Giant Waves in Lituya Bay Alaska

By DON J. MILLER

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

GEOLOGICAL SURVEY PROFESSIONAL PAPER 354-C

A timely account of the nature and possible causes of certain giant waves, with eyewitness reports of their destructive capacity

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1960

UNITED STATES DEPARTMENT OF THE INTERIOR

FRED A. SEATON, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C.

CONTENTS

ILLUSTRATIONS

TABLE

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

GIANT WAVES IN LITUYA BAY, ALASKA

By Don J. Miller

ABSTRACT

Lituya Bay, on the northeast shore of the Gulf of Alaska, is an ice-scoured tidal inlet with a maximum depth of 720 feet and a sill depth, at the narrow entrance, of only 33 feet. The northeastward-trending stem of the T-shaped bay, 7 miles long and as much as 2 miles wide, transects the narrow coastal lowland and foothills belt flanking the Fairweather Range of the St. Elias Mountains. The two arms at the head of the bay, Gilbert and Crillon Inlets, are part of a great trench along the Fairweather fault. Gentle slopes border the outer part of the bay, but the walls of the inner, fiordlike part rise steeply to altitudes of 2,200 feet to more than 6,000 feet.

Until recently, little notice was taken of the giant waves that have rushed out from the head of Lituya Bay, leaving sharp trimlines to mark the upper limit of total or near total destruction of the forest along the shores. The dates of occurrence of 4 known and 1 inferred giant waves, and the maximum altitudes of their trimlines are as follows: July 9, 1958—1,720 feet; October 27, 1936—490 feet; 1899 (?)—about 200 feet; about 1874—80 feet; and 1853 or 1854—395 feet.

In 1958 about 40 million cubic yards of rock, loosened either by displacement on the Fairweather fault or by the accompanying shaking, plunged into Gilbert Inlet from a maximum altitude of about 3,000 feet on the steep northeast wall. This rockslide caused water to surge over the opposite wall of the inlet to a maximum altitude of 1,740 feet, and generated a gravity wave that moved out the bay to the mouth at a speed probably between 97 and 130 miles per hour. Two of three fishing boats in the outer part of the bay were sunk, and two persons were killed. The interpretation that water was primarily responsible for destruction of the forest over a total area of 4 square miles, extending to a maximum altitude of 1,720 feet and as much as 3,600 feet in from the high-tide shoreline, is supported by eyewitness accounts of the survivors, by the writer's field investigation, and by R. L. Wiegel's study of a model of Lituya Bay and his calculations from existing theory and data on wave hydraulics.

The giant waves in 1936 were generated in Crillon Inlet. They were described by eyewitnesses at a point about midway along the bay as 3 waves of increasing height, in close succession and traveling about 22 miles per hour. Of the possible causes considered here, movement of a tidal glacier front or submarine sliding seems most likely but can be neither disproved nor conclusively supported from the information at hand.

The configuration of trimlines formed by giant waves in late 1853 or early 1854 (dated by tree ring count) and about 1874, suggests sliding from the south wall of Lituya Bay at Mudslide Creek as a likely cause. A slide, fault displacement, or some other disturbance in Crillon Inlet may have caused another giant wave during one of the great earthquakes in September 1899.

The frequent occurrence of giant waves in Lituya Bay, as compared to other similar bays, is attributed to the combined effect of recently glaciated steep slopes, highly fractured rocks and deep water in an active fault zone, heavy rainfall, and frequent freezing and thawing. These waves are likely to occur again, and should be taken into account in any future use of Lituya Bay. Other giant waves have been caused by sliding of part of a mountain into Shimabara Bay in Japan; repeatedly by falling or sliding of rock masses into Loen Lake, Tafjord, and Langfjord in Norway; by avalanching of a hanging glacier into Disenchantment Bay in Alaska; and repeatedly by landslides into Franklin D. Roosevelt Lake in Washington.

INTRODUCTION

Lituya Bay is an ice-scoured, nearly landlocked tidal inlet on the northeast shore of the Gulf of Alaska (fig. 14). Most descriptions of Lituya Bay, including that of its discoverer La Perouse (1798), have dwelt at length on the hazards of the strong tidal current in the narrow entrance, but until recently, little notice was taken of an even more remarkable and potentially more dangerous hydraulic oddity of the bay—its propensity for developing enormous waves. At least four times during a little more than a century giant waves have rushed out from the head of the bay, destroying the forest on the shores and leaving trimlines similar to those formed by glaciers. The latest and largest of these waves washed out trees to a maximum altitude of 1,720 feet, more than 8 times the maximum recorded height of a tsunami breaking on an ocean shore (Leet, 1948, p. 179).

The writer became interested in the giant waves while studying the Tertiary rocks in Lituya Bay and adjoining area in 1952 and 1953, as a part of the U.S. Geological Survey's program of petroleum investigations in the Gulf of Alaska region. The two trimlines then recognized were mapped and their approximate ages determined, inquiries were made of residents and former residents of the region, and a search was begun for references to the origin of the trimlines in Lituya Bay and to comparable features in other places. In a

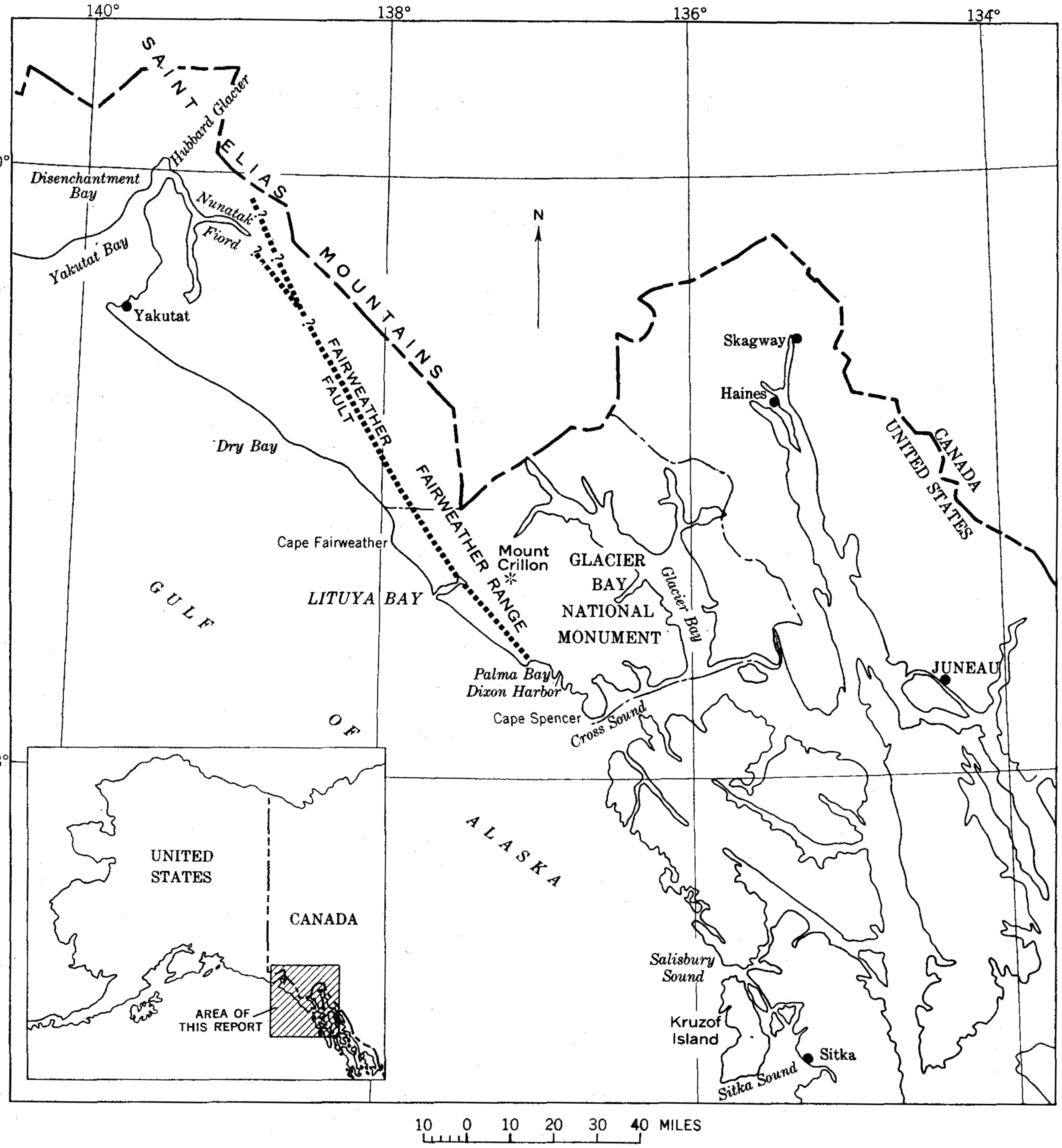


FIGURE 14.—Map of part of southeastern Alaska, showing location and regional geographic setting of Lituya Bay.

paper read at geological meetings in Seattle, Wash. and Anchorage, Alaska, and published in abstract (Miller, 1954) the trimlines in Lituya Bay were attributed to cataclysmic floods or waves of water moving out from the head of the bay at high velocity. The information then available did not give conclusive support to any of several possible mechanisms that were suggested for setting the water in motion.

The investigation of the cause of the floods or waves was laid aside, except for correspondence and the accumulation of additional references, until the spring of 1958 when assignment to a field mapping project based in Juneau afforded opportunities to resume the search for local sources of information. On July 9 much new information was provided in a dramatic and wholly unexpected way when a major earthquake centering near Lituya Bay was followed almost immediately by a wave that denuded an area of about 4 square miles in Lituya Bay, destroyed 2 of 3 fishing boats anchored in the bay, and killed 2 people. The problem of the cause of the waves, until then mainly of scientific interest, became overnight a matter of general public interest.

The earthquake late in the evening of July 9[1] was strongly felt on the U.S. Geological Survey power barge, *Stephen R. Capps*, at anchor in Glacier Bay about 60 miles east of Lituya Bay. Rocks fell into the water from steep cliffs nearby, causing small waves that broke with a height of not more than 2 or 3 feet on the shores; no large waves were seen, however. Upon learning by radio on the following morning of the destruction in Lituya Bay, the writer chartered a small pontoon-equipped airplane, and spent about 1½ hours flying over the bay at low altitude. Observation and photography were hampered by low ceiling, rain, and fog, and no landings could be made in the debris-choked bay. Early in August, when the power barge was anchored in Dixon Harbor about 30 miles southeast of Lituya Bay, a helicopter was used for 1½ days of ground and aerial observations and photography of the bay. In late August and early September the writer again photographed and examined Lituya Bay on several flights with fixed-wing aircraft, and camped for 3 days in the bay.

On August 29, 1958, a photographic mission of the U.S. Coast and Geodetic Survey photographed the entire Lituya Bay area with a 9-lens aerial camera, and also made single-lens vertical photographs of the entrance.

ACKNOWLEDGMENTS

D. L. Rossman, George Plafker, R. C. Ellis, E. A. Hainze, and Todd Nelson all assisted in the field at times during the 1952–53 seasons. R. L. Velikanje, C. L. Sainsbury, R. E. Marsh, Mrs. Caroline Jensen, and L. H. Bayers in the Juneau office of the U.S. Geological Survey canvassed potential sources of information by interview and letter. R. F. Taylor, forester in charge of the Alaska Forest Research Center in Juneau, gave advice on tree ring studies made in the field in 1953 and arranged for preparation of tree sections; R. M. Godman of the same organization counted and interpreted the growth rings.

A. J. Mitchell, superintendent of the Sitka and Glacier Bay National Monuments, in 1958 aided in gathering local information on the waves, provided logistic support and encouragement to the investigation, and accompanied the writer on one flight to Lituya Bay. J. P. McKee, E. L. Henrickson, V. I. Mann and Edward Berdusco of the Fremont Mining Co. provided a valuable record of conditions in Lituya Bay immediately preceding the 1958 wave and also called attention to evidence for movement along the Fairweather fault near Lituya Bay. Part of the logistic support for the 1958 field investigation was provided by the Geological Survey's southeastern Alaska project barge and helicopter and by Seventeenth Coast Guard District airplane. Special thanks are due to pilot Kenneth Loken of Juneau for making it possible to inspect Lituya Bay shortly after the 1958 wave, despite adverse weather.

Don Tocher of the University of California Seismographic Station joined the writer in making a field investigation of the effects of the 1958 earthquake, and contributed valuable suggestions on the interpretation of the giant waves and on the preparation of this report. R. L. Wiegel of the Institute of Engineering Research, University of California, made a model study of the 1958 wave and generously contributed the resulting observations for quotation in this report. A. R. Tagg of the U.S. Geological Survey made the photogrammetric measurements of trimline altitudes. The writer is indebted to F. H. Fredrickson, Mr. and Mrs. W. A. Swanson, and H. G. Ulrich for their cooperation in providing eyewitness accounts of the waves. Photographs of Lituya Bay and information on the waves were furnished by W. O. Field, Jr., of the American Geographical Society, Bradford Washburn, of the Museum of Science, Boston, Mass., and Tom Smith, Trevor Davis and Robert De Armond of Juneau. Finally, many other persons not specifically mentioned here have contributed suggestions as to the cause of the waves, sources of information and methods of attacking the problem, and helpful criticism of the manuscript.

DESCRIPTION AND HISTORY OF LITUYA BAY

GEOGRAPHIC SETTING

Lituya Bay is a **T**-shaped inlet that cuts through the coastal lowland and foothills belt flanking the Fairweather Range of the St. Elias Mountains, on the south coast of Alaska (fig. 14, pl. 2).

The entrance of the bay, at lat 58°36′45″ N., long 137°39′40″ W., is 122 miles west of Juneau and 99 miles southeast of Yakutat. The main part of the bay, corresponding to the stem of the letter **T**, is 7 miles long and ranges from three-fourths of a mile to 2 miles in width except at the entrance, which has a width of only

[1] Morning of July 10, Greenwich civil time; Pacific standard time (120° W. meridian time) is used throughout this report.

1,000 feet at low tide. Cenotaph Island divides the central part of the bay into two channels, two-fifths and four-fifths of a mile in width. Gilbert and Crillon Inlets extend northwestward and southeastward, respectively, from the head of the bay to form the upper part of the T, which in 1958 was about 3 miles long. The name "Lituya," according to Emmons (1911, p. 294), is a compound word in the Tlingit language meaning "the lake within the point," in reference to the nearly landlocked nature of the bay.

Lituya Bay was aptly described by Dall (1883, p. 204) as "a Yosemite Valley, retaining its glaciers and with its floor submerged six or eight hundred feet." The bay fills and slightly overflows a depression only recently occupied by a piedmont glacier lobe and its tributary valley glaciers, of which the present Lituya, Cascade, and North Crillon Glaciers are remnants (pl. 2). The maximum stand of the Lituya Glacier system is clearly recorded by the arcuate end moraine that forms La Chaussee Spit and is continuous with lateral moraines and trimlines rising gradually to an average altitude of about 1,800 feet at the head of the bay (pl. 3 *A*.). The Solomon Railroad (pl. 2), a part of the end and lateral moraine north of the bay, rises abruptly like a railroad embankment to a sharp, even crest standing as much as 600 feet above the adjoining lowlands.

Lituya and North Crillon Glaciers, each about 12 miles long and 1 mile wide, originate in ice fields at altitudes of 4,000 feet and higher near the crest of the Fairweather Range. Both glaciers flow southwestward down the flank of the Fairweather Range and make nearly right-angle turns into the northwestward-trending trench between this range and the foothills. In the summer of 1958 about 1,600 feet or one-third of the total width of the front of North Crillon Glacier was tidal at the head of Crillon Inlet. The surface of this glacier near the front was mostly debris covered and relatively smooth. Just prior to the earthquake and wave in 1958 about 3,000 feet of the front of Lituya Glacier was tidal. The surface of this glacier near the front was rough, with little debris cover except along the southwest margin and at a narrow medial moraine near the northeast margin. At the end of August 1958 almost the entire front of Lituya Glacier was tidal, and deeply crevassed. Cascade Glacier is about 4 miles long and very steep. Its terminus in recent years has been low and largely debris covered. At the end of August 1958 only a small part of the glacier terminus reached the high-tide shoreline at the head of Lituya Bay.

The shores around the outer part of Lituya Bay are mainly bouldery beaches, the adjoining land rising away from the beach at rates ranging from 100 feet in a horizontal distance of 6,000 feet, near Fish Lake, to 540 feet in a horizontal distance of 1,200 feet at The Paps (pl. 2). Around the head of the bay the walls are steep and fiordlike, rising to altitudes between 2,200 and 3,400 feet in the foothills immediately to the north and south, and to more than 6,000 feet in the Fairweather Range less than 2 miles from the shore of Crillon Inlet. The submarine contours, based on soundings made in 1926 and 1940 (U.S. Coast and Geodetic Survey, 1942), show a pronounced U-shaped trench with steep walls and a broad, flat floor sloping gently downward from the head of the bay to a maximum depth of 720 feet just south of Cenotaph Island, and rising again toward the outer part of the bay. The minimum depth in the entrance is 33 feet at mean lower low water; hence the bay has a closure of at least 687 feet. The tide in the bay is diurnal, with a mean range of 7 feet and a maximum range of about 15 feet (U.S. Coast and Geodetic Survey, 1957). The tidal current in the narrow entrance attains a velocity of 12 knots (U.S. Coast and Geodetic Survey, 1952), or about 13.8 statute miles per hour.

Weather records for the 2 stations nearest Lituya Bay, at Cape Spencer 47 miles to the southeast and at Yakutat 99 miles to the northwest (U.S. Weather Bureau, 1958), indicate that the total annual precipitation ranges from 111 to 134 inches and the mean annual temperature ranges from 39° to 41° F. in this coastal area. Because of the heavy precipitation and mild climate at low altitude, the lower slopes (from the high-tide line to an altitude of 1,700 to 2,000 feet) where not overly steep or poorly drained, normally are covered by a dense growth of trees and brush. Reforestation of land newly exposed by the retreat of glaciers or the sea, or, as in Lituya Bay, denuded by waves, under present climatic conditions at this latitude takes place in the following succession: dense stands of alder (*Alnus*) and willow (*Salix*) grow within a few years, but are soon exceeded in height by cottonwood (*Populus trichocarpa*); Sitka spruce (*Picea sitchensis*) next dominates but gradually becomes mixed with hemlock (*Tsuga heterophylla and T. mertensiana*); and finally Alaska cedar (*Chamaecyparis nootkatensis*) appears. At the time of the 1958 wave, forests of five distinct ages were growing on or near the shores of Lituya Bay. These zones, as identified on plate 8*A*, are: mixed alder, willow, cottonwood, and spruce with a known maximum age of 22 years (shore to *h*); 2 bands of mixed spruce and cottonwood with maximum ages of about 84 years (*h–j*) and of 105 years (*j–k*); mixed spruce and hemlock with an estimated age of 400 years or more (*k–m*);

and mixed spruce, hemlock, and cedar probably more than 1,000 years old (above *m*).

GEOLOGIC SETTING

Lituya Bay lies near the southeast end of and transects a geologic province in which sedimentary rocks of Tertiary age are exposed or inferred to underlie lowland areas (Gryc, Miller, and Payne, 1951, p. 159–162). The two arms at the head of Lituya Bay are part of a great trench that extends for many miles to the northwest and southeast along the southwest front of the Fairweather Range and the southern part of the St. Elias Mountains (fig. 14). Mertie (1931, p. 123) first recognized this trench as the topographic expression of a major fault, named more recently the Fairweather fault (Miller, 1953). Field investigations by the writer and by D. L. Rossman (written communication, 1957) indicate that the Fairweather fault from the vicinity of Lituya Bay southeast to Palma Bay is vertical or dips steeply to the northeast. Along this fault the crystalline rocks exposed on the northeast side are inferred to have moved up relative to less altered and in part younger rocks exposed in the lowland and foothills belt on the southwest side. St. Amand (1957, p. 1357–1359) suggested, however, that the fault is of lateral or oblique habit, and cited as evidence some of the effects of the 1899 earthquakes in Yakutat Bay.

Instrumental and field observations point to movement along the Fairweather fault as the cause of the earthquake immediately preceding the 1958 wave in Lituya Bay. Tocher and Miller (1959) studied the surface breakage where the trace of the fault is exposed near Crillon Lake, 6 to 10 miles southeast of Lituya Bay. At one point the southwest side moved northwestward at least 21½ feet and up 3½ feet. Slides and other evidence of strong shaking observed elsewhere along known or inferred trace of the Fairweather fault from Palma Bay to the latitude of Nunatak Fiord near Yakutat Bay, indicated tearing along the fault probably for 115 miles or more. The instrumental epicenter of the earthquake, as determined by the U.S. Coast and Geodetic Survey (Brazee and Jordan, 1958, p. 36), is lat 58.6°N., long 137.1°W., a point in the Fairweather Range about 7½ miles east of the surface trace of the Fairweather fault and 13 miles southeast of the head of Lituya Bay. A later determination from a larger number of stations (William Stauder, written communication, paper given at Tucson meeting of Geol. Soc. America; oral communication, Apr. 29, 1959) places the epicenter farther southeast but nearer the assumed surface trace of the Fairweather fault.

Bedrock is exposed or lies beneath only a thin veneer of soil, glacial drift, or talus at water level around most of Cenotaph Island and from a point 4½ miles inside the entrance on the south shore around the head of Lituya Bay to a point 5½ miles inside the entrance on the north shore. The rocks are largely hard schist on the northeast shore of Gilbert and Crillon Inlets. Diorite and slightly metamorphosed volcanic rocks, slate, and graywacke are exposed on the southwest shore of Gilbert Inlet and the adjoining north shore of the bay, on the southwest shore of Crillon Inlet, and on the south shore of the bay as far as the mouth of Coal Creek. Bedded sedimentary and volcanic rocks of Tertiary age are exposed on Cenotaph Island and on the south shore west of Coal Creek. Around most of the outer part of the bay boulder till is exposed at the surface or lies under a thin soil.

