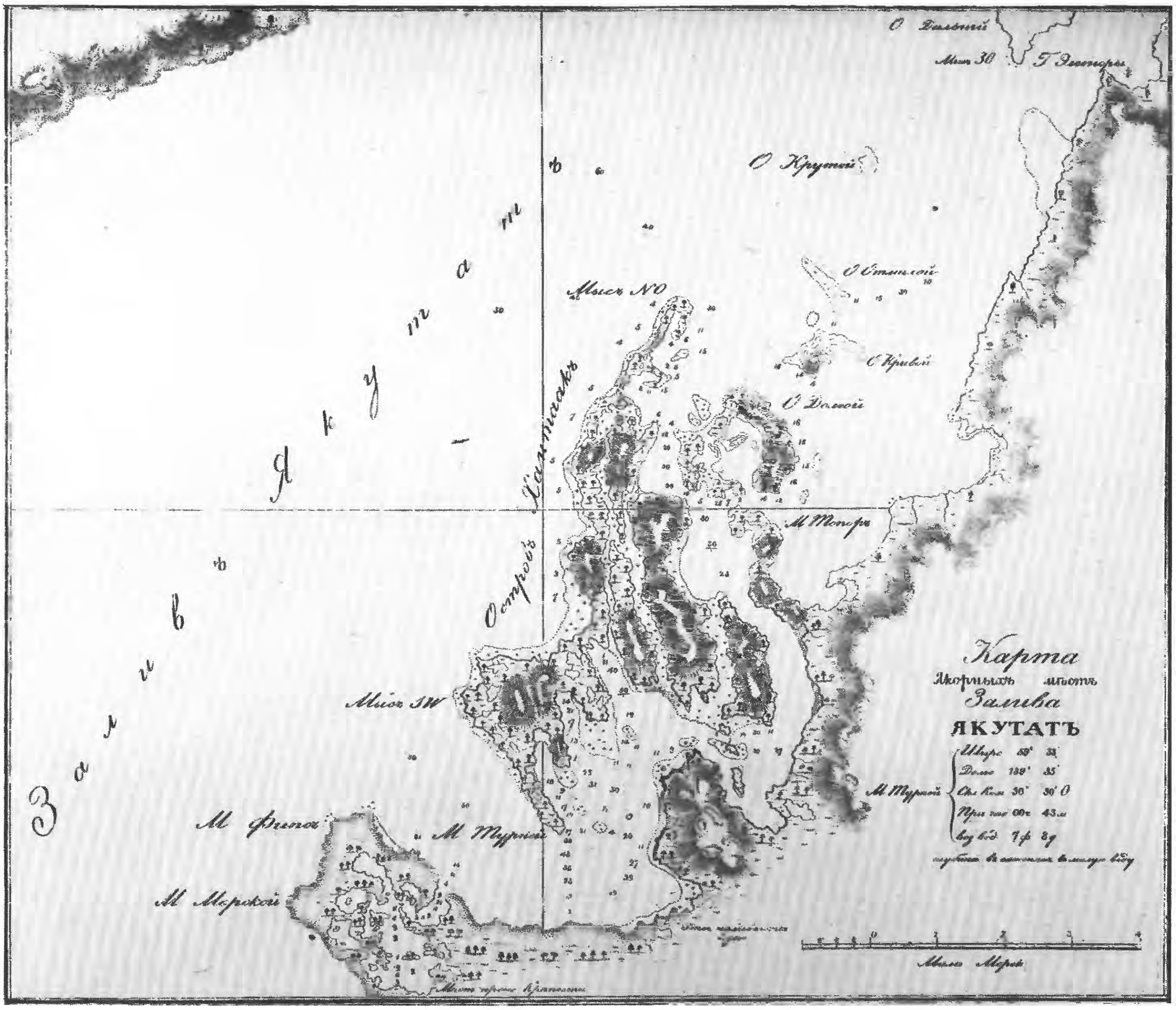
Reconnaissance Engineering Geology of the Yakutat Area, Alaska, With Emphasis on Evaluation of Earthquake and Other Geologic Hazards

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1074

RECONNAISSANCE ENGINEERING GEOLOGY OF THE YAKUTAT AREA, ALASKA, WITH EMPHASIS ON EVALUATION OF EARTHQUAKE AND OTHER GEOLOGIC HAZARDS



Map of Yakutat Bay, 1849 (Tebenkof, 1852, map 7)

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By LYNN A. YEHLE

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Coarse-grained surficial deposits (mostly in young moraines and associated outwash) underlie much of the Yakutat area close to deep-water Yakutat Bay. Earthquakes and related water waves are the prime geologic hazard; five very large earthquakes with magnitudes of 7.0–8.6 have shaken the area during the period 1893–1975

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By LYNN A. YEHLE

ABSTRACT

Yakutat, situated about 360 km northwest of Juneau, Alaska, near the shore of the Gulf of Alaska, has a setting that calls for superlatives. Within the Yakutat region are some of the tallest mountains, some of the heaviest snowfalls, and the largest glacier (Malaspina) in North America. Between the abrupt mountain front and the Gulf of Alaska lies a very gently sloping plain of outwash derived from repeated cycles of advance and retreat of glaciers during the Quaternary Period. The latest melting probably took place 500 to 600 years ago. Yakutat is built upon the moderately steep moraine that is the product of melting of one of these glaciers. Near Yakutat, surficial deposits may be more than 213 m thick and they may overlie siltstone, sandstone, and mudstone. The eight general categories of mapped surficial deposits are artificial fill, organic, eolian, beach, delta-estuarine, alluvial, and outwash deposits, and end and ground moraine deposits of the area.

The Yakutat region is part of an active tectonic belt that rims most of the North Pacific Ocean. The latest episode of activity probably began in early Miocene time. Many faults are active, as indicated by numerous earthquakes in the area. One fault is known to have broken the ground surface in historic time, the nearly vertical Fairweather fault, whose closest segment is about 53 km northeast of Yakutat. Movement along this fault caused the major earthquake of July 10, 1958 (magnitude 7.9). The great earthquake of September 10, 1899 (magnitude 8.6), probably was caused by tectonic uplift within a broad area centered about 47 km north of Yakutat. Uplift averaged 2–3 m; one small area shows uplift of about 14.4 m, the greatest onshore uplift ever measured for an earthquake sequence. A sequence of earthquakes in July 1973, centered offshore approximately southeast of Yakutat, has been related to an inferred fault, the Transition fault.

Many earthquakes have been felt at Yakutat since written historic records were first kept. Five very large earthquakes (magnitude 7.0 to 8.6) occurred within a radius of 130 km from Yakutat in the period from 1893 through 1975. Of these earthquakes, those of September 10, 1899, and July 10, 1958, were the strongest, causing some damage to buildings at Yakutat. Earthquakes of equally large size undoubtedly will shake the Yakutat area in the future.

Several geologic effects that have characterized large earthquakes in the past may be expected to accompany large earthquakes in the future. These effects include (1) tectonic uplift; (2) severe ground shaking; (3) liquefaction of some delta-estuarine, alluvial, and fine-grained outwash deposits; (4) ejection of water and sand as fountains from individual craters; (5) compaction and differential subsidence of some materials, especially young and intermediate delta-estuarine deposits and some artificial fills; and (6) landslides, where terrain is steep or where beach spits and delta-estuarine deposits are newly deposited and poorly consolidated.

Large water waves commonly are formed during large coastal earthquakes. Tsunami (seismic sea) waves arriving from large earthquakes at great distances can be forecast, but advance warnings of locally formed waves cannot be provided. To date, the highest recorded earthquake-related waves at Yakutat were about 5 m high and occurred during the largest earthquake of the sequence during September 10, 1899.

Geologic hazards in the Yakutat region not necessarily associated with earthquakes include (1) subaerial and submarine landsliding, (2) stream flooding and erosion of surficial deposits, (3) high waves, and (4) glacier advances and breakout of glacier-dammed lakes.

Recommended future geologic and geophysical studies in the Yakutat area and surrounding region could provide additional information needed for land-use planning. Expansion of general and detailed geologic mapping and collection of data on geologic materials, joints, faults, and stability of slopes are strongly recommended to help delineate areas of economic mineral deposits, to identify hazardous slopes, and to locate suitable areas for construction. There should be expansion of the studies of earthquakes in the region. Such work might lead to prediction of the location of future large earthquakes. Installation of additional seismological instruments could provide information on the location of any unknown active faults and an index of the overall tectonic activity of the region. Additional offshore geophysical studies are needed to determine the nature and position of submarine faults and their relationship to the stability of sediments on the sea floor. Determination of the natural periods of oscillation of Yakutat Bay and adjoining fiords as well as the nearby Continental Shelf would assist in the prediction of heights of tsunami and other water waves that might be associated with seismic shaking.

Other studies might concentrate on analysis of slopes that appear unstable and possibly are subject to landsliding. Finally, glaciers that (1) are advancing rapidly, (2) appear likely to form glacier-dammed lakes, or (3) appear susceptible to sudden breakage should be studied.

INTRODUCTION

Soon after the great Alaska earthquake of 1964, the U.S. Geological Survey started a program of geologic study and evaluation of earthquake-damaged cities in Alaska. Subsequently, the Federal Reconstruction and Development Planning Commission for Alaska recommended that the program be extended to other communities in Alaska that had a history of earthquakes, especially communities near tidewater. As a result, Yakutat and eight other communities in southeastern

Alaska were selected for reconnaissance investigation. Reports were previously completed for the communities of Haines (Lemke and Yehle, 1972a), Juneau (Miller, 1972), Ketchikan (Lemke, 1975), Metlakatla (Yehle, 1977), Petersburg (Yehle, 1978), Sitka (Yehle, 1974), Skagway (Yehle and Lemke, 1972), and Wrangell (Lemke, 1974); a generalized regional report was prepared for southeastern Alaska (Lemke and Yehle, 1972b).

The present report (and a predecessor (Yehle, 1975)) concerns the Yakutat area and describes highlights of the geology and emphasizes the evaluation of hazards associated with large earthquakes and of other geologic hazards, including subaerial landsliding, submarine landsliding, and high water waves of several types. These descriptions and evaluations, even though intended only as preliminary and tentative, should be helpful in some measure to land-use planning.

ACKNOWLEDGMENTS

Several U.S. Geological Survey colleagues gave assistance during different phases of the study: R. W. Lemke gathered data during the initial phase of the work; George Plafker and Austin Post contributed unpublished data on regional geology; W. H. Gawthrop and R. A. Page contributed unpublished data on regional seismicity; R. C. Trumbly, E. E. McGregor, and P. S. Powers analyzed samples; Meyer Rubin dated wood and shell samples by radiocarbon methods; R. P. Maley and B. L. Silverstein furnished information on earthquake-detection instruments; and V. K. Berwick and S. L. Obernyer prepared data on water wells and test borings. Information also was obtained through interviews and through correspondence with residents of Yakutat and with Federal, State, and city officials who were familiar with the Yakutat area. Especially acknowledged is the help of former Yakutat Mayors Byron Mallott and John Williams and personnel of the Alaska Departments of Highways and of Game and Fish, the U.S. Forest Service, and the U.S. Bureau of Public Roads.

GEOGRAPHY

Yakutat lies at lat 59°33′ N. and long 139°44′ W.; it is situated on the shore of Monti Bay, along an outer part of Yakutat Bay, about 360 km northwest of Juneau, Alaska (fig. 1, pl. 1). For purposes of discussion in this report, the Yakutat region is defined as extending to the boundaries shown in figure 2, and the Yakutat area is defined as extending to the boundaries shown on plate 1, encompassing most of the B-5 and C-5 quadrangles. The frontispiece shows part of the same area as it appeared before the development of Yakutat. Four principal concentrations of population exist in the area: (1) near the head of Monti Bay and containing the civic center of Yakutat; (2) near what is informally called Old Village, centered about 1.6 km to the northwest; (3) near Yakutat Airport; and (4) near Ocean Cape (McCabe, 1971; Sealaska Corporation, 1973). Landscape in the region near Yakutat is characterized by the spectacular peaks of the Saint Elias Mountains to the north and northeast, which rise above large glaciers and icefields, and by Yakutat Bay and its connecting waterways. Close to the city, the major geographic features include (1) the low hills and small lakes of the end moraines that rim the southeast shore of Yakutat Bay; and (2) the nearly flat plain of outwash deposits and shallow-water marine deposits, part of the Yakutat Foreland, extending from the city to the Gulf of Alaska, where there are several types of shore features.

Land near Yakutat has been subaerially exposed for only a relatively short period of time (Billings, 1970, p. 7). Land formed directly from glaciers probably is no older than about 500–600 years. Some land has emerged above tidal levels within only the last several hundred years, while other areas, notably the older beaches, might have had their beginnings as long ago as several thousands of years.

GLACIATION AND ASSOCIATED LAND- AND SEA-LEVEL CHANGES

Glaciers in the Yakutat region were vastly expanded on several occasions during the Pleistocene Epoch; they were moderately expanded at least several times during the Holocene Epoch. Most evidence of glacial erosion and deposition is obliterated by later glacial advances, especially in lowland areas. In a few places along mountain valleys and mountain fronts, however, evidence is preserved that is thought to be a record of glacial events rather than of other processes, such as tectonic uplift. Such places are the prominent, relatively gently sloping topographic surfaces at about 530- to 670-m altitude along the steep mountain front between Yakutat Bay and Russell Fiord and at about 400- to 500-m altitude southeast of Russell Fiord. These surfaces probably attest to the importance of glacial erosion in sculpting the mountains northeast of Yakutat. Surfaces at lower altitudes along the mountain front may owe their origin to glacial erosion, glacial deposition, or wave action.

Glacial drift deposits are abundant on the floor of

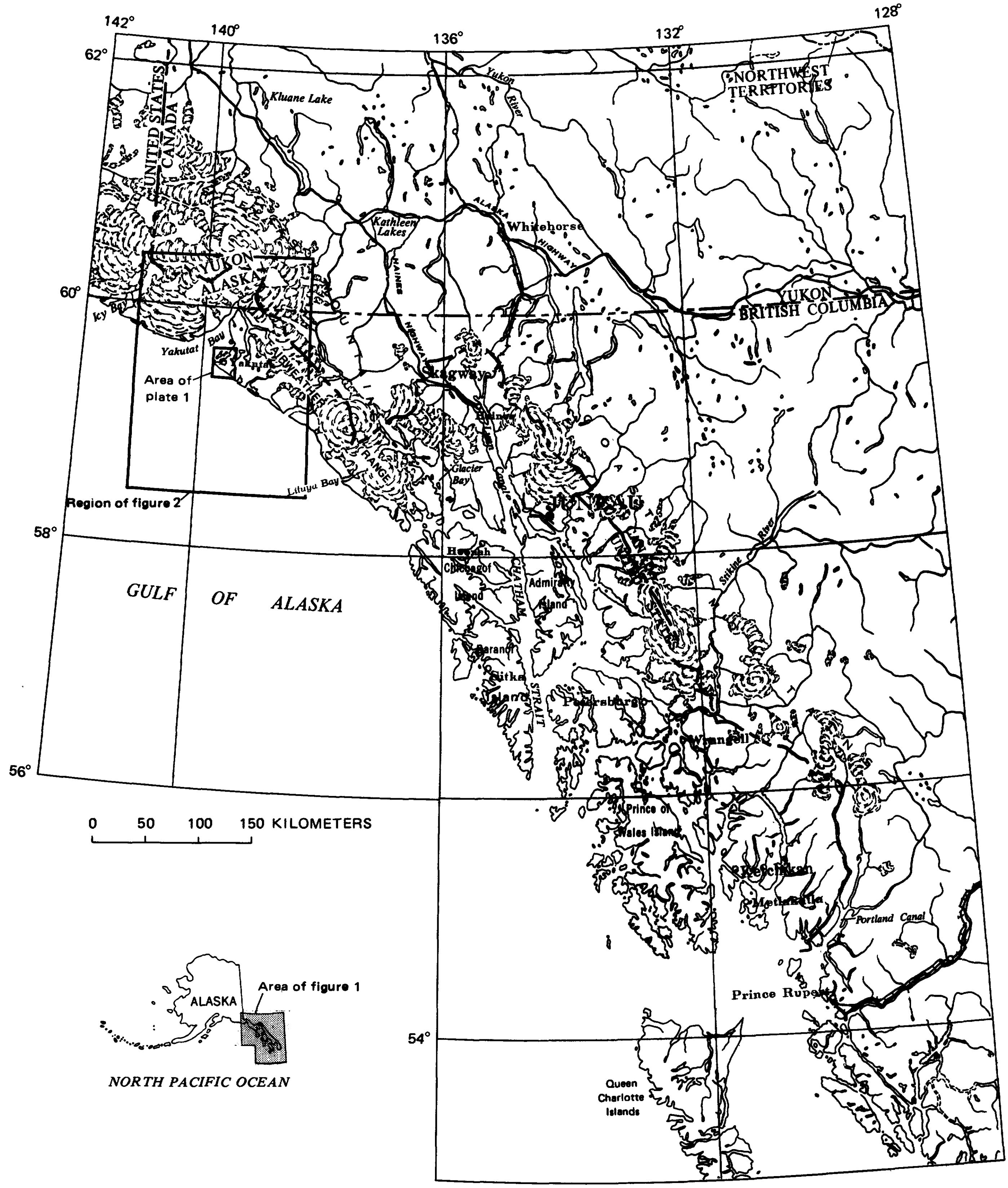


FIGURE 1.—Index map of southeastern Alaska and adjacent Canada showing location of Yakutat.

