Terrace I surface.

Vegetation on the terrace surface is a mixture of small, old growth cedar and hemlock patches interspersed in large open areas of muskeg. Where drainage is better developed, as along stream valleys or on the colluvial-alluvial aprons of the mountain front, a denser more pervasively developed spruce-hemlock forest is present. The seaward margin of the terrace is marked by a cliff in bedrock in places over 45 m high, whose base is at an elevation of about 10 m. This old seacliff is modified near Lituya Bay by outwash deposits and associated stream terraces. The base of this old seacliff marks the inland margin of the coastal plain.

The coastal plain varies from 1.1 to 2.4 km wide, and has outwash deposits and moraines deposited on it at Fairweather Glacier and Lituya Bay. Where the major drainages crossing the marine terrace enter onto the coastal plain, youthful alluvial fans of low relief are developed. Between these fans, the plain is nearly flat, poorly drained swamp and muskeg except for some abandoned beach ridges that are better drained and therefore forested. The seaward margin of the coastal plain, adjacent to the present shoreline, is a series of beach ridges up to 0.3 km wide and commonly 6 m high. These beach ridges, the youngest part of the coastal plain, are covered by a spruce-hemlock forest that is everywhere youthful but clearly becomes younger (as evidenced by tree size, amount of deadfall, and soil development) seaward from the older to younger beach ridges. These beach ridges are locally being eroded by storm waves, leaving residual concentrations of heavy minerals including gold that were placer mined during early parts of the century (Mertie, 1933).

The base of the abandoned seacliff between Terrace I and the coastal plain coincides with a youthful strandline along most of its length, but in three places (Justice Creek, between Echo and Eagle Creek, and between Eagle and Portage Creek; fig. 3) this strandline is separated from the abandoned seacliff by areas that are older than other parts of the coastal plain. Compared to most of the coastal plain these three areas are about the same elevation or higher but, in contrast, have patches of mature forest interspersed with muskeg rather than youthful forests and broad swamps. They probably represent remnants of a marine terrace (II?) and indicate that the sea advanced to near or at the base of the now abandoned seacliff at least twice.

The map relations therefore indicate one early stage of terrace cutting to produce Terrace I adjacent to the mountain front. The main terminal moraine complexes of Lituya Bay and Fairweather Glacier were deposited after Terrace I was cut as these complexes are graded to the coastal plain. The coastal plain has experienced two or more relative sea level rises that together have produced the high abandoned bedrock cliff between the coastal plain and Terrace I. The most recent relative sea level rise on the coastal plain post-dates all but the youngest glacial deposits of the northern segment. The seaward migration of the shoreline that followed this sea level rise culminated with the present constructional setting of the coastline in which large beach ridges have been successively developed and abandoned.

Central Segment

The central segment extends from Lituya Bay and its associated terminal moraines southward for 19 km to La Perouse Glacier. In sharp contrast to

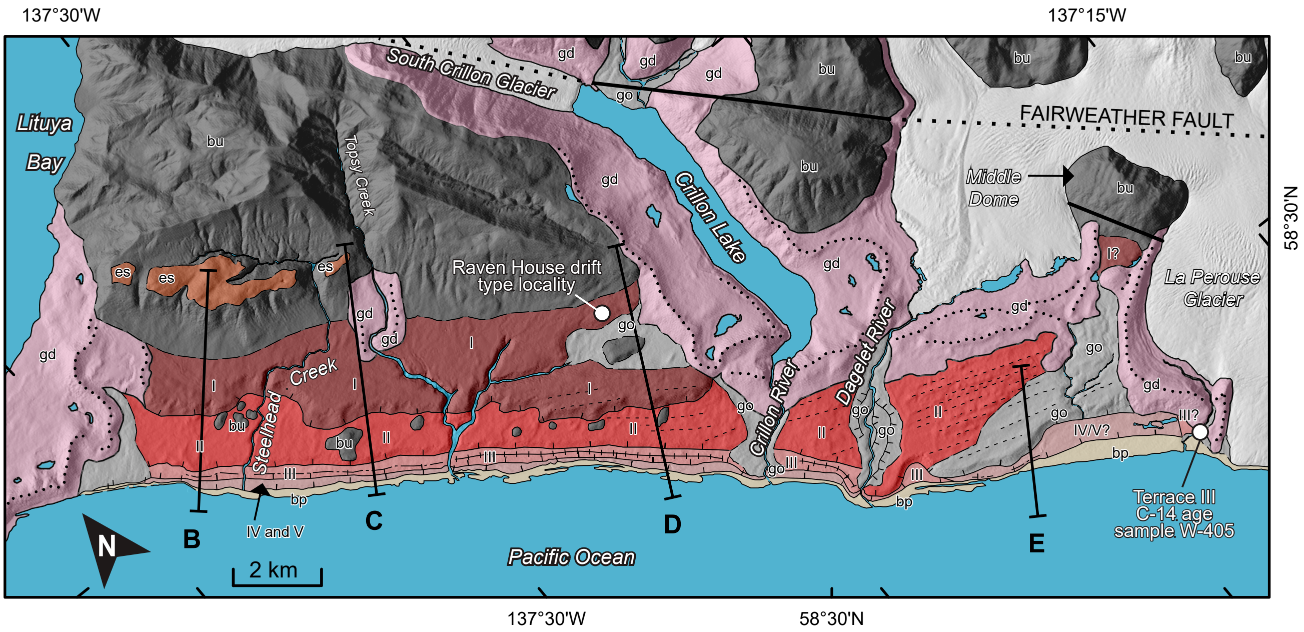

Figure 4. Map of surficial relations in the central segment of the terrace sequence, between Lituya Bay and La Perouse Glacier. Refer to legend in figure 3. Topographic profiles B–E are shown in figure 6.

the northern segment, the central segment lacks a prograded coastal plain. In its place over most of the central segment is a well-developed sequence of five marine terraces numbered successively I to V from the mountain front to the shoreline (fig. 4). However, this 3.2-km-wide terrace sequence changes character along strike to the south. It is interrupted near the center of the central segment by the breach in the mountain front at Crillon Lake where a well-developed terminal moraine complex is present. Further south, along the southern 4.8 km of the central segment in the vicinity of La Perouse Glacier, the terrace sequence is incompletely developed with most of the terraced belt represented by a single 3.2-km-wide wave-cut surface of Terrace II.

Terrace I is present along 10 km of mountain front between the terminal moraine complexes of Lituya Bay and Crillon Lake. A small area between the lobes of La Perouse Glacier may be an isolated remnant of this terrace (fig. 4). This 1.1- to 2.4-km-wide surface is generally similar, in position and geomorphic development, to the single terrace present north of Lituya Bay (Terrace I, fig. 3). Its inland margin is the slope break between the terrace surface and the steep mountain front. This slope break, which varies in elevation from about 180 m near Lituya Bay to about 245 m near Crillon Lake, marks the approximate location of the shoreline angle for this terrace. Colluvial and alluvial deposits mantle this slope break but, because these deposits are not as extensive as similar deposits north of Lituya Bay, they have not been shown separately on figure 4. The terrace surface is irregular with many broad undulations but in a general sense it increases in elevation toward the mountain front. It is deeply incised by the drainages that cross it, including a small outwash river valley from the Crillon Lake glacial terminus. Older, more subdued moraines have been deposited on the terrace near Lituya Bay, at Topsy Creek, and near Crillon Lake (Mann, 1986) but the main parts of the Lituya Bay and Crillon Lake terminal complexes eroded across and postdate Terrace I. Vegetation is similar to that on Terrace I of the northern segment—old growth cedar and hemlock forest patches and broad, open muskeg areas with localized more pervasive forest along streams and better drained areas. In many places the muskeg forms a thin (1 m ±) mantle directly on bedrock. The seaward margin of Terrace I is a 40- to 90-m-high cliff cut in bedrock that is mantled with colluvium and forms a steep, forested slope. This abandoned seacliff is the boundary between Terrace I and the next terrace seaward, Terrace II.