Field observations in 1952 and 1953 indicated that the forest inside the moraine enclosing the outer part of Lituya Bay, but above the highest trimline, is distinctly younger than the forest growing along the coast outside of the moraine. Although no tree ring counts were made, the writer noticed that there was much less deadfall in the forest inside the moraine, and that the spruce and hemlock trees were smaller inside the moraine. Moreover, Alaska cedar trees as much as 3 feet in diameter were found growing up to the outer edge of the moraine, but not even small cedars were seen inside the moraine. This evidence of a post-Wisconsin advance of ice to the mouth of Lituya Bay is now corroborated by evidence newly exposed by the 1958 giant wave. An ice-sheared stump, rooted in a humus-rich soil just below the surficial till on the south shore near the entrance of the bay (fig. 15, loc. *A*), has a radiocarbon age of 6,060 ±200 years B. P. (Meyer Rubin, written communication, U.S. Geological Survey lab. no W–800 report, May 26, 1959).

The evidence indicates that ice stood at or near the mouth of Lituya Bay within the time required for growth of a climax forest in this region, possibly less than 1,000 years ago. However, the ice fronts were farther back when the La Perouse expedition visited Lituya Bay in 1786 than at the present time. The map made under the direction of La Perouse (1798, opposite p. 146; also Klotz, 1899) shows two tidal glaciers at the head of each inlet, which indicates that the ice fronts had retreated to positions beyond the points where the Lituya and North Crillon Glaciers enter the trench at the head of the bay. The combined length of Gilbert and Crillon Inlets then was about 9 miles. By 1894 both Lituya and North Crillon Glaciers had readvanced nearly to their present positions (Klotz, 1899). Prior to the 1958 wave low deltas of gravel had built out into Gilbert Inlet at the southwest and northeast margins of the Lituya Glacier front, and into Crillon Inlet across about two-thirds of the width of the North Crillon Glacier front (fig. 15). These deltas formed after 1894, and they may be, or may have been, in part underlain by ice projecting from the glacier fronts below sea level.

EXPLORATION AND SETTLEMENT

Available records of the exploration and settlement of the northeastern Gulf of Alaska coast afford only a sketchy history of Lituya Bay beginning in 1786. Little information has been found for the period 1788–1874, during which time at least one destructive wave occurred and Indian settlements in the bay were abandoned, perhaps as a direct result of a wave. Records of visits to or settlement in the bay after 1874, including the accounts of geographic surveys and scientific investigations, contain few references to the occurrence of large waves.

The French explorer La Perouse (1798, p. 115–169) is generally credited with the discovery of Lituya Bay, which he named Port des François. In the course of a projected trip around the world La Perouse took his ships *La Boussole* and *L'Astrolabe* into Lituya Bay on July 2, 1786. During a stay of nearly a month the expedition mapped Lituya Bay on a scale of 1:50,000, traded with the Indians then living in and near the bay, and recorded observations on the native culture and the plant and animal life in the vicinity. Twenty-one men were drowned when three small boats engaged in a survey of the entrance were swept into the tidal bore and two were wrecked. In July 1788 Ismailof and Bocharof entered Lituya Bay on the ship *Three Saints* to claim the land for Russia and to induce the natives to accept Russian rule (Shelikof, 1812, p. 108–112). The lack of any reference to waves within the bay in either of these early accounts, together with the mention of trees and native dwellings near the shore, are indirect evidence that no giant waves had occurred in Lituya Bay for some time prior to 1788.

For the remainder of the period of Russian rule and the early years of American rule, until 1874, the literature examined contains only brief mention of exploration in Lituya Bay: in connection with an expedition of the Russian ship *Orel* to obtain sea otter skins in 1796 (Bancroft, 1886, p. 356–357); the reported discovery and mining of gold placer deposits on the beaches in the vicinity of Lituya Bay by the Russian censuses of the Tlingit tribe give the population American whaling ships (Dall, 1883, p. 202). Russian censuses of the Tlingit tribe give the population of the Lituya clan or settlement as 200 in 1835, and 590 in 1861 (Petroff, 1884, p. 96, 99). Perhaps only a small part of the clan lived in Lituya Bay, for the French and Russian expeditions in 1786 and 1788 reported that the main village was northwest of the bay.

A U.S. Coast and Geodetic Survey party entered Lituya Bay in 1874 to make geodetic observations and to revise the La Perouse chart of the outer part of the bay (Dall, 1878, p. 158; 1883). No natives were then living in the bay and the village on the south shore seemed to have been abandoned for a long time. In 1894 a topographic map of the region adjoining Lituya Bay was made by a Canadian party of the International Boundary Survey (U.S. Congress, 1904; International Boundary Commission, 1952, p. 254); observations on the glaciers at the head of the bay were later published by Klotz (1899, p. 524–526, maps). The bay was visited by field parties of the U.S. Geological Survey for 3 days in 1906 (Wright, F. E., and Wright, C. W. *in* Reid, 1908, p. 53; *in* Buddington and Chapin, 1929, p. 269–270) and in 1917 (Mertie, 1931), and for 5 days in 1943 (Kennedy and Walton, 1946, p. 67–72). Surveys of the bay were resumed by the U.S. Coast and Geodetic Survey in 1926 and 1940, resulting in the current navigation chart on a scale of 1:20,000 (U.S. Coast and Geodetic Survey, 1942). In 1926, and during part of each summer from 1930 to 1934, expeditions engaged in mountain climbing or geographical and geological exploration were based in or near Lituya Bay (Carpe, 1931; Washburn, 1935, 1936; Goldthwait, 1936). Except for the brief mention of "evidence of flooding or washing to a height of at least 10 feet," which Dall (1883, p. 203) attributed to damming of the entrance by ice during the winter, none of the reports on the expeditions just described contain any reference to the giant waves in Lituya Bay.

Placer mining of the gold in the sands along the ocean beach adjacent to the mouth of Lituya Bay was begun by the Americans in 1890 (Boursin, 1893, p. 230) and continued intermittently at least until 1917 (Mertie, 1931, p. 133). Since Lituya Bay served as a port for this operation, during this period it was probably occupied or at least visited frequently. One man, James Huscroft, lived on Cenotaph Island in Lituya Bay almost continuously from 1917 to about 1940. Huscroft and another man were on the island, and two men were in a boat nearby, at the time of the 1936 waves. Their eyewitness accounts, the observations of Tom Smith and others who visited the bay only a few days later, and the observations of J. P. Williams nearly a year later, led to the earliest known published references to the unusual "waves or floods" of water in Lituya Bay (Alaska Daily Press, 1936; Williams, 1938).

Lituya Bay was incorporated in the Glacier Bay National Monument when the boundary was extended in 1939 to include the coastal area from Cape Spencer north to Cape Fairweather (fig. 14). No one has lived permanently either in or near the bay since Huscroft died, but in recent years the bay has come into increasing use as an overnight anchorage and refuge in bad weather for the trolling boats of the fishermen who ply the adjoining waters of the Gulf of Alaska during the summer and early fall.

THE GIANT WAVES

EVIDENCE

Two kinds of evidence testify to the occurrence of at least four giant waves in Lituya Bay: (a) direct observation of the waves, including the published, written, or oral accounts of eyewitnesses and possibly tidal gage records from elsewhere in the Gulf of Alaska; (b) effects that remain for later observation, mainly the destruction and transportation of vegetation, but also the erosion and transportation of unconsolidated deposits, destruction of marine life, and the destruction of works of man. The wave on July 9, 1958, and the waves on October 27, 1936, are documented beyond any doubt by both types of evidence. At least 1 and possibly 2 waves between 1854 and 1916 are indicated by trimlines shown on photographs taken from 1894 to 1929. These trimlines were largely destroyed by the 1936 wave, and were entirely gone after the 1958 wave. An oral report placing one of these waves in 1899 has not been substantiated. A wave in 1853 or 1854 is recorded in a trimline and a band of even-aged trees that was examined and mapped on the ground and dated by tree ring counts in 1952 and 1953. Possible references to the 1853–54 wave in Indian legends have not been confirmed.

WAVE ON JULY 9, 1958

SETTING AND SOURCES OF INFORMATION

Three trolling boats, each about 40 feet long and with two persons aboard, were anchored in the outer part of Lituya Bay at the time of the wave on July 9 (fig. 15; pl. 3*B*). The *Edrie* rode out the wave inside the bay; the *Badger* was carried across La Chaussee Spit and wrecked on the outside; the *Sunmore*, under way near the entrance, was swamped by the wave and went down with her occupants. The wave reportedly was first sighted within 3 minutes after the earthquake was first felt, or, using the instrumentally determined origin time for the earthquake of $06^h15^m51^s$G.c.t., July 10 (Tocher and Miller, 1959), between 10:16 and 10:19 p. m. on July 9, local time. This is about sunset at this latitude and time of year; the weather was clear, with high scattered clouds, and the head of the bay was clearly visible from boat level at the outer part of the bay. The tide was ebbing and at about plus 5 feet (U. S. Coast and Geodetic Survey, 1957) or less than a foot above mean tide stage in the bay. The following eyewitness accounts are abstracted from articles published in newspapers and a magazine (Daily Alaska Empire, 1958a; Ulrich, 1958; Alaska Sportsman, 1958), from a personal interview with W. A. Swanson (oral communication, July 16, 1958) and correspondence with H. G. Ulrich (written communication, Oct. 24, 1958).

EYEWITNESS ACCOUNTS

ACCOUNT OF HOWARD G. ULRICH

Mr. Ulrich and his 7-year-old son, on the *Edrie*, entered Lituya Bay about 8:00 p.m. and anchored in about 5 fathoms of water in a small cove on the south shore (fig. 15). Ulrich was awakened by the violent rocking of the boat, noted the time, and went on deck to watch the effects of the earthquake—described as violent shaking and heaving, followed by avalanching—in the mountains at the head of the bay. An estimated 2½ minutes after the earthquake was first felt a deafening crash was heard at the head of the bay. According to Ulrich,

> The wave definitely started in Gilbert Inlet, just before the end of the quake. It was not a wave at first. It was like an explosion, or a glacier sluff. The wave came out of the lower part, and looked like the smallest part of the whole thing. The wave did not go up 1,800 feet, the water splashed there.

Ulrich continued to watch the progress of the wave until it reached his boat about 2½ to 3 minutes after it was first sighted. Being unable to get the anchor loose, he let out all of the chain (about 40 fathoms) and started the engine. Midway between the head of the bay and Cenotaph Island the wave appeared to be a straight wall of water possibly 100 feet high, extending from shore to shore. The wave was breaking as it came around the north side of the island, but on the south side it had a smooth, even crest. As it approached the *Edrie* the wave front appeared very steep, and 50 to 75 feet high. No lowering or other disturbance of the water around the boat, other than vibration due to the earthquake, was noticed before the wave arrived. The anchor chain snapped as the boat rose with the wave. The boat was carried toward and probably over the south shore, and then, in the backwash, toward the center of the bay. The wave crest seemed to be only 25 to 50 feet wide, and the back slope less steep than the front.

After the giant wave passed the water surface returned to about normal level, but was very turbulent,

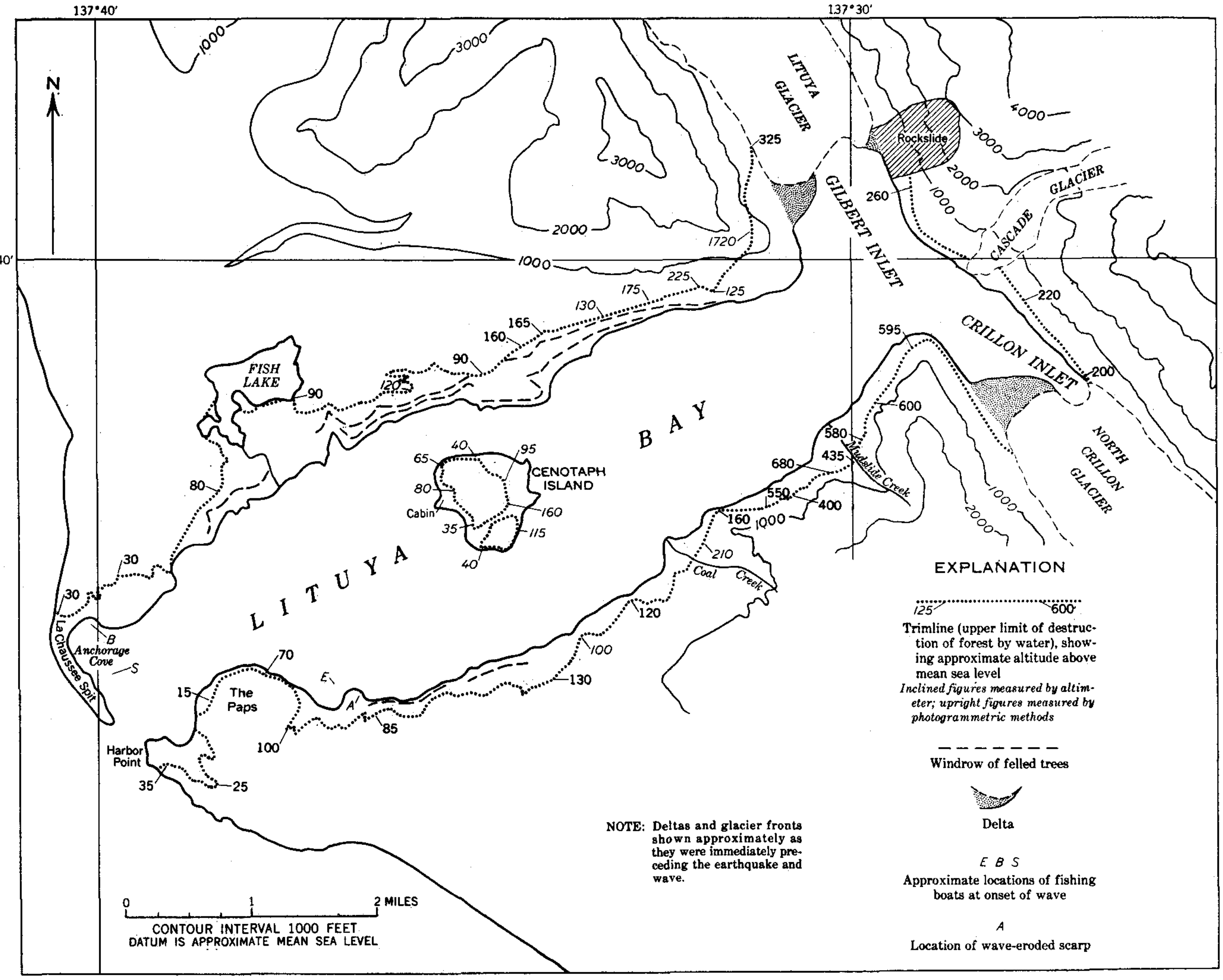


FIGURE 15. Map of Lituya Bay showing setting and effects of 1958 giant wave.

with much sloshing back and forth from shore to shore and with steep, sharp waves up to 20 feet high. These waves, however, did not show any definite movement either toward the head or the mouth of the bay. After 25 to 30 minutes the bay became calm, although floating logs covered the water near the shores and were moving out toward the center and the entrance. After the first giant wave passed Ulrich managed to keep the boat under control, and went out the entrance at 11:00 p.m. on what seemed to be a normal ebb flow.

ACCOUNT OF WILLIAM A. SWANSON

Mr. and Mrs. Swanson on the *Badger* entered Lituya Bay about 9:00 p.m., first going in as far as Cenotaph Island and then returning to Anchorage Cove on the north shore near the entrance, to anchor in about 4 fathoms of water near the *Sunmore* (fig. 15). Mr. Swanson was wakened by violent vibration of the boat, and noted the time on the clock in the pilot house. A little more than a minute after the shaking was first felt, but probably before the end of the earthquake, Swanson looked toward the head of the bay, past the north end of Cenotaph Island and saw what he thought to be the Lituya Glacier, which had "risen in the air and moved forward so it was in sight. * * * It seemed to be solid, but was jumping and shaking * * * Big cakes of ice were falling off the face of it and down into the water." After a little while "the glacier dropped back out of sight and there was a big wall of water going over the point" (the spur southwest of Gilbert Inlet). Swanson next noticed the wave climb up on the south shore near Mudslide Creek. As the wave passed Cenotaph Island it seemed to be about 50 feet high near the center of the bay and to slope up toward the sides. It passed the island about 2½ minutes after it was first sighted, and reached the *Badger* about 1½ minutes later. No lowering or other disturbance of the water around the boat was noticed before the wave arrived.

The *Badger*, still at anchor, was lifted up by the wave and carried across La Chaussee Spit, riding stern first just below the crest of the wave, like a surfboard. Swanson looked down on the trees growing on the spit, and believes that he was about 2 boat lengths (more than 80 feet) above their tops. The wave crest broke just outside the spit and the boat hit bottom and foundered some distance from the shore. Looking back 3 to 4 minutes after the boat hit bottom Swanson saw water pouring over the spit, carrying logs and other debris. He does not know whether this was a continuation of the wave that carried the boat over the spit or a second wave. Mr. and Mrs. Swanson abandoned their boat in a small skiff, and were picked up by another fishing boat about 2 hours later.

OTHER OBSERVATIONS ON JULY 9

So far as is known to the writer, no other persons were near enough to Lituya Bay to see the wave, and no photographs were taken. A party of eight mountain climbers was camped in tents on the shore of Anchorage Cove, at the base of La Chaussee Spit, until about 8:00 p.m. on July 9, when they left in an amphibious airplane only a little more than 2 hours before the wave washed over their campsite. They did not notice any unusual noises or disturbance of the water in the bay, nor any foreshocks of the earthquake up to the time they left (Paddy Sherman, written communication, Oct. 20, 1958). At least one foreshock of the earthquake was felt on the morning of July 9 on boats between Lituya Bay and Cape Spencer (William Swanson, oral communication, July 16, 1958), and on land as far away as Juneau (E. L. Keithahn, written communication, Apr. 3, 1959).

Minor anomalous waves which may have been a direct result of the giant wave in Lituya Bay were recorded on the U.S. Coast and Geodetic Survey tide gage at Sitka, on Sitka Sound, 137 miles southeast of the entrance of Lituya Bay. The waves began at 11:25 p.m., July 9, with a height of about 0.1 foot, and continued for many hours. The maximum wave height of about 0.3 foot occurred at about 2:40 a.m., July 10 (H. A. Karo, written communication, May 20, 1959). The first wave arrived at Sitka approximately 65 minutes after the giant wave washed over the entrance of Lituya Bay into the sea; the indicated average speed of about 126 miles per hour, assuming a nearly straight line route of travel through Salisbury Sound and the narrow waterways east of Kruzof Island, is comparable to the observed velocities of tsunamis. It is possible that the waves at Sitka were generated by fault displacement or some effect of the resulting earthquake at a point of origin other than Lituya Bay. Such waves were observed within a few minutes after the earthquake at Dixon Harbor 45 miles southeast of Lituya Bay (William Brammer, oral communication, July 10, 1958) and at Yakutat 99 miles northwest (Brazee and Jordan, 1958, p. 38), as well as on inland waters in Glacier Bay 60 miles to the east (observed by the writer).

OBSERVATIONS OF THE WRITER ON JULY 10

About 1½ hours were spent over Lituya Bay in a small airplane on the morning of July 10, beginning about 12 hours after the wave had passed through the bay. Observations made at this time on the more ephemeral phenomena associated with the earthquake and wave are described separately here because they bear particularly on the interpretation of the eyewitness accounts and on the nature and sequence of events in Lituya Bay on the day of the wave. The observations were recorded on a map, and by means of notes, still photographs, and movies. Kenneth Loken, pilot of the airplane, had flown over Lituya Bay on July 7 and was able to make an on-the-spot comparison of conditions before and after the July 9 earthquake and wave.

On the morning of July 10 Gilbert and Crillon Inlets and the upper part of the main trunk of Lituya Bay for a distance of 2½ miles from the head were covered by an almost solid sheet of floating ice blocks. Many of the blocks were much larger than are normally seen in the bay, with exposed dimensions, as estimated from oblique photographs, of as much as 50 by 100 feet. Nearly all of the larger blocks had flat upper surfaces and were heavily debris laden, and many had scattered, loose, large rounded boulders on their exposed surfaces. Only scattered small pieces of ice, in normal abundance, were floating in the outer part of the bay beyond Cenotaph Island. Only on the northeast shore of Gilbert and Crillon Inlets and on the large delta at the southeast end of Crillon Inlet was any great amount of ice left stranded on the beach above the high-tide line. The absence of stranded ice blocks on the spur southwest of Gilbert Inlet is especially significant as an indication that the glaciers were not involved in the generation of the initial splash or surge of water at the head of the bay.

The front of Lituya Glacier on July 10 was a nearly straight, vertical wall almost normal to the trend of the valley. Comparison of oblique photographs taken by the writer on July 10 and by Edward Berdusco on July 7 indicate that during the earthquake and wave as much as 1,300 feet of ice had been sheared off of the glacier front, but that the southwest margin had changed very little (fig. 16). The delta on the northeast side of Gilbert Inlet had completely disappeared, and the delta on the southwest side was much smaller. It is possible that ice projected beyond the subaerial part of the glacier front, beneath the inner parts of these deltas and that these projections are the source of the large debris-laden blocks of ice floating in the bay on July 10. The glacier surface for several hundred feet from the front was severely crevassed, probably more so than normal; beyond this terminal zone, however, the glacier as far up as the partly subglacial lake near the sharp bend in Lituya Glacier (pl. 2) showed no evidence of any unusual movement. The level of the lake, according to Loken, may have lowered as much as 100 feet since he had seen it 2 days earlier.

The front of North Crillon Glacier and the adjoining large delta showed no indications of any significant forward movement of the glacier or of any other disturbance except effects of washing by the component of the wave that had moved southeastward into Crillon Inlet. The front and lower part of Cascade Glacier similarly showed no effects other than of washing by the wave, which had exposed a narrow tongue of nearly clear ice extending to the shoreline.

The most striking change at the head of Lituya Bay, aside from the new trimline, was the fresh scar on the northeast wall of Gilbert Inlet, marking the recent position of a large mass of rock that had plunged down the steep slope into the water (fig. 16; pl. 4*A*). Loose rock debris on the fresh scar was still moving at some places, and small masses of rock still were falling from the nearly vertical rock cliffs at the head of the scar. The fresh scar is not present on an oblique photograph taken by Edward Berdusco on July 7. This evidence, as well as Ulrich's account, indicates almost certainly that the rockslide was triggered by the earthquake on July 9. The rockslide is described in greater detail on page 65.