Yakutat Bay and along adjacent lowland areas; they have been studied by several investigators (Tarr, 1909; Plafker and Miller, 1958; Miller, 1961; Plafker, 1967; Wright, 1972). At least three groups of moraines, and possibly four, have been recognized. The group of moraines looping along the southeast side of the outer part of Yakutat Bay is subaerially the most prominent of the groups. It was deposited about 500–600 years ago, according to interpretations of several radiocarbon dates. (See discussion of end and ground moraine deposits in section "Description of Mapped Geologic Units.") Glacier ice presumably has entirely melted from within the moraines. However, a special study of the mapped area was not undertaken to locate evidence of ground collapse and tilted trees which might indicate melting ice, such as the study undertaken in the Lituya Bay area (fig. 1) by Post and Streveler (1976) on moraines of probably similar age. The most recent major glacial event in the Yakutat region was the sudden breakup or retreat in the mid(?)-1800's of a glacier in ancestral Russell Fiord that fronted southward into a large lake, about 50 km^2 in size and having a maximum depth of about 330 m, in the southern part of the fiord. The lake apparently drained suddenly as the glacier retreated. These combined events drastically reduced the flow of the Situk River (pl. 1; de Laguna and others, 1964, p. 17; Post and Mayo, 1971). Before these events, the river carried the outflow of the dammed lake. The former lake and glacier may have a modern counterpart to the southeast in the form of Harlequin Lake (fig. 2) and its glaciers. Austin Post (oral commun., 1975) suggested that some of the largest glaciers draining toward Harlequin Lake fill a former fiord which extended far back into the mountains. The environment is marine, as indicated by fossils contained in glacial deposits at several localities near the lake, including the northeastern margin (S. R. Welty, written commun., 1967). Fossils from near the southeastern margin have been radiocarbon dated as having an age of 9,320 ± 350 yrs B.P. (before present) (U.S. Geol. Survey sample W-2917, Meyer Rubin, written commun., 1974).

Numerous glaciers and icefields still exist in the Yakutat region. Although most of these features are in a state of near equilibrium or are melting or otherwise retreating, at least one, Hubbard Glacier, at the head of Disenchantment Bay, is advancing.

The position of land in relation to sea level in the Yakutat area has changed greatly within the last tens of thousands of years; at present, land is emerging, as it has done for much of late Cenozoic time. Land-level change may be caused by one or more conditions. The expansion and contraction of glaciers affect sea level throughout the world as well as locally. The weight of a very large mass of glacial ice depresses land (Gutenberg, 1951, p. 172); 205 m of ice, theoretically, is capable of causing a land depression of 83 m. Melting of ice causes land to slowly rebound; however, in most areas there is a timelag between melting and rebound, and thus marine waters temporarily may occupy low areas. For glaciers of sufficiently large size, each cycle of advance and retreat, theoretically, is accompanied by relative subsidence and then an emergence of land.

Other possible causes for the relative emergence of land near Yakutat are not related to deglaciation but to tectonic movements, presumably mostly uplift, which result from stresses deep within the western part of the North American Continent and the adjacent Pacific Ocean.

The most recent sudden tectonic uplift in the region resulted in a large zone of emergence having an average uplift of about 2–3 m and maximum uplift at the surface of about 14.4 m. This value was recorded about 50 km north of Yakutat after the earthquakes of September 1899 (Tarr and Martin, 1912). Tectonic uplift, some of which may be gradual, probably is the cause of most of the relative emergence of the prominent, gently sloping topographic surfaces mapped by Miller (1961) along the mountain front east-northeast and east of Yakutat and mapped in part by Hudson, Plafker, and Rubin (1976) in the Lituya Bay region (fig. 1).

Measurements of the relative emergence of land at Yakutat indicate an average emergence of 0.53 ± 0.05 cm per year, on the basis of readings of the Yakutat tidal gage during the period 1940 through 1972 (Hicks and Crosby, 1974). Using that value and projecting it for a 50-year period, there is, in theory, a possible emergence of 26.7 cm, which could result in 17 m of new land where shore areas slope very gently (1°, 1.75 percent).

DESCRIPTIVE GEOLOGY

REGIONAL SETTING

Several reconnaissance as well as detailed studies have been completed that deal with various aspects of the geology of the Yakutat region. Of primary importance are reports by Tarr (1909), Tarr and Butler (1909), Plafker and Miller (1957, 1958), Miller (1961), Plafker (1967, 1971), Stoneley (1967), and MacKevett and Plafker (1970). Distribution of major groupings of bedrock and generalized locations of major faults in the region, as shown in figure 2, are based on these reports. Consideration of structure is given in the section "Structural Geology."

The known bedrock exposures closest to Yakutat are at the abrupt mountain front, about 24 km northeast of the city. These rocks are part of the Yakutat Group (within the upper Mesozoic unit, fig. 2) of Jurassic(?) and Cretaceous age (Plafker, 1967) that includes several types of interbedded, hard, generally metamorphosed sedimentary and volcanic rocks; namely, graywacke, siltstone, conglomeratic siltstone, conglomerate, and greenstone. Beneath the thick unconsolidated Holocene deposits that form the Yakutat Foreland are Tertiary sedimentary rocks penetrated by exploratory test wells during oil exploration (Plafker, 1967). These rocks probably are similar to rocks exposed west of Yakutat Bay, where there are moderately soft siltstone and sandstone and various types of mudstone. The average thickness of surficial deposits and depth to bedrock at Yakutat probably exceed 102 m, as shown by the fact that the city water well drilled to 102 m did not reach bedrock (V. K. Berwick, written commun., 1965). About 5 km east of the airport, a test well (pl. 1) penetrated 64 m of surficial deposits before reaching bedrock (George Plafker, written commun., 1976).

LOCAL GEOLOGIC SETTING

The distribution of geologic materials in the Yakutat area is shown on plate 1. Materials were examined in reconnaissance near roads, along some trails, along the Gulf of Alaska or outer coast, and along the northern and southern ends of Khantaak Island. Elsewhere, information was obtained largely by interpretation of airphotos, supplemented by data from borings for water wells and for highway locations (U.S. Army Corps of Engineers, 1959; Franklet, 1970; U.S. Bureau Public Roads, written commun., 1962). Seventeen types of geologic materials in the following eight categories were recognized and mapped—artificial fill, two types of organic deposits, eolian sand deposits, three types of beach deposits, four types of delta-estuarine deposits, three types of alluvial deposits, two types of glacial outwash deposits, and one heterogeneous group of materials comprising end and ground moraine deposits. Detailed descriptions of these geologic materials follow. Information on selected characteristics and physical properties of the mapped geologic materials is given in table 1. These include attitude of slopes, permeability, surface drainage, ground-water level, compactness, and frost susceptibility. The suitability of these materials for selected construction purposes—as construction aggregate, as fill, and as foundations for roads and large structures—is also shown in table 1.

DESCRIPTION OF MAPPED GEOLOGIC UNITS

ARTIFICIAL FILL

Artificial fill includes the larger areas of fill and also most of the areas of ground extensively modified during construction. Materials consist chiefly of (1) pebble gravel and sand, (2) some silty pebbly sand, and (3) cobbles. The thickness ranges from 1 to 10 m. Many of the active and abandoned borrow pits used as sources of fill and construction aggregate are shown on plate 1. Locally, materials probably have been obtained from intertidal areas, but evidence of such exploitation is quickly obliterated by the action of longshore currents and waves.

ORGANIC DEPOSITS

Areas that were interpreted, by use of airphotos, as being wet and containing considerable amounts of organic materials are placed in this map unit. Materials probably are derived from the decomposition of small woody plants, mosses, and sedges and other water plants. Areas denoted as marshes and swamps on the published topographic map delineate only a part of the total area of mapped organic deposits. Thickness of deposits probably averages 1.5 m and ranges from 1 to 2 m. The area covered by organic deposits has been broken down into two subunits on the basis of the type of underlying material: (1) Organic deposits thought to be underlain chiefly by coarse rock fragments; namely, sandy pebble gravel or silty, sandy pebble gravel deposited by streams. Cobbles form a part of the constituents near the end and ground moraine deposits along the southeast shore of Yakutat Bay. (2) Organic deposits underlain by fine-grained, stream-deposited materials, chiefly sand and silty sand, locally including silt. The silt probably owes its origin to wind and subsequent deposition in quiet waters of ponds, small lakes, and former tidal lagoons. The first subunit merges with the second subunit near the airport and northeastward.

EOLIAN SAND DEPOSITS

The eolian sand deposits, mostly in the form of dunes, are principally located near the estuary of the Situk River. Deposits probably range in thickness from 2 to 10 m. The underlying materials may include at least two types of delta-estuarine deposits. Eolian sand deposits merge laterally with mapped young beach and delta-estuarine deposits.

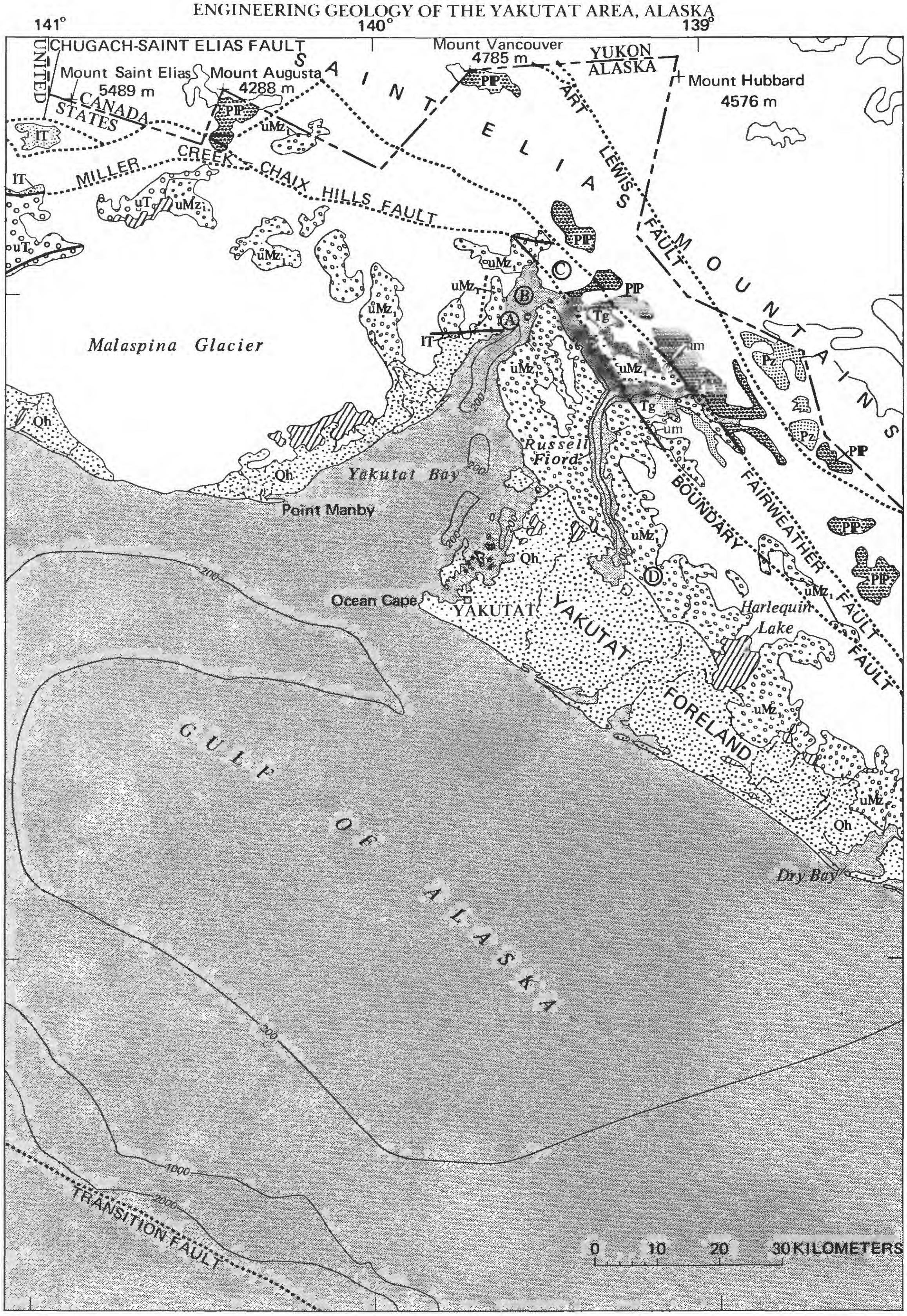


FIGURE 2.—General geologic map of Yakutat region, Alaska. (Modified from Richter, 1958, p. 599; Plafker, 1967, oral commun., 1974; Plafker and others, 1975; MacKevett and Plafker, 1970; Beikman, 1974, 1975; and Page, 1975.) Base modified from U.S. Geological Survey (1970) and U.S. National Ocean Survey (1975, chart 16016; 1974, chart 16760). Explanation on facing page.

BEACH DEPOSITS

Three subunits of beaches are shown on the geologic map on the basis of age—young, intermediate, and old. The young beach deposits include materials between the line of mean lower low water and the berm of the storm beach. Along most of the outer coast of the Gulf of Alaska, these young deposits consist of sand and some pebbly sand, while along the remainder of the gulf and among the islands, bays, and coves of Yakutat Bay, deposits consist, overall, of mixtures of sandy, pebbly cobble gravel with some boulders, and driftwood. Thickness of the deposits probably averages 2 m and ranges from 1 to 3 m. These deposits chiefly overlie end and ground moraine deposits and, in part, the clayey silt subunit of delta-estuarine deposits.

The intermediate-age beach deposits consist of sand and some pebbly sand, and they extend along the coast of the Gulf of Alaska. Thickness of the deposits probably averages 5 m and ranges from 2 to 7 m. Generally, either end and ground moraine deposits or clayey silt of the delta-estuarine deposits underlies these beaches, but near Aka and Summit Lakes they probably are underlain by intermediate or older delta-estuarine deposits. Most of the deposits form timbered linear ridges, some crests of which are as much as 5 m above adjacent parts of the deposits. Origin and emergence of the intermediate beaches probably occurred mostly following formation of the end and ground moraine deposits.

The old beach deposits are composed of sand and pebbly sand; thickness probably averages 5 m and ranges from 2 to 7 m. These form a series of timbered ridges that is inland from intermediate-age beaches near Tawah Creek and Lost and Situk Rivers. Crests of some ridges probably rise to as much as 7 m above adjacent parts of the deposits. The underlying geologic materials are possibly the clayey silt subunit of the delta-estuarine deposits. Formation of the old beach deposits probably was largely completed a few thousand years ago. This estimate generally is in accord with trends of radiocarbon dates of organic materials overlying similar landforms at several localities elsewhere within the Gulf of Alaska region (Hudson and others, 1976).

DESCRIPTION OF MAP UNITS

Qh HOLOCENE DEPOSITS – Alluvial, glacial, lacustrine, swamp, landslide, and beach deposits

uT UPPER TERTIARY ROCKS – Mostly siltstone, sandstone, and conglomeratic sandy mudstone (marine tillite)

lT LOWER TERTIARY ROCKS – Chiefly arkose, sandstone, siltstone, and some coal

Tg TERTIARY GRANITIC ROCKS – Mainly quartz diorite, granodiorite, and quartz monzonite

uMz CRETACEOUS AND JURASSIC(?) ROCKS – Mostly Yakutat Group; consists of interbedded graywacke, siltstone, conglomeratic sandstone, conglomerate, and greenstone

PIP PERMIAN AND PENNSYLVANIAN ROCKS – Probably chiefly slate, phyllite, mica schist, migmatite, amphibolite, greenschist, and marble

Pz PALEOZOIC ROCKS – Mostly marble, metavolcanics, and mica schist

um ULTRAMAFIC ROCKS OF UNCERTAIN AGE – Mostly serpentinite

Contact – Approximately located

Major fault – Approximately located; dotted where concealed, inferred, or postulated

Stream

200 Depth curves, in meters

(A) Bancas Point

(B) Disenchantment Bay

(C) Hubbard Glacier

(D) Beasley Creek

Glacier

Lake

DELTA-ESTUARINE DEPOSITS

Four subunits of delta and estuarine deposits are recognized and shown on the geologic map on the basis of apparent ages—young, intermediate, older, and oldest or silt-rich deposits. The first subunit, the young deposits, comprises the active deltas and estuaries of Lost, Situk, and Ahrnklin Rivers and consists chiefly of silty sand or fine sand. Thickness of the deposits possibly averages 7 m, ranging from 5 to 17 m. Merging with these deposits are young beach and intermediate delta-estuarine deposits; underlying the deposits are sediments of older cycles of delta-estuarine deposition.