Terrace II, extending the length of the central segment (19 km) and 0.8- to 1.6-km-wide, gradually changes height and character southward. The inland boundary of Terrace II is the cliff in bedrock separating it and Terrace I from Lituya Bay to Crillon River. However, between Crillon and Dagelet rivers, this cliff is replaced by a slope break developed against the terminal moraine of Crillon Lake. South of Dagelet River a distinct inland boundary to Terrace II is not apparent. Sharp-crested terminal and lateral moraines adjacent to La Perouse Glacier are deposited on this terrace and older, more subdued moraines appear to separate it from the suspected Terrace I remnant west of Middle Dome. The approximate elevation of the shoreline angle for this terrace, estimated from the elevation at the base of the inland-bounding cliff and slope break, varies from less than 60 m near Lituya Bay to about 140 m near Crillon River. South of Dagelet River, the location of the shoreline angle is not preserved but measured surface elevations on this part of the terrace are as high as 180 m.

The geomorphic character of Terrace II changes as it gains elevation to the south. Near Lituya Bay the Terrace II surface is level to gently sloping with local small north-south drainages that have developed 40-meter-wide and 10- to 20-meter-deep swales. The major drainages deeply incise the terrace in narrow bedrock-walled canyons that cut directly across the terrace without significant tributary development. Bedrock prominances on this surface identify former shoals and sea stacks at several localities including a former island between Steelhead and Topsy creeks. Large boulders on this surface north of Steelhead Creek and near Crillon River represent the wave-worked remnants of older terminal moraines of Lituya Bay and Crillon Lake (Mann, 1986). An unknown thickness of gravel and sand deposits, probably alluvial as well as beach deposits, are present on the northern one-third of this terrace but the southern two-thirds of the surface is characterized by the development of distinct ridges of resistant sedimentary beds in the underlying bedrock of the wave-cut platform (fig. 4). Where Terrace II becomes wider and higher southward, the bedrock ridges become more prominent, even though outwash and moraine incompletely mantle the surface near La Perouse Glacier.

Vegetation on Terrace II is a mixture of open muskeg areas with scattered, stunted cedar and patches of old growth hemlock-cedar forest. In a general way the distribution of forest and muskeg is similar to that on Terrace I. The seaward margin of Terrace II is a former seacliff (about 15 to over 45 m high) separating Terrace II from Terrace III except for that part of the central segment south of Dagelet River where younger terraces are not developed and the seaward margin of Terrace II coincides with the present seacliff along the shoreline.

Terrace III, less than 0.5 km wide, is present along 14 km of the central segment north of Dagelet River. South of Dagelet River, terraces IV and V have not been clearly identified. A small terrace remnant at the southern end of the central segment, adjacent to La Perouse Glacier (fig. 4), is considered correlative with Terrace III. Terrace III commonly has a level surface and drainages are restricted to the major streams which deeply incise the terrace in narrow bedrock canyons that lack tributaries. Sand and gravel deposits are present on the surface which, at least along its southern parts, includes an old beach ridge and associated back-beach deposits. The vegetation on this terrace contrasts with that in all other terraces of the area. It characteristically lacks open muskeg areas and instead is very nearly completely mantled by a dense hemlock-cedar forest with abundant deadfall. The abundant deadfall makes this terrace the most difficult of all to traverse. The seaward margin of Terrace III is a sharp 60° slope break, about 6 m high, that marks the old seacliff along the inland margin of Terrace IV.

Table 1. Radiocarbon data from the Lituya Bay area.

Lab no.	Field no.	Location	Elevation (m)	Lab-reported Age (1σ ^{14}C yr B.P)[a]		Calibrated Age (2σ cal yr B.P.)[b]		Description of Material Dated[c]	
Terrace I									
W-3317	75ARu129	Northern segment 58°44’45”N, 137°47’12”W	70	7230	± 250	8540	– 7610	Peat from 1 m depth	Same bog
W-3304	75ARu130	Northern segment 58°44’48”N, 137°47’06”W	70	5360	± 250	6680	– 5600	Peat from 1 m depth	
W-3292	75ARu131d	Northern segment 58°44’52”N, 137°47’15”W	76	7930	± 250	9460	– 8340	Peat from 3.7 m depth	Same core
W3756	75ARu131d	Northern segment 58°44’52”N, 137°47’15”W	76	7700	± 200	9030	– 8050	Peat from 3.5 m depth	
W-3369	75ARu131e	Northern segment 58°44’52”N, 137°47’15”W	76	7840	± 250	9400	– 8190	Peat from 4.3 m depth	
W-3315	75ARu132b	Northern segment 58°43’06”N, 137°44’00”W	33	8590	± 300	10490	– 8790	Peat from 1.8 m depth	Same bog
W-3316	75ARu133c	Northern segment 58°43’10”N, 137°44’06”W	33	7450	± 250	8980	– 7790	Wood from 2.4 m depth	
W-3365	75ARu126b	Northern segment 58°40’38”N, 137°38’57”W	62	7090	± 250	8400	– 7510	Peat from 1.7 m depth (sterile clay bottom)	Same bog
W-3294	75ARu127c	Northern segment 58°40’33”N, 137°39’03”W	62	7600	± 250	9080	– 7940	Peat from 2.3 m depth	
W-3300	75ARu104c	Central segment 58°35’03”N, 137°30’39”W	150	7260	± 250	8560	– 7610	Peat from 2.7 m depth	Same bog
W-3751	75ARu104c	Central segment 58°35’03”N, 137°30’39”W	150	7050	± 300	8520	– 7340	Peat 0.08 m above W-3300	
W-3298	75ARu105b	Central segment 58°34’58”N, 137°30’45”W	150	5400	± 350	7150	– 5330	Peat from 2.4 m depth	
W-3286	75ARu106b	Central segment 58°35’08”N, 137°31’36”W	150	6670	± 250	8020	– 7010	Peat from 1.5 m depth	
W-3352	75ARu121a	Central segment 58°33’32”N, 137°27’24”W	178	7900	± 300	9490	– 8180	Peat from 1 m depth	Same bog
W-3356	75ARu121a	Central segment 58°33’32”N, 137°27’24”W	178	8160	± 250	9600	– 8430	Split of W-3352	
W-3367	75ARu122	Central segment 58°33’34”N, 137°27’15”W	178	7500	± 300	9030	– 7700	Peat from 0.6 m depth (bottom in gravel)	
W-3287	75ARu123c	Central segment 58°33’55”N, 137°27’00”W	170	9240	± 300	11240	– 9610	Peat from 2.7 m depth (bottom in wood)	

Table 1, continued. Radiocarbon data from the Lituya Bay area.

Lab no.	Field no.	Location	Elevation (m)	Lab-reported Age (1σ ^{14}C yr B.P)[a]		Calibrated Age (2σ cal yr B.P.)[b]		Description of Material Dated[c]	
Terrace II									
W-3283	75ARu101	Central segment 58°34’37”N, 137°31’15”W	63	8840	± 300	10740	– 9140	Peat from 1 m depth	Same bog 3 cores
W-4328	75ARu101	Central segment 58°34’37”N, 137°31’15”W	63	8410	± 800	11950	– 7790	Peat 0.08 m above W-3283	
W-3750	75ARu101	Central segment 58°34’37”N, 137°31’15”W	63	8310	± 200	9700	– 8650	Split of W-4328	
W-4323	75ARu102	Central segment 58°34’33”N, 137°31’24”W	63	3410	± 90	3890	– 3450	Peat from 0.6 m depth	
W-3302	75ARu103	Central segment 58°34’41”N, 137°31’06”W	63	6970	± 300	8400	– 7310	Peat from 0.6 m depth	
W-4325	75ARu103	Central segment 58°34’41”N, 137°31’06”W	63	4390	± 90	5300	– 4840	Peat 0.08 m above W-3302	
W-3289	75ARu107a	Central segment 58°35’03”N, 137°32’00”W	60	6600	± 250	7960	– 6960	Peat from 0.6 m depth	Same bog
W-3299	75ARu108b	Central segment 58°35’08”N, 137°31’42”W	60	7320	± 250	8640	– 7630	Peat from 1.2 m depth	
W-3319	75ARu109	Central segment 58°34’13”N, 137°29’51”W	77	6840	± 250	8190	– 7260	Peat from 1 m depth (hard bottom, gravel?)	
W-3366	75ARu114a	Central segment 58°33’07”N, 137°28’21”W	32	2030	± 200	2680	– 1530	Peat from 0.23 m depth (shovel hole)	
W-3311	75ARu114b	Central segment 58°33’07”N, 137°28’21”W	32	2040	± 200	2680	– 1540	Peat from 0.38 m depth (base in sand)	
W-3330	75ARu117	Central segment 58°32’57”N, 137°27’51”W	32	3390	± 200	4230	– 3170	Peat from 0.3 m depth (shovel hole, base in iron-stained sand)	
W-3291	75ARu118b	Central segment 58°33’07”N, 137°27’36”W	61	6700	± 300	8170	– 6960	Peat from 0.3 m depth (bottom in wood)	Same bog
W-3344	75ARu119c	Central segment 58°33’10”N, 137°27’33”W	61	6070	± 250	7460	– 6400	Peat from 1.5 m depth	
W-3288	75ARu120d	Central segment 58°33’12”N, 137°27’24”W	61	6940	± 300	8380	– 7280	Peat from 2.7 m depth	
W-3321	75ARu120d	Central segment 58°33’12”N, 137°27’24”W	61	6170	± 250	7560	– 6500	Peat from 0.8 m above W-3288	

Table 1, continued. Radiocarbon data from the Lituya Bay area.