Floating logs and other vegetation formed a nearly continuous raft as much as 1,200 feet wide along the outer 3 miles of the north shore of the bay. Small rafts of logs and individual logs were evenly distributed throughout the rest of the bay, beyond the limits of the ice, and over a fan-shaped area of the sea as much as 5 miles from the entrance of the bay.

Water was still dripping from the wave-washed slopes around the shore of the bay as high as the new trimline on the morning of July 10. The volume of water in streams flowing from Fish Lake and other lakes reached by the wave on both the north and south shores was much larger than normal.

EFFECTS OF THE WAVE

DESTRUCTION OF VEGETATION

The trimline (upper limit of total or near total destruction by water of the forest and other vegetation) along the shores of Lituya Bay is plotted on figure 15 and is illustrated by several photographs (pls. 3*B*, 4*B*, 5*A*, 6*B*, 7 *A* and *B*). The altitude at the highest point on the trimline and at other critical points was measured by means of an altimeter that was set at mean sea level, carried up to the trimline, and read again at sea made within a period of 1 hour or less. The horizontal level. At most stations the series of three readings was position of the trimline was plotted by transferring its trace by inspection from the oblique photographs taken by the writer in 1958 to vertical photographs taken in 1948, and thence to the maj of the bay. Additional altitudes were determined photogrammetrically from the 1948 vertical photographs and from the 1958 U.S. Coast and Geodetic Survey single-lens vertical photographs covering the outer mile of the bay. Prints of some 9-lens photographs taken after the 1958 wave were obtained in February 1959. Since suitable photogrammetric equipment was not available, they could be used only to add details to the trimlines in areas of low relief around the outer part of the bay. A map of Lituya Bay on a scale of 1:10,000, with a 50-foot contour interval, has been compiled from the 9-lens photographs by the U.S. Coast and Geodetic Survey (H. A. Karo, written communication, Apr. 28, 1959).

The trimline formed by the 1958 wave extended to a maximum height of 1,720 feet above mean sea level, on the spur southwest of Gilbert Inlet, (pl. 4*B*). Its maximum horizontal distance was about 3,600 feet from the high-tide shoreline, in the vicinity of Fish Lake. Along a 1-mile segment midway between the head and entrance of the bay the band of destruction on the north and south shores averages 1,200 feet in width and extends to an average altitude of about 110 feet. The total area between the trimlines and the high-tide shorelines in the bay is about 4 square miles. This figure includes small lakes and small areas of steep slopes and beaches where little or no vegetation was growing, but it is a measure of the total area over which the wave was capable of felling a large proportion of the trees. The total area inundated by the wave is still larger, probably at least 5 square miles.

One of the most impressive aspects of the 1958 wave is the thoroughness of its destruction of the forest nearly extending to the upper limit of inundation; this can best be conveyed by photographs. In most places the trees were washed out and carried away, leaving bare ground (pl. 5*A*). In some places, mostly on steep slopes where the roots were anchored in bed-

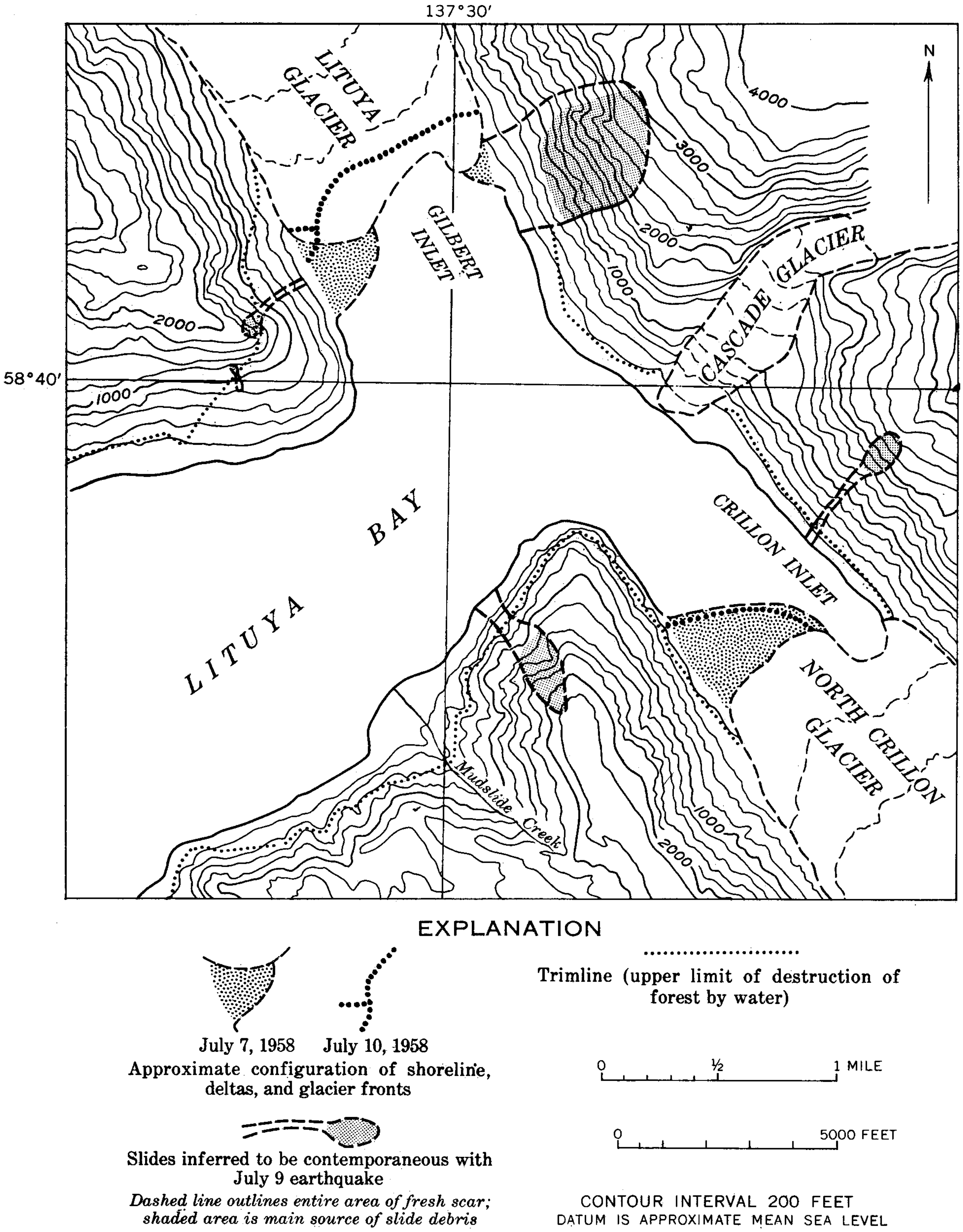


FIGURE 16.—Detailed map of head of Lituya Bay, showing slides, changes in the shoreline and glacier fronts, and trimlines resulting from the 1958 earthquake and giant wave.

rock, the trunks were twisted or broken off just above ground level. At Harbor Point a living spruce tree was broken off cleanly about 3 feet above the root system, where it measured 4 feet in minimum diameter (pl. 5*B*). At a few places, mainly at the edge of the trimline, trees were pushed over but not washed out (pl. 7*B*, lower left). Only along the outer mile of the bay were clumps of trees left standing within the trimline. The forest was left standing to the high-tide line at only two points, on the south shore 0.4 mile from the entrance and on the north shore 1.4 miles from the entrance (fig. 15). The wave's competency is shown also by the sharp trimline and by the narrow channels cut through the trees on Cenotaph Island (pl. 6*A*), into a small lake east of Fish Lake and into the lakes east of Harbor Point. On steeper slopes from Cenotaph Island toward the heard of the bay the water had washed into the forest generally not more than 10 to 20 feet vertically above and 30 to 100 feet horizontally beyond the trimline. On low slopes in the outer part of the bay, however, the water at some places flowed through the forest for much greater distances, probably as much as a quarter of a mile, beyond the trimline. Salt poisoning of some bushes and plants was indicated by the brown tone of the foliage just above the trimline; this was particularly noticeable on steep slopes at the head of the bay in late August. The larger trees showed no effects of the brief submergence in salty water, although the lower trunks of many trees bordering the trimlines were injured by impact with other trees felled or transported by the wave (pl. 6*A*).

Many of the trees felled by the 1958 wave were reduced to bare stems, with the limbs, roots, and even the bark removed (pl. 6*B*). Removal of the projecting limbs and roots was due to grinding action as the trees were rotated in the turbulent water. On many of the trees, however, the cambium layer was still smooth or even slippery and showed little evidence of abrasion, suggesting that water under high pressure or moving at high velocity stripped off the bark by a process analogous to that used for peeling logs in plywood and pulpmills.

Along much of the north shore of Lituya Bay and for short distances along the south shore and on Cenotaph Island part of the felled timber is concentrated in poorly defined to well-defined windrows at variable heights above the high-tide line. The more conspicuous of the windrows are shown on figure 15. The longest continuous line of debris can be traced for about 2 miles along the north shore.

OTHER EFFECTS

No attempt was made to measure accurately the amount of erosion accomplished by the 1958 wave, and probably at only a few points along the shore of the bay are measurements made or photographs taken before 1958 sufficiently detailed to allow more than a rough estimate. From the effect on the vegetation an average minimum thickness of a foot of soil almost certainly was removed over the entire area between the trimline and the shore. This alone represents a volume of more than 4 million cubic yards. Cut banks 1 to 3 feet high were seen along the trimline at some places in the bay. At the small rounded projection of the south shore, 1.7 miles east of Harbor Point (fig. 15 loc. *A*), the wave cut a nearly vertical cliff about 25 feet high into till and underlying stratified sand and gravel. Large areas of bedrock were newly exposed and left as bare and clean as though washed down with a hose on the spur west of Gilbert Inlet, along most of the steep south shore from Crillon Inlet to a point 1 mile west of Coal Creek, and around much of the shore of Cenotaph Island.

Marine plants attached to rocks and marine invertebrates attached to rocks or burrowed in mud or sand were largely destroyed by the wave, at least down to mean lower low water level. On Cenotaph Island and on the south shore of Lituya Bay near the entrance, where in 1952–53 barnacles and mussels almost completely covered the rocks in the intertidal zone, and many edible clams were dug, not one living shellfish was seen in August 1958. At these localities even the basal attachment plates of most of the barnacles had been removed from the rocks. The shells of clams, barnacles, and crabs were scattered along the shore above the high-tide line and a few were seen at or near the upper limit reached by the water on Cenotaph Island and at several other places in the outer half of the bay. Failure to find the remains of any fish or deep-water shells suggests that the wave had little immediate effect on the larger swimming vertebrates and did not bring up bottom-dwelling invertebrates from a depth of more than a few tens of feet. The writer had no opportunity to examine closely the forest adjoining the trimlines near the entrance of the bay, however, where the water flowed out through the trees and where stranded fish would most likely be found. Probably many bottom-dwelling invertebrates in deep water were killed in place by settling of sediment eroded and transported by the wave. Some fresh-water organisms probably were also killed by the invasion of salt water into Fish Lake and smaller lakes and ponds along the shores of the bay, but these bodies of water were not examined.

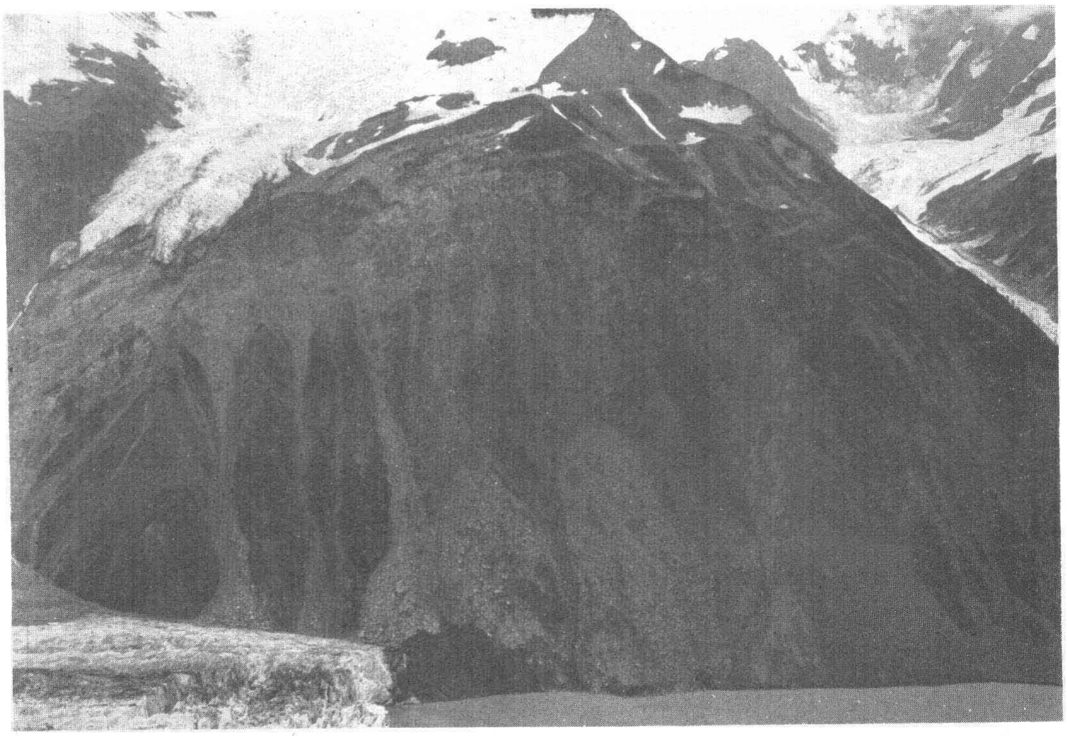
Few works of man existed in Lituya Bay at the time of the 1958 wave, but judging from the effects on the vegetation and the boats, the wave would have wreaked enormous destruction on ordinary buildings and on

A. VIEW OF LITUYA BAY, 1954

Trimlines of the 1936 giant waves (*g*) and the 1853–54 giant wave (*k*). Lateral moraines (*m*) and the end moraine in the right and left foreground record a recent advance of ice to the mouth of the bay. Mount Crillon, altitude 12,726 feet, is the highest peak on the skyline

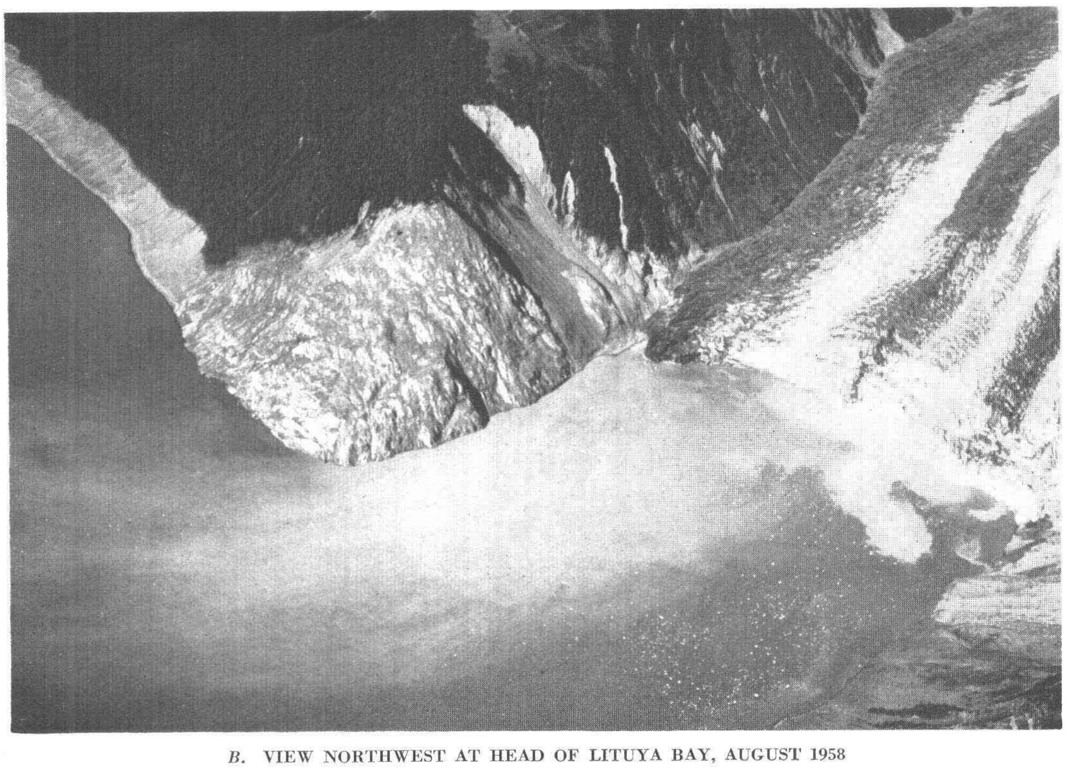
B. VIEW IN AUGUST 1958

A giant wave generated on July 9, 1958, by a rockslide from the cliff (*r*) at the head of the bay destroyed the forest over the light areas to a maximum altitude of 1,720 feet at *d* and to a maximum distance of 3,600 feet in from the high-tide shoreline at Fish Lake (*F*). A fishing boat anchored in the cove at *b* was carried over the spit in the foreground; a boat under way near the entrance was sunk and a third boat, anchored at *e* rode out the wave



A. NORTHEAST WALL OF GILBERT INLET, AUGUST 1958

Shows scar of rockslide. Head of slide, at about 3,000 feet altitude, was just below snowfield in upper center. Front of Lituya Glacier at lower left corner



B. VIEW NORTHWEST AT HEAD OF LITUYA BAY, AUGUST 1958

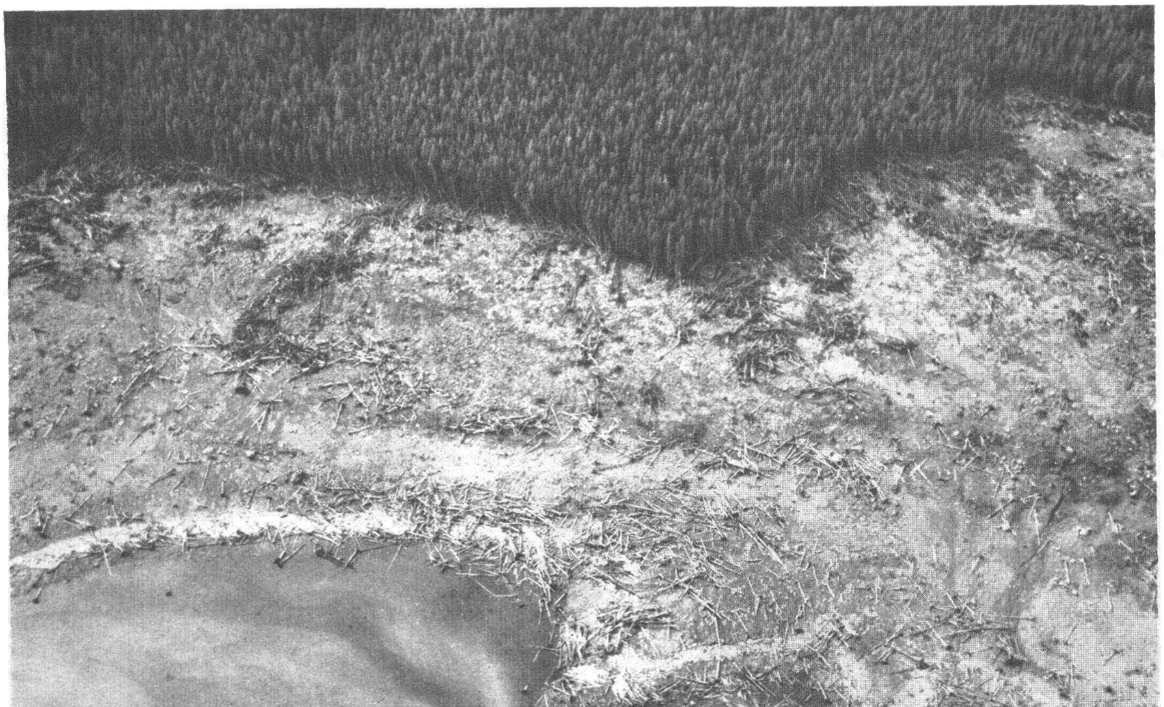
Large rockslide plunged into Gilbert Inlet at lower right corner, shearing off part of the front of Lituya Glacier and causing water to surge over the spur opposite. The trimline slopes down to right, across scars of slides that occurred before the 1958 earthquake

A. View west from Coal Creek, on south shore of Lituya Bay, August 1958. Trimline at left margin is at an altitude of about 180 feet, and is 1,000 feet in from the high-tide shoreline

B. Stump of living spruce tree broken off by the 1958 giant wave at Harbor Point, mouth of Lituya Bay. Brim of hat is 12 inches in diameter

A. VIEW WEST ON CENOTAPH ISLAND

Shows channel cut through forest by the 1958 giant wave. Note injured tree standing at portal of channel, on right



B. NORTH SHORE OF LITUYA BAY, AUGUST 1958

View is 2 miles from entrance, August 1958; forest as dense as that in the upper part of view formerly extended nearly to the shoreline. Width of zone of destruction by the 1958 giant wave is about 1,700 feet at right margin of photograph. Note trees with limbs and bark removed, in foreground shore structures such as docks. At the foundation sites, no trace could be found of the well-constructed cabin on the west or lee side of Cenotaph Island, used by the writer as a base camp in 1952 and 1953, or of the lighthouse mounted on concrete piers at Harbor Point. A few cut pieces of wood and some metal utensils from the cabin on Cenotaph Island were found several hundred feet from the former site.

Equipment left by a mining company at an intended campsite near the south shore was washed away (Henrickson, 1959, p. 18). Monuments marking U.S. Coast and Geodetic Survey triangulation points at Harbor Point and several other stations along the north and south shores of the bay are believed to have been washed out or moved. Station "Ice," marked by a bronze disk set in a large boulder on the shore at the head of the bay was found by the writer and apparently had not moved. Markers set in bedrock on the north and south shores just west of the two arms at the head of the bay, and one marker set in a concrete post on La Chaussee Spit seem, from study of photographs, to have remained in place also.