The second subunit consists of the intermediate-age delta-estuarine deposits, which form a small, low-relief plain inland from deposits of the first subunit and generally are located near Tawah Creek and Lost, Situk, and Ahrnklin Rivers. Geologic materials are largely sand, and include some silt and small pebbles. Thickness of the deposits possibly averages 7 m and ranges from 3 to 13 m. Most mapped deposits are timbered. Organic deposits locally overlie intermediate delta-estuarine materials to thicknesses exceeding 1 m; several such areas are near the airport. Toward the outer shore, intermediate deposits merge with young delta-estuarine deposits, and landward they merge very gradually with alluvial and some outwash deposits. The origin and emergence of these intermediate delta-

TABLE 1.—*Geologic materials mapped in the Yakutat area—their characteristics and suitability for certain construction purposes*

Mapped geologic materials (pl. 1)	Attitude of slopes	Characteristics	
		Permeability; surface drainage, ground-water level	Compactness
Artificial fill.	Nearly flat, except in Yakutat, where commonly steep along margin of Monti Bay.	Generally good, but locally poor where content of silt is high; surface drainage good for well-constructed, gently to steeply sloping fills; water table dependent upon height of fill over natural terrain (much natural terrain has very high water table).	Well-constructed fills generally firm; many small fills probably loose.
Organic deposits underlain by coarse-grained deposits.	Nearly flat to very gently sloping.	Low; surface drainage poor; ground-water table at surface or at very shallow depths.	Loose to very loose, but many sectors are fibrous and thus relatively firm.
Organic deposits underlain by fine-grained deposits.	Nearly flat--------	Very low; surface drainage very poor; ground-water table at surface or at very shallow depths.	Loose to extremely loose; a few sectors fibrous and thus relatively firm.
Eolian sand deposits.	Mostly gently to moderately steeply sloping.	Excellent to good; drainage excellent; ground-water table probably at depth of 2-5 m.	Very loose to loose-
Young beach deposits.	Gently sloping to nearly flat.	Excellent; drainage excellent, dependent upon tidal stage.	Moderately firm to loose, except very loose where newly deposited, as near ends of lengthening spits.
Intermediate beach deposits.	Gently to locally moderately sloping, especially in direction perpendicular to shore.	Excellent; drainage excellent; water table probably at depth of 2-3 m.	Moderately firm-----
Old beach deposits.	Gently to moderately sloping.	Excellent; drainage excellent; water table probably at depth of 2-5 m.	----do--------------
Young delta-estuarine deposits.	Very gently sloping to nearly flat.	Fair; drainage fair to good, dependent upon stage of tide.	Very loose----------
Intermediate delta-estuarine deposits.	Very gently sloping except along streambanks where gently to moderately steeply sloping.	Fair to good; drainage fair; water table probably within a meter of surface.	Loose---------------

TABLE 1.—*Geologic materials mapped in the Yakutat area—their characteristics and suitability for certain construction purposes*—Continued

	Suitability for certain construction purposes		
Frost susceptibility	Construction aggregate	Fill	Foundation for roads and large structures
Generally low where silt content low and fill height greater than frost penetration. (Probably about 1.5 m.)	Not applicable------	Not applicable-----	Not applicable.
High to very high--	Unsuited-----------	Unsuited----------	Generally unsuited unless overlain by filter blanket and a few meters of granular fill.
Probably very high-	----do-------------	----do------------	Unsuited unless overlain by filter blanket and at least several meters of granular fill.
Very low----------	Limited suitability because of lack of coarse rock fragments.	Fair--------------	Excellent where thick, shore position probably not appropriate for some uses.
Not applicable-----	Limited suitability, depending upon percentage of appropriate grain sizes.	Generally good, very good where full range of rock-fragment sizes present.	Excellent, but shore position not appropriate for some uses.
Very low----------	Limited suitability because of general lack of coarse-sized rock fragments.	Good--------------	Limited suitability where less than 2 m thick; excellent where thicker. Position along outer coast not appropriate for some uses.
----do------------	----do-------------	Fair to good-------	Generally excellent.
Not applicable-----	Unsuited-----------	Generally unsuited-	Unsuited.
Very high---------	Generally poorly suited because of relative lack of coarse-grained rock fragments and abundance of fines.	Poor--------------	Poor to fair.

TABLE 1.—*Geologic materials mapped in the Yakutat area—their characteristics and suitability for certain construction purposes*—Continued

Mapped geologic materials (pl. 1)	Attitude of slopes	Characteristics	
		Permeability; surface drainage, ground-water level	Compactness
Old delta-estuarine deposits.	Gently sloping-------------	Probably good to fair; drainage probably good; ground water probably more than 2 m beneath surface, except shallower near margin of deposits.	Probably ranges from somewhat loose to moderately firm.
Clayey silt delta-estuarine deposits.	Generally exposed only in stream cuts, most of which are moderately steep.	Extremely low; other aspects not applicable because of intertidal position.	Dense---------
Coarse-grained alluvial deposits.	Mostly gently sloping; locally, moderately steeply sloping along margins of some streams and between stream channels. Steeply sloping along shores of Yakutat Bay.	Moderately good; drainage mostly good except in some former stream channels, where poor; water table probably within a meter of surface.	Loose---------
Fine-grained alluvial deposits.	Mostly gently sloping; moderately steep along some streambanks and between some stream channels of different ages. Steep along shores of Yakutat Bay.	Probably fair to good; drainage fair, except poor along floors of abandoned stream channels; water table probably within a meter of surface.	Mostly loose---
Old alluvial deposits.	Gently to very gently sloping.	Probably fair; drainage fair; water table probably within a meter of surface.	Loose to somewhat firm.
Coarse-grained outwash deposits.	Gently to moderately steeply sloping along margins of active and abandoned channels.	Excellent; drainage very good except locally where minor swales poorly drained (much drainage is subsurface); ground-water level probably within 1-5 m of surface.	Loose---------
Fine-grained outwash deposits.	Gently sloping-------------	Probably good to excellent; drainage good; ground-water level probably within a meter of surface.	Generally loose.
End and ground moraine deposits.	Possibly averages moderately steeply sloping but widely variable, ranging from gentle to locally very steep.	Probably averages moderate, but ranges widely from poor (where silt rich) to very good (where sandy till and ice-contact deposits abundant); drainage variable from good to poor; water table variable and probably within a meter of surface in many places.	Varies widely from deposit to deposit, ranging from firm to loose.

TABLE 1.—*Geologic materials mapped in the Yakutat area—their characteristics and suitability for certain construction purposes*—Continued

	Suitability for certain construction purposes		
Frost susceptibility	Construction aggregate	Fill	Foundation for roads and large structures
Moderate to low--------	Probably poorly suited because of probable low content of coarse material.	Poor----------	Good to fair.
Not applicable---------	Unsuited-----------	Unsuited------	Poorly suited because of exposure to sea and very high percentage of fine-grained constituents.
Moderately high--------	Good to excellent---	Excellent-----	Generally good, poor where water table high and wet abandoned stream channels exist.
High-------------------	Generally poor, locally good.	Poor to good--	Fair to poor.
Moderately high--------	Probably good-------	Excellent-----	Fair to good.
Low, but locally moderate, close to moraine where some silt probably present.	Generally excellent after removal of cobbles.	----do--------	Excellent.
Low to moderate--------	Good to locally excellent where some pebbles present in the sand.	----do--------	Good to excellent where depth to water table at least a meter.
Moderate, locally high--	Generally poor; locally, excellent when screened.	Very good-----	Very good except where drainage poor and directly exposed to sea.

estuarine deposits probably followed development of the outermost end moraine along the southeast side of Yakutat Bay.

The third subunit, older delta-estuarine deposits, occurs near Ophir Creek and the Situk River. Constituents probably are mostly sand and some pebbles and silt. Total thickness possibly is 10 m. The deposits appear to form low mounds related topographically to the intermediate delta-estuarine deposits. Some linear ridges are present within the area of the deposits. The deposits are older than the intermediate deposits and probably originated a few thousand years ago by limited wave action on coarse-grained delta deposits.

The fourth subunit, the oldest delta-estuarine deposits, is composed of firm clayey silt and is exposed on the intertidal shore area between mean lower low water and about a meter above mean high water in the estuary of Lost River and southeastward. The greatest observed thickness of the deposit is about 2 m. In the upper part of one exposure of the deposit, lenses of a diamicton of pebbly silt include some fragments of wood (sample C, pl. 1) and marine mollusk shells (sample D, pl. 1) identified as *Macoma balthica* (Linné) by W. O. Addicott (written commun., 1972). Although the relationship of the silt-rich delta-estuarine subunit to other deposits is not entirely clear, it is speculated that the subunit underlies much of the southern part of the map area at a depth of from 17 to about 70 m and is similar to marine deposits that probably underlie most of the end and ground moraine deposits. The age of at least a part of the clayey silt, as interpreted from a radiocarbon date on the marine shells (sample D), is about 2,180 ± 250 yrs B.P. (U.S. Geol. Survey sample W-2598; Meyer Rubin, written commun., 1971).

ALLUVIAL DEPOSITS

The alluvial deposits are located chiefly near the Situk River; they consist of pebble gravel, sand, and some cobble gravel, the percentage of sand increasing southward. Deposits are in beds as much as 1 m thick, and the total thickness of the deposits may average 8 m, but it varies greatly; the maximum probably is as much as 33 m. Organic materials locally overlie alluvial deposits which in turn probably overlie delta-estuarine deposits. Larger alluvial deposits merge toward the present shore of the Gulf of Alaska with delta-estuarine deposits and merge very gradually away from shore with outwash deposits. Alluvial sediments originate by deposition from streams; most sediments are not directly related to glacier melting but do include large quantities of reworked glacial outwash. Three subunits of alluvial deposits are recognized on the basis of differences in age and grain size. The first and second subunits are the youngest. The first subunit is coarse grained and is composed mostly of pebble gravel and, in abandoned stream channels, includes some sand, cobbles, and silty sand. Along the Situk River the materials of this subunit merge with those of the second subunit, which is fine grained and consists mostly of sand and some pebble gravel and silt. A few small deposits of the second subunit are mapped near the shores of Yakutat Bay. The third subunit is the oldest, and it probably is composed of sand and silty sand which, near the base, include sandy pebble gravel. The deposits are related mostly to streams like Old Situk Creek that drained from the glacier-dammed lake which existed in the southern part of present Russell Fiord until the mid(?)-1800's.

OUTWASH DEPOSITS

Melting and retreat of the glacier that deposited the end and ground moraines along the southeast side of Yakutat Bay about 500–600 years ago released vast quantities of frozen-in rock fragments. Numerous melt-water streams transported fragments outward from the glacier and deposited them as outwash. Individual streams developed, shifted, and were abandoned as the various sectors of the glacier melted. Two subunits of outwash are shown on plate 1.

The first, heavily timbered, is the coarse-grained subunit of the outwash deposits, situated within several kilometers or less of the outermost end moraines and consisting mostly of sandy pebble gravel. Close to the moraines, cobble gravel is a major constituent of the outwash, and some silty, sandy gravel is present, derived from direct melting of the glacier ice to form kame and other types of ice-contact deposits too small to show on the geologic map. Deposits of the coarse-grained subunit are bedded and moderately well sorted within individual beds. Coarse rock fragments at many places are silt coated. The overall thickness of the coarse-grained outwash subunit may average 7 m and range from 1 to 17 m. The coarse outwash is thought to overlie delta-estuarine sediments and probably some buried morainal deposits. In many places organic deposits cover the coarse outwash.

The second subunit, the fine-grained outwash deposits, is chiefly sand, ranging from pebbly to silty. The thickness of the subunit may average 7 m and range from 1 to 13 m. Underlying the fine-grained outwash are intermediate and old delta-estuarine deposits and, locally, coarse-grained outwash. In many places organic materials cover the fine-grained outwash.

The approximate age of the outwash is provided by a generalized study of the ages of trees rooted on the surface of the outwash. Ages averaged 550 years (Plafker and Miller, 1958).

END AND GROUND MORAINE DEPOSITS

The predominant deposits within the area of this map unit are end- and ground-moraine deposits; they are not separated on the geologic map (pl. 1). Subordinate landforms and deposits, most of which are too small to show on the map, are noted below. The Yakutat area (pl. 1) is topographically dominated by curvilinear end-moraine ridges that parallel the general alinement of shores along the southeast side of Yakutat Bay. These end moraines formed by the Yakutat Bay glacier are part of a group of moraines along both sides of the mouth of Yakutat Bay which are joined by an arcuate line of relatively shallow areas that cross the bay between Ocean Cape and Point Manby (fig. 2). In the Yakutat area (pl. 1) the group of end-moraine ridges is oriented perpendicular to the apparent direction of flow of the Yakutat Bay glacier; individual ridges may represent sequential thrusting of the glacier. (A slightly different orientation of some groups of ridges, like those northeast of Redfield Cove, may indicate a minor readvance of the glacier.) Crests of some ridges are as much as 10 m above adjacent parts of the moraines. Interridge areas commonly contain organic deposits, some of which are large enough to show on plate 1; locally the organic materials may overlie fine-grained deposits of former ponds or small lakes.

Most of the ground-moraine deposits in the Yakutat area are located either (1) on the mainland between the end-moraine ridges and Yakutat Bay, or (2) on islands in the bay. The surface configuration of the ground moraine is commonly smoother than the surface of the end moraines. Locally, ground moraine is ridged (pl. 1) in a direction that is apparently parallel to the flow of the glacier. Ridges are especially common on Khantaak Island; crests probably average 3 m above adjacent land.

The most prevalent type of geologic material in the largely timbered moraines is a generally unstratified mixture called till—a diamicton of glacial origin. The mixture consists mostly of granule- and pebble-laden silt or sand, in varying proportions, and, subordinately, of cobbles, clay, some boulders, and rarely, organic material. The less prevalent materials are quite variable in grain size; they range from sandy pebble gravel or sandy cobble gravel to silty, fine sand. Locally, in beds, they may be as much as 3 m thick; sorting is very good. Although deposits generally are firm, in many places they are loose.

Subordinate landforms, many of which contain stratified and sorted deposits, include kames, eskers, crevasse fillings, and minor outwash. Characteristically, these landforms contain mostly pebble gravel, sand, and silt; kames commonly contain sandy pebble gravel.

The total thickness of the morainal deposits, as interpreted from a few drill logs (provided by V. K. Berwick, written commun., 1965), may average 25 m and have a maximum of 67 m. The morainal deposits overlie (1) thin deposits of organic materials that include some wood, and (2) marine sediments of unknown thickness that include sand, silt, and clay.

A large part of the morainal deposits was formed about 500–600 years ago, on the basis of interpretation of several radiocarbon dates on samples of wood from the outer coast. Two of the sample localities (A, B, pl. 1) are within the area of end-moraine deposits. Sample A was dated as 560 ± 75 years B.P. (Isotopes, Inc. I-439; Miller, 1966); it was collected from the stump of a tree that was mostly sheared off by the glacier that deposited the end and ground moraine deposits. Sample B from a locality apparently very close to the locality of Sample A was dated as 830 ± 160 years B.P. (U.S. Geol. Survey sample W-559; Hartshorn, 1960). A third wood sample (C, pl. 1) was dated as 500 ± 250 years B.P. (U.S. Geol. Survey sample W-2167; Meyer Rubin, written commun., 1968). The third sample, although 12 km beyond the mapped outer limit of the end moraine, was contained in a diamicton that seemed to relate to the same depositional sequence as the end moraine.

STRUCTURAL GEOLOGY

REGIONAL SETTING

The Yakutat region is part of an active tectonic belt that rims the Gulf of Alaska and much of the rest of the North Pacific Ocean. Since early Paleozoic time, profound tectonic deformation, plutonic intrusion, and widespread metamorphism have occurred in this belt. The latest major events in the Yakutat region probably began in early Miocene time and have continued to the present, as evidenced by frequent earthquakes that have produced uplift as well as lateral offsets along faults in the region (Tarr and Butler, 1909; Stoneley, 1967; Plafker, 1967, 1971, and oral commun., 1974; MacKevett and Plafker, 1970).

Three major fault zones occur in the Yakutat region (fig. 2)—one generally northeast of Yakutat Bay, one northwest of Yakutat Bay, and one offshore, southwest of Yakutat. Most of the indicated faults consist of groups of closely spaced, subparallel zones of fractured bedrock which extend to great depth and which may have a total width of several hundreds of meters.

The fault zone generally northeast of Yakutat Bay includes the northwest-trending, nearly vertical Boundary and Fairweather faults, and, farther to the northeast, the Art Lewis fault.

The fault zone northwest of Yakutat Bay contains the Miller Creek-Chaix Hills, Chugach-St. Elias, and other generally west trending thrust faults, most of which dip gently northward (Plafker, 1971, 1972a, b; Plafker and others, 1975). A broad area of uplift, probably related to the second of the two large earthquakes of September 10, 1899, is about 29 by 48 km in size and is centered near Bancas Point, about 47 km north of Yakutat (fig. 2; George Plafker, written commun., 1976). The amount of uplift averages 2–3 m, although one small area, presumably bounded by faults, shows greater uplift and a maximum of about 14.4 m, the greatest onshore uplift ever measured for an earthquake sequence (Tarr and Martin, 1912).

The fault zone offshore, southwest of Yakutat, is an inferred thrust fault, the Transition fault (Gawthrop and others, 1973; Chandra, 1974; Page, 1975; Plafker and others, 1975). In the same general offshore region, Naugler and Wageman (1973, p. 1577) identified an area roughly parallel to the fault where the magnetic field is abruptly different from the magnetic field to the southwest.

ACTIVE FAULTS CLOSE TO YAKUTAT

Many of the major faults in the Yakutat region are thought to be active. An active fault, in general, is considered to be a type of fault along which continuous or intermittent movement is taking place; motion may be abrupt or, in some cases, very slow. The active fault nearest Yakutat on which historic surface displacements have been measured is the Fairweather fault, whose closest segment is about 53 km to the northeast. From the historic record of earthquakes, it is inferred that other active faults exist. Such faults, including those that moved during the September 1899 earthquakes, either have not ruptured the surface or, if they have ruptured the surface, are concealed by glaciers or bodies of water.

The present type of movement along the Fairweather fault is known to be similar to movement along the San Andreas fault system in California; namely, right-lateral, strike-slip faulting, with northwestward movement of that part of the earth's crust lying on the southwest side of the fault relative to points on the other side of the fault. Both faults are thought to be involved, at present, in the same tectonic movement of a large block, the Pacific plate, past an adjacent plate, the North American plate (Isacks and others, 1968; Atwater, 1970; Plafker, 1972a). (A popularized account of these plate movements was presented by Yanev, 1974, p. 26.) Northwest of Yakutat Bay, where the Fairweather fault merges with a group of faults including the Miller Creek-Chaix Hills and Chugach-St. Elias faults, motion between these plates changes from horizontal to an oblique underthrusting. Theoretical calculations indicate that the rate of horizontal motion along the Fairweather fault and its inferred offshore fault connections to the south-southeast may average about 5.7 cm per year. This rate is generally supported by work of Plafker, Hudson, and Rubin (1976) through radiometric dating and measurement of offsets of moraines and stream courses crossing the Fairweather fault southeast of Lituya Bay (fig. 1). Further, their work indicates that this relatively high rate of horizontal displacement might have begun as recently as about 100,000 years ago.