Lab no.	Field no.	Location	Elevation (m)	Lab-reported Age (1σ ^{14}C yr B.P)[a]		Calibrated Age (2σ cal yr B.P.)[b]		Description of Material Dated[c]
Terrace III								
W-3295	75ARu113	Central segment 58°33’05”N, 137°28’27”W	27	2420	± 200	2950	– 1990	Peat from 1 m depth
W-3329	75ARu116	Central segment 58°32’53”N, 137°27’57”W	30	2480	± 200	3030	– 2040	Peat from bottom 0.2 m of 1.5 m core (bottom in sand)
Terrace IV								
W-3368	75ARu112	Central segment 58°33’02”N, 137°28’30”W	15	710	± 200	1060	– 310	Basal 0.2 m of organic muck (shovel hole)
W-3324	75ARu115	Central segment 58°32’51”N, 137°28’00”W	16	810	± 200	1230	– 490	Peat from 0.38 m depth (shovel hole)
W-4261	78AH83c	Central segment 58°35’03”N, 137°33’20”W	17	2970	± 80	3360	– 2930	Organic rich layer in stream terrace deposits
W-4269	78AH83b	Central segment 58°35’03”N, 137°33’20”W	17	2520	± 80	2750	– 2370	Charcoal and wood from clean sand 0.15 m below W-4261
Coastal Plain north of Lituya Bay								
W-3284	75ARu128	Northern segment 58°44’18”N, 137°48’36”W	5	1020	± 200	1310	– 570	Wood from base of 4 m core
W-3318	75ARu124	Northern segment 58°40’07”N, 137°40’36”W	1	840	± 200	1230	– 510	Peat from 1 m depth
W-3290	75ARu125b	Northern segment 58°40’09”N, 137°40’27”W	1	2450	± 200	2970	– 2000	Peat from 1.8 m depth (bottom in wood)
W-3753	75ARu125b	Northern segment 58°40’09”N, 137°40’27”W	1	2420	± 200	2950	– 1990	Split of sample W-3290
Legacy dates from previous studies								
W-405	nr	Central segment	45	3250	±200	3990	– 2960	Driftwood at base of Terrace III[d]
nr	nr	Southern segment	nr	12430	±100	15275	– 13,930	Wood in till deposited on Terrace II[e]

[a] Age reported by the USGS laboratory, Reston, VA (1975, 1977, 1979, 1980).

[b] Calibrated ages in solar years reported to the nearest decade and calculated using OxCal (version 4.2.4,Ramsey [2009]; 95 percent probability distribution at 2σ) with the IntCal13 dataset of Reimer and others (2013).

[c] Samples are terrestrial material deposited above marine platform, so the accelerator mass spectrometer (AMS) ages are minimum ages for the time when marine platforms were abandoned.

[d] Sample collected by Don J. Miller, published in Rubin and Alexander (1958).

[e] Data published by Mann (1986).

Terrace IV is a narrow surface, about 40 m wide, that closely parallels Terrace III throughout the northern 14 km of the central segment. A distinct terrace corresponding to Terrace IV has not been clearly identified between Dagelet River and La Perouse Glacier. The wavecut platform is incised by other major drainages but remnants of stream terraces, apparently graded to the Terrace IV surface, are still locally present along some drainages. The terrace surface is level and covered by a mature spruce-hemlock forest with distinctly less deadfall than on Terrace III. Lag boulders, gravel, and sand deposits, locally at least 1 m thick, are present on this surface but the seaward margin is commonly a nearly vertical cliff in bedrock. This cliff is 6 to 7 m high and in some places, as at Steelhead Creek, it has only partly been eroded through by the cross-cutting stream channels. In these places a subdued bedrock slope break (nick point) with as much as 1.5 m of relief is present in the stream channel marking the transition from the stream valley floor inland to that on the youngest terrace, Terrace V.

Terrace V lies adjacent to the present shoreline and its associated beach deposits throughout the central segment except south of the Dagelet River. Terrace V is generally narrow, covered by lag boulders adjacent to the inland-bounding cliff, and with hummocky deposits of beach sand that merge seaward with sand and gravel of the present shoreline. An immature hemlock forest without significant deadfall and a humus layer only centimeters thick is developed on the beach deposits. Grass-covered storm beaches with abundant driftwood and some young spruce trees mark the seaward edge of Terrace V.

South of Dagelet River an inland strandline abuts the colluvial mantle at the base of a 60-m-high bedrock cliff. This strandline is separated from the present beach by back-beach lagoonal deposits and a series of abandoned beach ridges that may be deposited on a wavecut platform correlative with Terrace V, although the width (0.3 km) and prograded nature of this area is unlike that of Terrace V to the north of Dagelet River. This low surface (IV/V?, fig. 4) could be either Terrace IV or V, or a composite of these.

Southern Segment

The southern segment (fig. 5) is the 13 km of coast south of La Perouse Glacier to Icy Point. The part of this segment between La Perouse and Finger Glacier lies adjacent to the mountain front, and further south the terrace sequence is bounded inland by Finger Glacier, its associated terminal moraines, and the 0.8- to 1.6-km-wide and 5-km-long outwash river valley of Kaknau Creek that is developed along the Fairweather fault. Glacial features and faulting complicate the terrace relations in the vicinity of La Perouse and Finger Glaciers but south of Finger Glacier a well-developed sequence of four terraces and the possible remnants of an additional older terrace are present (fig. 5).

The area between La Perouse and Finger Glaciers is characterized by incomplete and obscured terrace relations. A narrow and low terrace, similar to Terrace V of the central segment, lies adjacent to the present beach. Its inland boundary is a 12-m-high bedrock cliff. Inland from this cliff is a 50-m-wide forested surface that slopes seaward and is in turn bounded inland by a 2.5-m-high scarp. This scarp could be a bedrock ridge and it is not clear that it marks the inland boundary of a separate terrace. Inland of this scarp is a seaward-sloping surface up to 0.3 km wide, commonly mantled with outwash deposits. It is not bounded inland by a distinct slope break, but instead seems to merge with the 3-km-wide bedrock platform that extends inland to the mountain front. This bedrock platform, locally irregular but in general sloping seaward, has resistant bedrock ridges similar to those on Terrace II north of La Perouse Glacier. Glacial moraine and outwash is deposited on this platform and colluvial deposits have subdued the original slope break between the platform and the mountains. Major drainages are deeply incised on this irregular platform and the vegetative cover includes many open muskeg areas. A possible continuation of the