With regard to the destructiveness of the wave, R. L. Wiegel (written communication, Mar. 31, 1959) commented as follows:

> The method by which the wave broke and uprooted trees is easily explained using existing theory and data on wave-induced forces (Wiegel and Beebe, 1956; Wiegel, Beebe, and Moon, 1957); Wiegel and Skjei, 1958). For example, taking a conservative estimate of wave height and water depth, the total moment about the bottom of a tree 50 feet high with an effective dense crown diameter of 20 feet and trunk diameter of 2 feet was computed to be of the order of 25 million foot-pounds, which is far in excess of the conservative 300,000 foot-pounds necessary to snap the tree or uproot it (Fons and Pong, 1957).
>
> The problem of peeling the bark off a tree is a little more difficult. It may be due to the high water particle velocities in the waves. A solitary wave 100 feet high moving in water 400 feet deep will have a horizontal component of water particle velocity in excess of 100 feet per second just under the wave crest. This, combined with the observation in the model that the wave crest along the edges of the bay moved at the same velocity as the wave in the center of the bay, indicates that a water particle velocity of this magnitude would have existed over a substantial portion of the forested slope. The shear stress on the bark due to this velocity and extreme hydraulic roughness of the bark might have been adequate to strip the bark from the trees, especially as cracks probably formed in the bark as the trees were being bent prior to breaking.
>
> The water particle velocities along the edges of Cenotaph Island would have been great also, and this might explain the stripping of barnacles from the rocks.
>
> The water particle velocities at the bottom of the main portion of the bay would have been much lower.

NATURE AND CAUSE OF THE WAVE

From the foregoing evidence the nature, sequence, and approximate time of events associated with the July 9, 1958, wave in Lituya Bay are interpreted as follows:

Beginning at about 10:16 p.m. the southwest side and probably most of the bottom of Gilbert and Crillon Inlets moved northwestward and possibly up relative to the northeast shore at the head of the bay, on the opposite side of the Fairweather fault. Observations of the surface breakage along the Fairweather fault 6 to 10 miles southeast of Crillon Inlet indicate that the displacement occurred in several pulses and that the total movement was about 21 feet horizontally and 3 feet vertically (Tocher and Miller, 1959). Intense shaking in Lituya Bay continued for at least 1 minute according to the account of William A. Swanson, and possibly as much as 4 minutes according to Howard G. Ulrich. Slides and avalanches started in the mountains at the head of the bay within a minute after the shaking was first felt. Not less than 1 minute nor more than 2½ minutes after the earthquake was first felt a large mass of rock slid from the northeast wall of Gilbert Inlet. The initial movement of this rock mass, with attendant clouds of rock dust and avalanching snow and ice, may account for the "moving glacier" observed by Swanson. The impact of the large rockslide on the surface of the water caused the "deafening crash" heard by Ulrich and caused a huge sheet of water to surge up over the spur on the opposite side of Gilbert Inlet. The sudden displacement of a large volume of water as the rock mass plunged into Gilbert Inlet set in motion a giant gravity wave with a steep front, traveling at high velocity and with its greatest force directed initially about due south. The gravity wave, probably supplemented by the surge of water over the spur southwest of Gilbert Inlet, struck first against the steep cliffs on the south side of the bay in the vicinity of Mudslide Creek; the maximum force of the wave was then reflected and refracted toward the north shore a little farther out the bay, and again back to the south shore near Coal Creek. Variations in the height and intensity of the gravity wave as it moved out the bay, as recorded in the trimlines, may have been caused also by the interaction of diagonally refracted waves, by seiche wave motion, and by reflection of waves from the narrow entrance. Estimates by Ulrich and Swanson of the time elapsed from the first sighting of the wave front until it reached their boats indicate that the crest of the gravity wave moved out the bay at an average speed between 97 and 130 miles per hour. After the giant wave passed, the water in the bay was set into turbulent wave motion and continued to surge from shore to shore for 25 minutes or more.

532776—60——3

According to R. L. Wiegel (written communication, Mar. 31, 1959), the wave speed as calculated from the estimated time elapsed is in good agreement with the theoretical speed as calculated from the formula

$$C=\sqrt{g(d+H)}$$

where g is the acceleration due to gravity, d is the depth of water below sea level, and H is the height of the wave above sea level. He states:

> If the water depth averaged between 400 and 500 feet and the wave height averaged between 200 and 300 feet the wave would travel at a theoretical speed of about 100 miles per hour. If the water depth were taken as a conservative 400 feet and the wave height at a conservative 100 feet the theoretical wave speed would be about 86 miles per hour.

From evidence observed and photographed from an airplane on July 10, the writer with Kenneth Loken as pilot, concluded that water had risen to a height of about 1,800 feet on the spur southwest of Gilbert Inlet and caused destruction of the forset to the sharp trimline across this spur (Daily Alaska Empire, 1958b; Seismol. Soc. America Bull., 1958, p. 406). This conclusion was based on the following evidence: (a) The "washed" appearance of the bedrock below the trimline on the spur; (b) the sharp and even appearance of the trimline, and its similarity to and continuity with the trimline known to have been caused by water action farther out the bay; (c) at the highest point on the trimline, where the 1,800-foot altitude was estimated from the airplane altimeter, about 30 large trees were turned upslope and back into the forest. The roots of some of the upturned trees were bare and white, as though they had been washed out rather than merely pulled out of the soil (pl. 7*A*).

The initial report of wave damage to 1,800 feet above a water surface was widely doubted both on theoretical grounds and on the basis of aerial observations and study of photographs by others. This figure is more than 8 times the maximum height attributed to a 179) and nearly 8 times the maximum height reached by the largest of the slide-generated waves in Norway. Brazee and Jordan (1958), from study of aerial photographs and evaluation of reports of field observations, including those of the writer and Don Tocher, concluded that the spur southwest of Gilbert Inlet "has been denuded to a height of 1,800 feet either by avalanche, wave action or a combination of the two." Jordan later stated (written communication, Dec. 29, 1958) "More information is now available and it seems that landsliding is the major activity for any elevation above 300 feet or so," and this view is expressed also in an announcement of plans for a field investigation of Lituya Bay by the U.S. Coast and Geodetic Survey (Daily Alaska Empire, 1959). T. N. Davis, from aerial observations in Lituya Bay on July 12, 1958 first attributed the destruction of trees at high altitude on the spur southwest of Gilbert Inlet to "earthslide" (paper read at Alaska Science Conf., Sept. 2, 1958), but on reexamination of his photographs he found a few trees stripped of bark high on the slope and now believes that this damage to the trees is more likely due to action of high-velocity water than to slide action alone (written communication, Apr. 6, 1959).

After examining the area of the high trimline again from the air and on the ground later in the summer, it is still the writer's conclusion that water was primarily responsible for destruction of the forest cover. Examination on the ground confirmed that trees just above the highest point on the trimline, at 1,720 feet altitude as remeasured by a hand-carried altimeter, had been washed out and overturned by water. At this point on the crest of the spur the water rose about 20 feet higher than the highest overturned trees and flowed across the ridge and at least a quarter of a mile down the opposite side into the forest, leaving rocks and driftwood on the moss. It is true that rockslides either accompanied or closely followed the earthquake on the northeast side of the spur. Cracks trending parallel to the scar were seen in the forest on the crest of the spur, just above the trimline. Comparison of the 1958 oblique photographs taken after the earthquake with the 1948 vertical photographs show, however, that the 1958 slides occurred mainly in old landslide or rockslide scars, and that the volume of new sliding was small. Moreover, the trimline which the writer believes was formed by water, cuts across the tracks of these slides (pl. 4*B*). After the water had dashed over the spur there was minor sliding from the unstable scarp at the trimline. The conspicuous streaks of debris left by small slides on the otherwise washed, bare bedrock surface of the southwest face of the spur (pl. 7*B*) provide further convincing evidence against landsliding or avalanching as the primary cause of the destruction here. Also, along the margin of the trimline on the southwest face of the spur from the low point to an altitude of about 700 feet the trunks of many large trees knocked down but not washed out by the water are oriented parallel to the trimline, with their tops turned to the west (pl. 7*B*). These trees, if felled by avalanching or sliding, should be preferentially oriented parallel to the gradient of the surface.

Small slides occurred, presumably at the time of the earthquake, on the south side of Lituya Bay between Mudslide Creek and Crillon Inlet. The area affected by new slides is much smaller than is shown by Brazee and Jordan (1958, fig. 3). The trimline formed by the wave continues across this area, between slide scars, at altitudes ranging from 500 to 600 feet (fig. 16).

The large mass of rock that plunged into Gilbert Inlet from the northeast wall during the 1958 earthquake is referred to as a rockslide in this report, although it is near the borderline between rockslide and rockfall as defined in two classifications of landslides (Sharpe, 1938, p. 76–78; Varnes *in* Eckel, 1958, p. 20–32 and pl. 1). This rockslide as stated on page 63 probably caused the 1958 giant wave at Lituya Bay. The rockslide occurred in an area of previously active sliding and gulleying to an altitude of about 3,000 feet on a slope averaging 40°. The rocks in this area, as mapped by D. L. Rossman (written communication, 1957), are mainly amphibole and biotite schists; bedding and schistosity strike about N. 50° W. and dip steeply northeastward, into the slope.

The new slide area on the northeast wall of Gilbert Inlet, as shown on figure 16, was plotted by transferring the outer limits of the new scar by inspection from oblique photographs taken after July 9, 1958, to the vertical photographs taken in 1948, and thence by photogrammetric methods to the map. The dimensions of the slide on the slope are reasonably accurate, but the thickness of the slide mass normal to the slope can be estimated only roughly from the data and photographs now available. The main mass of the slide, as outlined on figure 16, is a prism of rock that is roughly triangular in cross section, with dimensions of 2,400 feet and 3,000 feet along the slope, a maximum thickness of about 300 feet normal to the slope, and a center of gravity at about 2,000 feet altitude. From these dimensions and an assumed specific gravity of 2.7, the volume and weight of the rock mass are, respectively, 40 million cubic yards and 90 million tons. It is highly probable that this entire mass plunged into Gilbert Inlet as a unit at the time of the earthquake, although the only known fact is that it fell between about noon on July 7 and about 10 a.m. on July 10.

The writer went to Lituya Bay in 1958 with a strong belief that fault displacement was the most likely mechanism for generating the giant waves originating in the fault zone at the head of Lituya Bay. The magnitude of the slide on the northeast wall of Gilbert Inlet was not fully realized from the aerial inspection on July 10, and it was first considered to be only a minor factor in the generation of the 1958 wave. Tocher (written communication, Aug. 1, 1958), however, suggested avalanching of rock or ice from the northeast wall of Gilbert Inlet as a possible generating mechanism before he was informed that a rockslide had occurred there. Arguments advanced by Tocher, information obtained later in the field and from the literature on similar waves elsewhere in the world, and the model studies made by Wiegel all have contributed to the writer's present acceptance of the rockslide as the major, if not the sole cause of the 1958 giant wave. Among the arguments against fault displacement as an important contributing mechanism to the generation of this wave, the following seem most significant: (a) Eyewitness reports of a lapse of 1 to 2½ minutes between the onset of the earthquake and the first sighting of the wave at the head of the bay: (b) The predominantly horizontal movement along the Fairweather fault, as indicated by ground breakage a few miles southeast of Lituya Bay. If the fault trace lies near the northeast side of Gilbert and Crillon Inlets, nearly the entire area under water at the head of the bay moved relatively northwestward and possibly up; wave motion resulting from this displacement should be directed toward the northwest and southeast side of the bay and (or) toward the head of the bay. (c) Vertical displacement of the bottom of the bay along the Fairweather fault probably would generate waves as a line source. An eyewitness account and the configuration of the trimlines, however, indicate radial propagation from a point source in Gilbert Inlet.

The comments of R. L. Wiegel on the nature and cause of the wave follow (written communication, Mar. 31, 1959):

It is a well documented fact that waves with large energy content are generated impulsively by such varying mechanisms as underwater seismic disturbances, islands exploding, atomic bombs, and large masses of water added suddenly to a body of water. The characteristics of waves generated by such mechanisms depend upon the disturbing force and the rate at which it is applied. The resulting waves may be oscillatory in character, nearly solitary in form, a complex multicrested non-linear wave existing entirely above the initial undisturbed water surface, or a bore (Prins, 1958a, 1958b).

The size of the slide, the water depth, and the general dimensions of Lituya Bay indicated that a wave similar to a solitary wave should form, but with a complex "tail" to the wave. A rough model was constructed at the University of California, at a 1:1,000 scale. Motion pictures were taken of the model tests and measurements were made of the water surface time histories at two points. Observations of the effects of various types of slides in the model indicated that the prototype must have fallen almost as a unit, and very rapidly. If the slide occurred rapidly then a sheet of water washed up the slope opposite the landslide to an elevation of at least three times the water depth. At the same time a large wave, several hundred feet high, moved in a southerly direction, causing a peak rise to occur in the vicinity of Mudslide Creek. This same wave swung around into the main portion of Lituya Bay, due to refraction and diffraction. The movements of the main wave and the tail were complicated within the bay due to reflections and due to the effect of bottom hydrography. One further wave characteristic was noticed when large waves were obtained, and this was that the crest appeared to move at a nearly uniform velocity across the bay even though the water

TABLE 1.—*Data on localized giant waves generated by falling or sliding of solid masses*

Location, date, and time of occurrence	Generating mechanism	Nature of water body, velocity and height of waves	Effects of waves	References
Japan				
Shimabara Peninsula, Kyushu Island, May 21, 1792, about 8 p.m.	During period of intense earthquakes and volcanic activity about 700 million cu yds of rock and soil to a maximum altitude of 1,700 ft on the east flank of Maye-yama slid 1¾ miles down a slope averaging 10°, and plunged into the sea along a front 3 miles wide.	Shimabara Bay, length about 60 miles, average width 10 miles, maximum depth 210 ft near the slide; opens into East China Sea at southwest end. At Shimabara 3 waves in rapid succession, the second and largest wave rising on land to a maximum height of about 33 ft.	Trees as much as 9 ft in diameter felled, buildings destroyed. More than 15,000 people were killed, most of them by the waves. Wave destruction extended about 50 miles along the shores of the bay.	Omori (1907); Ogawa (1924, p. 219–224, pls. 6, 7).
Norway				
Langfjord, Feb. 22, 1756	About 15.7 million cu yds of bedrock and soil to a maximum altitude of 1,312 ft on the fiord wall at Tjelle slid down a slope averaging 25° or more, and plunged into the fiord. Landslide may have been triggered by heavy rainfall.	Langfjord (fiord), length about 20 miles, average width 1.5 miles, maximum depth about 1,100 ft; opens into Norddalsfjord to west. Three waves observed, rising to a maximum height of 130 ft on shore opposite the slide.	Vegetation, soil, buildings, and boats destroyed, 32 people killed. Effects of the waves were noticed as much as 25 miles from slide.	Jørstad (1956).
Loen Lake, Jan. 15, 1905, about 11 p.m.	About 450,000 cu yds of bedrock and talus to a maximum height of 1,640 ft on Ravnefjell (Raven Mountain) fell and slid down a slope averaging 65°, and plunged into lake.	Loen Lake, length 7 miles, average width 0.6 mile, maximum depth 436 ft. Wave 10 ft high in middle of lake; rose to maximum height of 131 ft on shore opposite the slide and to 19 ft at the far end of the lake, 4.8 miles from the slide.	Vegetation, soil, buildings, and boats destroyed; iron steamboat 48 ft long was carried 820 ft and stranded 56 ft above lake level; 61 people killed.	Holmsen (1936, p. 173–177, figs. 2, 3); Bugge (1937, especially figs. 1, 8, and 10); Brigham (1906); Holtedahl (1953, p. 1044–1045).
Loen Lake, Sept. 13, 1936, 5 a.m.	About 1.3 million cu yds of bedrock to a maximum height of 2,625 ft on Ravnefjell fell at the same locality as the 1905 slide. Slide about 1,300 ft wide at lakeshore.	Loen Lake, see above. Wave appeared 3–6 ft high in center of lake; it rose to a maximum height of 230 on shore opposite the slide, and to 50 ft at the far end of the lake.	Vegetation, soil, buildings, boats and bridges destroyed, 73 people killed. Remains of stranded steamboat carried on up to 164 ft above lake level.	Holmsen (1936, p. 183–186, photograph opposite p. 176); Bugge (1937, figs. 8 and 10, p. 357); Holtedahl (1953, p. 1045–1046).
Loen Lake, Sept. 21, 1936, in evening.	Rockslide or rockfall from Ravnefjell.	Loen Lake, see above. Wave rose to maximum height of 49 ft on shore.	Boats used for rescue work were damaged.	Holmsen (1936, p. 186).
Loen Lake, Nov. 11, 1936, at night.	Rockslide or rockfall from Ravnefjell; volume as large as that on Sept. 13, 1936.	Loen Lake, see above. Wave rose to about the same height as on Sept. 13.	Nothing left to destroy	Holmsen (1936, p. 190), supplement, in German.
Tafjord, April 7, 1934, 3 a.m.	Overhanging rock mass of nearly 2 million cu yds volume fell from maximum altitude of 2,395 ft on fiord wall with an average slope of 45°, and plunged into the fiord along a front 750 ft wide. Rockfall triggered by melting of ice in fractures.	Tafjord (fiord), length about 5.6 miles, average width 0.7 mile, maximum depth 700 ft; opens into Norddalsfjord to west. Three waves of increasing height were observed at several places. Water rose to maximum height of 204 ft about 650 ft from the slide margin, to 122 ft on shore opposite the slide, and to 3 ft above normal high-tide line about 31 miles from the slide. Approximately measured velocities range from 13.4 to 26.8 miles per hour.	Vegetation, soil, buildings, and boats destroyed, 44 people killed along fiord within 2 miles of the slide; extensive damage to boats and docks as much as 31 miles from the slide.	Kahldol and Kolderup (1937); Holmsen (1936, p. 177–183, figs. 4 and 5); Bugge (1937, especially figs. 4, 5 and 6); Holtedahl (1953, p. 1046).
Norddalsfjord, across from Stranda, 1938.	Landslide from Skafjell.	Norddalsfjord (fiord). Three waves reported.	Not described in reference.	Jørstad (1956, p. 330). Incidental mention only; no detailed description found.
United States				
Disenchantment Bay, Alaska, July 4, 1905.	Fallen Glacier, a hanging glacier about 3,500 ft long and 1,200 ft wide, avalanched from an altitude of 1,000 ft down a slope averaging about 16°, and plunged into bay along a front 0.5 mile wide.	Disenchantment Bay, length about 10 miles, average width 3 miles, maximum depth 942 ft; opens into Yakutat Bay to south and into Russell Fiord to east. Waves 15–20 ft high observed for half an hour on Russell Fiord 15 miles from the avalanche; water rose to maximum height of 115 ft about 2.5 miles from the avalanche.	Unconsolidated deposits eroded, bushes broken off or washed out; area uninhabited.	Tarr (1909, p. 67–68). According to Indian legend falling glaciers in this area generated similar waves at least twice before; reportedly 100 Indians were killed by a wave about 1845.
Reed Terrace area near Kettle Falls, Columbia River valley, Washington; from April 8, 1944, to Aug. 19, 1953.	Landslides in terrace scarps underlain by bedded unconsolidated deposits. Narrow segments of the scarp on slopes averaging about 23° suddenly gave way and slid into the lake. Debris came down from maximum height of 210 ft above water level.	Franklin D. Roosevelt Lake, average width 5,000 ft, maximum depth 160 ft at slide area. Waves were generated by at least 11 different slides; the largest wave rose to maximum height of 65 ft on opposite shore, and was observed 6 miles up the lake. Observed velocity of one series of waves was about 45 miles per hour.	Vegetation destroyed, unconsolidated deposits eroded; barges and boats broke loose from dock 6 miles from slide area.	F. O. Jones and W. L. Peterson (written communications, Mar. 16 and May 7, 1959); Jones *in* Eckel (1958, figs. 31, 32, p. 40–41).
Mouth of Hawk Creek near Lincoln, Columbia River valley, Washington, July 27, 1949.	Landslide in terrace scarp underlain by bedded unconsolidated deposits. A narrow segment of the scarp on a slope averaging about 31° suddenly gave way and slid into the lake. Debris came down from maximum height of 340 ft above lake level.	Franklin D. Roosevelt Lake, in bay about 1,200 ft wide and 120 ft deep at slide area. Wave rose 65 ft on shore opposite the slide.	Trees knocked down.	F. O. Jones and W. L. Peterson (written communications, Mar. 16 and May 7, 1959).
East side of Columbia River valley north of Kettle Falls, Washington, Feb. 23, 1951.	Debris slide in bedded unconsolidated deposits and talus from maximum height of several hundred feet above lake level.	Franklin D. Roosevelt Lake.	Not described in references.	Jones in Eckel (1958, fig. 23 on p. 33); W. L. Peterson (written communication, May 7, 1959).

depths at the edge were considerably less than the water depth in the center of the channel. It is believed that this phenomenon is associated with the phenomenon studied by Perroud (1957).[3] The model study movies showed that the wave elevation was higher along the edges of the bay than in the center.

The action of the wave over the center of Cenotaph Island and at La Chaussee Spit are due to shoaling effects which have not been studied in detail for solitary, or similar, waves.

The energy in a solitary wave 100 feet high in water 400 feet deep with a channel width of 8,000 feet can be computed using an equation given by Ippen and Mitchell (1957). It is about 6×10^{12} foot-pounds. The potential energy of the landslide was about 3.5×10^{14} foot-pounds. Hence, only about 2 percent of the potential energy of the slide went into the main wave. This is of the same order of magnitude as obtained by model studies of a similar type of disturbance (Wiegel, 1955).