The surface offset reported in the geologic literature (Tocher, 1960, p. 289) as closest to Yakutat along the Fairweather fault was at a locality about 175 km southeast of Yakutat, where, following the earthquake of July 10, 1958, u.t. (universal time), 6.6 m of right-lateral movement was measured along with 1 m of vertical uplift on the southwest side of the fault. Tocher (1960) suggested that, during this earthquake, movement occurred along much of the Fairweather fault northwestward to Yakutat Bay. George Plafker (oral commun., 1975) reported a segment of the fault located about 58 km north-northeast of Yakutat that is 5 km long with offset drainages indicative of about 1.7 m of right-lateral displacement during the earthquake. The ground cracks along the Fairweather fault near long 139° W. that were reported by Tarr and Martin (1912, p. 37–38) as active surface faults were interpreted by George Plafker (oral commun., 1974) to be massive landslides of bedrock.

EARTHQUAKE POTENTIAL

Accurate prediction of the exact place and time of occurrence of destructive earthquakes is not yet possible. However, the likely location, size, and frequency of earthquakes can be estimated. One such region is the wide belt that roughly parallels the coast of the Gulf of Alaska. For the Yakutat area, an evaluation of earthquake probability is based on two factors: (1) the local seismicity as determined largely from historic records of earthquakes, and (2) the local geologic and tectonic setting.

SEISMICITY

The Yakutat area lies within the earthquake region along the Gulf of Alaska and outer coast of southeastern Alaska. Unfortunately, the written record of earthquakes in this region is meager because of (1) the relatively short time that written records have been kept, (2) the sparse population, and (3) the absence of permanent seismograph stations in the region prior to 1973.

The earthquakes that have been instrumentally recorded and located by seismologists during the period 1899 through 1975 are shown in figure 3. Because detection and recording techniques have improved over the years, the record probably is complete in the Yakutat region for all magnitude-5 and greater earthquakes since April 1964, for all magnitude-6 and greater earthquakes since the early 1930's, and for all magnitude-7.75 and greater earthquakes since 1899 (Page, 1975). The earthquakes shown in figure 3 are thought to be of shallow origin (typically less than 30 km) and to have properties similar to those of shallow-focus earthquakes occurring elsewhere. Of the earthquakes of magnitude 5 or greater that are known to have occurred since 1899, at least 13 occurred within about 130 km of Yakutat and 26 occurred within 210 km of Yakutat (4 of the 26 occurred west of long 142° and thus are not shown in fig. 3). Also, within those boundaries, earthquakes of lesser or unknown magnitudes have been widespread. At least one earthquake of magnitude 5 or larger occurred, on an average, each year within about the last 10 years of record.

Extremely small earthquakes, or microearthquakes, though not shown in figure 3 because of the difficulty of detection, are nevertheless very important, because they may indicate the location of unknown active faults that may be capable of causing large earthquakes sometime in the future.

Permanent seismograph stations, some of which have been operating intermittently and some of which have been operating continuously in the region west, north, and east of the Yakutat area since 1973, should provide extensive data on many sizes of earthquakes after a few years of continuous recordings (Lahr and others, 1976). The closest station (PNL) is about 25 km northeast of Yakutat (J. C. Lahr, oral commun., 1975). In 1965, other types of seismological instruments were installed in the Yakutat area (pl. 1; B. L. Silverstein, written commun., 1975); namely, a strong-motion accelerograph and six seismoscopes. These seven instruments respond to only intense earthquake ground motion. Two of the seismoscopes are on morainal deposits at Yakutat, two are on intermediate beach deposits, and two are on sandy, small-pebble gravel at the airport. The strong-motion accelerograph also is housed at the airport. At all locations the surficial deposits probably are at least 35 m thick.

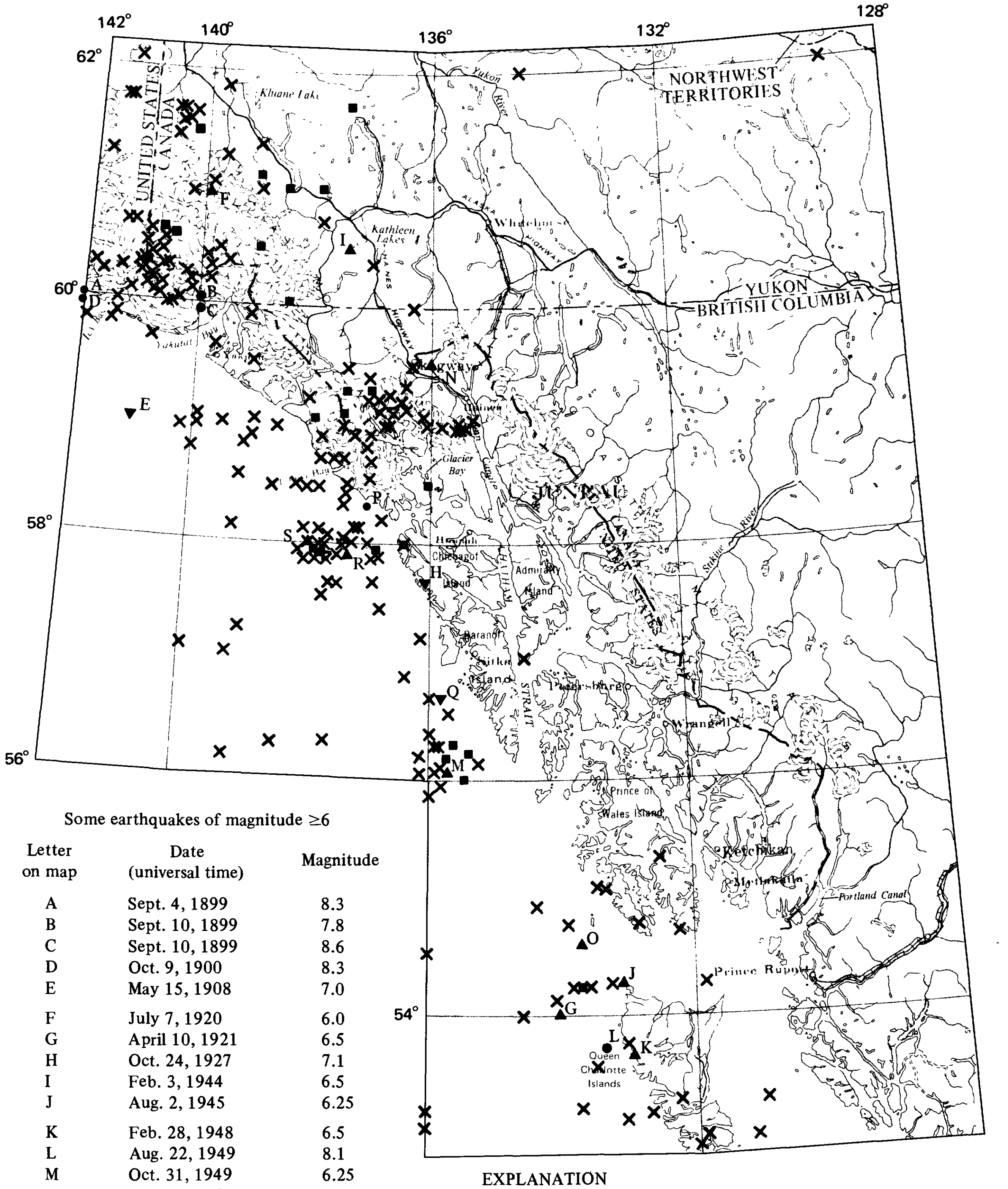
Earthquakes that were felt or that were large enough to have been felt at Yakutat from 1893 through 1975 are listed in table 2. The list was compiled and interpreted from the more readily available published reports and from instrumental records from seismological stations. Among the major earthquakes listed are those of September 1899, October 1900, May 1908, July 1958, and March 1964. Other earthquakes, mostly small, undoubtedly could be added to the list if the population of the region were more widespread and thus able to report earthquakes over a larger area. See also table 3, which relates earthquakes of different intensities and magnitudes.

Among the group of most severe earthquakes, only the 1899, 1958, and 1964 earthquakes will be considered here, because data on the 1900 and 1908 earthquakes are too limited. The group occurring in September 1899 included one of the largest known earthquakes in the world. Despite the severity of the earthquakes, very little damage was done to the few buildings at Yakutat.

Shaking from the earthquake of September 4, 1899 (designated A on fig. 3) lasted about 2–5 minutes (Tarr and Martin, 1912); the magnitude of the earthquake is estimated as 8.3 (Wood, 1966). Tarr and Martin (1912) reported that one informant noted ground motion consisting of a general "shivering" that ended with a "jerk" from west to east. Another observer noted the violent rocking and shaking of buildings, with earth vibrations being 2–3 seconds in duration and traveling from northwest to southeast.

Shaking from the first of the large earthquakes that occurred on September 10, 1899 (B on fig. 3), lasted about 3 seconds, with several long aftershocks. The earthquake had a magnitude estimated as 7.8. Tarr and Martin (1912) reported one observer as noting that ground movement initially was north-south but that, as motion continued, movement swung around to west-east. During ground shaking, buildings creaked and groaned.

The second earthquake of September 10, 1899 (C on fig. 3), was the most severe "felt" earthquake of the group and presumably was the one responsible for most of the earthquake effects reported at later dates by observers and presented by Tarr and Martin (1912). Reports of the duration of the earthquake varied, depending on the observer, with estimates ranging from 5 seconds to 5 minutes. The earthquake had a magnitude estimated as 8.6 and a Modified Mercalli intensity estimated as XI (Meyers, 1976; Meyers and others, 1976). Plate 1 shows shore areas near Yakutat that were thought by Tarr and Martin (1912) to exhibit uplift or subsidence. Some of their areas of subsidence probably were not tectonic but instead were related to



Some earthquakes of magnitude ≥6

Letter on map	Date (universal time)	Magnitude
A	Sept. 4, 1899	8.3
B	Sept. 10, 1899	7.8
C	Sept. 10, 1899	8.6
D	Oct. 9, 1900	8.3
E	May 15, 1908	7.0
F	July 7, 1920	6.0
G	April 10, 1921	6.5
H	Oct. 24, 1927	7.1
I	Feb. 3, 1944	6.5
J	Aug. 2, 1945	6.25
K	Feb. 28, 1948	6.5
L	Aug. 22, 1949	8.1
M	Oct. 31, 1949	6.25
N	Mar. 9, 1952	6.0
O	Nov. 17, 1956	6.5
P	July 10, 1958	7.9
Q	July 30, 1972	7.25
R	July 1, 1973	6.7
S	July 3, 1973	6.0

EXPLANATION

Magnitude

- ● ≥8
- ▼ ≥7 - <8
- ▲ ≥6 - <7
- ■ ≥5 - <6
- ✕ <5 or not computed

0 50 100 150 200 KILOMETERS

gravitational adjustment of shore areas to severe shaking. Of special note were two possible submarine landslides(?)—one along the south end of Khantaak Island, where 10 ha of land subsided about 3 m (A on pl. 1; Tarr and Martin, 1912), and the other along the northern end of the island (B on pl. 1). Both slide areas are zones of rapid deposition of loose beach-spit sediments of pebbly sand and, as such, are not firm and are easily disturbed by earthquake shaking. In the same general areas, sliding apparently also occurred during the July 10, 1958, earthquake. Other earthquake effects—namely, fountaining and ground fissuring or fracturing—were inferred from the presence of craters and lines of ground cracks on (1) Blacksand Island (southeastern part of the map area, pl. 1), where at an unspecified locality a crack developed that was about 135 m long in a north-south direction, 3 m wide, and 3 m deep; and (2) near The Ankau on Phipps Peninsula, where fissures and sand fountains occurred (pl. 1; Tarr and Martin, 1912). Emitted sand covered about 1 ha to a depth of 0.2 m; craters were 1–2 m deep. Fissures in this vicinity affected about 4 ha; cracks were about 1–2 m deep and about 1 m apart (Martin, 1910, p. 362–363). Fissures also were reported at a few places about 1.6 km northwest of Yakutat (de Laguna, 1972, p. 288).

High waves and great fluctuations in level of water were observed in Monti Bay in response to the earthquake (Tarr and Martin, 1912). Apparently there was a heavy flow of water out of Monti Bay during the earthquake, but the water returned in a short time as a strong current and big swell that washed around (some of?) the houses about 1.6 km northwest of Yakutat. Most houses probably were situated about 2 m to possibly as much as 3(?) m above present high tide. There were three large waves in Monti Bay at intervals of about 5 minutes. The total rise of water was about 5 m, extending from near or somewhat below low tide to about 0.3 m above highest tide. A sawmill chute was torn away by wave action, and trees, driftwood, and lumber were rapidly churned and whirled around in the bay.

◀ FIGURE 3.—Map showing location of earthquakes in southeastern Alaska and adjacent regions, 1899–1975 (Davis and Echols, 1962; Internat. Seismol. Centre, 1967–1973; Lander, 1973; Meyers, 1976; Page and Gawthrop, 1973; R. A. Page and W. H. Gawthrop, written commun., 1973; Rogers, 1976; Seismol. Service of Canada (Horner and others, 1974, 1975, 1976; Meidler, 1962; Milne, 1956, 1963; Milne and Lombardo, 1953a, b, 1955a, b; Milne and Lukas, 1961; Milne and Smith, 1961, 1962, 1963, 1966; Smith, 1961; Smith and Milne, 1969, 1970; Stevens and others, 1972, 1973, 1976; Wetmiller, 1976a, b); Tobin and Sykes, 1968; U.S. Coast and Geod. Survey, 1930–1970; U.S. Natl. Geophys. and Solar-Terrestrial Data Center, 1969, 1973, 1975, 1976; U.S. Natl. Oceanic and Atmospheric Adm., 1971–1973, 1974; U.S. Natl. Oceanic and Atmospheric Adm. and U.S. Geol. Survey, 1975, 1976; W. H. Gawthrop, oral commun., 1975; and Wood, 1966). Location accuracy 15–25 km at best; worst, 110 km.

The earthquake of July 10, 1958 (P on fig. 3), had a magnitude of 7.9. Although the earthquake was strongly felt in the Yakutat area, structural damage to buildings was generally slight. The Modified Mercalli intensity was considered to be VIII–IX (table 2).

The most complete account of earthquake effects in the area was by Davis and Sanders (1960); some of their account is abstracted here. Ground shaking lasted 3–4.5 minutes at Yakutat; the most intense shaking in the mapped area probably was felt near the mouth of the Situk River. Fountains ("sand blows") of sand and water were especially common on lower parts of the Yakutat Foreland near tidewater, where generally fine grained sediments are abundant. Most areas in which fountains formed also experienced some ground fracturing. The eruptions of sand and water from craters and fractures were restricted mainly to areas of ground where the water table was high; some fountains were located in stream valleys. Sand cones remaining after fountaining ceased had volumes of as much as 8.5 m^3. Plate 1 shows areas near the outer coast that, on the basis of inspection of aerial photographs taken about 1 month after the earthquake, are thought to have developed fountains.

At the airport, several earthquake effects were experienced. The airport is built mostly on sandy pebble gravel, an exception being the southwestern part of the northeast-southwest runway, which is built mostly on sand but which toward the southwest end contains increasingly large amounts of silt. The ramp in front of the single large airport hangar, near the junction of the runways, undulated during ground shaking, individual concrete-slab components rising and falling in a wavelike motion. The hangar, a large steel building, swayed violently; walls of the hangar buckled, and many windows cracked.

The most severely damaged part of the airport was the southwestern 665 m of the northeast-southwest runway. That runway and the northwest-southeast runway and the aircraft parking area were all constructed with 4-m-square concrete slabs 18 cm thick. Individual slabs were separated by asphalt-filled cracks 1.3 cm wide, and larger asphalt-filled cracks 2.5 cm wide were spaced 8 blocks (32 m) apart. Relative movement occurred between all blocks on the 2.5-cm joints, but only those in the southwestern 665 m of the northeast-southwest runway acquired permanent offsets greater than 1.3 cm; maximum net displacement on any joint was 7.6 cm.