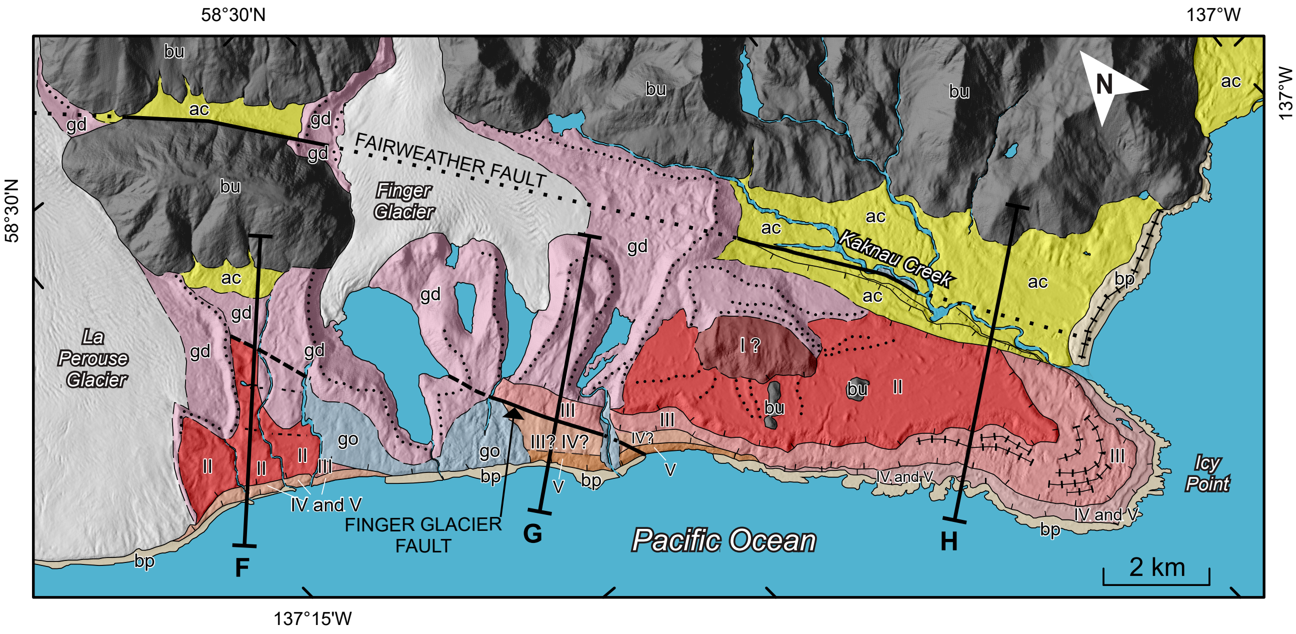

Figure 5. Map of surficial relations on the southern segment of the terrace sequence, between La Perouse Glacier and Icy Point. Refer to legend in figure 3. Topographic profiles F–H are shown in figure 6.

Finger Glacier fault (see below), trending N 30 W and defined by alignment of treelines, drainages, and breaks in recent lateral moraines of La Perouse and Finger Glaciers, appears to cross this platform 0.8 to 1 km west of the mountain front (fig. 5). Terraces in addition to the wide irregular platform and the low terrace(s) near the shoreline are not clearly definable. For this reason the low terraces in this area are not separately identified—remnants of III, IV, or V may be present (fig. 5).

South of Finger Glacier and its associated outwash plains, the terrace sequence is more complete and, in a general way, correlations can be made with terraces of the central segment. The oldest terrace, at elevations greater than 240 m (Terrace I?, fig. 5), appears to be present as an isolated remnant that was mantled with older moraines and partly overridden by younger glaciers. The younger overriding glaciers have eroded eastern parts of this surface and deposited narrow sharp-crested terminal moraines upon it. These younger southerly trending moraines are nearly at right angles to two boulder-strewn rises that mark the older moraine ridges on the remnant surface. This irregular, relatively small, and largely muskeg-covered surface is cliff-bounded to the west and south. This bedrock cliff, several tens of meters high, separates the remnant surface from the next youngest terrace.

The terrace seaward of the old terrace remnant is a well-defined, gently sloping surface, 6 km long and up to 1.6 km wide, that extends from Finger Glacier to near Icy Point (this is the Main terrace of Mann, 1986). Generally, this terrace (Terrace II, fig. 5) has a gentle slope to the south locally interrupted by lag boulder deposits that probably represent recessional moraines. Near Finger Glacier, however, three distinct terminal moraines have been deposited on the terrace. Two larger knobs, representing former sea stacks, are present in the central part of the terrace. Bedrock ridges are not developed on the surface, but deposits other than lag boulders and the Finger Glacier moraines do not appear to be present. Vegetation is a fairly pervasive cover of muskeg with forest development restricted to the immediate vicinity of drainages, the moraines on the terrace, and the terrace margin. The terrace is bounded inland by some areas of recent glacial erosion but it is mostly bordered by stream terrace slope breaks that are developed along the west side of the outwash valley of Kaknau Creek. To the west and south the margin of this terrace is a distinct cliff in bedrock that has 50 to 60° slopes. This cliff separates Terrace II (fig. 5) from Terrace III.

The next youngest terrace, Terrace III of figure 5, varies from 0.16 to about 1 km in width and throughout its greater-than-8-km length it is characterized by the development of linear beach ridges parallel to the present shoreline. These ridges, up to 10 m high and composed mostly of clean sand, locally had lagoons developed between them that are now low, poorly drained muskeg-covered areas. The Terrace III surface, although made uneven by the beach ridges, gradually slopes seaward. This terrace is deeply incised by the outwash river valley of Kaknau Creek and by the drainages that emanate from the southern lobe of Finger Glacier. Vegetation on the terrace is a mature, hemlock forest with abundant deadfall that is very similar to that on Terrace III of the central segment. Near Finger Glacier, an active fault (Finger Glacier fault discussed below) cuts this surface The seaward margin, where examined near Icy Point, is an abandoned seacliff less than 6 m high.

This low-relief abandoned seacliff is the inland boundary of Terrace IV (fig. 5), which is narrow (10–30 m) at Icy Point and may not be preserved 5 km north of Icy Point, but is apparently about 0.5 km wide near Finger Glacier. Near Finger Glacier this terrace appears to be stepped and has several beach ridges deposited on it; here it may actually be a zone of several narrow terraces stepped upward to Terrace III. This anomalous condition may be caused by the relatively local effects of recent faulting that have apparently resulted in the episodic uplift of this area during the time Terrace IV was being developed. The Terrace IV surface, therefore, changes character from a wider and possibly stepped surface with abandoned beach ridges at Finger Glacier to a narrow, essentially level, surface at Icy Point. Even at Icy Point though, this terrace has a 3-m-high bedrock ridge on it that could indicate a stepped character and episodic uplift in this area during terrace cutting. The surface is covered by mature hemlock forest, although it is distinctly younger, judging from the smaller amount of deadfall, than that on Terrace III. It is incised by drainages at Finger Glacier and Kaknau Creek. The seaward edge of this terrace is a 3- to 10-m cliff that separates it from the youngest distinct terrace of the southern segment.

The youngest terrace (Terrace V, fig. 5) resembles its counterpart west of Finger Glacier where active outwash plains extend onto the present beach. It is a narrow, very youthful surface, that extends from a 3- to 10-m-high bedrock cliff inland to the present storm beach deposits seaward. The surface has patches of immature spruce trees and the humus layer amongst these trees, developed on underlying beach sands and gravels, is only several centimeters thick.

The terraces on the southern segment have some similarities to those of the central segment but Terraces III and IV differ significantly from their possible counterparts to the north in that beach deposits are in general better developed upon them and there is some suggestion that they may be stepped, especially near Finger Glacier, where uplift may be locally tied to the recently active Finger Glacier fault trending across the terraces to the present shoreline. This fault has clearly affected the present morphology of the shoreline in that rocky headlands, localized south of this fault, attest to very recent uplift of Icy Point. The area between Finger Glacier and La Perouse Glacier lacks a distinct terrace sequence such as that at Icy Point and instead is mostly one deformed bedrock platform, sloping irregularly towards the sea, that shares many characteristics with the area near La Perouse Glacier on the central segment. The irregularities in the terrace sequence near La Perouse Glacier, on both the central and southern segments, combined with deformation of the terraces, requires that their correlation along strike be more rigorously considered.

TERRACE CORRELATION

Correlation of the terraces from one segment to another is challenging because they lack continuity and have been deformed. Continuity of a multiple terrace sequence is only present along the central segment between the Lituya Bay terminal moraine complex and Dagelet River and along the southern segment south of Finger Glacier. In these areas, abandoned seacliffs that mark the terrace boundaries can be traced along their length as continuous and distinct topographic features. The major discontinuities in the terrace sequence are at Lituya Bay and La Perouse Glacier. The 8-km gap across Lituya Bay and its associated moraines separates the northern segment with one distinct terrace and coastal plain from the five-terrace sequence of the central segment. La Perouse Glacier and its associated moraines create a 4- to 5.6-km gap in the terrace sequence, but terrace discontinuity begins about 8 km north of this glacier (Dagelet River) and extends south to the Finger Glacier fault, a total distance of about 16 km. In the La Perouse Glacier area, glacial deposits, an incompletely preserved terrace sequence, and deformation combine to complicate correlations from the central to the southern segment. Uplift of the terraces is greatest in this area (see below) and, as is characteristic of the entire study area, correlation of terraces cannot be based solely on their height above sea level. In spite of the complications at Lituya Bay and La Perouse Glacier, the setting, geomorphic character, and vegetation of some terraces allows their correlation across the major gaps. Some of these correlations are also supported by age data.