COMPARABLE WAVES IN OTHER PARTS OF THE WORLD

Waves similar to the 1958 giant wave in Lituya Bay have been generated by the sliding of part of a mountain into Shimabara Bay in Japan, by the sliding or falling of large masses of rock into a lake and several fiords in Norway, by the avalanching of a hanging glacier into a bay in Alaska, and by landslides into a lake in Washington. References and significant data on several such localized waves that have come to the writer's attention are summarized on table 1. An exhaustive search of the literature no doubt would reveal many other such occurrences in parts of the world where steep or unstable slopes are adjacent to bodies of water. Earthquakes acted as a triggering mechanism for the slide in Japan, but no earthquake was reported at the time of the 1905 wave in Alaska or at the time of any of the large waves in Norway and Washington. Some waves that accompanied earthquakes in uninhabited or sparsely inhabited areas and were attributed to tectonic movement, as for example the 1899 wave in Yakutat and Disenchantment Bays and Russell Fiord in Alaska (Tarr and Martin, 1912, p. 46–47) may have been generated instead by slides or avalanches triggered by the earthquakes. On the other hand one interpretation of the April 2, 1868 tsunami on the south coast of the Island of Hawaii as the result of a mudflow (Omori, 1907, p. 144) is not correct, according to G. A. Macdonald (written communication, Apr. 15, 1959).

WAVES ON OCTOBER 27, 1936

SETTING AND SOURCES OF INFORMATION

Four men were in Lituya Bay on October 27, 1936. James Huscroft and B. V. Allen were in a cabin on the west shore of Cenotaph Island (fig. 17) and Nick Larsen and F. H. Frederickson were on a 38-foot trolling boat *The Mine*. Larsen and Frederickson, who had entered Lituya Bay on October 26, anchored their boat first near the north shore south of Fish Lake and, after the first wave was sighted, moved to the west shore of the island near the cabin. According to the most detailed accounts, there were three giant waves in close succession, beginning at about 7:00 a.m., about an hour before sunrise. According to Frederickson the weather was clear but it was too dark to see much at the head of the bay; moreover, after *The Mine* was moved to the lee of Cenotaph Island, the head of the bay was hidden from all four observers. The tide at the time of the waves was flooding and about at mean tide stage (U.S. Coast and Geodetic Survey, 1935).

Two nearly identical articles based on an oral report by Allen (called to the writer's attention by Robert De Armond, oral communication, July 22, 1958) were published in newspapers soon after the waves occurred (Alaska Daily Press, 1936; Alaska Weekly, 1936). Information related by Huscroft about a year later was incorporated in an article on Lituya Bay by Williams (1938). De Armond also recalled seeing another account in a Ketchikan newspaper, based on the oral report by Larsen and Frederickson, but attempts to find this article have failed (L. H. Bayers, written communication, Apr. 7, 1959). The eyewitness account of F. H. Frederickson is abstracted from his recollections as related to the writer in a telephone conversation and a letter in September 1958.

EYEWITNESS ACCOUNTS

ACCOUNT OF FRED H. FREDRICKSON

During the night of October 26–27, 1936, *The Mine* was anchored near the north shore of Lituya Bay, a mile due west of the cabin on Cenotaph Island (fig. 17). About 2 hours before sunrise on October 27, at about 6:20 a.m. local time, a loud, steady roar was heard. It seemed to be coming from the mountains beyond the head of the bay, but, although the weather was clear, it was too dark to see much there. No shaking was felt on the boat. The roar continued until about 6:50 a.m., at which time a large wave was first seen in the narrow part of the bay, just west of the two arms at the head. The wave at this position appeared as a steep wall of water extending from shore to shore and possibly 100 feet high. On first sighting the wave the men raised the anchor and started the boat toward the Cenotaph Island; an estimated 10 minutes later, when the first wave arrived, the boat had reached a position about 1,300 feet northwest of the cabin, in the water at least 70 feet deep. No lowering or any other unusual dis-

[3] Perroud, P. H., 1957, The solitary wave reflection along a straight vertical wall at oblique incidence: Calif. Univ., [Berkeley], Ph.D. thesis, 93 p.

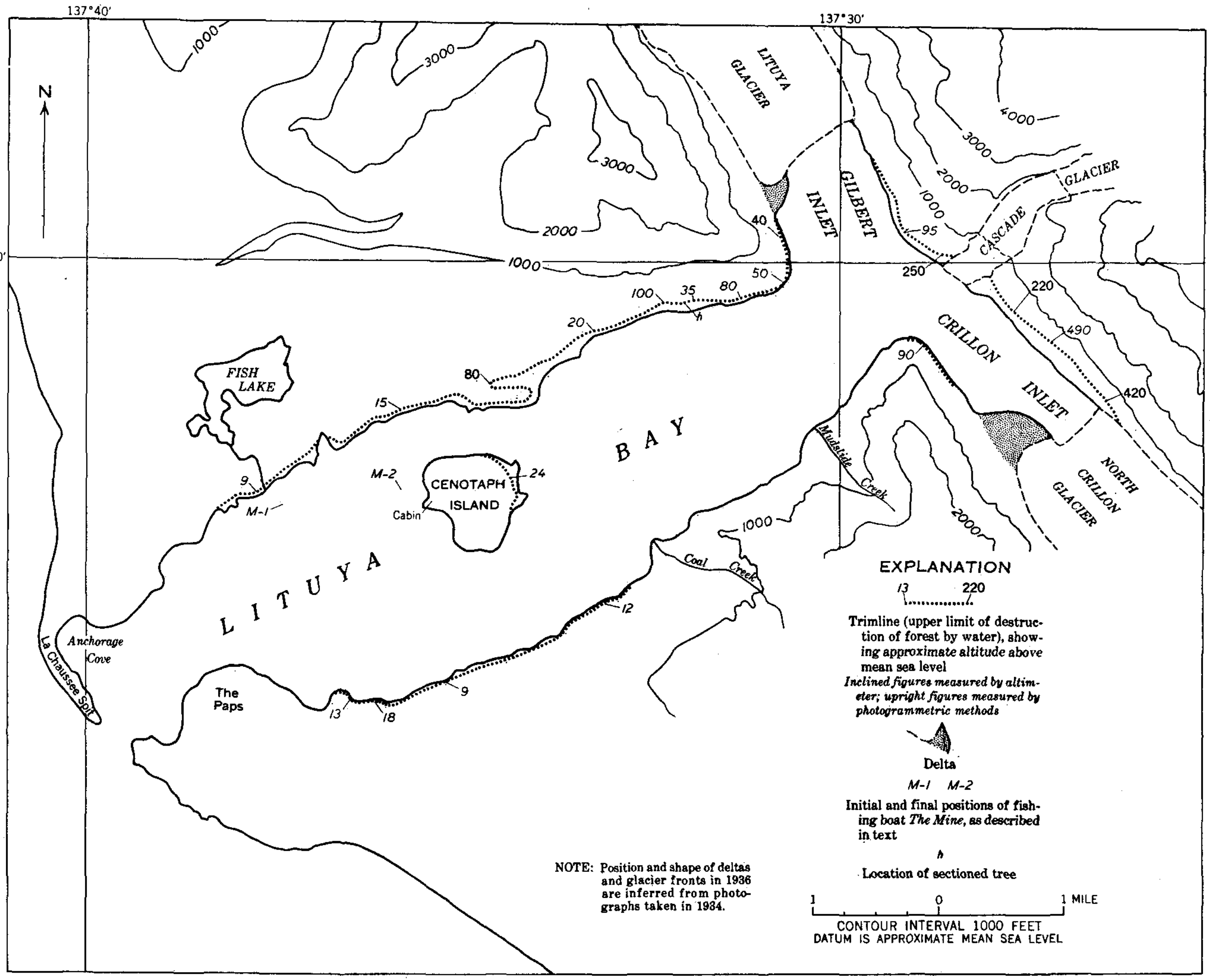


Figure 17. Map of Lituya Bay showing setting and effects of 1936 giant waves.

turbance of the water surface was noticed up to this time.

The first wave raised *The Mine* about 50 feet above normal water level; out of the lee of the island, to the north and south, the wave was possibly 50 feet higher. Immediately after the passing of the first wave the water surface fell below normal level. Huscroft's seining boat, anchored nearby in 48 feet of water, touched bottom. The first wave was followed at estimated 2-minute intervals by the second and third waves, each larger than the preceding one. The water surface receded below normal level after each of these waves also. Smaller waves continued for about half an hour after the third large wave passed. The direction of wave movement was always toward the mouth of the bay; there was no sloshing of the water back and forth in the bay. Floating logs and ice appeared around the boat about half an hour after the third large wave passed.

ACCOUNTS OF BERNARD V. ALLEN AND JAMES HUSCROFT

The more complete of two newspaper articles based on the account of Allen (Alaska Daily Press, 1936) states that he and Huscroft were awakened at 7:00 a.m. on October 27, 1936, by a roar like "the drone of 100 airplanes at low altitude," to find the water already up to their cabin on Cenotaph Island. As seen from a higher, safer point on the island, the water is described by Allen as sweeping over the shore in 3 waves of increasing altitude, at an estimated velocity of about 20 knots (23 miles per hour). In the published account the maximum height of the waves is given at 250 feet, but in a shorter account recorded in the log book of Osa Nolde (Caroline Jensen, written communication, Dec. 23, 1958) Allen stated that the waves reached a height of from 150 to 200 feet. These accounts agree in most respects with the recollections of Fredrickson; in the log book, however, Allen described the weather in

Lituya Bay on October 27, 1936, as cool, with rain, hail, thunder, and lightning.

The observations attributed to Huscroft by Williams (1938) differ from the other accounts in the following respects: Huscroft was preparing breakfast in his cabin at the time the roar was first heard; the water rushed toward the entrance in a single "mountainous tidal wave" followed by an immense "back wave," and then by waves that surged and resurged over the length of the bay a number of times. This was on a morning in the fall of 1936, during a period of unusually heavy rainfall.

EFFECTS OF THE WAVES

The observations attributed to Huscroft by Williams of Lituya Bay by the 1936 waves, as shown on figure 17, was mapped from field observations made by members of U.S. Geological Survey field parties in 1952–53, from single-lens vertical photographs at a scale of about 1:40,000, taken in 1948 by the U.S. Navy, and from an oblique aerial photograph taken in 1937 by Bradford Washburn. The upper limit of wave destruction around much of the inner part of the bay is readily seen on the 1948 vertical aerial photographs due to the difference in tone, texture, and average height of the vegetation growing above and below the trimline. Around the outer part of the bay and on some steep slopes near the head of the bay, however, field examination was required to determine the effects of the 1936 wave. At several places on steep slopes in the upper part of the bay the upper limit of wave destruction was no longer recognizable even in the field, due to the scarcity of large trees. The altitude of the trimline was measured at 14 points by means of a hand-carried altimeter, and at other points using the Kelsh plotter.

The identity of the trimline with the known 1936 wave was confirmed by tree ring counts in two ways: (a) sections cut in 1953 from the largest trees among the three principal types growing below the trimline on the northwest shore near point *h* (fig. 17), showed the following ages: cottonwood, 17 years; alder, 15 years; spruce, 14 years; (b) a section cut from a tree just above the trimline at point *h* (fig. 17, pl. 8*A*), showed, on the side toward the bay, an injury believed to have been caused by debris carried by the waves (pl. 8*B*). The section showed 17 annual growth rings outside the injury. The tree-ring counts were made by R. M. Godman of the Alaska Forest Research Center R. F. Taylor, written communications, Oct. 26 and Nov. 20, 1953). The second method (see page 77), was used to date the oldest known trimline in Lituya Bay. The assumption that the injuries were caused by the waves was convincingly confirmed by the many similarly damaged trees found along the trimline of the 1958 wave (pl. 6*A*).

The trimline of the 1936 waves has a maximum height of 490 feet or more above sea level on the northeast wall of Crillon Inlet (pl. 9*A*). The exact upper limit of wave destruction could not be determined by field examination in this area in 1953, due to the scanty growth of trees on the steep slope and to the possibility that the alinement of trees at the position tentatively mapped as the trimline was accidental. The position mapped in the field was later confirmed by an aerial photograph taken in 1937 by Bradford Washburn, on which the slope below the trimline is virtually bare of vegetation. Destruction of the forest extended to a maximum distance of 2,000 feet from the shoreline in the reentrant northeast of Cenotaph Island. Along a 1-mile segment midway along the bay—the same reference interval cited for the 1958 wave on page 60—the band of destruction on the north and south shores averages 50 feet in width and extends to an average altitude of 10 feet. The total area between the trimlines of the 1936 waves and the high tide shoreline is about 0.8 square mile.

Much of the evidence of destruction by the 1936 waves was obliterated by the wave in 1958. Short segments of the 1936 trimline still remained above the 1958 trimline from Cascade Glacier northwest about 1,500 feet and about 3,000 feet along the northeast wall of Crillon Inlet.

The total destruction of the forest up to a sharp trimline by the 1936 waves is mentioned in all of the available eyewitness accounts and is recorded in photographs taken during the latter part of 1936 by Tom Smith. One of these photographs is reproduced as plate 9*B*. Allen (Alaska Daily Press, 1936) reported that trees and shrubs were cleared away to a maximum altitude of 400 feet. The same article reported that within a few days uprooted trees had drifted along the beach as much as 50 miles south of Lituya Bay. Fredrickson (written communication, Sept. 1958) said that although not many trees were felled in the outer part of the bay, the water flowed for some distance out through the forest. Crabs and clams were found as much as half a mile back from the beach north of the mouth of the bay. According to Fredrickson most of the trees felled by the waves were washed out by the roots but still had roots, limbs and bark attached after the waves had passed. This difference in the damage caused by the 1936 waves, as compared to that caused by the 1958 wave is confirmed also by other eyewitness accounts and by the photographs taken by Smith.

One of the accounts attributed to Allen (Alaska Daily Press, 1936) describes the 1936 "flood" as "cutting a new bank from the soil and stone, and hurling rocks and trees." Williams (1938, p. 18), either from information furnished by Huscroft or from his own observations in 1937, states that "corrasion was complete down to bedrock, including all forest growth and even boulders 10 feet or more in diameter." This was not true in all areas below the trimline, for the photographs taken by Smith show stretches northwest of Cascade Glacier and along the north shore of the bay where many trees were left lying at or near their original positions. Even after the 1958 wave the bedrock was not exposed at many places touched by the 1936 waves. In 1952–53 scarps as much as 4 feet high were seen at a few places along the 1936 trimline; at most places, however, evidence indicated removal of not more than a thin soil layer containing the root systems of the trees. The erosive power of the 1936 waves, even at the head of the bay, was much less than that of the 1958 wave.

The 1936 waves (only the third wave according to Fredrickson and to one account by Allen) washed into Huscroft's cabin on the west shore of Cenotaph Island without causing much damage, but destroyed at least two small frame buildings nearby. Two triangulation stations established by the U.S. Coast and Geodetic Survey in 1926 could not be found in 1940 (U.S. Coast and Geodetic Survey "Lithographic List of Descriptions of Triangulation Stations, Alaska No. 57," not dated). One was on the north shore near Cenotaph Island marked by bronze disks set in boulders and one was on the south shore at Coal Creek marked by concrete blocks. Don Tocher (oral communication, Sept. 2, 1958) suggested that these markers may have been carried away or moved by the 1936 waves.

NATURE AND CAUSE OF THE WAVES

All eyewitness accounts agree that the 1936 waves were preceded by or accompanied by a loud noise, and the two most detailed accounts agree that there were three waves of increasing size in the vicinity of Cenotaph Island, with estimates of maximum height ranging from 100 to 250 feet. The account of one of the men on the boat, in a better position for observation than the men on the island, indicates that the roaring noise from the head of the bay was heard as much as half an hour before the first wave was sighted. This account also indicates that the waves were spaced about 2 minutes apart, and were followed by recession of the water below normal level. One observer on the island estimated the rate of water movement (not necessarily the speed of the waves) at about 23 miles per hour. The time required for the first wave to travel from near the head of the bay to the west side of Cenotaph Island, as estimated by one observer on the boat, gives a speed of about 22 miles per hour. Evidence preserved in the trimlines indicates that the waves were generated at or near the head of Crillon Inlet, where at least one of them dashed up on the valley wall to a height of 490 feet or more. The maximum height of the trimlines near Cenotaph Island is 24 feet, suggesting that the observers' estimates of the height of the waves at this position in the bay is too large.

Possibly significant in the consideration of the origin of the 1936 waves is the fact that they occurred "during a period of unusually heavy rainfall" (Williams, 1938, p. 18). Although two eyewitness accounts differ as to the weather on the day of the waves, the weather records at other places in southeastern Alaska do indicate that the occurrence of these waves was preceded by heavy rainfall (U.S. Weather Bureau, 1938). At the two coastal stations nearest Lituya Bay—Sitka (fig. 14), and Cape St. Elias, about 260 miles northwest of Lituya Bay—precipitation averaged 45 percent above normal for the entire month of October 1936, and 150 percent above normal for the 6-day period preceding October 27. At the three nearest inland stations—Juneau, Haines, and Skagway (fig. 14)—precipitation averaged 42 percent above normal for the month of October, and 111 percent above normal for the 6-day period preceding October 27. These departures are based on weather records through 1957 (U.S. Weather Bureau, 1958).

Allen, in both the published account (Alaska Daily Press, 1936) and in the account related to Nolde (Jensen, Caroline, written communication, Dec. 23, 1958), attributed the 1936 destructive "flood" and waves in Lituya Bay to the sudden draining of an ice-dammed lake in the basin of North Crillon Glacier. Williams (1938, p. 18) presented this hypothesis in detail, showing in a diagram the supposed course followed by the wall of water as it rushed down the surface of the glacier and into the head of Crillon Inlet. Williams (written communication, Mar. 3, 1954) stated that when he visited Lituya Bay after the "flood" (in 1937) he climbed along the sides of the Crillon Glacier and noticed the highwater marks there.

Floods due to the sudden draining of ice-dammed lakes are a frequent and well-known phenomenon in southern Alaska, and it is understandable that this hypothesis was proposed and generally accepted as the cause of the destruction in Lituya Bay in 1936. In papers given orally in 1954 the writer presented evidence opposing the ice-dammed lake hypothesis as follows: North Crillon Glacier is an actively moving, much crevassed stream of ice that has an average gradient of about 500 feet per mile; its drainage basin, now mapped from vertical aerial photographs and well known from aerial and ground observations (D. L. Rossman, written communication, 1957), lacks any topographic configuration in which a large body of water could be ponded, unless it is a chamber concealed beneath the glacier. An aerial photograph taken by Bradford Washburn in June 1937, less than a year after the supposed "flood," shows no derangement of the surficial moraine patterns on the surface of the lower part of North Crillon Glacier, such as certainly should have occurred if water had flowed down over the surface of the ice as inferred by Williams. The high-water marks mentioned by Williams may have been the scars of fresh rockslides.

Crillon Lake, into which the South Crillon Glacier discharges (pl. 2), has been mentioned also as the lake that drained at the time of the 1936 waves. Seismic investigation by Goldthwait (1936, p. 508), indicates, however, that the bedrock sill on the divide beneath the drainage of North Crillon Glacier into Lituya Bay and South Crillon Glacier into Crillon Lake is about at the same level as the surface of the lake.

The writer, after reviewing the evidence available in 1954, concluded that serious objections could be raised against many of the possible causes of the 1936 waves that had been suggested until then, and that conclusive support could not be marshaled for any of them. Despite the additional evidence obtained since then about the 1936 waves and despite the wealth of information gained from the 1958 wave, this opinion is still held as this report is written. It is necessary therefore, as in 1954, to present several possible causes, some more convincing than others, but none definitely proven.

SUDDEN DRAINING OF AN ICE-DAMMED BODY OF WATER

The writer has already given convincing arguments opposing the hypothesis of surface drainage from an ice-dammed lake in the North Crillon Glacier basin, although this hypothesis perhaps best explains the roaring sound heard before the waves were seen.

Two other variations of this hypothesis warrant consideration: (a) The water could have been ponded in a chamber within or beneath the North Crillon Glacier, or on the divide separating the drainage of the North and South Crillon Glaciers, then suddenly released beneath the glacier or through an ice tunnel below sea level in the tidal front of North Crillon Glacier. This might account for the sudden upwelling immediately in front of the glacier. However it seems unlikely that a chamber of sufficient size could form in a glacier as active as North Crillon. Also, if the chamber were very high in the glacier, as would be required to obtain a substantial hydraulic head, it seems unlikely that the water could have jetted out rapidly enough to generate giant waves. (b) A partly subglacial lake is present now, and existed in 1936 in the trench tributary to Gilbert Inlet, just northwest of the sharp bend in the Lituya Glacier (pl. 2). Aside from the probability of relatively slow drainage from this lake, it is also unlikely that drainage from beneath the Lituya Glacier would set up waves that rose highest at the opposite end of the trough forming the head of Lituya Bay.

FAULT DISPLACEMENT

In 1954, displacement along the Fairweather fault was suggested as a possible cause of the 1936 "flood wave," although evidence of an earthquake was lacking (Miller, 1954). Through the eyewitness accounts that were obtained since then, the date and approximate hour of occurrence of the 1936 waves are now known and it is possible to state definitely that no earthquake was felt in Lituya Bay and that no earthquake with an epicenter near Lituya Bay was recorded at that time on seismographs at Sitka, Alaska, or more distant stations (Tocher, Don, written communication, Aug. 1, 1958). Perry Byerly (oral communication, Jan. 22, 1954) believes that fault displacement sufficiently large to cause the waves could not fail to have caused an earthquake that would have been felt in the bay and recorded at seismographic stations more distant than Sitka. Therefore, it seems that fault displacement can be ruled out as a cause for the 1936 waves.

ROCKSLIDE, AVALANCHE, OR LANDSLIDE

The roaring sound reported by three eyewitnesses to the 1936 waves and said by one of the observers to have come from the head of the bay and to have preceded the waves, suggests a rockslide or avalanche. Some of the observed differences between the 1936 and 1958 waves, particularly the occurrence of three waves of increasing size in 1936, and the much higher velocity of the 1958 wave, might be advanced as an argument against a common origin. On the other hand, these differences in the wave patterns might be due to differences in the location of the sliding or falling rock mass and the manner in which it entered the water. This was demonstrated in 1934 in Tafjord, Norway, where a rockfall generated waves of about the same height and velocity as the 1936 waves in Lituya Bay, and where three waves of increasing height were observed (Kaldhol and Kolderup, 1937; table 1, this report). Three waves reportedly were generated also by two other landslides into Norwegian fiords, Langfjord in 1746 and Norddalsfjord in 1938 (Jørstad, 1956, p. 326, 330–331).