At Yakutat the most intense ground motion was es-

TABLE 2.—*Partial list of earthquakes felt or large enough to have been felt at Yakutat, Alaska, 1893–1975*

[N.a., not available; Unk., unknown]

Date[1]	Effects[2] and intensity (table 3) of earthquakes at Yakutat	Distance, km, and direction to epicenter if instrumentally located (fig. 3)	Magnitude of instrumentally located earthquake[3]	Radius of perceptibility for given magnitude, km	Distance, km, direction, and locality (if any) nearest Yakutat at which earthquake felt. Data on earthquake	Reference[4]
1893 Mar.	Felt	N.a.	Unk.	N.a.	N.a.	1
1894 Nov. 3	Three light shocks	N.a.	Unk.	N.a.	N.a.	1
1896 Late May.	Felt?	N.a.	Unk.	N.a.	360 WNW, near Orca, very severe, shaking about 25 sec.	1
1897 Jan. 11	Severe	N.a.	Unk.	N.a.	N.a.	1
May 6	V	N.a.	Unk.	N.a.	385 NNE, Fort Selkirk, Yukon.	1, 2
1899 Sept. 4	VII. Lasted 2-5 min	120 WNW	8.3	>575	N.a.	1, 2
Sept. 10	VII. Lasted about 3 sec. Several long aftershocks.	55 NNW	7.8	550	N.a.	1, 2
Sept. 10	XI. Lasted 5 sec-5 min	55 NNW	8.6	>575	N.a.	1, 2
Sept. 16	Severe	N.a.	Unk.	N.a.	N.a.	1
Sept. 23	Moderately severe	N.a.	Unk.	N.a.	N.a.	1
Dec. 14- 1900 Aug. 10.	12 shocks, each about III; a few shocks long or heavy.	N.a.	Unk.	N.a.	N.a.	1, 2
1900 Oct. 9	Two shocks, one of intensity III.	120 WNW	8.3	>575	N.a.	1, 2
Dec. 17- 1901 Sept. 29.	Six shocks, each about III	N.a.	Unk.	N.a.	N.a.	1, 2
1902 Aug. 17	III	N.a.	Unk.	N.a.		1, 2
1903 Mar. 10	III	N.a.	Unk.	N.a.		1, 2
July 26	Felt?	N.a.	Unk.	N.a.	80 SE, Dry Bay.	2
Sept. 10	III	N.a.	Unk.	N.a.		1, 2
1905 Summer	Several felt; slight	N.a.	Unk.	N.a.		1
Aug. 30	Slight shock	N.a.	Unk.	N.a.		1
1906 Summer	A few shocks felt?	N.a.	Unk.	N.a.	Near shores of Yakutat Bay, slight.	1
1908 May 15	Felt?	95 SW	7	385	160 WNW, Yakataga, felt from Sitka to Seward.	2
1909 Feb. 16	V	N.a.	Unk.	N.a.	N.a.	1, 2
May 6	V	N.a.	Unk.	N.a.	N.a.	1, 2
July 16	III	N.a.	Unk.	N.a.		1, 2
1910 Aug. 8	IV. Shook buildings along shore, but no damage.	N.a.	Unk.	N.a.	N.a.	1, 2
1911 Early Sept.	Severe	N.a.	Unk.	N.a.	N.a.	1
1920 July 7	Felt?	160 NNW	6	210	N.a.	2
1923 Apr. 25	Felt?	110 SE	5.75	200	345 SE, Juneau. (In opposite direction from Yakutat.)	3
1925 Feb. 23	Felt?	440 NW	Unk.	N.a.	250 ESE, Haines.	2
1927 Oct. 24	Felt?	295 SE	7.1	415	225 SE, Cape Spencer.	2
Nov. 13	Felt?	415 SE	Unk.	N.a.	250 ESE, Haines.	2
1933 Mar. 2	III	N.a.	Unk.	N.a.	N.a.	2
Mar. 17	III. Lasted 45 sec	N.a.	Unk.	N.a.	N.a.	2
May 6	Felt	N.a.	Unk.	N.a.	N.a.	4
Aug. 31	Felt?	150 ESE	5.25	170	250 ESE, Haines. (In opposite direction from Yakutat.)	2
Sept. 16	Felt	N.a.		N.a.	N.a.	4
Sept. 19	Felt?	135 ESE	5.6	190	255 E, Skagway. (In opposite direction from Yakutat.)	2
1938 Oct. 14	Felt	240 SE	5	145	N.a.	3, 4
1941 Aug. 10	Felt?	130 ESE	5.25	175	255 E, Skagway. (In opposite direction from Yakutat.)	2
1942 June 12	Felt?	190 NE	5.75	200	N.a.	3
1944 Feb. 3	Felt?	170 NE	6.5	290	265 NE, Aishihik, Yukon.	5

TABLE 2.—*Partial list of earthquakes felt or large enough to have been felt at Yakutat, Alaska, 1893–1975*—Continued

Date[1]		Effects[2] and intensity (table 3) of earthquakes at Yakutat	Distance, km, and direction to epicenter if instrumentally located (fig. 3)	Magnitude of instrumentally located earthquake[3]	Radius of perceptibility for given magnitude, km	Distance, km, direction, and locality (if any) nearest Yakutat at which earthquake felt. Data on earthquake	Reference[4]
1945	Aug. 17	Felt?	70 NNW	Unk.	N.a.	N.a.	5
	Oct. 15	Felt?	60 S	Unk.	N.a.	265 SE, Gull Cove	4
1947	Apr. 30	Felt?	70 SE	Unk.	N.a.	215 E, Mosquito Lake.	4
1949	Mar. 12	Felt?	215 W	Unk.	N.a.	575 NW, Anchorage. (Epicenter probably poorly located.)	2
1952	Mar. 9	Felt?	210 E	6	210	265 NE, Aishihik, Yukon.	5
	Sept. 9	Felt	N.a.	Unk.	N.a.	N.a.	6
1954	Oct. 3	III	670 WNW	6.75	320	N.a.	2
1955	July 31	Felt?	N.a.	Unk.	N.a.	545 WNW, Seward. (Possibly different earthquakes.)	2
	Oct. 28	Felt?	150 SE	Unk.	N.a.	350 SE, Sitka.	2
1956	May 3	Felt?	95 S	Unk.	N.a.	N.a.	3
	Nov. 3	Felt?	175 NNE	5.7	200	175 NE, Haines Junction, Yukon. (Felt location near epicentral region.)	5
	Nov. 4	Felt?	185 NNE	5.4	175	N.a.	5
1957	June 1	Felt?	210 SE	Unk.	N.a.	N.a.	7
	June 23	Felt?	200 SE	5.7	190	210 E, Moose Valley.	4
1958	Feb. 1	Felt?	120 NW	Unk.	N.a.	N.a.	3
	Apr. 9	V	375 S	Unk.	N.a.	N.a.	2
	Apr. 29	Felt?	135 NW	Unk.	N.a.	N.a.	7
	July 10	VIII. Numerous aftershocks during next few months, but no written record of the total number felt; only magnitude given (Wood, 1966) is for aftershock of July 13, 1958 (M about 5.6); others probably less than magnitude 5.	225 SE	7.9	560	N.a.	2, 8
	Sept. 24	Felt?	185 W	6.3	255	N.a.	7
	Nov. 26	V	N.a.	Unk.	N.a.	N.a.	2
1959	Jan. 9	IV. Trembling and swaying motion.	N.a.	Unk.	N.a.	N.a.	2
	Feb. 4	IV. Trembling motion followed by sharp jar.	35 E	Unk.	N.a.	N.a.	2
	Oct. 17	Felt?	80 NE	5.6	190	N.a.	5
1960	Oct. 14	V. Moderate earth noises heard by a few persons before shock.	190 ENE	Unk.	N.a.	N.a.	2
1962	Mar. 26	IV. Strong jolt, abrupt onset.	N.a.	Unk.	N.a.	N.a.	2
1963	June 17	Felt?	120 NW	5.4	175	N.a.	7, 2
	June 27	Felt?	120 NW	4.6	120	N.a.	7, 2
	Nov. 19	Felt?	65 WNW	4.2	95	N.a.	2
1964	Mar. 28	IV-VI. East-west rolling or swaying motion, 5±1 min.	480 NW (not on fig. 3)	8.4	>575	N.a.	2, 9
	Apr. 1	Felt?	120 NW	4.4	110	N.a.	2
	Apr. 3	Felt?	135 NW	4.5	120	N.a.	2
	Apr. 8	Felt?	130 NW	4.3	105	N.a.	2
	Apr. 13	Felt?	190 W	5.1	310	N.a.	2
	Apr. 28	Felt?	90 SE	4.6	120	N.a.	2
	Apr. 30	Three shocks felt?	80 SE 80 SE 150 NW	4.4 4.4 4.9	110 110 145	N.a.	2 10
	May 17	Felt?	170 WSW	5.1	185	N.a.	2

TABLE 2.—*Partial list of earthquakes felt or large enough to have been felt at Yakutat, Alaska, 1893–1975*—Continued

Date[1]		Effects[2] and intensity (table 3) of earthquakes at Yakutat	Distance, km, and direction to epicenter if instrumentally located (fig. 3)	Magnitude of instrumentally located earthquake[3]	Radius of perceptibility for given magnitude, km	Distance, km, direction, and locality (if any) nearest Yakutat at which earthquake felt. Data on earthquake	Reference[4]
1964	May 18----	Felt?-------------------------	170 W	4.9	135	N.a.	2
	May 23----	Felt?-------------------------	90 WSW	Unk.	N.a.	N.a.	10
	July 18---	Felt?-------------------------	90 N	3.8	65	N.a.	2, 10
	Sept. 4---	Felt?-------------------------	80 SE	3.8	65	N.a.	2
1965	Apr. 26---	III. Moderate tremor----------	185 SW	5.3	170	N.a.	2
			105 NW	5.3	170		
	June 27---	Three felt?--------------------	105 NW	4.8	135	N.a.	2
			110 NW	4.3	105		
	Dec. 23---	Felt--------------------------	130 NW	5.8	200	N.a.	2
1966	Feb. 8----	Felt?-------------------------	95 NW	3.8	65	N.a.	2
	June 19---	Felt?-------------------------	130 E	4.4	110	N.a.	2
1967	Nov. 27---	Felt?-------------------------	105 NW	4.6	120	160 WNW Yakataga.	2
1968	Aug. 27---	Felt?-------------------------	110 SSE	4.3	105	N.a.	2
	Aug. 29---	Felt?-------------------------	15 N	4.4	110	Epicenter possibly poorly located.	2
	Sept. 22--	Felt?-------------------------	110 WNW	3.9	70	N.a.	2
1969	May 27----	Felt?-------------------------	120 NW	4.3	105	N.a.	2
1970	Apr. 11---	III---------------------------	160 WNW (not on fig. 3)	6.2	240	N.a.	2
	Apr. 16---	III---------------------------	160 WNW (not on fig. 3)	6.8	320	N.a.	2
	Apr. 19---	III---------------------------	175 W (not on fig. 3)	5.8	200	N.a.	2
	Sept. 6---	Felt?-------------------------	105 NW	4.7	130	N.a.	2
1971	Mar. 25---	III---------------------------	N.a.	5.0	145	N.a.	2
	Mar. 26---	IV----------------------------	110 NW	5.9	190	N.a.	2
	Apr. 24---	Felt?-------------------------	110 NE	5.1	160	N.a.	2
1972	July 30---	V-VI--------------------------	385 SE	7.25	465	N.a.	2
				7.3			11
1973	July 1----	V-----------------------------	240 SE	6.7	320	N.a.	11
	July 3----	IV----------------------------	200 SE	6.0	210	N.a.	11
	Sept. 12--	Felt?-------------------------	80 NW	3.9	70	N.a.	2
1974	Jan. 6----	Two shocks felt?--------------	65 SW	4.1	90	N.a.	2
	Feb. 21---	Felt?-------------------------	95 NW	3.9	70	N.a.	2
	Mar. 4----	Felt?-------------------------	70 NW	3.6	55	N.a.	2
	Apr. 18---	II----------------------------	55 SW	4.4	110	N.a.	2, 11
	Sept. 28--	Felt?-------------------------	90 NW	4.6	120	N.a.	2
	Nov. 5----	Felt?-------------------------	90 NW	4.1	90	N.a.	2

[1]Dates are intended as u.t. (universal time) except first five entries and 11th, 13th, 18th, 20th, 26th, and 47th, which are local time.

[2]Felt--Published report of single or multiple earthquake shocks of unknown intensity at Yakutat.

Felt?--Earthquake possibly felt at Yakutat, but as far as can be determined there is no readily available published report of the event's being felt at Yakutat. The occurrence of the earthquake is known, however, because of (1) a published report of its being felt elsewhere in region, and (or) (2) an instrumental recording and an instrumentally determined epicenter. (Tabulation based on (1) radius of average distance perceptibility of earthquakes, as described by Gutenberg and Richter (1956, p. 141), if epicenter and magnitude are known, and (2) general evaluation of regional geologic structure.)

Roman numeral--Published report of earthquake intensity, Modified Mercalli scale. (See table 3.)

[3]Magnitude, Richter (1958).

[4]1. Tarr and Martin (1912).
2. Meyers and others (1976), U.S. Coast and Geodetic Survey (1930-1970), U.S. National Geophysical and Solar Terrestrial Data Center (1976), U.S. National Oceanic and Atmospheric Administration (1971-1973 and 1974), U.S. National Oceanic and Atmospheric Administration and U.S. Geological Survey (1975, 1976), Wood (1966).
3. Davis and Echols (1962).
4. U.S. Weather Bureau (1918-1958).
5. Milne (1956), Milne and Lombardo (1953b), Milne and Lukas (1961).
6. de Laguna (1972, p. 793).
7. Tobin and Sykes (1968).
8. Davis and Sanders (1960).
9. Plafker and others (1969).
10. International Seismological Centre (1967-1973).
11. U.S. Geological Survey (1975), Stover and others (1976), Simon and others (1976).

TABLE 3.—*Description of Modified Mercalli intensity scale of earthquakes*[1] *and approximate distance of perceptibility of earthquakes of various magnitudes*[2]

I	Detected only by sensitive instruments.
II	Felt by a few persons at rest, especially on upper floors; delicate suspended objects may swing.
III	Felt noticeably indoors, but not always recognized as a quake; standing autos rock slightly, vibration like passing truck.
IV	Felt indoors by many, outdoors, by a few; at night some awaken; dishes, windows, doors disturbed; motor cars rock noticeably.
V	Felt by most people; some breakage of dishes, windows, and plaster; disturbance of tall objects.
VI	Felt by all; many frightened and run outdoors; falling plaster and chimneys; damage slight.
VII	Everybody runs outdoors; damage to buildings varies, depending on quality of construction; noticed by drivers of cars.
VIII	Panel walls thrown out of frames; fall of walls, monuments, chimneys; sand and mud ejected; drivers of autos disturbed.
IX	Buildings shifted off foundations, cracked, thrown out of plumb; ground cracked; underground pipes broken.
X	Most masonry and frame structures destroyed; ground cracked; rails bent; landslides.
XI	Few structures remain standing; bridges destroyed; fissures in ground; pipes broken; landslides; rails bent.
XII	Damage total; waves seen on ground surface; lines of sight and level distorted; objects thrown up into the air.

DISTANCE, IN KILOMETERS	15	80	150	220	400	600
MAGNITUDE	3	4	5	6	7	8

[1] Adapted from Wood and Neumann (1931).

[2] From Gutenberg and Richter (1956, p. 141) and Hodgson (1966, p. II-9).

timated by observers as having lasted 3 minutes or more. The U.S. Coast and Geodetic Survey (1960) reported surface fissures that trended west-northwest. Damage to most commercial and residential buildings was slight; many of the buildings were small frame structures without plaster and were well able to withstand fairly severe ground motion. Near the head of Monti Bay, a large wooden water tank collapsed; the tank was 4 m high by 5 m in diameter and was built on a platform 13 m above the ground surface.

The 1-m waves reported in Monti Bay probably were due to the submarine landslide on the south end of Khantaak Island. In addition, there was about a 0.2-m wave at the time of the earthquake.

Khantaak Island experienced two large submarine landslides: one at the southern end of the island and one at the northern end of the island. Both apparently were in areas of rapid deposition and loose sediments and perhaps occurred in the same areas that slid during the earthquakes of 1899. The slide at the southern end of the island (C on pl. 1) encompassed an area about 50 m wide and 335 m long and involved most of Point Turner, the southernmost end of the island. The slide caused a wave estimated to be at least 5–7 m high as seen by an observer about 1.6 km northwest of Yakutat; however, by the time the wave reached upper(?) Monti Bay it was reported as only 1 m high. Two later waves also were reported as about 1 m high. Total amount of material involved in the submarine landslide was estimated to be at least 500,000 m^3; the nearly vertical cliff left by the slide was approximately 4 m high and trended about parallel to the former shoreline. Behind the cliff there were several cracks subparallel to the shore and several grabens, some as deep as about 1.5 m. Near the slide two other areas were heavily fissured—one at the easternmost part of Point Turner and the other approximately 200 m to the northwest.

The submarine landslide, on the northern end of Khantaak Island (D on pl. 1), where an unknown amount of subsidence occurred, left a cliff estimated to be 3–5 m high. Many small fissures were in evidence back from the cliff and on the northeasternmost 0.8 km of the island. In addition, an area near the southern end of Gilbert Spit was extensively fissured, mostly in a northeast-southwest direction; a graben that developed was 5 m wide and 1 m deep.

The great Alaska earthquake of 1964 (the March 28 or Good Friday earthquake), with an epicenter about 480 km west-northwest of Yakutat, was felt strongly in parts of the Yakutat area, especially on the Yakutat Foreland. The earthquake shaking lasted between 4 and 6 minutes, depending on the observer (Plafker and others, 1969, p. G35). One observer reported an east-west rolling or swaying motion that built to a peak in about half a minute and lasted a total of 6 minutes (timed). Damage in the area as a whole generally was very minor; no structural damage to buildings was reported.

At the Yakutat airfield there was some damage to the parking ramp and runways built of concrete slabs; ground motion was strong enough to cause parked trucks on the ramp to roll back and forth as much as 3 m. The damage to the slabs apparently was caused by differential up-and-down movement of the slabs, resulting in cracking of some of them. Damage to the ramp and runways was considered somewhat greater than the damage that occurred during the July 10, 1958, earthquake.

Several earthquake-related water waves affected shore areas during and after the 1964 Alaska earthquake; none of the waves reached above extreme high water level or caused damage in the vicinity of Yakutat (Plafker and others, 1969, p. G35). At Yakutat during the earthquake, a single wave was observed along the shore of Monti Bay. The churned, muddy water seen in the vicinity the next day indicated the possibility that the wave had been caused by a submarine slide near the southern end of Khantaak Island, probably close to where slides occurred during the July 10, 1958 (C on pl. 1), and September 1899 earthquakes (Plafker and others, 1969, p. G35). Some slumping of a beach near Point Turner was observed (E on pl. 1; U.S. Coast and Geodetic Survey, 1966, p. 56). About 1 hour and 25 minutes after the earthquake started, the far-reaching tsunami waves, generated by movement of the earth's crust near the earthquake epicenter, began arriving in Monti Bay. These waves were recorded on the tidal gage and were interpreted as showing a maximum wave height of about 2.5 m (table 5; Cox and others, 1976). The series of tsunami waves continued for at least 7 hours, and erratic tides continued for several days.

The most recent relatively large earthquakes felt at Yakutat were those of July 30, 1972, and July 1 and 3, 1973. The one of July 30, 1972 (Q on fig. 3), with its main shock of a magnitude of 7.25 and centered offshore from Sitka, Alaska, was distinctly felt in the Yakutat area, where it had a Modified Mercalli intensity of V–VI (table 2); damage was light. Among the effects noted were the following: water in some wells became muddy, trees swayed, hanging objects swayed violently, and part of a sewage facility was damaged. This earthquake probably was the first recorded by the seismoscopes and strong-motion accelerograph in the Yakutat area (pl. 1). Only two of the six seismoscopes in operation had a measurable response to the earthquake, and those were on the relatively less firm foundations of water-saturated, sandy, small-pebble gravel at the airport. Seismoscopes on firmer ground of the intermediate beach deposits and those on morainal deposits at Yakutat had responses that were too small to be measured accurately. Of the two seismoscopes at the Yakutat airport, one registered a relative displacement of 0.49 cm in the principal direction S. 75° W., and the other registered 0.56 cm in the principal direction S. 40° E. (R. P. Maley and B. L. Silverstein, written commun., 1973). On the component oriented N. 53° E., the strong-motion accelerograph registered a value of 1 percent gravity and a period of 1.7 seconds (U.S. National Oceanic and Atmospheric Administration, 1974); neither of the other components had responses that were large enough to be measured accurately. The earthquake did not generate a tsunami significant enough to register on the tidal gage at Yakutat.