The oldest terrace we have studied (Terrace I, figs. 3–5) can be correlated from the northern to central segments across the Lituya Bay gap and a remnant of this terrace may be preserved on the southern segment. Features that link this terrace across Lituya Bay are its setting adjacent to the mountain front, the subdued colluvially mantled shoreline angle, the undulating but locally deeply incised surface, the similar vegetation cover of muskeg and old growth forest, and the presence of the oldest moraines of the area upon it. The correlation across the gap at La Perouse Glacier, from the central to the southern segment, is tenuous because the entire terrace sequence south of Finger Glacier is separated from the reference setting of the mountain front by the broad valley occupied by Kaknau Creek. However, the ~240 m elevation, the presence of old moraine deposits, and the muskeg-mantled character of the small but highest area south of Finger Glacier suggest that it is a remnant of Terrace I.

The terraces younger than Terrace I do not have well-defined correlatives north of Lituya Bay but they can be correlated across the La Perouse Glacier area. Terrace II may have a correlative north of Lituya Bay if the low (<15 m) remnants of the erosional surface that is locally present between Terrace I and the coastal plain of the northern segment (fig. 3) are related to Terrace II. Terrace II (seaward of Terrace I, figs. 4 and 5) shows the following characteristics north and south of La Perouse Glacier: (1) geomorphic features such as the inland-bounding abandoned seacliff, seastacks, and shoals; (2) a vegetation cover of widespread muskeg and old growth forest that is generally similar to that on Terrace I but distinctly different from that on all younger terraces; (3) deeply incised major drainages but only minor tributary development on the terrace itself, and (4) similar relations to terminal moraines—the oldest moraines of the area were cross-cut by development of this terrace but younger ones were deposited on or across it. The lack of terrace development younger than Terrace I on the northern segment together with physical contrasts and the lack of correlation with the central and southern segments implies long-term differential uplift of areas on either side of Lituya Bay.

We correlate terraces younger than Terrace II across the La Perouse Glacier area on the basis of their position relative to the present shoreline and Terrace II as well as the nature of the vegetation developed on them. North and south of La Perouse Glacier, Terrace III shares the characteristics of being youthful (with distinct abandoned seacliffs bounding inland and seaward margins) and covered by a uniform mature hemlock forest with abundant deadfall. The forest cover distinguishes this terrace from all others in the study area, but the terrace is wider, has a greater number of distinct abandoned beach ridges upon it, and may be locally stepped south of Finger Glacier. Terrace IV separates the youngest terrace from Terrace III and characteristically is narrow, flat, and covered by a mature forest that has much less deadfall than that on Terrace III on both the central and southern segments. Terrace V is the youngest terrace of the area and on both the central and southern segments this narrow surface merges seaward with the present storm beaches and is only partially covered by a youthful forest.

TERRACE AGES

The ages of the marine terraces help confirm correlations and are important to understanding their origin and subsequent deformation. The ages of the terraces relative to other geomorphic features and specific surficial units can be identified from the field and map relations. However, their absolute ages are only generally constrained by C-14 dating of surficial units, primarily unconsolidated glacial deposits, or by the minimum limiting ages provided by C-14 dating of peat accumulations on their surfaces.

An older moraine sequence has been identified on Terrace I outboard to the north of the main complex at Lituya Bay (fig. 3), outboard to Crillon Lake lateral moraines (fig. 4; Mann and Ugolini, 1985; Mann, 1986), and as small remnants that are present above 240 m south of Finger Glacier on the southern segment (fig. 5). These older moraines have not been directly dated. They are called the Raven House drift by Mann (1986) who concluded they are late Wisconsin in age (12,000 to 25,000 years BP). Raven House drift is deeply weathered on Terrace I; remnants of this drift on younger terraces are wave-worked (Mann, 1986).

The C-14 data available for the terminal moraines at Lituya Bay, Crillon Lake, La Perouse Glacier, and Finger Glacier (compiled by Mann and Ugolini, 1985, table 2) show that each terminal complex is a composite of several Holocene or Holocene/Late Pleistocene moraines. The oldest dated advance is at Finger Glacier where Mann (1986) collected and dated a pine log in till that overlies sand and well-rounded pebbles and cobbles deposited on a horizontally planed bedrock surface. The calibrated C-14 age (Beta-10647) for this log is 13,930–15,275 cal yr BP (table 1) and the enclosing till (105 m elevation) appears to have been deposited on beach deposits of the Terrace II surface.

The C-14 data for cores from peat bogs indicate a Holocene age for vegetation developed on the Terrace I surface. These data, listed in table 1, are of peat and some wood from cores taken in bogs on both the northern and central segments at 13 different localities. The ages of basal peats range from 5,330–7,150 cal yr BP (W-3298, table 1) to 9,610–11,240 cal yr BP (W-3287, table 1). These data indicate a minimum limiting age of 9,610–11,240 cal yr BP for Terrace I development but, as discussed further below, the oldest C-14 peat ages on Terrace I primarily represent the onset of climatic and soil-forming conditions conducive to podzolisation (Ugolini and Mann, 1979). Terrace I is crosscut by Holocene terminal moraine complexes at Lituya Bay, Crillon Lake, La Perouse Glacier, and Finger Glacier. It is clearly older than the oldest dated till in the Finger Glacier terminal moraine—13,930–15,275 cal years BP (Mann, 1986)—but how much older is not known. Mann (1986) concluded that Terrace I, which Raven House drift is deposited on and possibly graded to, is between 20,000 and 40,000 years old. Direct C-14 dating of this drift is needed to better constrain the age of both Terrace I and Terrace II (which crosscuts it).

The vegetation cover on Terrace II is similar to that on Terrace I and C-14 dates from peats at 11 different localities on the central segment range in age from 1,530–2,680 cal yrs BP (W-3366, table 1) to 7,790-11,950 cal yrs BP (W-4328, table 1). These data, indicating a minimum limiting age of 7,790–11,950 cal yrs BP for Terrace II, probably also reflect the climatic shift at the beginning of the Holocene that eventually led to the present vegetation cover (Ugolini and Mann, 1979). Terrace II crosscuts the oldest mapped part of the terminal moraine complex at Lituya Bay (fig. 4). This moraine is undated but could be older than the oldest dated moraine at Finger Glacier (13,930–15,275 cal years BP, table 1). Terrace II is also wide, commonly 0.8 to 1.6 km in width, and probably formed during a period of rising and high sea level. Mann (1983) and Mann and Ugolini (1985) concluded that Terrace II (their "C" terrace) was most likely late Wisconsin in age (11,000 to 18,000 years BP). Terrace II is therefore at least about 14,000 years old but additional dating is needed to better constrain its age.

Vegetation cover and peat development on Terraces I and II are markedly different from the vegetation cover on the three youngest terraces. The C-14 dating of basal peat on Terrace I and Terrace II shows that the older peats from each terrace are essentially the same age. Both terraces also display similar vegetative cover characterized by large open muskeg areas interspersed through old growth forest of hemlock and cedar. Terrace II is clearly much younger than Terrace I, but the difference in age that is so obvious in their geomorphology is not as markedly reflected in the present vegetation developed on them. Because the vegetation on both these terraces probably represents the late successional cover reached following climatic changes at the beginning of the Holocene (Ugolini and Mann, 1979), the younger three terraces must be Holocene in age. If any of the youngest three terraces had been abandoned prior to the Holocene, they too should have widespread bogs containing basal peats about 10,000 years or older and they do not.

The vegetation contrasts between the three younger terraces are distinctive and provide insight into the temporal evolution of forests in the Lituya Bay area. Terrace V has a forest that is mostly immature spruce with a forest floor that lacks deadfall and has only a few centimeters of humus, Terrace IV has a forest of mature hemlock and spruce on a forest floor covered by moderate deadfall and a well-developed humus layer, and Terrace III has a mature forest of hemlock and cedar with a forest floor characterized by abundant deadfall. With the exception of certain back-beach lagoonal localities on Terrace III, peat bogs are not developed on the three youngest terraces. As recognized by Ugolini and Mann (1979), the three youngest terraces provide an excellent temporal succession that enables one to reconstruct the forest and soil evolution that took place upon them.