By analogy with the 1958 wave, a falling mass that caused the 1936 waves in Lituya Bay should have come from the southwest wall of Crillon Inlet, opposite the high point on the trimline. None of the previously published eyewitness accounts mention any evidence that a large mass of rock or ice had fallen into Lituya Bay at the time of the 1936 waves, and Fredrickson (written communication, Sept. 1958) states that he did not notice any such evidence when he went to the head of the bay a short time after the waves had occurred. Comparison of the trilens photographs of Lituya Bay taken in 1929 by the U.S. Navy with the 1948 vertical photographs indicate that sliding had occurred on the valley wall above and just south of the front of North Crillon Glacier at some time between 1929 and 1948. This slide scar, however, is directly above the delta that formed in front of North Crillon Glacier before 1929, and some evidence of a large slide in 1936 should have been preserved on the delta and should be visible in the 1948 photographs. The 1929 and 1948 photographs show scattered large blocks of rock on the delta surface, also small talus cones along the base of the cliff, suggesting that sliding in this area has taken place frequently but in small increments.

Elsewhere on both walls of Crillon Inlet the correspondence between the 1929 and 1948 photographs is so close, even as to individual trees, gulleys, and other distinctive patterns, as to definitely eliminate the possibility that a large slide occurred during this interval. Small fields of permanent snow and ice are on the northeast wall of Crillon Inlet above 3,400 feet altitude, but these too show close correspondence in shape and size on photographs taken by Bradford Washburn in 1934 and 1937, eliminating the possibility of a large avalanche. There is a possibility that a rockslide or avalanche of ice fell on the North Crillon Glacier causing movement that was transmitted through the glacier to the tidal front. This possibility may be eliminated at least for the lower 2 miles of the glacier by inspection of the 1937 photographs; it seems unlikely that any movement higher on the glacier would be transmitted to the front.

The photographs indicate the occurrence of small rockslides into Gilbert Inlet from both the southwest and northeast sides, and into Lituya Bay between Mudslide Creek and Crillon Inlet, at some time between 1929 and 1948, but these locations are all incompatible with the trimline pattern of the 1936 waves. If the writer's interpretations of the photographs are correct, and falling or sliding of a mass of a size greater than a few thousand cubic yards into Crillon Inlet is required to generate the 1936 waves, then landsliding or avalanching may virtually be eliminated as a possible cause.

SUBMARINE SLIDING

Submarine slides (submarine "landslides") have long been included among two or more hypothetical causes of tsunamis in the oceans. For example, Gutenberg (1939), and Shepard, Macdonald and Cox (1950, p. 394–395), offer opposing viewpoints. The tsunami associated with the 1908 earthquake in the Straits of Messina has been attributed to a turbidity current originating in a submarine slump (Heezen, 1957). Recent laboratory experimental work indicates that submarine slides are capable of generating tsunamis (Wiegel, 1955).

Soundings in Crillon and Gilbert Inlets indicate slopes of as much as 28°, through vertical distances of nearly 500 feet. Unconsolidated material was available in 1936 in the deltas built out from the fronts of both North Crillon and Lituya Glaciers, and may have been present in substantial thickness at other places around the head of the bay. Submarine slides could also have occurred in bedrock. Perhaps one of the most attractive aspects of submarine sliding as a possible cause of the 1936 waves is that it cannot be definitely disproved because the evidence, if any, is hidden beneath the bay. Considering the magnitude of the slopes available and the probability that a large submarine slide would involve material at least partly above water, submarine sliding seems unlikely as the cause of the 1936 waves, however. Unless two or more slides occurred in close succession, or the waves were reflected at the head of the bay, it is difficult to account for the observed fact that the third wave, rather than the first, was the largest.

MOVEMENT OF A TIDAL GLACIER FRONT

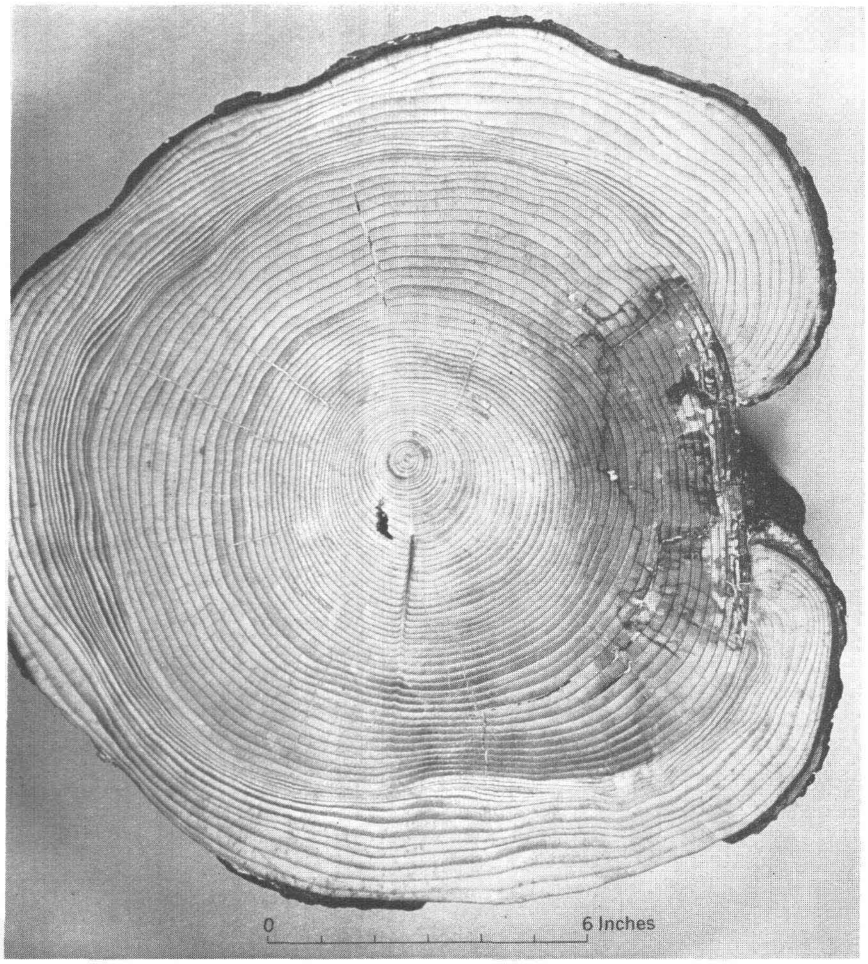
The trimlines at the head of Lituya Bay show clearly that at least the largest of the 1936 waves was generated at or near the tidal front of North Crillon Glacier, and attained maximum height on the northeast wall of Crillon Inlet within 3,500 feet of the glacier front. This evidence, reinforced by the known generation of waves at the fronts of other glaciers that discharge into water, lends strong support to some kind of movement of the Crillon Glacier front as the cause of the 1936 waves. Three types of movement must be considered: (a) calving of ice from the subaerial part of a glacier front into the water; (b) calving and sudden surfacing of ice from a submarine projection of a glacier front; and (c) almost instantaneous forward movement of a glacier front. One aspect of the 1936 wave pattern, the occurrence of three waves of increasing

A. Trees washed out and turned upslope by water at altitude of 1,720 feet. Small slides occurred on steep slope at right during the 1958 earthquake, but destruction of forest in middle and lower left part of view is due mainly to water

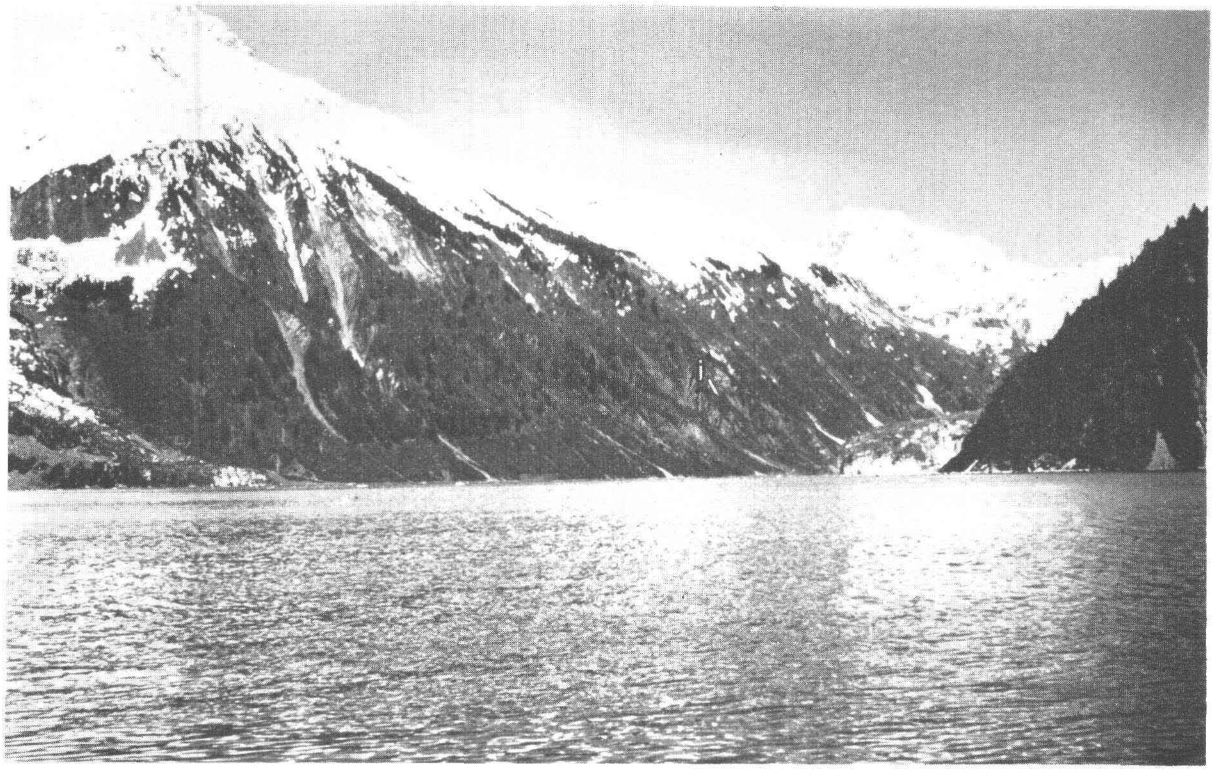
B. West side of spur; note washed appearance of bedrock at lower right, in contrast to slide *area* just below trimline at *t*. Height of view, from bay at lower left to upper right corner, is about 1,200 feet

SPUR SOUTHWEST OF GILBERT INLET, AUGUST 1958

A North shore of Lituya Bay between Cenotaph Island and Gilbert Inlet, showing forests of different ages in zone denuded by 1936 giant waves (shore to *h*), in upper part of zone denuded by giant wave about 1874 (*h* to *j*), in upper part of zone denuded by giant wave in 1853 or 1854 (*j* to *k*), in upper part of recently glaciated zone (*k* to *m*), and above lateral moraine at *m*. Photograph taken in 1953



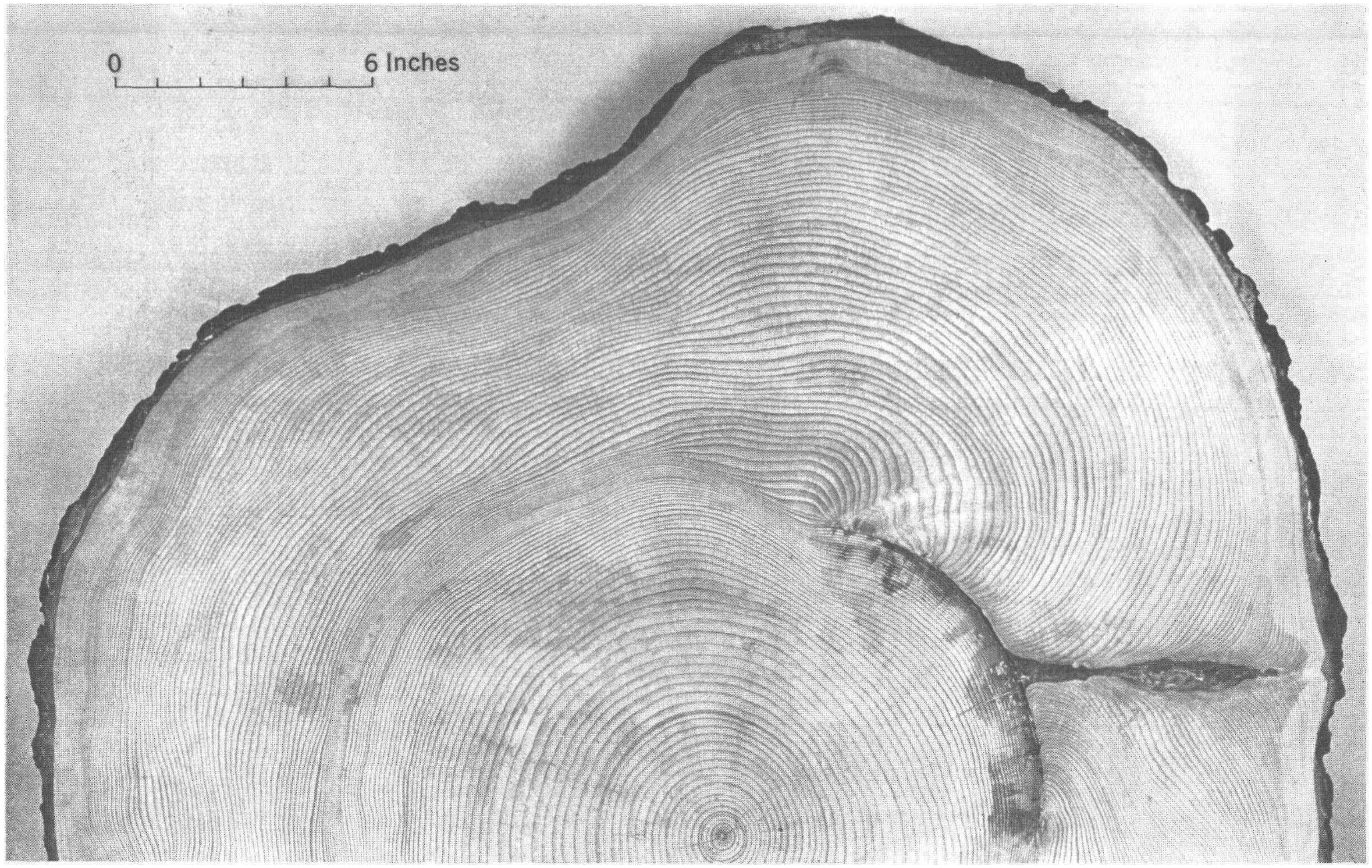
B. Section cut in 1953 from spruce tree growing just above trimline of 1936 giant waves (loc. *h*, in *A* and in fig. 17). There are 17 growth rings outside injury on right



A. Crillon Inlet and head of Lituya Bay in 1952; Trimline begins above tidal front of North Crillon Glacier; altitude 490 feet at *i*. Front of Cascade Glacier at left margin

B. Destruction to an altitude of about 90 feet at head of Lituya Bay, half a mile northwest of Cascade Glacier. Photograph by Tom Smith in 1936

DESTRUCTION OF FOREST BY 1936 GIANT WAVES



SECTION CUT IN 1953 FROM SPRUCE TREE GROWING JUST ABOVE TRIMLINE OF 1853–54 GIANT WAVE

There are 100 growth rings outside injury on right. Locality (L), on figure 19 height in the vicinity of Cenotaph Island, could be explained either by repeated movements of any of these three types, or by interference, refraction or reflection of waves near the point of generation at the head of the bay. Calving from an ice front could have caused the roaring sound reported by eyewitnesses, although it seems unlikely that calving could have occurred continuously for as much as half an hour before the first wave was sighted.

No photographs showing the North Crillon Glacier front shortly before or shortly after the occurrence of the 1936 waves are available, but oblique aerial photographs taken by Bradford Washburn in the summer of 1934 and in June 1937 show little change in the position and configuration of the northeast half of the front. The delta and southwest half of the front on Crillon Inlet are not shown on the 1937 photographs. Based on the photographs taken in 1934, and assuming little change in the following 2 years, the tidal front of North Crillon Glacier at a time just preceding the occurrence of the 1936 waves was a nearly vertical wall of ice about 2,700 feet long and 200 to 300 feet above water level, extending across about half of the total width of Crillon Inlet (fig. 17). If the ice front extended to the bottom of the inlet, as seems likely, its maximum height below water level was about 290 feet.

Calving of subaerial ice into water has been observed at the fronts of many glaciers discharging into lakes, rivers, bays, and even into the open ocean in Alaska, as well as in many other parts of the world. From observation or indirect evidence such calving has formed waves capable of eroding as much as 5 feet above high tide a mile or more from the ice front (Tarr, 1909, p. 33–34), but according to available data no waves even approaching the magnitude of the 1936 waves in Lituya Bay have resulted from glacier calving in Alaska. If calving were the cause of the giant waves in 1936, such waves should occur with greater frequency, not only in Lituya Bay but also at the fronts of many other tidal glaciers in Alaska. This would be true unless, as suggested by C. C. Bates (written communication, Apr. 7, 1955), simultaneous calving from two or more glacier fronts is a further requirement.

In the course of the model study of Lituya Bay, R. L. Wiegel and Don Tocher found that rotational fall of a partly submerged weight with a flat face, simulating the Crillon Glacier tidal front, formed wave traces that compare closely in configuration to the trimlines on the walls of Crillon Inlet. The maximum height reached by the wave in the model, however, was about equal to the height of the face of the weight above water level. This gives some basis for doubting that ice falling from the Crillon Glacier front could have raised a wave to a height much greater than the height of the front. C. C. Bates (written communication, Apr. 7, 1955) suggested that although ice falling from the front of North Crillon Glacier might provide only about 10 percent of the necessary volume increment, the remainder of the rise indicated by the trimline on the northeast shore of Crillon Inlet might come from uprush or local refraction effects.

Submarine calving from the glacier front was suggested as a possible cause of the 1936 waves by W. O. Field, Jr. (written communication, Dec. 5, 1952). Evidence of ice projecting below water level as much as 1,000 feet beyond the subaerial part of glacier fronts has been reported for glaciers in the Yakutat Bay area (Russell, 1891, p. 101–102; Tarr, 1909, p. 31–32). Field states that waves 25 feet or more in height are formed by calving of projecting submarine ice masses at the front of Muir Glacier in Glacier Bay. The configuration of the submarine parts of the tidal ice fronts in Lituya Bay is not known. The possibility that the deltas in front of the Lituya Glacier may have been underlain by ice was mentioned on page 60. In the few hours that either or both the North Crillon and Lituya Glacier fronts were in sight during the 1952, 1953, and 1958 field investigations, the writer did not see any calving of submarine ice. The appearance of the delta in front of North Crillon Glacier in the 1948 vertical photographs does not give evidence of disturbance by the sudden rise of an ice mass beneath it, and the remaining tidal part of the glacial front seems to be too small to provide a mass of sufficient size to generate the 1936 waves.

Slippage of an ice mass over its floor is generally accepted by glaciologists as a major mechanism of movement for glaciers on slopes (Sharp, 1954, p. 826). However, an instantaneous advance of a glacier front of more than a few inches has not been proven. Prospectors in Disenchantment Bay reported that during the largest of the Yakutat Bay earthquake shocks, on September 10, 1899, the tidal front of the Hubbard Glacier advanced or was thrust forward from one-half to three-quarters of a mile, but Tarr and Martin (1912, p. 16) believed this to be an erroneous interpretation of the enormous calving of ice from the glacier front. It seems likely that forward movement of the Crillon Glacier front of a few feet or even a few tens of feet would be required to raise a wave to the height indicated by the 1936 trimline in Crillon Inlet. Such movement of the glacier front should have disrupted the surface of the glacier for some distance above the front to such an extent that the changes should be evident on photographs taken in 1937 and later. An oblique aerial photograph taken by Bradford Washburn in June 1937 shows no unusual crevassing or disruption of the surficial moraine patterns on North Crillon Glacier.

TSUNAMI IN THE OCEAN

Perry Byerly and J. P. Eaton (oral communication, Jan. 22, 1954) offered the suggestion that wave motion from a tsunami generated at sea might be transmitted either through the narrow entrance or through the spit at the mouth of Lituya Bay, causing a seiche wave or some other type to form inside the bay. In further support of this suggestion Byerly (written communication, Feb. 1, 1954) called attention to the following statement by McNown (1952, p. 163): "It has been amply proved that the motion produced in a port can have an amplitude not only equal to but even a number of times greater than the amplitude of the wave that produces it. Furthermore, from theoretical considerations, this amplitude can occur equally well with an entrance width that is extremely small."

According to tide-gage records (Neuman, 1938, p. 26) no tsunami occurred in the northeastern Pacific Ocean in October 1936. It is difficult, also, to understand how wave motion introduced at the mouth of Lituya Bay could have been transmitted without any obvious surface effects to the head of the bay, there to be amplified into three giant waves that traveled out the bay at high velocity.

OTHER POSSIBLE CAUSES

For the sake of completeness several other agents capable of generating waves are mentioned, although there is little or no evidence to recommend them as possible causes of the 1936 waves in Lituya Bay. Submarine volcanic activity is known to have given rise to large tsunamis in the sea, as, for example, the destruction of Krakatoa in 1883 (Williams, 1941, p. 255–256, 261). Waves caused by tidal action and by wind are well known. As examples of water waves set in motion by air waves, Press (1956) cited a sea wave with a 2-foot amplitude that followed the Krakatoa explosion, and a 10-foot wave at Chicago in 1954. Finally, Olaf Holtedahl (oral communication, 1957) suggested that a falling meteorite be added to the list of possible causes.

WAVES BETWEEN 1854 AND 1916

EYEWITNESS ACCOUNTS

When the writer first visited Lituya Bay in 1952 stories of "floods" were heard from several fishermen who anchored their boats in the bay. One described catastrophic floods caused by breaking of a glacial lake near the head of the bay in 1890 and again in 1928. Another mentioned a flood about 1899 that destroyed a native village and a fish saltery near the mouth of the bay, and a second flood about 1928, when Huscroft was living on Cenotaph Island. Others reported that both floods occurred after sharp earthquakes. It is clear now that these accounts referred at least in part to the 1936 and 1853–54 waves, but the mention of dates 1890–99, of earthquakes, and of a saltery near the mouth of the bay suggest the occurrence of another wave of intermediate age. In 1958 James Betts of Angoon, Alaska reported that his grandfather had experienced a flood or wave in Lituya Bay in 1899 (Tom Smith, oral communication, Aug. 1958). The writer has been unable to obtain further information on this report.