The earthquakes of July 1 and 3, 1973 (R and S, respectively, on fig. 3), with magnitudes of 6.7 and 6.0, respectively, were felt in the Yakutat area (table 2). The earlier shock had a Modified Mercalli intensity of V (U.S. National Oceanic and Atmospheric Administration, and U.S. Geological Survey, 1975). There was rattling of doors, windows, and dishes, and there were reports of buildings creaking loudly and hanging objects swinging moderately (U.S. Geological Survey, 1975). The earthquake of July 3, 1973, had a Modified Mercalli intensity of IV (U.S. National Oceanic and Atmospheric Administration and U.S. Geological Survey, 1975). Although the sense of motion of the presumed faulting that caused the earthquake was oblique underthrusting (Gawthrop and others, 1973) and might have been expected to produce significant tsunami waves if the earthquake focus had been shallower, no waves were prominent enough to be detected on the Yakutat tidal gage.

Of recent importance to the study of regional seismicity has been the occurrence since about January 6, 1974, of a large number of relatively small earthquakes concentrated within an area about 50 km south of Yakutat (U.S. National Geophysical and Solar-Terrestrial Data Center, 1975, 1976; Lahr and others, 1976). Although most of the earthquakes recorded through 1975 were small, one of them had a magnitude of about 4 and was felt at Yakutat (table 2).

RELATION OF EARTHQUAKES TO KNOWN OR INFERRED FAULTS AND RECENCY OF FAULT MOVEMENT

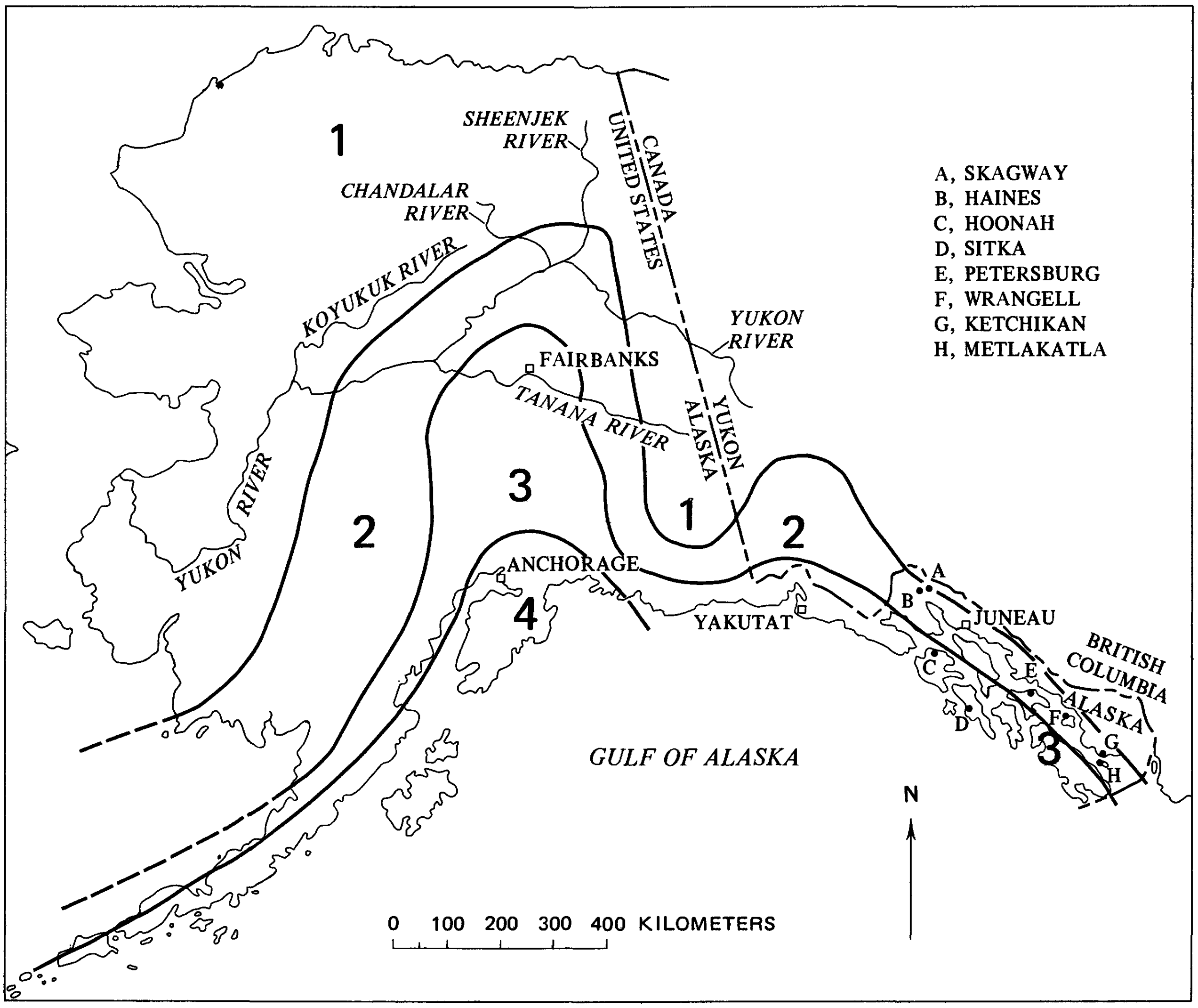
In some earthquake regions of the world, close spatial relationships have been demonstrated between earthquakes and specific faults. In most of southeastern Alaska, however, such relationships cannot yet be established, for two reasons: most earthquake epicenters are located, at best, with an accuracy of only 15–25 km, and exact location of many faults is unknown because of concealment by water or surficial deposits. There appears, however, to be a general relationship between some extensive groups of earthquakes and certain zones of faults. In the Yakutat region, despite its widespread distribution of earthquakes (fig. 3), it is thought that most earthquakes are caused by movements along the named faults and associated branches.

The Fairweather fault is the only active onshore fault in the region that is known at some localities to have ruptured the ground surface. The most recent known surface breaks reported in the geologic literature (Tocher, 1960) occurred at several localities along the Fairweather fault during the earthquake of July 10, 1958. Minor amounts of movement appear to be continuing along the Fairweather fault, as interpreted from the occurrence of localized microearthquakes during a few days in 1968 (Page, 1969). As additional earthquake-detection instruments are installed and operated in the region, movement along specific faults will be more clearly defined.

ASSESSMENT OF EARTHQUAKE POTENTIAL IN THE YAKUTAT AREA

Only a general assessment of earthquake potential can be made for the Yakutat area, because information on many aspects of seismicity is limited. Details still must be studied that concern geologic structure and the tectonic framework of much of the region as it relates to Yakutat. To portray the earthquake potential for an area, two basic types of maps are available. One type considers only the maximum level of shaking that can be expected to occur in a region sometime in the future; the second type considers the expectable levels of shaking with regard to specific periods of time. Both types of maps generally are derived from analysis of the historic seismicity and some consideration of the tectonic framework.

The Yakutat area is shown on two examples (figs. 4, 5) of the first type of seismic risk map. These maps do not predict the frequency of earthquake occurrence. The first example is a redrawn, enlarged rendition of the seismic zone map included in the 1976 edition of the Uniform Building Code (fig. 4; International Conference of Building Officials, 1976). The map relates a particular zone to the Modified Mercalli intensities of earthquakes expected to affect that zone. The Yakutat area is shown as being in the zone of maximum expectable earthquake damage, one which



EXPLANATION

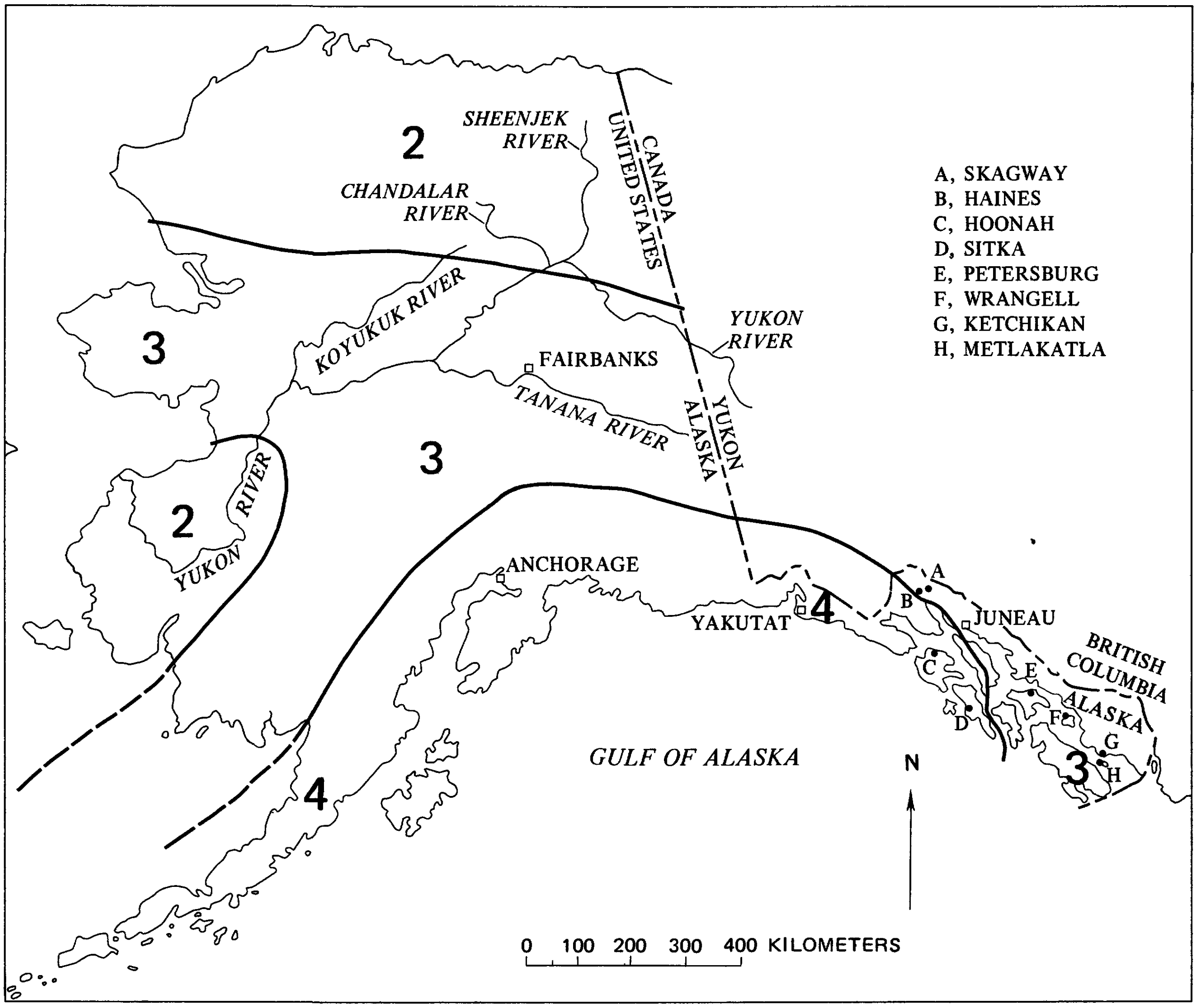
Zone	Damage	Comment
1	Minor	Distant earthquakes may cause damage to structures with fundamental periods >1.0 s; corresponds to intensities[1] V and VI
2	Moder-ate	Corresponds to intensity[1] VII
3	Major	Corresponds to intensity[1] ≥VIII
4	Major	Those areas within zone 3 determined by proximity to certain major fault systems

[1] Modified Mercalli intensity scale (table 3)

FIGURE 4.—Seismic zone map of Alaska modified from Uniform Building Code, 1976 edition (International Conference of Building Officials, 1976).

might experience Modified Mercalli intensities of VIII or higher (table 3). For the Yakutat area, the map depicts the area west of Yakutat as subject to larger earthquakes and greater possible damage than do maps of seismic probability included in publications by Johnson and Hartman (1969, pl. 49) and Alaska Industry (1970).

The second example of the first type of earthquake hazard map is a suggested preliminary map termed a seismic risk map (fig. 5) that was prepared by the U.S.



EXPLANATION

Zone	Possible maximum damage to structures	Magnitude[1] of largest probable earthquake
2	Moderate	<6.0
3	Major	≥6.0
[2]4	Major to very severe	≥6.0

[1] Largest earthquakes of the world have had recorded magnitudes of 8.9 (Richter, 1958, p. 711-712).

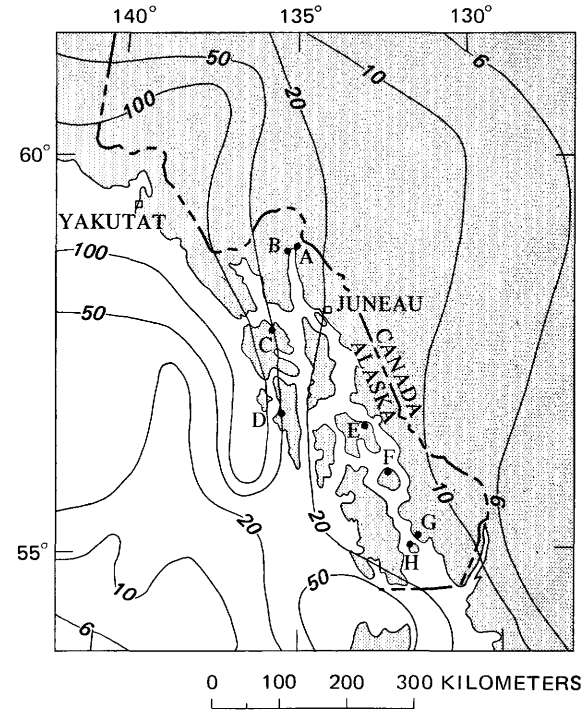
[2] Zone characterized by frequent earthquakes of long duration; extensive faults, some of which are active; and areas with thick surficial deposits which tend to increase ground shaking and which in many places are susceptible to liquefaction.

FIGURE 5.—Suggested preliminary seismic risk map of Alaska by U.S. Army Corps of Engineers, Alaska District. Modified from description developed by E. L. Long and G. H. Greeley (H. W. Holliday, written commun., 1975).

Army Corps of Engineers, Alaska District, in 1973 (H. W. Holliday, written commun., 1975; Selkregg, 1974, 1976). The map relates possible damage during earthquakes to the magnitude of the largest probable earthquake and shows the Yakutat area subject to major to very severe damage from earthquakes which would have magnitudes equal to or greater than 6. The highest zone was determined after a generalized consideration of certain geologic factors, most of which can be related to regional patterns of earth movements and the response of ground to shaking during earthquakes. Factors include (1) presence of extensive faults in the region, some of which are active; (2) probable duration of earthquake shaking; and (3) presence of thick unconsolidated deposits, many of which are subject to liquefaction.

The Yakutat area also is depicted on the second type of seismic hazard map (fig. 6), which shows probable peak acceleration of earthquakes as a percent of gravity during any period of 100 years (Milne and Davenport, 1969; Klohn, 1972). For the Yakutat area, the map indicates that a peak acceleration of as much as 100 percent gravity might be expected within any 100-year period. A slightly different analysis of earthquakes in part of the same area as shown in figure 6 has been accomplished by Stevens (1974) and Stevens and Milne (1974).

Any evaluation of earthquake risk for specific sectors of land smaller than the Yakutat area must await expanded as well as more detailed geologic and related geophysical studies in the region. Of special importance are studies of (1) the degree of activity along the Fairweather fault and subsidiary faults and along the Miller Creek-Chaix Hills and Chugach-St. Elias faults and subsidiary faults, (2) the lack of very large earthquakes in the recent past in the area west of Yakutat (Sykes, 1971; Kelleher and others, 1974; Page, 1975; Plafker and others, 1975), and (3) the nature of the inferred Transition fault and associated faults offshore from Yakutat. Concerning the last, it is important to know the faults' relationship to regional movement of the earth's crust and to know whether the faults can generate very large earthquakes and tsunamis or whether they can generate only moderate to large earthquakes, such as those of July 1973 (Gawthrop and others, 1973).



EXPLANATION

—10— Contour–Showing peak accelerations from earthquakes as a percent of gravity

A	Skagway	E	Petersburg
B	Haines	F	Wrangell
C	Hoonah	G	Ketchikan
D	Sitka	H	Metlakatla

FIGURE 6.—One-hundred-year probability map showing distribution of peak accelerations from earthquakes as percent of gravity for southeastern Alaska and part of Canada. Modified from Milne and Davenport (1969). Map is based upon the amount of energy released by the largest earthquake (magnitude >2.5) that occurred each year in a unit area of 10,000 km^2 during the period from 1899 through 1960, projected to a 100-year interval.

INFERRED EFFECTS FROM FUTURE EARTHQUAKES

The following discussion and evaluation of the geologic effects of future large earthquakes are based upon the assumption that large earthquakes will continue to affect the Yakutat area.

Specific evaluation of possible geologic effects in the Yakutat area is based partly on observations by others during earthquakes felt in the area and partly on estimates of the response of local geologic materials, inferred from the response of similar materials during earthquakes elsewhere.