Terrace III has accumulated organic material on its surface dated at 1,990–2,950 and 2,040–3,030 cal yr BP (W-3295 and W-3329, table 1). These are minimum ages for the terrace and the oldest peat on Terrace II (9,140–10,740 cal yr BP, W-3283, table 1) provides a maximum age. In 1952, Don J. Miller collected wood that he described as beach-worn driftwood from the base of a 3 m section of stratified, interbedded, well-rounded gravel and sand, lying on a wave-planed bedrock surface at an approximate altitude of 45 m. This locality was exposed in a bluff forming the northeast bank of the unnamed stream along the northwest margin of La Perouse Glacier about 0.5 km inland from the present shoreline (sample W-405, fig. 4). The calibrated C-14 age of this wood (original data reported by Rubin and Alexander, 1958, p. 7–8, sample W-405) is 2,960–3,990 cal yr BP (table 1). A remnant of Terrace III is the only wave cut surface in this area (fig. 4) and Miller's sample appears to date it well. Terrace III is therefore concluded to be 3,000–4,000 years old.

Terrace IV has a minimum age defined by accumulated organic material dated at 310–1,060 and 490–1,230 cal yrs BP (W-3368 and W-3324, table 1). This terrace appears to be graded to a stream terrace that has deposits that include organic materials dated at 2,930–3,360 and 2,370–2,750 cal yrs BP (W-4261 and W-4269, table 1). The inverted age sequence of these two samples (the 2,930–3,360 cal year age is from material stratigraphically above that giving a 2,370–2,750 cal year age) combined with the fact that the ages are similar to that of organic accumulations on Terrace III (table 1) suggests that the stream terrace material is reworked from Terrace III. If this is the case, then the 2,370–2,750 cal year age would represent a maximum age for Terrace IV. Because Terrace III is significantly wider than Terrace IV, we conclude it is probably close to the age of the vegetation matter on it and about 1,000 years old. Terrace V has trees as old as about 400 years growing upon it (Ugolini and Mann, 1979); this terrace is about the age of these trees or a little older, but probably not older than 500 years.

In summary, field relations and C-14 data variably constrain the age of the terraces. Terrace I is a pre-Holocene surface that is not well dated and needs further study. Field relations show that Terrace II formed after the maximum Wisconsin glacial advance. This terrace is older than 13,930–15,275 cal years BP and may be related to the post-Wisconsin sea level rise (Mann, 1983, p. 114–117). As the early Holocene age that characterizes the oldest dated peats on Terraces I and II reflects the climatic shift at the beginning of the Holocene that enabled the present vegetation's development to begin, the beginning Holocene basal peat ages from both Terraces I and II independently show that Terraces III, IV, and V are Holocene. Terrace III seems to be the best dated as Don J. Miller's driftwood sample from beach deposits on this terrace shows it to be 2,960–3,990 cal years old. Terrace IV is about 1,000 years old and Terrace V is not older than 500 years. Additional work would undoubtedly lead to considerable resolution of these ages, but even as presently definable they have important implications for the origins of the terraces and provide a basis for evaluating the tectonic history of the area.

TERRACE DEFORMATION

Deformation of the terraces is readily apparent from their differential development and their variation in shoreline angle elevation along strike. Figure 6 shows topographic profiles obtained from 5-m resolution topographic data (U. S. Geological Survey, 2016) and altimeter traverses across the terraces. These profiles clearly show the differential development of the terraces including the lack of younger terraces on the northern segment, five terraces on the central segment with the youngest three being low and narrow, an irregular but generally seaward sloping broad platform near La Perouse Glacier with distinct terraces present only locally at lower elevations, and four well-defined terraces at Icy Point that are bounded to the east by the valley of Kaknau Creek. Observations from the air above La Perouse Glacier indicate that Terraces I and II on the central segment are tilted northward, Terrace II on the southern segment is tilted southward, and the wide bedrock platform in the La Perouse Glacier area (Terrace II) slopes markedly seaward. These observations suggest that uplift of the terraces is greatest in the La Perouse Glacier area and this relation is confirmed by the variations in shoreline angle elevations (fig. 7).

Shoreline angle elevation estimates obtained with surveying altimeters and from projections on the transverse profiles (fig. 6) are plotted in the longitudinal profiles of figure 7. The measured elevations are approximations to the shoreline angle elevation as they were obtained on the present terrace surfaces near the base of the abandoned seacliffs (seaward of colluvial aprons if present). In addition, altimeter-measured spot elevation on terrace surfaces are shown on figure 7. The profiles in figure 7 primarily identify general characteristics of the terrace deformation.

One general conclusion from the profiles in figure 7 is that the terraces have been differentially uplifted—essentially arched—about an axis oriented perpendicular to the shoreline that is located in the La Perouse Glacier area. The Finger Glacier fault (discussed more below) trends obliquely across the terrace sequence in the vicinity of Finger Glacier and is recently active, but slip on this fault appears to postdate most of the terrace arching.

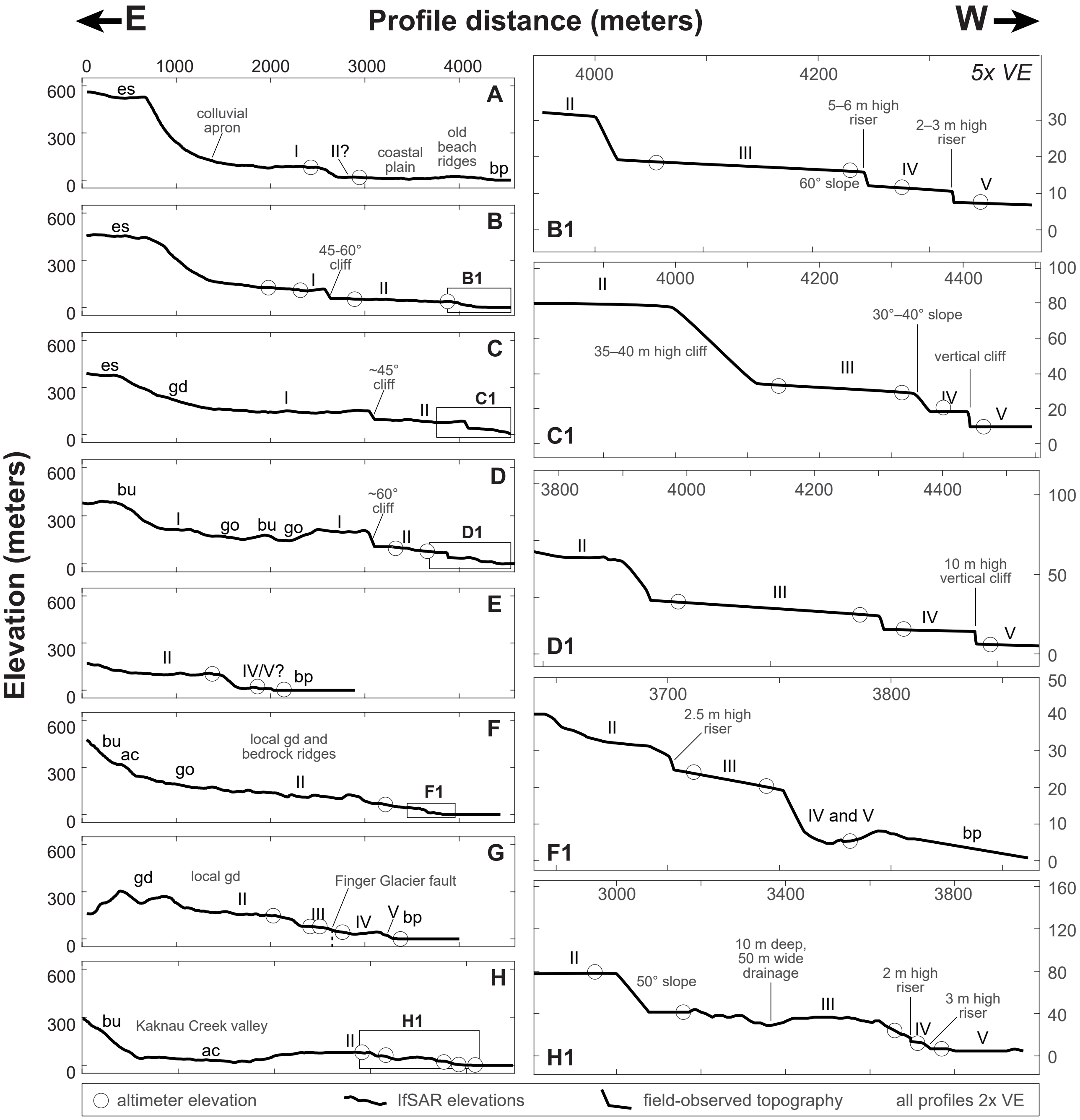

Figure 6. Topographic profiles across the terraces based on 5-m resolution DEM data (U.S. Geological Survey, 2016). Circles locate sites of field measurements. Location of profiles are shown in figures 3, 4, and 5.