OTHER EVIDENCE

Possible evidence for the occurrence of at least one giant wave in Lituya Bay between the 1853–54 wave and the 1936 waves was first noticed during the 1953 field investigation, on the north shore near the mouth of the creek draining from Fish Lake. At this locality, in a narrow belt midway between the 1936 and 1853–54 trimlines, the spruce and hemlock trees appeared to be a little smaller in average size than in the forest adjoining and just below the 1853–54 trimline. This impression was not tested at the time by sectioning the trees. In the course of later study of ground photographs taken in 1917, photographs of the north shore of the bay between Cenotaph Island and Gilbert Inlet (J. B. Mertie, nos. 604, 605, 619, and 620, U.S. Geological Survey Photolibrary, Denver) showed not only the 1853–54 trimline but also, in the interval about 0.8 to 1.8 miles west of Gilbert Inlet, a probable lower trimline that had about the same height and configuration as the 1936 trimline in the same area. This segment can be identified with certainty as a trimline on a photograph taken in 1894 by a Canadian Boundary Survey party (McArthur no. 128; print loaned by W. O. Field, Jr., Mar. 3, 1959). The lower trimline in this area shows faintly on the 1929 trilens photographs and on these can be traced westward along the north shore, with decreasing certainty, to the locality of the field observation near Fish Lake. The eastward extent of this trimline near Gilbert Inlet is also uncertain. It probably falls to or near the shoreline, as shown on figure 18, but the photograph taken in 1894 suggests that it may rise eastward to or nearly to the 1853–54 trimline in this area.

Possible trimlines that may be at least in part younger than the definitely identified trimline on the north shore are shown in ground photographs taken in 1916 by Trevor Davis (oral communication, July 1958) near Cascade Glacier and on the spurs southwest of Gilbert and Crillon Inlets, and in photographs of the north shore of Anchorage Cove taken in 1917 (Mertie nos. 98, 99). The supposed trimline at Cascade Glacier is recognizable on the 1929 trilens photographs and can be projected about a mile to the southeast as an irregular lower limit of scattered clumps and groves of spruce trees. A few scattered spruce trees of about the same size are standing below this line, however. None of these supposed trimlines shown on 1916 and later photographs can be recognized on the few copies of 1894 photographs that are available, but because of incomplete coverage and the poor quality of some of the prints, their existence at that time cannot be disproved.

DATES

The lower trimline definitely identified in a photograph of the north shore of Lituya Bay taken in 1894 indicates that at least one giant wave occurred before this date but later than the 1853–54 wave. The stage of vegetation growth below the lower trimline, as shown on the photograph, suggests that the trimline was formed about midway in the interval 1854 to 1894. Hence the "evidence of flooding and washing" noted in 1874 by Dall (1883, p. 203) may have resulted from this wave.

The other possible trimlines shown on 1916–17 photographs, on the basis of the previously mentioned unsubstantiated eyewitness account and on the basis of the stage of vegetation growth, are attributed tentatively to a wave occurring in 1899. The occurrence during that year of the great Yakutat Bay earthquakes and the report of a great amount of drift timber and muddy water in the ocean between Cape Fairweather and Yakutat 2 days after the largest of the earthquake shocks (Tarr and Martin, 1912, p. 79) are further evidence for this date. The absence of any reference to Lituya Bay among the many reports of those who experienced the Yakutat Bay earthquakes probably means either that no report was received by Tarr and Martin (1912, p. 65–68) or that no one was in Lituya Bay at that time, because the shocks were felt throughout a large area in southern Alaska and adjacent Canada.

EFFECTS OF THE WAVES

The trimlines plotted on figure 18 were reconstructed mainly from the 1916 photographs by Davis and the 1929 trilens photographs. Altitudes on the trimlines were obtained by transferring points by inspection to the 1948 vertical photographs, from which the approximate height above water level was then estimated or measured photogrammetrically. Trimlines formed by two different waves were tentatively identified. The older wave apparently destroyed all or nearly all vegetation up to a sharp trimline for a distance of 4 miles or more along the north shore. A maximum altitude of 80 feet and a maximum width of 2,100 feet back from the high-tide line were measured for this trimline. The younger wave destroyed vegetation to a maximum altitude of about 200 feet on the northeast shore of Crillon Inlet and to lesser heights on the spurs southwest of Gilbert and Crillon Inlets, and possibly to a height of a few feet on the north shore of Anchorage Cove. On the south shore of Lituya Bay, west of Mudslide Creek, destruction of vegetation by either wave, if any, must have been limited to a narrow zone bordering the beach. The total area of substantial destruction of vegetation below all of the tentatively identified trimlines in less than 0.4 square mile. Most of the evidence of destruction by the waves between 1854 and 1916 was removed by the 1936 wave and any remaining evidence was wiped out by the 1958 wave.

NATURE AND CAUSE OF THE WAVES

Photographs taken in 1894 by McArthur (nos. 105A, 128) show fresh, bare surfaces on the upper slopes of the northeast wall of Gilbert Inlet and the valley of Mudslide Creek, suggesting that slides had occurred in these areas not long before. It is doubtful that the older wave was generated by a slide from the northeast wall of Gilbert Inlet, because McArthur's photographs do not show a trimline on the opposite shore of Gilbert Inlet. By analogy with the 1958 wave, destruction of vegetation should have been greatest there. A slide in the valley of Mudslide Creek could account for the maximum known destruction obliquely opposite on the north shore of the bay, and also for the absence of a conspicuous trimline in the inlets at the head of the bay.

The trimline of the wave inferred to have occurred about 1899, as reconstructed from photographs, compares most closely in magnitude and configuration with the trimline of the 1936 waves. It seems likely, therefore, that the 1899 (?) wave was generated in Crillon Inlet, possibly by the same unknown mechanism that caused the 1936 waves. However, if a wave did occur at the time of one of the great earthquake shocks in 1899, displacement along the Fairweather fault warrants consideration as a possible cause. By analogy with the 1958 wave, a rockslide into Crillon Inlet must also be considered. St. Amand (1957, p. 1357–59) suggested that at least one of the earthquakes in 1899 resulted from movement on the Fairweather fault. Evidence in support of this suggestion was found by Tocher and Miller (1959) after the 1958 earthquake. New surface breaks were seen from the air near the scarps on Nunatak Fiord described by Tarr and Martin (1912, p. 37-40); along the Fairweather fault southeast of Lituya Bay

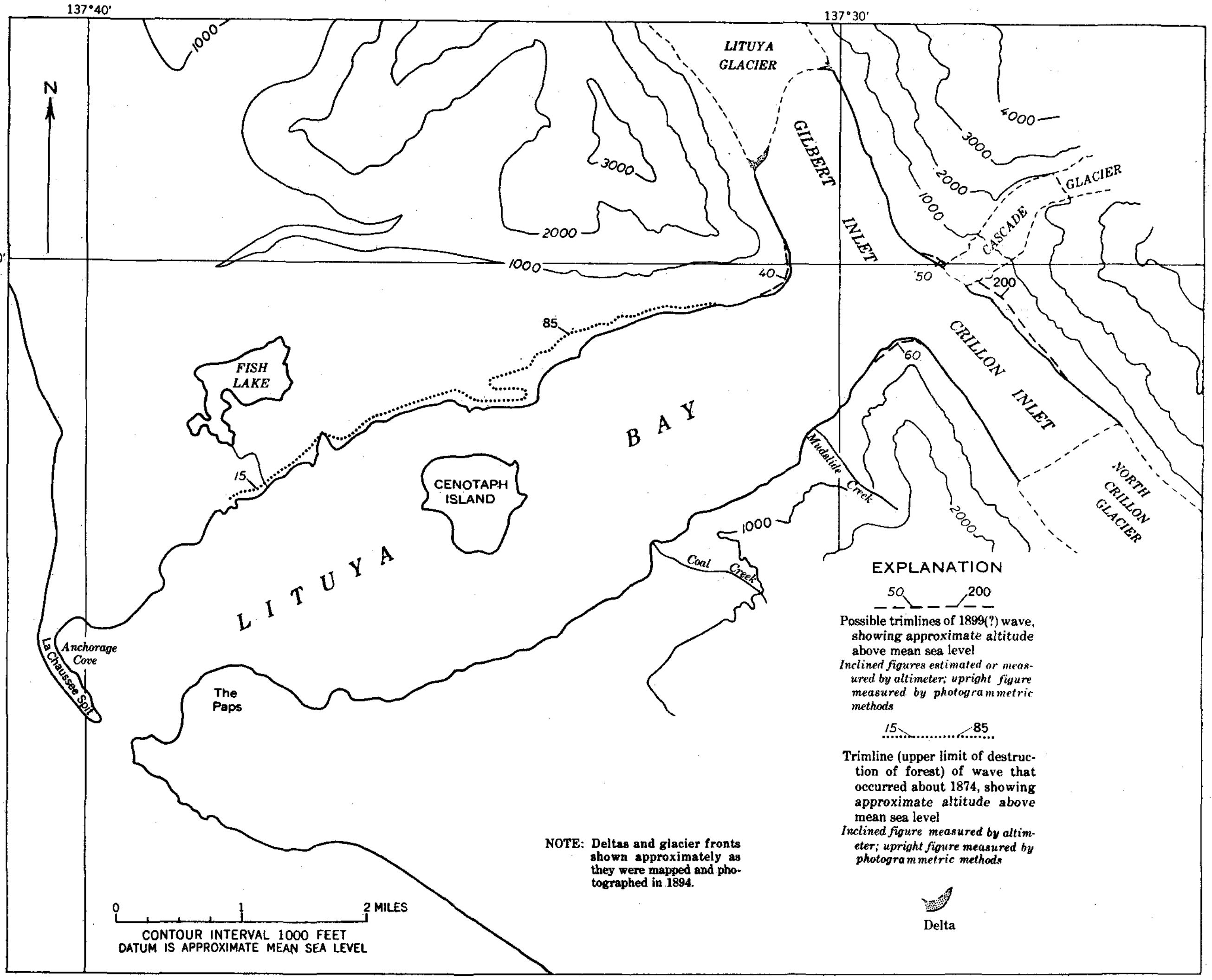


FIGURE 18.—Map of Lituya Bay, showing trimlines of one or more giant waves that occurred between 1854 and 1916.

much of the new breakage had taken place along old scarps. The few oblique photographs taken at the head of Lituya Bay at the turn of the century are not adequate to either prove or disprove the occurrence of a rockslide in Crillon Inlet.

WAVE IN 1853 OR 1854

EYEWITNESS ACCOUNTS

Williams (1938, p. 19) related the formation of the oldest trimline in Lituya Bay to an old Indian story about the catastrophic destruction of a village near the entrance. The source of this legend was not cited. Emmons (1911, p. 294–298) and de Laguna (1953, p. 55) were told the story of the meeting between La Perouse and the Tlingit in Lituya Bay in 1786 by natives living at Yakutat, near Juneau, and at Angoon. Emmons (1911, p. 295) also recorded the Tlingit legend about a monster who dwelt in Lituya Bay near the entrance and who, with his assistant, caused tidal waves by grasping the surface of the water and shaking it as if it were a sheet. De Laguna (written communication, Nov. 19, 1957) was told a story about a flood in Dry Bay that killed a great many people, possibly between 1850 and 1860, and also the story of a village near Dry Bay that was abandoned about 1850 because eight canoe loads of men from the village were lost in Lituya Bay when their canoes tipped over. W. A. Soboleff (oral communication, June 7, 1958) was unable to find any specific information about Lituya Bay among the people of Tlingit origin in the Juneau area, other than that the Indians had left the bay for an unknown reason and at an unknown date. These stories may indeed refer to the giant wave that formed a trimline in Lituya Bay in 1853 or 1854, but some of the stories might also refer to incidents related to the treacherous tidal current in the entrance or to an earlier or later wave.

None of these stories are of any value for determining the nature and cause of the 1853–54 wave or for dating the wave more accurately.

OTHER EVIDENCE

The only positive evidence now known for the occurrence of a giant wave in Lituya Bay in 1853–54—the destruction of vegetation along the shores—is clearly recorded on many photographs taken between 1894 and 1954. The evidence was also studied in the field in 1952–53. Only two segments of the 1853–54 trimline, totaling about a mile in length, remain on the north shore of the bay since the 1958 wave.

DATE

An approximate date of late 1853 or early 1854 for the occurrence of the oldest known giant wave in Lituya Bay was obtained from a tree ring count using the second method described on page 69. A section cut by Rossman and Plafker from a large spruce tree growing just above the oldest trimline at point *L* on figure 19 showed an injury on the side toward the bay (pl. 10). According to R. L. Godman of the Alaska Forest Research Center (R. F. Taylor, written communication, Oct. 26, 1953) the injury occurred after the end of the 1853 growing season and before the beginning of the 1854 growing season, or between mid-August and the early part of May. Rossman and Plafker estimated the age of the largest spruce tree seen in the forest below the trimline at this site in 1953 to be about 92 years.

EFFECTS OF THE WAVE

The trimline formed by the 1853-54 wave, as shown on figure 19, was mapped from field observations in 1952 and 1953, and from the single-lens verticle photographs taken in 1948. The altitude of the trimline was measured on the ground at 12 points with an altimeter, and at other points with a Kelsh plotter. Destruction of the forest by the 1853-54 wave seems to have been complete up to a sharp trimline that is easily seen on the 1948 vertical photographs and on oblique photographs (pl. 8*A*) of the north shore west of Gilbert Inlet, around Cenotaph Island, and from Coal Creek west on the south shore. These trimlines seem to intersect the beach about 1½ miles inside the entrance, on the north shore, and about 2 miles inside the entrance on the south shore. A trimline to a maximum height of 18 feet was identified by field examination in 1953 for a short distance along the steep slope north of The Paps. In 1953, along both shores in the outer part of the bay, and on La Chaussee Spit, spruce trees older than 100 years were found growing to the edge of the forest above the beach.

Field examination in 1953 indicated that on the spur southwest of Gilbert Inlet the trimline sloped down, and also became gradually less well defined toward the east. This is confirmed by McArthur's photograph (no. 128), taken in 1894. No evidence of the trimline was found, either in the field or on the photographs, along the walls of Gilbert and Crillon Inlets or on the south shore between Crillon Inlet and Mudslide Creek. This could be due to the scarcity of large trees on these steep slopes, but probably the wave had little effect at the head of the bay or along the south shore at Mudslide Creek.

Destruction of the forest on the shores of Lituya Bay by the giant wave in 1853 or 1854 extended to a maximum height of 395 feet above mean sea level and to a maximum horizontal distance of 2,500 feet inland from the high-tide shoreline, a total area of at least 1 square mile. In the 1-mile long segment used as a reference for comparison with the other waves (p. 60, 69) the band of destruction on the north and south shores averages about 620 feet in width and about 80 feet in altitude. Scarps as much as 25 feet high were seen at a few places along the trimline of the 1853–54 wave. These scarps, plus the evidence of the effects on the forest, indicate that the erosive power of the giant wave in 1853 or 1854 was comparable to that of the 1958 wave, although it did not affect as large an area. Part of the trees remained standing at the sites of the native dwellings shown at the shore near the entrance of the bay on the map of La Perouse (1798, opposite p. 146). However, the water almost certainly inundated these sites and may have destroyed the village, as indicated by native legend and by the observations in 1874 by Dall (1883, p. 203).

NATURE AND CAUSE OF THE WAVE

At the present time (1959) the only basis for speculation on the nature and cause of the 1853–54 wave is a comparison of its effects on the vegetation with the effects of the two most recent giant waves in Lituya Bay. In extent and thoroughness of its destruction, the 1853–54 wave compares most closely with the 1958 wave. From the configuration of its trimline the 1853–54 wave probably was generated at or near the head of the bay, but either at a different point or by a different cause than the 1958 wave.

A rockslide from the steep wall on the south side of Lituya Bay at the present position of or just east of Mudslide Creek (fig. 19) seemingly would best account for the maximum known height of destruction almost directly opposite on the north shore of the bay. It would also account for the minimum destruction or total lack of destruction of vegetation on the south

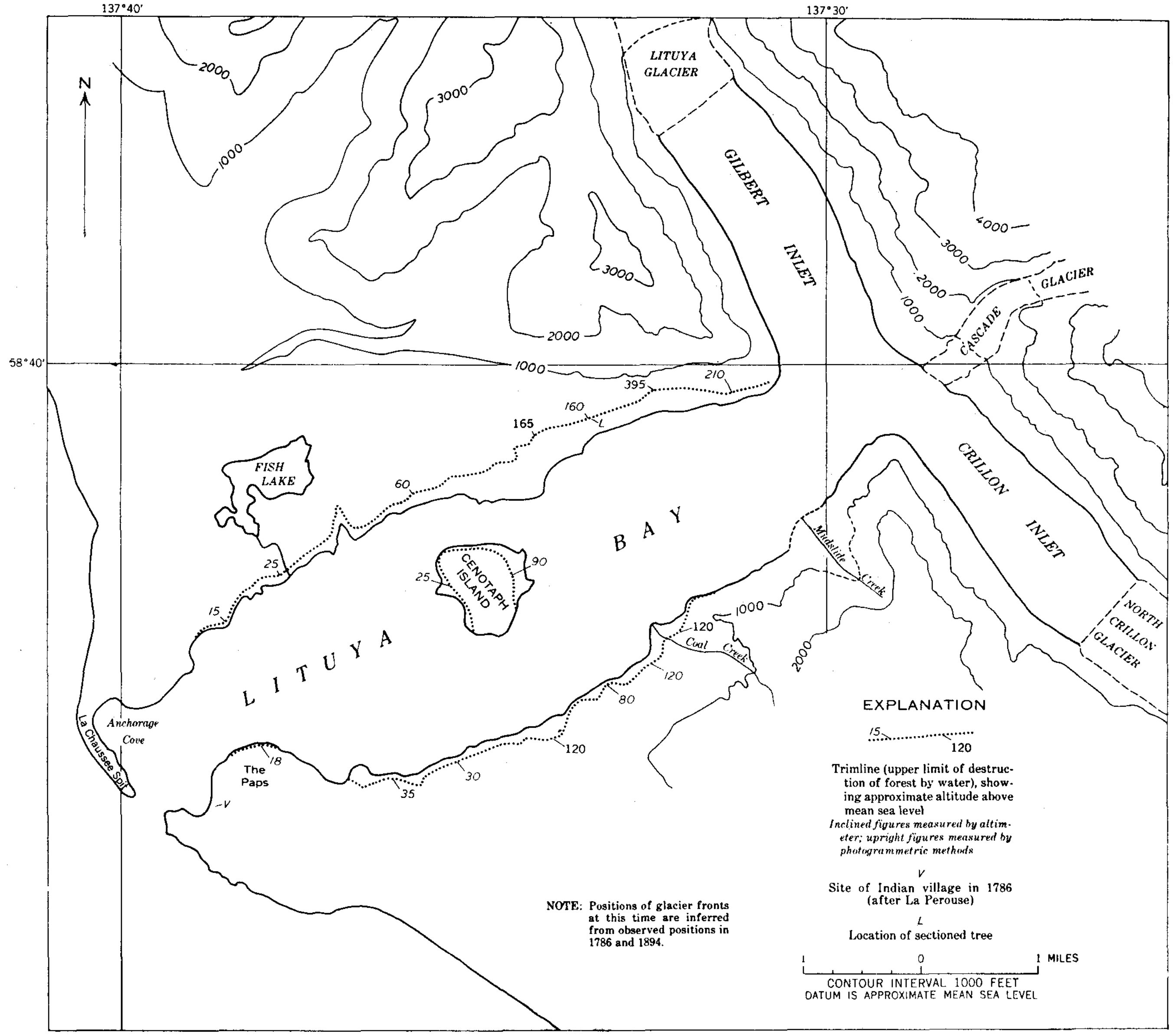


FIGURE 19.—Map of Lituya Bay showing setting and effects of giant wave that occurred in 1853 or 1854.

shore in the vicinity of Mudslide Creek, in Gilbert Inlet and in Crillon Inlet. The valley of Mudslide Creek, and particularly the east wall of the valley, is an area of active sliding at the present time, and sliding in the past probably played an important part in the formation of the valley. Photographs taken in 1894 by McArthur (nos. 105A and 128) show that the shape of the Mudslide Creek valley was similar to that shown on the 1948 vertical photographs, so any major sliding must have occurred before 1894. The sketch map of Lituya Bay made in 1874 and issued in 1875 as U.S. Coast Survey Chart 742 is almost identical to the La Perouse map in the part of the bay east of Cenotaph Island, indicating that little or no resurveying was done in the upper part of the bay. Hence a comparison of these maps gives no information on the possible occurrence of a large slide at Mudslide Creek between 1786 and 1874. The modern U.S. Coast and Geodetic Survey chart of Lituya Bay (no. 8505) shows a more pronounced bulge in the shoreline at Mudslide Creek than does the La Perouse map. The difference is slight and, in view of the small scale and questionable accuracy of the La Perouse map, only suggests but does not prove that a large slide occurred there sometime after 1786.

No major earthquakes in the region adjoining Lituya Bay are known to have been reported between 1847 (Dall, 1870, p. 342) and 1862 or 1863 (Musketov and

Orlov, 1893, p. 349, 386). The paucity of records for this period in Alaska, however, cannot be taken as proof that no earthquake occurred in conjunction with the 1853–54 wave in Lituya Bay.

POSSIBILITY OF FUTURE WAVES

Giant waves have occurred in Lituya Bay at least four times, and possibly five times within 105 years, or on the average, once every 21 to 26 years. Hence, based on the historical record only, the odds against one of these waves occurring on any single day spent in the bay are comfortably large (about 9,000 to 1). The writer believes that the odds may be much less than this at the present time because of a larger than average potential for slides resulting from (a) shaking and ground breakage associated with the 1958 earthquake; (b) removal of vegetation and unconsolidated deposits by the 1958 wave. Areas especially susceptible to sliding are outlined in figure 20. The rockslide on the northeast wall of Gilbert Inlet in 1958 created new unstable slopes at the head of the slide scar and along its southeast margin. Planes of weakness parallel to bedding or schistosity in the upper part of the 1958 rockslide area continue southeastward toward Cascade Glacier; Tocher, in August 1958 (oral communication) from the air noticed open fractures along some of these planes just southeast of the slide scar. In the field during the same month the writer found many open fractures above and generally parallel to steep slopes at altitudes ranging from 1,700 to 2,500 feet along the crests of the spurs southwest of Gilbert and Crillon Inlets. Destruction of vegetation by the 1958 wave will result in accelerated erosion of unconsolidated deposits by running water for some time to come, and therefore in further undermining of steep and unstable slopes.