Evaluations are given in table 4 for (1) sudden tectonic uplift, (2) sudden tectonic subsidence, (3) ground shaking, (4) liquefaction, (5) ground fracturing and water and slurry fountains, (6) compaction and related subsidence, and (7) landsliding. These factors and several others are discussed briefly in following sections of this report.

EFFECTS FROM SURFACE MOVEMENTS ALONG FAULTS AND OTHER TECTONIC LAND-LEVEL CHANGES

In southeastern Alaska and along the Gulf of Alaska coast, movements of surface faults have been documented for only a few of the considerable number of earthquakes in historic time. During the more numerous small earthquakes, displacement along faults occurs mostly at depth; however, during the less frequently occurring moderate and large earthquakes, there may be movement along faults at depth as well as up to the ground surface. At Yakutat the likelihood

TABLE 4.—*Possible effects of earthquake activity on geologic materials mapped in the Yakutat area*

Mapped geologic materials	Earthquake effects near Yakutat Bay or the outer coast		
	Sudden tectonic uplift	Sudden tectonic subsidence	Ground shaking
Artificial fill.	Promotion of better drainage; less accessibility by boat of some fills.	Flooding of margins of some deposits near tidewater.	High to moderate, especially around periphery of upper part of fill if poorly compacted during emplacement and if water table very high.
Organic deposits underlain by coarse-grained deposits.	Probably none-------	Probably none-------	Severe-----------------------
Organic deposits underlain by fine-grained deposits.	Locally, better drainage and increased erosion by streams.	Flooding in many places near outer coast.	Severe to very severe--------
Eolian sand deposits.	Promotion of the enlargement of several deposits.	Flooding of some deposits near the community of Situk.	Probably moderate to severe, locally, where thin and overlying saturated young delta-estuarine deposits.
Young beach deposits.	Along gentle slopes, enlargement of deposits.	Increased wave erosion of deposits, especially during storms.	Moderate to severe, depending upon stage of tide and degree of saturation.
Intermediate beach deposits.	Probably none-------	Possible wave erosion, during storms, of some deposits along outer coast.	Moderate---------------------
Old beach deposits.	----do--------------	Flooding of margin of some deposits.	----do-----------------------

TABLE 4.—*Possible effects of earthquake activity on geologic materials mapped in the Yakutat area*—Continued

Earthquake effects in Yakutat area as a whole			
Liquefaction	Ground fracturing and water and slurry fountains	Compaction and related subsidence	Landsliding
Low; may respond to liquefaction of underlying deposits.	Low to moderate; may be affected by fracturing of underlying material.	Low to high; high where overlies (at shallow depth) saturated silty sand or if fill is not compacted to optimum density during emplacement.	High along margins of fills; might be involved in movement of underlying deposits.
Generally low, moderate in some localities.	Moderate to low; fractures may open where certain types of horizontally moving landslides occur. Very low potential for fountaining.	Low------------------	Low; locally some horizontally moving landsliding might be expected toward bodies of water.
High because of generally high water table and the fine grain size of underlying materials.	High because of fine-grained size of underlying material and relation to high water table.	Expected to a moderate degree in underlying material. This action should affect these organic deposits.	Probably moderate with horizontally moving slides spreading toward bodies of water.
Very low, except high where thin and overlies saturated delta-estuarine deposits.	Very low; where thin, may be fractured along with underlying deposits.	Low------------------	Low; possibly moderate where newly deposited.
Low to moderate------	Low-----------------	Low to moderate; probably higher where newly deposited; however, such deposits even more subject to submarine landsliding.	Low; locally very high where newly deposited.
Low-----------------	----do--------------	Low------------------	Low.
----do--------------	Very low------------	Very low-------------	Very low.

TABLE 4.—*Possible effects of earthquake activity on geologic materials mapped in the Yakutat area*—Continued

Mapped geologic materials	Earthquake effects near Yakutat Bay or the outer coast		
	Sudden tectonic uplift	Sudden tectonic subsidence	Ground shaking
Young delta-estuarine deposits.	Major enlargement of deposits.	A large inland shift of all tidal stages and increased erosion by storm waves.	Very high----------
Intermediate delta-estuarine deposits.	Increased drainage and accelerated stream downcutting.	Inundation of several areas of deposits and worsening of drainage.	----do--------------
Old delta-estuarine deposits.	Probably none-----------	Inundation of margins of a few deposits.	Moderate to high----
Clayey silt delta-estuarine deposits.	Further stream down-cutting of deposits.	Burial of some deposits by young delta sediments.	Probably moderate to high.
Coarse-grained alluvial deposits.	Probably none-----------	Probably none-----------	High to moderate----
Fine-grained alluvial deposits.	Probably improved drainage because of accelerated stream downcutting.	Flooding of lower margins of small deposits.	Very high----------
Old alluvial deposits.	Probably none-----------	Probably none-----------	----do--------------
Coarse-grained outwash deposits.	----do------------------	----do------------------	Low to moderate-----
Fine-grained outwash deposits.	----do------------------	----do------------------	Moderately high because well saturated.
End and ground moraine deposits.	Disruption of some shore facilities.	Disruption of some shore facilities and increased wave erosion of many deposits.	Relatively low to moderate.

TABLE 4.—*Possible effects of earthquake activity on geologic materials mapped in the Yakutat area*—Continued

Earthquake effects in Yakutat area as a whole			
Liquefaction	Ground fracturing and water and slurry fountains	Compaction and related subsidence	Landsliding
High, locally very high.	Very high; emitted sediments might cover large areas.	High to moderate, especially near newly deposited materials.	Very high because of saturation, looseness, and fine-grained nature of deposits. Submarine landslides probably common.
High------------------	Moderate to high----	Moderate to high-	Moderate to low; some horizontally moving slides may progress toward streambanks.
Low to moderate at lower margins where thinnest and probably saturated.	Probably low--------	Probably low to moderate.	Moderate at margins of some deposits.
Low because deposit well compacted.	Low because deposit well compacted.	Low because deposit well compacted.	Probably low to moderate.
Probably moderate to high.	Moderate-----------	Low-------------	Probably low except along banks of streams.
High------------------	High, especially near abandoned stream channels.	Moderate--------	Low except along streambanks. Possibly massive, horizontally moving slides.
Probably high---------	High. especially near channels of formerly active streams.	Probably low-----	Do.
Probably none---------	Probably very low---	Low-------------	Low.
Probably moderate to high because of saturation and fineness of deposit.	Moderate to low-----	Possibly moderate to low.	Probably low, but horizontally moving slides might occur.
Very low; locally moderate where deposits are saturated and have a large content of fine sand.	Low----------------	Generally low----	Probably moderate to high, especially in steep-sloped areas of the deposits.

of faults breaking the surface during a nearby major earthquake is unknown.

Large-scale sudden uplift or subsidence may occur during some large earthquakes; the Yakutat region bears ample evidence of large-scale tectonic uplift having occurred as part of the large earthquakes of September 1899. If a sudden vertical change in level of land of only several centimeters took place, the change would cause no adverse effects in the Yakutat area; however, a change in level of about a meter might affect the area greatly. The effect of such changes in level on geologic deposits is given in table 4.

GROUND SHAKING

Ground shaking causes most of the damage to buildings and other structures during earthquakes. At a given locality, ground shaking is controlled by several factors (Page and others, 1975, p. 601). Major factors are (1) the earthquake energy released, (2) the distance of the particular locality from the causative fault, and (3) the response of geologic materials to the motion of the bedrock beneath the locality. Other factors of importance are the earthquake mechanism and type of fault motion. The severity of ground shaking during earthquakes is largely determined by three aspects of motion: amplitude, frequency content, and duration.

During a single large earthquake occurring outside, but near, the Yakutat area, ground shaking probably would be most severe on geologic materials that are loosely consolidated, fine grained, water saturated, and thick. Conversely, shaking probably would be less severe on geologic materials that are hard, firmly consolidated, and unfractured. However, for even a moderate-sized earthquake occurring within the area, distance from the causative fault may be an overriding factor. The possible characteristics of ground shaking of mapped geologic materials during large earthquakes occurring near the Yakutat area are presented in table 4.

LIQUEFACTION

Ground shaking during major earthquakes in other areas has caused liquefaction of certain types of saturated, unconsolidated deposits. Especially susceptible are those deposits that contain materials of very low cohesion and uniform, well-sorted, fine- to medium-grained particles such as coarse silt and fine sand. A major consequence of liquefaction is that sediments that are not confined at the margin of the body of sediment will tend to flow or spread toward those unconfined margins and will continue to flow or spread as long as pore-water pressures remain high and shaking continues (Youd, 1973). If liquefaction occurs in saturated sediments that are confined at the margin of the body of sediment, the result is the familiar quicksand condition. Liquefaction accompanies other earthquake effects like ground fracturing and water-sediment ejection.

A generalized evaluation of the potential for liquefaction of mapped geologic deposits in the Yakutat area is shown in table 4, based in part on analysis of effects during the July 10, 1958, earthquake. To develop detailed maps showing liquefaction potential during large earthquakes (Youd and others, 1975, p. A70), extensive data on physical properties, especially on density of geologic materials, would be required.

GROUND FRACTURING AND WATER-SEDIMENT EJECTION

Ground fracturing and ejection above the ground surface of water or slurries of water and sediments from certain deposits are common during the strong shaking that accompanies many large earthquakes. The ejection process is called fountaining, or spouting; compaction and differential subsidence of ground often accompany ejection. Ejection takes place most often where loose, sand-sized materials are dominant in a deposit and where the water table is shallow and restricted by a confining layer—which can even be seasonally frozen ground. Seismic shaking of confined ground water and sediment causes hydrostatic pressure to increase and liquefaction to occur. If the confining layer ruptures, the water and sediment erupt from point sources or along ground fractures. In the Yakutat area, ejected material during the July 10, 1958, earthquake covered some areas to depths of about a meter (pl. 1), and the craters and fractures may have been many meters deep. Table 4 lists the relative susceptibility of mapped deposits in the Yakutat area to ground fracturing and fountaining.

COMPACTION AND RELATED SUBSIDENCE

Strong shaking of loose geologic materials during major earthquakes may result in volume reduction and compaction of some deposits. Compaction often is accompanied by liquefaction and by ejection of water or water-sediment mixtures, sometimes in the form of fountaining or spouting. As a result of the operation of these processes, the surface of the ground locally may settle differentially by as much as about a meter. The greatest settlement of ground probably will occur where (1) the ground-water table is high and some of the water can be expelled, (2) the deposits are loose and thick and consist of silt to small pebble-sized materials, and (3) strong shaking persists for at least a few minutes. The possibilities of compaction and subsidence of deposits in the Yakutat area are evaluated in table 4.

EARTHQUAKE-INDUCED SUBAERIAL AND UNDERWATER LANDSLIDES

During earthquake-caused ground shaking, geologic materials may experience a variety of downslope mass movements termed, collectively, "landslides." Movements may consist of single or multiple sliding events that include failures of active delta fronts or extending spits, land spreading, small-scale slumping, earth flowage, and minor creep (Eckel, 1970). Loose, water-saturated deposits on steep slopes are especially prone to downslope movement. Liquefaction may trigger sliding and flowage of material even on very gentle slopes of less than 1° (1.75 percent).

Steep delta fronts, because of their large content of loose material, are particularly susceptible to sliding during the strong shaking that accompanies major earthquakes. Shaking during the 1964 Alaska earthquake triggered landsliding of delta fronts at numerous places in southern Alaska. Some of the slides, in turn, triggered large waves that swept onto the land. Rapidly extending beach spits are another geologic setting where submarine landsliding probably is frequent during earthquakes. For the Yakutat area, susceptibility of mapped deposits to landsliding during earthquake shaking is shown in table 4.

EFFECTS OF SHAKING ON GROUND WATER AND STREAMFLOW

The flow of ground water may be changed by strong ground shaking and by any resultant permanent ground displacement. Examples of changes reported by Waller (1966, 1968) from south-central Alaska show that the 1964 Alaska earthquake especially affected semiconfined ground water in alluvial and delta deposits. After the earthquake, ground-water levels locally were raised because of (1) subsidence of ground, (2) increase in hydrostatic pressure, or (3) compaction of sediments. Other ground-water levels locally were lowered because of (1) pressure losses, (2) rearrangement of sediment grains, (3) lateral spreading of deposits, or (4) greater discharge of ground water after sliding of delta fronts. Waller reported that some changes in hydrostatic pressure and ground-water level were temporary, while others lasted for at least a year; some changes may be permanent.

In the Yakutat area, the ground-water table and ground-water flow are very near the surface in alluvial and young and intermediate delta-estuarine deposits. Intense shaking and earthquake effects that would alter ground-water flow include water-sediment ejection, ground compaction, and large-scale sliding or spreading of these deposits south and southwestward toward the outer coast.

Alterations to streamflow often are important consequences of major earthquakes. Streams flowing on alluvial and deltaic deposits can experience a temporarily diminished flow because of water loss into fractures opened by ground shaking. The sediment load of streams often will be increased temporarily following a major earthquake. Streams may be dammed by earthquake-caused landslides and, if the dams break suddenly, downstream flooding can result.

EFFECTS OF EARTHQUAKE SHAKING ON GLACIERS

Strong ground shaking and tectonic change of land levels during earthquakes have caused short- and long-term changes in glaciers and related drainage features in the Yakutat region (Tarr and Martin, 1912, 1914; Post, 1967). The triggering of large numbers of avalanches and landslides that can spread over extensive areas on glaciers is one of the important results of ground shaking. However, the advances of glaciers, postulated by Tarr and Martin as having been caused by extensive avalanching during and following the September 1899 earthquakes, are thought not to be controlled by effects of the earthquake. Other results of ground shaking include (1) massive icefalls from breakage of hanging glaciers and (2) extensive icebergs from breakage of floating glaciers. In upper Yakutat Bay and adjacent fiords during the September 1899 earthquakes, enough icebergs were produced to block passage of boats for a considerable time in both upper Yakutat Bay and in the western part of outer Yakutat Bay. Waves generated by ice breakage probably would be mostly dissipated before arriving at Yakutat.

TSUNAMIS, SEICHES, AND OTHER EARTHQUAKE-RELATED WATER WAVES

Earthquake-induced water waves often develop during major earthquakes and may affect shore areas, even at great distances, for several days thereafter. Types of waves include tsunamis (seismic sea waves), seiches, waves generated by subaqueous and subaerial landslides, and waves generated by local tectonic displacement of land. The following discussion considers each of these types of earthquake-induced waves and the likelihood that they may develop to heights that might affect the Yakutat area.

Tsunamis are long-period water waves that are caused by sudden displacement of water. The largest tsunamis originate where widespread vertical offsets of the sea floor occur, such as those accompanying major underthrust earthquakes around the rim of the Pacific

Ocean. In the deep ocean, groups of tsunami waves travel long distances at great speed and with low height, but as they approach the shallower water of the Continental Shelf and shore areas their speed decreases greatly and their height increases manyfold. In shallow water, wave height and type are controlled largely by the initial size of the wave, the configuration of the ocean bottom, the shoreline configuration, the natural period of oscillation of the water on the shelf or bay, and the stage of the tide (Wilson and Tørum, 1968). Wiegel (1970) noted that many waves that strike coastal areas along the Pacific Ocean have been as high as 15 m and that a few waves have been as high as 35 m.

At Yakutat and in Yakutat Bay and adjoining fiords, several tsunamis and non-storm-generated waves have been experienced in the last about 130 years. Known wave events are listed in table 5, along with wave heights as noted by eyewitnesses or as interpreted from records derived from tidal gages maintained by personnel of the former U.S. Coast and Geodetic Survey, now the U.S. National Oceanic and Atmospheric Administration. Undoubtedly many small tsunami and other waves are not listed. At Yakutat, the highest earthquake-related wave originating nearby occurred during the larger earthquake of September 10, 1899. Although estimates varied, the wave at Yakutat may have had a height of about 5 m. The wave probably was part of a sequence of waves formed by submarine landsliding of delta fronts in upper Yakutat Bay. The highest known tsunami wave originating at a considerable distance from Yakutat in part of the Pacific Ocean was the wave, about 2.5 m high, that arrived March 27, 1964 (local time), as one of the group of tsunami waves resulting from the 1964 Alaska earthquake.

Seiches are water waves that are set in motion as sympathetic oscillations or sloshings of closed or semiclosed bodies of water; they are caused by (1) the passage of air-pressure disturbances or seismic waves, (2) the tilting of enclosing basins, or (3) the impact of large landslides into bodies of water. The natural period of oscillation of a water body is controlled by the configuration of the enclosing basin. Although seiches often are small and masked by other types of waves, there were reports of seiches or possible seiches as much as 8.5 m high occurring during the 1964 Alaska earthquake (McCulloch, 1966; McGarr and Vorhis, 1968; U.S. Geological Survey, unpub. field data, 1964). At Yakutat, a seismically induced seiche developed about 4 minutes after the initial shock and was about 0.2 m high, as recorded on the tidal gage; it had a duration of 14 minutes (McGarr and Vorhis, 1972). Another of the set of waves affecting the Yakutat tidal gage was interpreted by Wilson and Tørum (1968, p. 100) as having developed a maximum height of 1.7 m and a period of 30 minutes. Earthquakes originating in other regions may generate different seismic waves and thus cause higher or lower oscillations of water.

Massive underwater and subaerial landslides related to shaking during earthquakes have caused small to very large waves in some bodies of water in Alaska. Although some waves were local and dissipated within short distances, others traveled far. Delta fronts, especially, can respond to shaking by extensive landsliding and generation of waves. Several deltas that failed elsewhere during the 1964 Alaska earthquake generated waves as much as 10 m high, including one wave that had a maximum vertical runup of 57 m (Kachadoorian, 1965; Coulter and Migliaccio, 1966; Lemke, 1967; Von Huene and Cox, 1972). Subaerial landsliding triggered by earthquake shaking also generated high waves. The world's record height of wave runup is probably 530 m, triggered by a landslide in Lituya Bay, about 165 km southeast of Yakutat, during the July 10, 1958, earthquake (fig. 1; Miller, 1960). Along the steep walls of upper Yakutat Bay and adjoining fiords, numerous waves formed because of earthquake-generated landsliding and, undoubtedly, submarine landsliding. The highest known waves occurred during the earthquake of September 10, 1899, and washed to heights of as much as 12 m (table 5) (Tarr and Martin, 1912).