A second general conclusion is that Terrace I can be projected across the Lituya Bay gap without significant discontinuity. The projected shoreline angle elevations for the four younger terraces have elevations north of Lituya Bay that are at or lower than the coastal plain. Remnants of Terrace II could be present at low elevations north of Lituya Bay but the three Holocene terraces were not developed there.

The third general conclusion from the profiles in figure 7 is that the principal deformation of the terraces postdates development of Terrace II as the profiles for the shoreline angle elevations of Terraces I and II are essentially parallel along the central segment. Both terraces appear to have been deformed in a similar fashion and in similar amounts as each have about 100 m of relief.

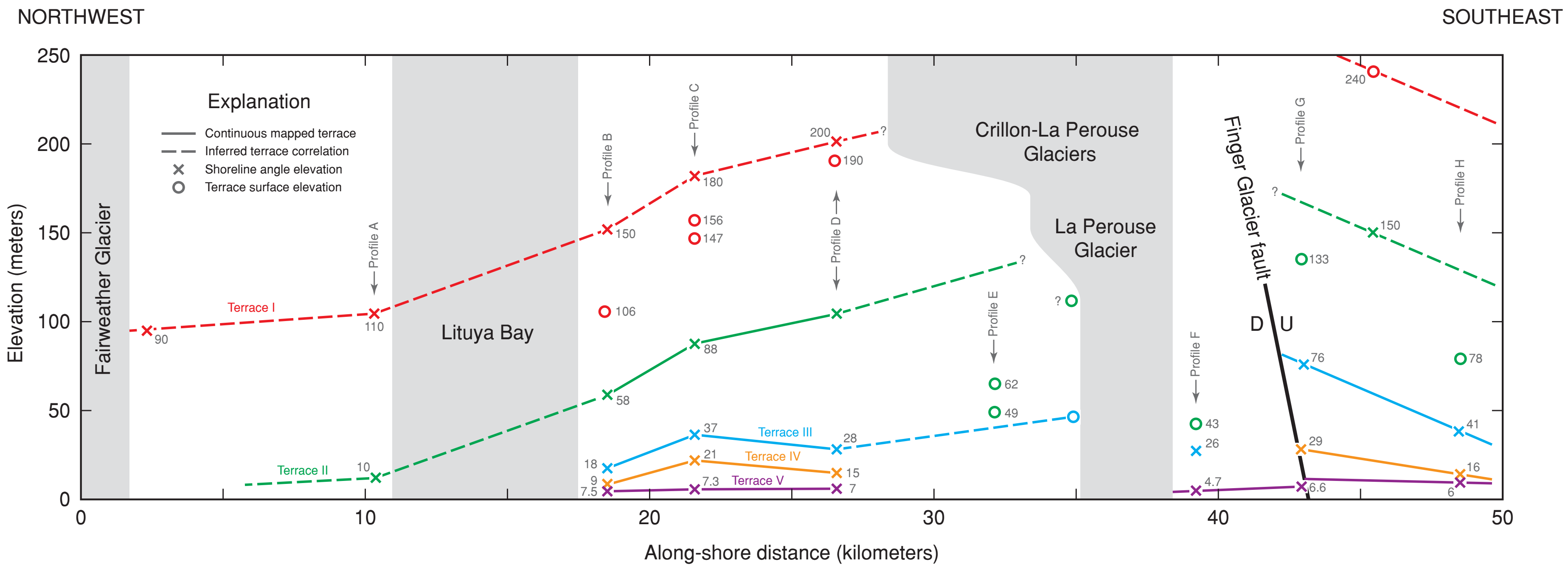

Figure 7. Longitudinal profiles of estimated shoreline angle elevations for terraces between Fairweather Glacier and Icy Point.

Finger Glacier Fault

The Finger Glacier fault offsets geomorphic features but may also be a boundary to bedrock structures (fig. 2). The elevation traverse across the Finger Glacier fault (profile G, fig. 6) showed the surface trace to be a degraded scarp with about 15 m of total relief across it. The scarp and offset terraces (fig. 7) indicate that the southeast side is up across the fault. Because the Finger Glacier fault crosscuts Terraces III and IV of the southern segment, it has had late Holocene displacement (fig. 5). It probably offsets Terrace V as well and is likely responsible for the rocky shoals that now characterize the shoreline south from the Finger Glacier fault to Icy Point.

The bedrock structure discontinuity, which is primarily defined by the bedrock folding of the central segment that cannot be carried south to the southern segment (fig. 2), may indicate that the Finger Glacier fault has an older history of displacement. If this is the case, displacement prior to the Holocene offsets of the terraces may have been related to the folding of the bedrock units. The Finger Glacier fault could have been one of a family of high-angle reverse faults that trend subparallel to the coastline. Such a fault has been inferred offshore along the central segment (fig. 2; Plafker, 1971b, p. 86). If the Finger Glacier fault does have an older history tied to post-early Pleistocene folding in the area, then it is a structure that has been present during development of all the terraces and possibly active during formation of the younger ones. Figure 7 suggests that Terrace III has been displaced some 30 to 40 m across the fault. Finger Glacier fault displacements, combined with post-Terrace II arching at La Perouse Glacier, need to be taken into consideration in assessing the general Holocene uplift of the coastline from Lituya Bay to Icy Point.

The active strike-slip Fairweather fault is a major crustal structure that juxtaposes geologic terranes of different metamorphic grade and structural history (figs. 1 and 2; Plafker and others, 1978; Plafker and Campbell, 1979). Late Quaternary displacements along this fault, as determined in the Lituya Bay area, suggest an average dextral displacement rate of about 5 cm/year for about the last 100,000 years (Plafker and others, 1978). This displacement rate indicates that most, if not all, of the transform motion between the Pacific and North American plates is now being taken up on the Fairweather fault (Plafker and others, 1978; Elliott and others, 2010). The most recent surface displacements on the fault accompanied the 1958, 7.9 magnitude Lituya Bay earthquake (Miller, 1960; Tocher, 1960) at which time there was up to 6.6 m horizontal slip near Crillon Lake and 2.4 m near Icy Point along Kaknau Creek. In our study of the 1958 displacements (Plafker and others, 1978) we were unable to identify a fault trace along the segment of the fault between Finger Glacier and Palma Bay (in the valley of Kaknau Creek, fig. 5). However, the reported offset near Icy Point can only account for about half the displacement observed near Crillon Lake. In addition, the results of offshore studies show that the most recent trace of the Fairweather fault system trends just offshore from the Icy Point area southeastward to the shelf-edge break offshore from Sitka (Carlson and others, 1988). The active offshore trace clearly does not connect with the Kaknau Creek segment of the Fairweather fault at Palma Bay. We postulate that the Finger Glacier fault is a possible connection between the active onshore and offshore segments of the Fairweather fault. This does not preclude some displacement being taken up by the segment of the Fairweather fault southeast of Middle Dome as suggested by the reported displacement at Kaknau Creek during the 1958 earthquake (Tocher, 1960).

If the Finger Glacier fault is a connection between the active onshore and offshore segments of the Fairweather fault, it has become so very recently because dextral offsets across it are not obvious and similar terrace sequences are developed on both sides of the fault. The gross similarity of the terrace sequences (of the central and southern segments) argues this point more strongly, but because the nature of the younger terraces on these two segments is not exactly similar (for example, Terrace III is wider and possibly stepped on the southern segment), the Finger Glacier fault appears to mark a discontinuity in detail between them.