Further movement along the Fairweather fault, particularly of the magnitude of the 1958 movement, could cause new slides from steep slopes around the head of Lituya Bay. Slides could also be started by freezing and thawing of water in the open fractures during the spring or fall, by unusually heavy rainfall, or merely by rock or soil failure without any triggering mechanism. In addition to the subaerial slides there may be at least one other mechanism, not yet identified, that has generated one or more giant waves in Lituya Bay in the past and might do so again in the future.

Whatever the odds against their occurring during any given short period of time, the giant waves probably will occur in Lituya Bay in the future; this potential danger should be known to those who enter the bay. Steady increase in the permanent and transient population of Alaska, as well as the development of the Glacier Bay National Monument, under normal circumstances, would result in steadily increasing use of Lituya Bay as a harbor for small boats and landing place for amphibious aircraft and, eventually, in permanent settlement. Before the 1958 wave the U.S. National Park Service was considering Lituya Bay as a site for a ranger station, for, despite the then known hazard of the entrance and the somewhat vague history of earlier waves, the bay is advantageously located on the coastline of the Glacier Bay National Monument and affords the only protected anchorage for many miles in either direction along the coast (Mitchell, L. J., written communication, Mar. 13, 1959). The giant waves thus have increased the difficulty of providing safe access to this part of the National Monument, but at the same time they have greatly enhanced the interest in the bay and its value for recreational and scientific purposes.

SUMMARY AND CONCLUSIONS

A rockslide triggered either by movement on the Fairweather fault or the accompanying shaking, on July 9, 1958 plunged into Gilbert Inlet, causing water to surge over the opposite wall of the inlet to an altitude of about 1,740 feet and generating a gravity wave that moved out from the head of Lituya Bay at a speed of about 100 miles per hour. Field investigation indicates that this surge and the giant water wave were primarily responsible for the nearly total destruction of the forest up to a sharp trimline that has a maximum altitude of about 1,720 feet opposite the rockslide and extends along the shores of the bay to the mouth. This conclusion is supported by R. L. Wiegel's study of a model of Lituya Bay and his calculations from existing theory and data on wave hydraulics.

The giant waves that rose to a maximum height of 490 feet in Lituya Bay on October 27, 1936 were generated in Crillon Inlet by some disturbance other than the previously reported flood of water from an ice-dammed lake in the basin of North Crillon Glacier. The waves of 1936 were not associated with an earthquake, and evidence is lacking that a large subaerial slide into Crillon Inlet caused them. Among other possible causes, movement of a tidal glacier front or submarine sliding seem the most plausible, but none are conclusively supported by the information at hand. Further study of a hydraulic model of Lituya Bay will probably be the most fruitful method of solving the problem of the origin of the 1936 waves. However, the necessary clue or clues may be found in contemporary photographs or observations not available in the present investigation, or in the literature on similar waves elsewhere.

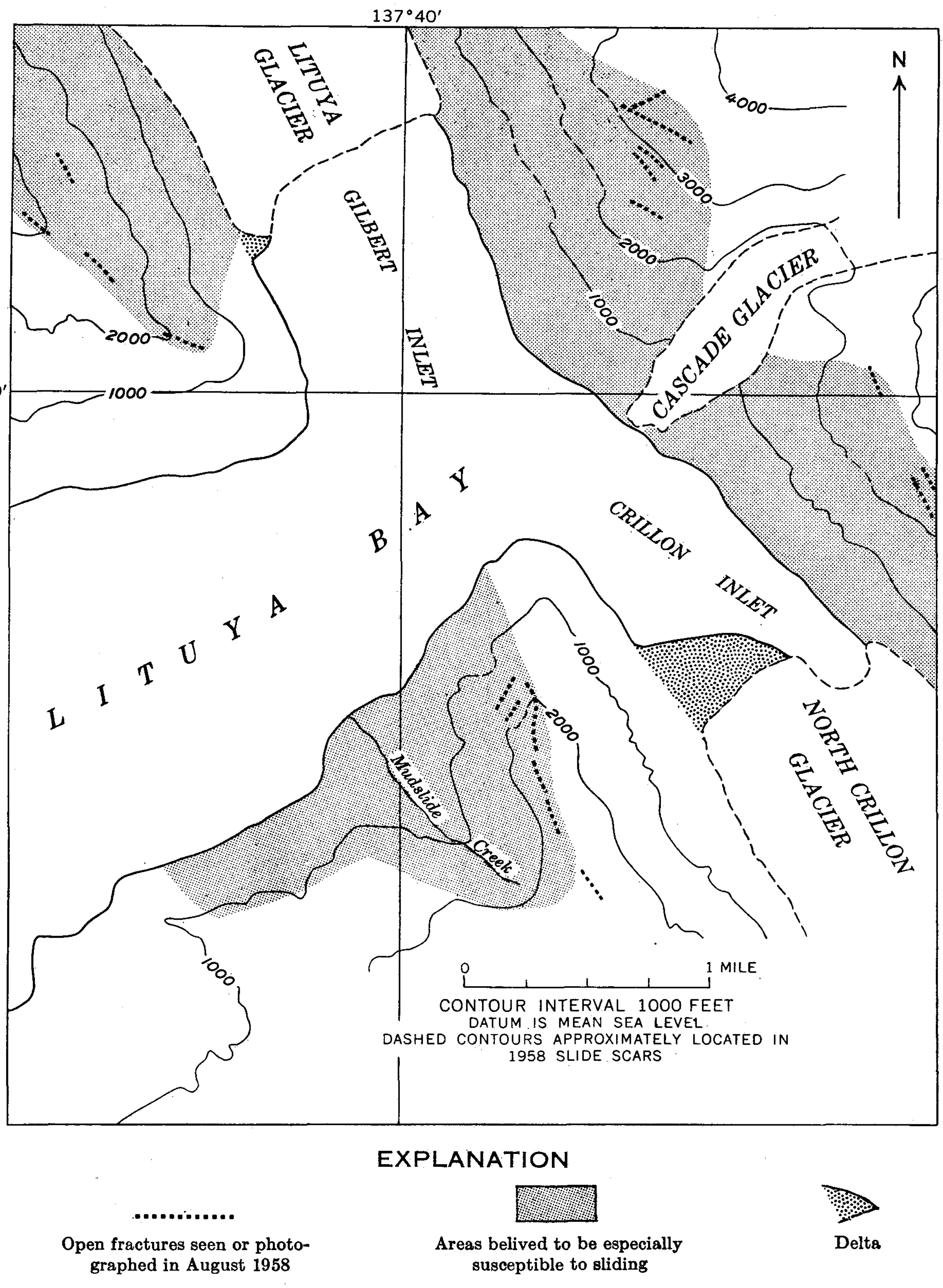


FIGURE 20.—Map of head of Lituya Bay, showing open fractures and areas believed to be especially susceptible to sliding.

Unsubstantiated oral accounts, and a possible trimline shown on photographs taken in 1916 and later, suggest that a wave 200 feet high may have been generated by a disturbance in Crillon Inlet at the time of one of the great earthquakes in 1899.

A trimline having a maximum altitude of about 80 feet on the north shore of Lituya Bay, shown clearly in photographs taken in 1894, records a giant wave that occurred after 1854 and is tentatively dated about 1874. The configuration of the trimline, as partly reconstructed from photographs, suggests sliding in the vicinity of Mudslide Creek as the cause of this wave.

A trimline having a maximum height of 395 feet on the north shore records the earliest known giant wave in Lituya Bay. Based on a tree-ring count, this wave occurred in late 1853 or early 1854. Configuration of the trimline suggests sliding in the vicinity of Mudslide Creek as the cause. No major earthquakes are known to have occurred in southern Alaska during 1853 or 1854.

The fact that giant waves have occurred more frequently in Lituya Bay than in other seemingly similar bays may be due to the following factors in combination: (a) Presence of an active fault under water at the head of the bay; (b) presence of recently glaciated, steep slopes on highly fractured and sheared rocks along the fault zone; (c) presence of deep water immediately below the steep slopes in and near the fault zone; (d) heavy rainfall and frequent freezing and thawing. The glaciers discharging into the head of the bay along the fault zone may also contribute to generation of the waves, but little direct evidence is available now to support this.

The potential for generation of localized but enormously destructive waves by the falling or sliding of solid masses into water deserves wider recognition by geologists, by engineers concerned with the planning of dams and reservoirs, and by anyone concerned with the safety or permanency of structures or equipment near the water level in lakes or bays that adjoin steep slopes. Many of the fiordlike inland waterways of southeastern Alaska, for example, have the necessary topographic and hydrographic requirements and seemingly are susceptible to the occurrence of localized waves comparable in magnitude to those in Lituya Bay, although much less frequently than in Lituya Bay.

The 1958 giant wave in Lituya Bay affords geologists and biologists an example of catastrophic destruction of plant and animal life, and also an opportunity to study the rate and nature of reestablishment of marine life in the intertidal and nearshore zones, and of plant life in the recently denuded zone above the shoreline.

REFERENCES CITED

Alaska Daily Press, 1936, 250-foot wave sweeps shore of Lituya Bay; 4 men endangered: Alaska Daily Press, Juneau, v. 39, no. 2437 (Nov. 5), p. 5.

Alaska Sportsman, 1958, Where hell breaks loose: Alaska Sportsman, Juneau, v. 24, no. 10 (October), p. 6–10.

Alaska Weekly, 1936, Wall of water sweeps Lituya; bay region hit by wave 250 feet high; much damage reported: Alaska Weekly, Seattle, Wash,; v. 39, no. 35 (Nov. 27), p. 3.

Bancroft, H. H., 1886, History of Alaska: San Francisco, Calif., 775 p.

Boursin, Henry, 1893, Mining and other industries of Alaska, *in* Report on population and resources of Alaska at the eleventh census, 1890: Washington, U.S. Government Printing Office, p. 229–241.

Brazee, R. J., and Jordan, J. N., 1958, Preliminary notes on southeastern Alaska earthquake: Earthquake Notes, v. 29, no. 3, p. 36–40.

Brigham, A. P., 1906, A Norwegian landslip: Geog. Soc. Bull. Philadelphia, v. 4, p. 292–296.

Buddington, A. F., and Chapin, Theodore, 1929, Geology and mineral deposits of southeastern Alaska: U.S. Geol. Survey Bull. 800, 398 p.

Bugge, Arne, 1937, Fjellskred fra topografisk og geologisk synspunkt: Norsk geog. tidsskr., Oslo, v. 6, no. 6, p. 342–360, 14 figs.

Carpe, Allen, 1931, The conquest of Mount Fairweather: London, Alpine Jour., v. 43, p. 221–231.

Daily Alaska Empire, 1958a, Earthquake kills three; Idaho Inlet couple missing; comparable to 'Frisco quake (by Assoc. Press): Daily Alaska Empire, Juneau, v. 92, no. 14,008 (July 10), p. 1.

——— 1958b, Lituya Bay shoreline stripped clean by huge tidal wave, ice slides: Daily Alaska Empire, Juneau, v. 92, no. 14,009 (July 11), p. 1.

——— 1959, Survey teams to study Lituya Bay earthquake area: Daily Alaska Empire, Juneau, v. 93, no. 14,227 (Mar. 31), p. 1.

Dall, W. H., 1870, Alaska and its resources: Boston, Mass., Lee and Shepard, 627 p.

——— 1878, Report on Mount St. Elias, Mount Fairweather, and some of the adjacent mountains (Alaska), *in* U.S. Coast Survey Rept. 1875: U.S. 44th Cong., 1st Sess., H. Ex. Doc. 81, p. 157–188.

——— 1883, *in* U.S. Coast and Geodetic Survey Pacific Coast Pilot, Alaska, pt. 1, p. 202–204.

de Laguna, Frederica, 1953, Some problems in the relationship between Tlingit archaeology and ethnology: Soc. Am. Archaeology, Mem. 9 (supp. to Am. Antiquity), v. 18, no. 3, pt. 2, p. 53–57.

Eckel, E. B., ed., 1958, Landslides and engineering practice: Highway Research Board Spec. Rept. no. 29 (NAS–NCR Pub. 544), 232 p.

Emmons, G. T., 1911, Native account of the meeting between La Perouse and the Tlingit: Am. Anthropologist, n. ser., v. 13, p. 294–298.

Fons, W. L., and Pong, W. Y., 1957, Tree breakage characteristics under static loading; ponderosa pine: U. S. Dept. Agriculture, Div. Fire Research, Forest Service, Interim Tech. Rept. AFSWP–867, 51 p.

Goldthwait, R. P., 1936, Seismic soundings on South Crillon and Klooch Glaciers: London, Geog. Jour., v. 87, p. 496–517.

Gryc, George, Miller, D. J., and Payne, T. G., 1951, Possible future petroleum provinces of North America; chapter on Alaska: Am. Assoc. Petroleum Geologists Bull., v. 35, p. 151–168.

Gutenberg, Beno, 1939, Tsunamis and earthquakes: Seismol. Soc. America Bull., v. 29, p. 517–526.

Heezen, B. D., 1957, 1908 Messina earthquake, tsunami, and turbidity current [abs.]: Geol. Soc. America Bull., v. 68, p. 1743.

Henrickson, E. L., 1959, Alaskan adventure: Voice [Carleton Alumni], v. 24, no. 4 (Jan.), p. 14–19.

Holmsen, Gunnar, 1936, De siste bergskred i Tafjord og Loen, Norge: Svensk geog. årsbok, årg 12, p. 171–190, 5 figs., 1 pl., Lund.

Holtedahl, Olaf, 1953, Norges Geologi: Norges Geologiske Undersökelse, no. 164, v. 2, p. 1044–1048, figs. 461–462.

International Boundary Commission, 1952, Joint report upon the survey and demarcation of the boundary between Canada and the United States from Tongass Passage to Mount St. Elias: U.S. Dept. State, Washington, 365 p.

Ippen, A. T., and Mitchell, M. M., 1957, The damping of the solitary wave from boundary shear measurements: Mass. Inst. Tech. Hydrog. Lab. Tech. Rept. no. 23, 50 p.

Jørstad, F. A., 1956, Fjellskredet ved Tjelle; et 200-års minne: Naturen årg 80, no. 6, p. 323–333.

Kaldhol, H. and Kolderup, N. H., 1937, Skredet i Tafjord 7. april 1934: Bergens Museums Årbok 1936, nat. rekke, v. 2, no. 11, 15 p., 4 figs., map.

Kennedy, G. C., and Walton, M. S., 1946, Geology and associated mineral deposits of some ultrabasic rock bodies in southeastern Alaska: U.S. Geol. Survey Bull. 947–D, p. 65–84.

Klotz, O. J., 1899, Notes on glaciers of southeastern Alaska and adjoining territory: Geog. Jour., v. 14, p. 523–534.

La Perouse, J. F. de G., 1798, The voyage of La Perouse round the world in the years 1785, 1786, 1787, and 1788, arranged by M. L. A. Milet-Mureau: London, printed for John Stockdale, v. 1, A1–A—4, p. 1–290. (English translation of the 1st ed. in French, Paris, Imprimerie de la République, 1897. The section on Alaska is reproduced also in Le voyage de LaPérouse sur les côtes de l'Alaska et de la Californie (1786), avec une introduction et des notes par Gilbert Chinard: Baltimore, Md., Johns Hopkins Press, p. 1–144, 1937).

Leet, L. D., 1948, Causes of catastrophe: New York, McGraw-Hill, 232 p.

McNown, J. S., 1952, Waves and seiche in idealized ports, *in* Gravity Waves, a symposium: Natl. Bur. Standards Circ. 521, p. 153–164.

Mertie, J. B., Jr., 1931, Notes on the geography and geology of Lituya Bay, Alaska: U.S. Geol. Survey Bull. 836–B, p. 117–135.

Miller, D. J., 1953, Preliminary geologic map of Tertiary rocks in the southeastern part of the Lituya district, Alaska: U.S. Geol. Survey open-file report.

——— 1954, Cataclysmic flood waves in Lituya Bay, Alaska (abs.): Geol. Soc. America Bull., v. 65, p. 1346; 5th Alaskan Sci. Conf., Anchorage, Sept. 7–10, 1954; Proc., 1957, p. 56–57.

Musketov, I., and Orlov, A., 1893, Catalog of earthquakes of the Russian Empire: Contr. Russian Geog. Soc., in general geography. v. 26, 582 p.

Neuman, Frank, 1938, United States earthquakes, 1936: U.S. Coast and Geod. Survey Pub. no. 610, 45 p.

Ogawa, Takuji, 1924, Notes on the volcanic and seismic phenomena in the volcanic district of Shimabara, with a report on the earthquake of December 8th, 1922: Kyoto Imp. Univ., Mem. Coll. Sci., ser. B., v. 1, p. 201–254.

Omori, F., 1907, Note on the eruptions of the Unsen-daké in the 4th year of Kansei (1792): Imp. Earthquake Inv. Committee Bull., Tokyo, v. 1, p. 142–144.

Petroff, Ivan, 1884, Report on the population, industries, and resources of Alaska: Tenth Census of the United States, v. 8, 189 p.

Press, Frank, 1956, Volcanoes, ice, and destructive waves: Engineering and Science, v. 20, no. 2 (Nov.), p. 26–28, 30.

Prins, J. E., 1958a, Characteristics of waves generated by a local disturbance: Am. Geophys. Union Trans., v. 39, p. 865–874.

——— 1958b, Water waves due to a local disturbance: Proc. 6th Conf., Coastal Engineering, Council Wave Research, Eng. Found., Berkeley, Calif., p. 147–162.

Reid, H. F., 1908, The variations in glaciers, XII: Jour. Geology, v. 16, p. 46–55.

Russell, I. C., 1891, An expedition to Mount St. Elias: Natl. Geog. Mag., v. 3, p. 53–204.

Seismological Society of America Bulletin, 1958, Seismological notes: Seismol. Soc. America Bull., v. 48, p. 403–407.

Sharp, R. P., 1954, Glacier flow: a review: Geol. Soc. America Bull., v. 65, p. 821–838.

Sharpe, C. F. S., 1938, Landslides and related phenomena: New York, Columbia Univ. Press, 137 p.

Shelikof, G. I. [Shelekhof], 1812, Voyages: St. Petersburg; [English translation by Ivan Petroff], Bancroft Library, Calif. Univ.

Shepard, F. P., Macdonald, G. A., and Cox, D. D., 1950, The tsunami of April 1, 1946: Scripps Inst. Oceanography Bull., v. 5, no. 6, p. 391–528.

St. Amand, Pierre, 1957, Geological and geophysical synthesis of the tectonics of portions of British Columbia, the Yukon Territory, and Alaska: Geol. Soc. America Bull., v. 68, p. 1343–1370.

Tarr, R. S., 1909, The Yakutat Bay region, Alaska: Physiography and glacial geology: U.S. Geol. Survey Prof. Paper 64, pt. 1, p. 1–144.

Tarr, R. S., and Martin, Lawrence, 1912, Earthquakes at Yakutat Bay, Alaska, in September, 1899, with a preface by G. K. Gilbert: U.S. Geol. Survey Prof. Paper 69, 135 p.

Tocher, Don, and Miller, D. J., 1959, Field observations on effects of Alaska earthquake of 10 July, 1958: Science, v. 129, no. 3346, p. 394–395.

Ulrich, Howard, [as told to Haynes, Vi], 1958, Night of terror: Alaska Sportsman, v. 24, no. 10 (October), p. 11, 42–44.

U.S. Coast and Geodetic Survey, 1935, Tide tables, Pacific Coast and Indian Ocean for the year 1936: ser. no. 576, p. 65.

——— 1942, Chart 8505, Lituya Bay.

——— 1952, Coast Pilot, Southeast Alaska, p. 474.

——— 1957, Tide tables, West coast of North and South America, 1958, p. 120, 182.

U.S. Congress, 1904, Proceedings of the Alaskan Boundary Tribunal: U.S. 58th Cong., 2d Sess., Doc. No. 162, atlas, pt. 3, sheet no. 16.

U.S. Weather Bureau, 1938, Climatological data, Alaska, summary for 1936: v. 22, no. 13, p. 69–79.

——— 1958, Climatological data, Alaska, summary for 1957: v. 43, no. 13, p. 204–215.

Washburn, Bradford [H. B., Jr.], 1935, The conquest of Mount Crillon: Natl. Geog. Mag., v. 67 p. 361–400.

——— 1936, The Harvard-Dartmouth Alaskan expeditions: London, Geog. Jour., v. 87, p. 481–495.

Wiegel, R. L., 1955, Laboratory studies of gravity waves generated by movement of a submerged body: Am. Geophys. Union Trans., v. 36, p. 759–774.

Wiegel, R. L., and Beebe, K. E., 1956, The design wave in shallow water: Jour. Waterways Div., Am. Soc. Civil Engineers, v. 82, no. WW1, paper 910, 21 p.

Wiegel, R. L., Beebe, K. E., and Moon, James, 1957, Ocean wave forces on circular cylindrical piles: Jour. Hydrol. Div., Am. Soc. Civil Engineers, v. 83, no. HY2, paper 1199, 36 p.

Wiegel, R. L., and Skjei, R. E., 1958, Breaking wave force prediction: Jour. Waterways Div., Am. Soc. Civil Engineers, v. 84, no. WW2, paper 1573, 14 p.

Williams, Howel, 1941, Calderas and their origin: Calif. Univ. Pub., Bull. Dept. Geol. Sci., v. 25, p. 239–346.

Williams, Jay [J. P.], 1938, Lituya the bewitcher: Alaska Sportsman, v. 2, no. 2 (February), p. 6, 18–19, *incorporated with little change in Williams, J. P.*, 1952, Alaskan Adventure: Harrisburg, Pa., Stackpole Co., p. 133–138.

Wood, H. O., 1914, On the earthquake of 1868 in Hawaii: Seismol. Soc. America Bull., v. 4, p. 169–203.

INDEX