DISCUSSION

There are only three local areas of the eastern Gulf of Alaska that have well-developed marine terrace sequences: (1) Lituya Bay to Icy Point; (2) Cape Yakataga to Icy Bay; and (3) Middleton Island (fig. 1). In addition to the general tectonic setting of these areas, all are located near the margins of a small crustal block, the Yakutat block (fig. 1; Lahr and Plafker, 1980). These three areas are characterized by the presence of very youthful anticlinal structures: (1) Lituya Bay-Icy Point uplift and arching may mark a renewal of folding along the lines of that responsible for deforming the late Cenozoic bedrock (during the mid-Pleistocene) of the area; (2) the Cape Yakataga-Icy Bay coastline is on the flanks of the asymmetric Sullivan anticline; and (3) Middleton Island is on the axis of a growing faulted anticline on the continental shelf (Plafker and Rubin, 1978). These three areas are not the only areas where such youthful folds, at the margins of the Yakutat block, are present in the eastern Gulf of Alaska, but these three are the areas where such folds have been identified at the present coastline. It appears to us that tectonism—involving development of local anticlinal structures and perhaps related faulting, and indirectly tied to regional deformation accompanying major plate motions—is the underlying factor necessary to development of sequences of more than two marine terraces in the eastern Gulf of Alaska.

One of the principal reasons why this study was initiated was the need to understand that part of the tectonic history of the region that may have played a role in the formation of the terraces. Following the lead of terrace studies on Middleton Island (Plafker and Rubin, 1978), it was especially pertinent to understand any relation between terrace formation and major seismic events in the region. At Middleton Island, coseismic uplifts were commonly 7 to 8 meters.

The three Holocene terraces are clear evidence of the uplift of the shoreline relative to sea level. From figure 7 (central segment) we estimate that the undeformed shoreline angle elevation for Terrace III is about 28 m, for Terrace IV about 15 m, and for Terrace V about 7 m (rates of post-glacial sea level rise were low during this time). If Terrace V represents a single uplift event about 500 years ago, this coastline moved up relative to sea level about 7 m. Terrace IV could represent two such events and Terrace III about five such events. We therefore conclude that this coastline may have experienced about five co-seismic uplift events during the last 3,000 to 4,000 years. This uplift history matches the Holocene terrace development between Lituya Bay and La Perouse Glacier the best. The uplift history south of the Finger Glacier fault is probably more complicated. The wider Terrace III surface with several abandoned beach ridges and possibly locally stepped character may indicate many smaller uplifts and/or more gradual uplift between larger events for the Icy Point area. We propose that Pleistocene folding and Holocene uplift related to continued folding reflects compression between onshore and offshore segments of the Fairweather fault. Development of the Finger Glacier fault is the expected culmination of this deformation and future deformation is expected to include significant displacements on this fault.

The seismic future of the Lituya Bay area is determined both by activity of the Fairweather fault system and by less frequent terrace-forming uplift events. Holocene uplift was probably accompanied by earthquakes and at least five of these uplifts may have occurred during the last 3,000 to 4,000 years. The suggested recurrence interval of about 500 years is distinctly more than that expected for the Fairweather fault which, with a 5 to 6 cm/year long-term displacement rate, may have a recurrence interval for major events of between 50 and 100 years. This difference in recurrence intervals suggests that coastal uplift and displacements on the Fairweather fault are independent events. However, as deformation continues, more displacements on the Finger Glacier fault are expected and these could be significant seismic events more closely linked to Fairweather fault activity.

An additional geomorphically interesting relation may be explained by Holocene tectonism in the area. La Perouse Glacier fronts on the open ocean, an unusual and perhaps unique situation in the northern hemisphere. This relation would seem to be unstable, but it has apparently existed for at least a few hundred years if not more. Any potential advance of the glacier past the present shoreline is effectively prevented by wave undercutting of the glacier front. If much of the glacier inland from the coast was below sea level, this undercutting would likely continue inland and a bay, similar to Lituya Bay, would have formed. Since such a bay is not present, the base of La Perouse Glacier is inferred to be at or above sea level. One explanation for this phenomenon is that uplift of the coastal zone has kept the base of La Perouse Glacier above sea level and thus been chiefly responsible for the longer-term position of this glacier adjacent to the Pacific Ocean.

This study highlights the role of tectonic processes in developing and changing coastal features of the Lituya Bay area. In the nearby Glacier Bay area, and other parts of Southeast Alaska, ongoing isostatic rebound is significantly changing coastal features. In our view though, isostatic processes are subordinate influences on the character of the terraces in the study area. We reach this view because of the following observations and relationships.

- The Lituya Bay area is a glacial refugium where ice cover was restricted to valleys and a few spill points from the high Fairweather Range during the Holocene and late Pleistocene (Mann, 1983, 1986). It is a different glacial setting than that of northern Southeast Alaska.
- The eastern Gulf of Alaska coast was generally emergent during the Holocene. Tectonic influences on the Yakutat block seem to be the control on this coastal character.
- Because the Holocene was a time of absolute sea level rise, coastal uplift is required to form Holocene terraces.
- Formation of Holocene terrace flights requires episodic uplift, not the continuous uplift characteristic of isostatic rebound.
- The Holocene terraces are local, not regional, features—we do not see why they are absent north of Lituya Bay if isostatic processes are a control.
- The onshore Fairweather fault, the Finger Glacier fault, and the offshore active trace of the Fairweather fault (Carlson and others, 1988) make the study area the most tectonically impacted coastline in Alaska.
- Uplift on the Finger Glacier fault is the control on the present shoreline character south to Icy Point.
- If ongoing uplift is present, it can be aseismic tectonic uplift as at Middleton Island (Savage and others, 2014).
- The onshore Fairweather fault may mark a discontinuity in the regional character of isostatic processes.

CONCLUSION

This study of the marine terraces in the Lituya Bay area is of a reconnaissance nature and in many ways should be considered a first step. This first step was taken over 40 years ago before technology such as GPS and lidar were available (excellent airphotos were the foundation of this study). More detailed and comprehensive studies of this exceptionally interesting area, where coastal, glacial, and tectonic processes are so active and interwoven, are needed. The general conclusions warranted by this study are:

1) The terrace sequence is differentially developed. The northern segment between Fairweather Glacier and Lituya Bay has one terrace adjacent to the mountain front and a wide prograded coastal plain, the central segment from

Lituya Bay to near La Perouse Glacier has five well-developed terraces seaward of the mountain front, and the southern segment from near Finger Glacier to Icy Point has four principal terraces and the possible remnant of another.

2) The terrace sequence has been deformed. Measured and estimated shoreline angle elevations show that differential uplift, as much as 100 m or more on the oldest two terraces, has arched them and that maximum uplift is in the La Perouse Glacier area. The La Perouse Glacier area is a discontinuity in the terrace sequence accentuated by seaward tilting, a complicated glacial history, and recent displacements on the Finger Glacier fault. The discontinuity in the terrace sequence across Lituya Bay has primarily resulted from the absence of tectonic uplift and tilting north of the bay.

3) The terraces are of late Pleistocene and Holocene age. The oldest terrace studied (Terrace I) is not well dated but Terrace II could be related to post-Wisconsin sea level rise. Terrace III is at least 3,000–4,000 years old, Terrace IV about 1,000 years old, and Terrace V is about 500 years old.

4) Because Terrace I is Pleistocene and likely related to interglacial sea level changes, it could have correlatives developed elsewhere in the Gulf of Alaska. Terrace II could locally have correlatives but its place appears to have been taken by a prograded coastal plain in most parts of the eastern Gulf of Alaska. Terraces III, IV, and V do not have known temporal equivalents and are not expected to. Holocene terrace sequences at Lituya Bay and elsewhere appear to be related to local active structures.

5) Terraces III, IV, and V apparently formed in response to co-seismic tectonic uplifts of the coastline. Terrace V may represent one uplift event of about 7 m, Terrace IV two such events, and Terrace III about five such events during the last 3,000 to 4,000 years. The indicated uplift recurrence interval is about 500 years. Holocene uplift is likely related to folding and faulting of Pleistocene bedrock; continued folding is thought to reflect compression between onshore and offshore segments of the Fairweather fault.

6) The seismic future of the Lituya Bay area will be determined by displacements on the Fairweather fault, coastal uplift events, and displacements on the Finger Glacier fault.

7) The Finger Glacier fault may mark an incipient connection between the active onshore and offshore segments of the Fairweather fault.

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