Some of the locally generated waves that caused damage in southern coastal Alaska during the 1964 Alaska earthquake apparently were triggered neither by earthquake-induced landslides nor by seiches or tsunamis. Instead, Plafker (1969) and Von Huene and Cox (1972) suggested that these local waves were generated by sudden direct tectonic displacement of the land; wave height probably was controlled by bottom configuration, shore orientation, and the direction and amount of land displacement. In the Yakutat area, earthquake-induced waves of this type have not been recognized but may have been included as part of the complex of waves developed during the September 1899 earthquakes.

Damage to Yakutat from tsunamis and seiches is one of the most likely consequences of earthquakes. The occurrence of such waves should be anticipated at Yakutat as at other coastal cities. Unfortunately, wave heights and amount of damage related to hypothetical waves cannot be predicted. If all tsunamis were of the nonbreaking type and of low height and occurred at low tide, no damage would result. On the other hand, if a group of moderately high, breaking-type waves were to strike at highest high tide, locally, extensive damage probably would result.

TABLE 5.—*Known tsunami and non-storm-generated waves that reached or possibly reached Yakutat, Alaska, or elsewhere in the region, 1845 through 1974*[1]

Date, local time	Max. runup height or amplitude,[2] max. wave height,[3] or max. rise or fall of wave[4] (meters)	General region of earthquake and generation of tsunami; comments
1845(?)----------	[2]?-------------------------	Probably not earthquake related; icefall into Disenchantment Bay (B, fig. 2); 100 deaths from waves.
Mid(?)-1800's-----	?--------------------------	Probably not earthquake related; breakup of glacier damming large lake, located at southern end of present Russell Fiord.
Sept. 10, 1899----	[3]12 in upper Yakutat Bay; local waves, 5 Yakutat.	Upper Yakutat Bay; many waves caused by landslides.
July 4, 1905------	[2]35 in Disenchantment Bay (B, fig. 2).	Probably not earthquake related. Icefall from "Fallen Glacier" (3.5 km north of Bancas Point, A, fig. 2; Tarr, 1909, p. 67).
((Nov. 10, 1938))[5]-	(([2]0.2 at Sitka, 370 km to southeast; [2]0.1 at Seward, 560 km to west.))	Western Gulf of Alaska near Alaska Peninsula.
Apr. 1, 1946------	[2]0.2 Yakutat----------------	Northern North Pacific Ocean near Aleutian Islands.
Nov. 4, 1952------	[2]0.3 Yakutat; [4]0.6 Yakutat--	Northern North Pacific Ocean near U.S.S.R.
Mar. 9, 1957------	[2]0.4 Yakutat; [4]0.7 Yakutat--	Northern North Pacific Ocean near Aleutian Islands.
July 9, 1958------	[2]0.2 Yakutat; [6]1 Yakutat; probably from local waves generated in Yakutat Bay.	Northeastern Gulf of Alaska, southeast of Lituya Bay.
May 22, 1960------	[2]0.9 Yakutat; [4]1.7 Yakutat--	Southeastern South Pacific Ocean near Chile.
Mar. 27, 1964-----	[2]2.2 Yakutat; [4]2.5 Yakutat. Seiche waves to about 0.2.[7]	Northwestern Gulf of Alaska along south coast of Alaska.
((Feb. 3, 1965))[5]--	(([8]0.2 at Sitka, 370 km to southeast.))	Northern North Pacific Ocean near Aleutian Islands.
((May 16, 1968))[5]--	(([8]0.1 at Sitka, 370 km to southeast.))	Northwestern North Pacific Ocean near Japan.

[1]Additional tsunami or other non-storm-related waves, especially those of low height, undoubtedly have occurred but were not listed in publications about tsunamis and other waves because of the difficulty of detecting such events on tidal records in general, and because of the scarcity of observers.

[2]Cox, Pararas-Carayannis, and Calebaugh (1976); used term "runup height or amplitude."

[3]Tarr and Martin (1912).

[4]Spaeth and Berkman (1967); used term "rise or fall of wave."

[5](( )) Far-reaching tsunamis apparently not detected at Yakutat; however, event was recorded at possibly similar location(s) indicated.

[6]Tocher (1960).

[7]McGarr and Vorhis (1972).

[8]U.S. Coast and Geodetic Survey (1967, 1970).

One may speculate on several possible wave heights of tsunamis that might strike the Yakutat area. When considering these heights, it must be borne in mind that wave focusing and sympathetic resonance of local waves in a particular bay, cove, or fiord could increase wave heights by several meters. Tending to reduce the height of waves arriving from the Pacific Ocean are the submerged moraines at the mouth of Yakutat Bay which form an arcuate group of relatively shallow areas between Point Manby and Ocean Cape (fig. 2). The numerous islands and shallows near Yakutat in the lower part of Yakutat Bay also would tend to reduce the height of waves.

The U.S. Coast and Geodetic Survey (1965a) cautioned that all land with direct access to the open ocean and less than 17 m above sea level and within 1.6 km of the coast should be considered potentially susceptible to tsunamis generated at considerable distances. Most of Yakutat and much of the shore area along Monti Bay are above an altitude of 17 m and have steep slopes down to tidewater (pl. 1).

A somewhat less conservative approach is indicated by the data of Wiegel (1970), who noted that many of the larger Pacific Ocean tsunamis have been about 13 m high. If such a wave spread into Monti Bay at midtide, and if one discounted local shore and bottom configuration, there would be flooding of some land (1) in the old village area about 1.6 km northwest of Yakutat, (2) along parts of some nearby islands, (3) at the small-boat area, (4) along a narrow strip of the Monti Bay shore, including some harbor facilities, and (5) along part of The Ankau on Phipps Peninsula. Along the outer coast of the Gulf of Alaska, and especially near the estuaries of Lost, Situk, and Ahrnklin Rivers, waves possibly would spread inland as much as 1.6 km.

Another evaluation of the height of tsunamis that could affect Yakutat is available from a study by Dames and Moore (1971, p. B5–B6) on potential damage to the airport at Sitka, Alaska (fig. 1), from tsunamis generated in the Pacific Ocean. Because of the somewhat similar positions of Yakutat and Sitka relative to the Pacific Ocean and because of the use by Dames and Moore of data similar to that shown in table 5 on tsunamis generated in the Pacific Ocean, their study is thought to be applicable in general to Yakutat. The principal conclusion of Dames and Moore was that "there is a 63-percent chance that a tsunami will hit Sitka in a 100-year interval, with a maximum wave height of at least 20 feet [6 m]***, a 25 percent chance that such a wave will occur in 29 years and [a] 10 percent [chance] that such a wave will hit***in 10 years."

Warnings to coastal Alaska regarding the arrival time of potentially damaging tsunamis are issued by the International and the Alaska Regional Tsunami Warning System of the U.S. National Oceanic and Atmospheric Administration and the National Weather Service (Butler, 1971; Cox and Stewart, 1972; Haas and Trainer, 1974; Cox and others, 1976). For Yakutat, such warnings about tsunamis that are generated at great distances should allow sufficient time to move ships and evacuate the harbor and other low-lying areas. However, warning times probably would be insufficient for tsunami or other potentially destructive waves that might be generated in Yakutat Bay and adjoining fiords, or for waves that might be generated relatively close offshore in the Pacific Ocean. Estimates of traveltimes determined by the U.S. National Oceanic and Atmospheric Administration (unpub. data, 1971) for tsunamis that might be generated in the Pacific Ocean are shown in figure 7. Actual traveltimes, of course, may vary from the estimates.

Wave damage to shore areas from earthquake-triggered subaerial and submarine landslides may occur at several places in the Yakutat region. The potential for damage is high along the shores of narrow upper Yakutat Bay and adjoining fiords, where there are steep slopes, deep water, and probably steep-fronted deltas. As they have in the past, most such waves should dissipate rapidly as they travel into the much wider expanse of the lower part of Yakutat Bay.

INFERRED FUTURE EFFECTS FROM GEOLOGIC HAZARDS OTHER THAN EARTHQUAKES

In addition to the hazards from earthquakes, a potential for damage in the Yakutat area from other geologic hazards exists. These include (1) subaerial and underwater landslides, (2) stream floods and erosion of deposits by running water and sheet floods, and (3) high water waves not associated with local or distant earthquakes.

SUBAERIAL AND UNDERWATER LANDSLIDES

Numerous slopes in the Yakutat region are subject to various types of subaerial and underwater landsliding. Although many slope failures occur during earthquakes, as discussed previously, most occur at other times—on steep subaerial slopes during heavy rainfall, rapid snowmelt, and seasonal freezing and thawing, or as a result of man's alteration of slopes. The underwater slopes of active deltas and extending spits fail during normal oversteepening by deposition.

Subaerial landslides are rare in the Yakutat area, because there most slopes are gentle, but they are not

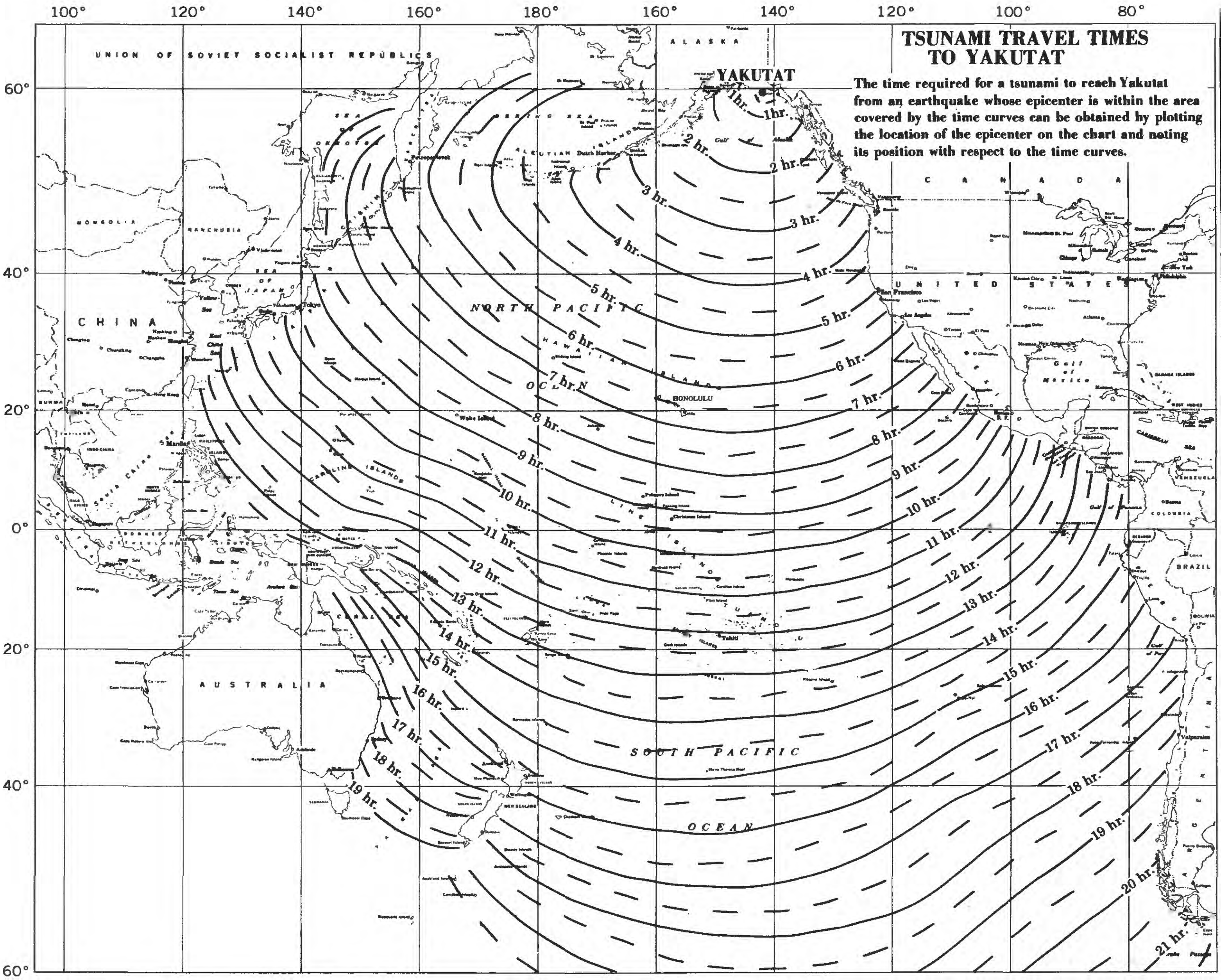


FIGURE 7.—Estimated traveltimes for tsunamis generated in the Pacific Ocean to reach Yakutat, Alaska (published with permission of U.S. National Oceanic and Atmospheric Administration, unpub. data, 1971).

uncommon in some shore areas of the lower part of Yakutat Bay, where slopes are steep (table 1). Such places that do slide probably are characterized by loose, unconsolidated geologic materials that are saturated. Relative susceptibility of various geologic deposits to general landsliding is presented in table 6.

In much of the Yakutat region north and northeast of Yakutat, slopes commonly are steep to very steep, especially along (1) the mountain front, (2) margins of most valleys, and (3) the margins of the upper part of Yakutat Bay and adjoining fiords (fig. 2). In this region, subaerial landslides probably are relatively frequent. Noteworthy are the massive slides and fissured bedrock of the valley sides of the uppermost part of Beasley Creek valley (D, fig. 2), about 5 km east of the south end of Russell Fiord. Some of the slides may have originated because of the loss of lateral support when the adjacent glacier, whose melt waters feed the creek, melted back rapidly within the last hundred(?) years.

Although earthquake shaking undoubtedly contributes to the frequency of sliding, the extensive research by Miller (1960) regarding the history of landslide-

TABLE 6.—*Evaluation of mapped geologic materials for degree of susceptibility to certain non-earthquake-related geologic hazards: landsliding, erosion by running water and sheet floods, and damage by high water waves*

Mapped geologic materials (pl. 1)	General susceptibility to all types of landsliding	Ease of erodibility by running water and sheet floods	Susceptibility to damage from high water waves
Artificial fill.	High where slopes of margins are steep and saturation is great; low elsewhere.	Low to moderate; high on steep margins if compaction was minimal at time of emplacement.	Greatly variable, depending in part on (1) compaction at time of emplacement and (2) direction of exposure and relation to pileup or focusing of waves.
Organic deposits underlain by coarse-grained deposits.	None because of lack of steep slopes.	Moderate where fibrous.	Moderate for a few deposits near Summit Lake.
Organic deposits underlain by fine-grained deposits.	----do----------------	Moderate where very fibrous; usually not developed where large amounts of water occur.	High for deposits near estuaries of Lost Creek and Situk River.
Eolian sand deposits.	Low where not actively developing; high elsewhere.	Very high-----------	Very high--------------
Young beach deposits.	Very low to very high; highest where newly deposited, as at ends of lengthening spits.	Not applicable-------	----do-----------------
Intermediate beach deposits.	Very low-------------	Moderate------------	High-------------------
Old beach deposits.	----do---------------	----do--------------	Low--------------------
Young delta-estuarine deposits.	Moderate to very high; highest where newly deposited.	Very high; major changes can take place in channel configuration within short time.	Very high; many deposits directly exposed to waves.
Intermediate delta-estuarine deposits.	Low because of gentleness of slopes.	Probably moderate to high.	Low for most deposits; high where merged with delta-estuarine deposits.

TABLE 6.—*Evaluation of mapped geologic materials for degree of susceptibility to certain non-earthquake-related geologic hazards: landsliding, erosion by running water and sheet floods, and damage by high water waves*—Continued

Mapped geologic materials (pl. 1)	General susceptibility to all types of landsliding	Ease of erodibility by running water and sheet floods	Susceptibility to damage from high water waves
Old delta-estuarine deposits.	Low-------------------	Moderate to low------	Low for those deposits near Ophir Creek.
Clayey silt delta-estuarine deposits.	Probably low but difficult to evaluate because of position and relation to fluctuations of tidewater.	Low------------------	Low because of high degree of compaction.
Coarse-grained alluvial deposits.	Low-------------------	Moderately high; frequent shifting of channels.	Inapplicable.
Fine-grained alluvial deposits.	----do----------------	High-----------------	Low.
Old alluvial deposits.	----do----------------	----do---------------	Inapplicable.
Coarse-grained outwash deposits.	Very low-------------	Moderately high------	Low for those deposits near Aka Lake.
Fine-grained outwash deposits.	----do----------------	High-----------------	Inapplicable.
End and ground moraine deposits.	Probably moderate because of abundance of steep slopes and a generally high level of saturation.	Moderate to low------	High only along some low, shore-exposed parts of deposits and at heads of bays and coves; mostly low susceptibility because of deposit height of more than 17 to 35 m.

generated waves in Lituya Bay strongly indicates a high degree of hazard from landslides along the steep walls of fiords, even if no earthquakes were to occur.

Intermittently occurring submarine landslides of various sizes in Yakutat Bay probably characterize fronts of (1) actively growing deltas and (2) extending beach spits that are located in down-current directions from shore areas being rapidly eroded by wave action. Some of the more prominent spits in the Yakutat area are Point Carrew on Phipps Peninsula and the north and south ends of Khantaak Island. Large deltas are present only southeast of Yakutat, where Lost, Situk, and Ahrnklin Rivers enter the Gulf of Alaska. Fronts of these deltas are continually being modified by the powerful longshore current of the gulf; thus, their fronts rarely become oversteepened. In contrast, in upper Yakutat Bay and adjoining fiords and along the west side of the lower part of the bay, the fronts of the large deltas formed by predominantly glacial streams probably are very susceptible to submarine landslides. Some slides might be capable of generating waves of moderate size.

STREAM FLOODS AND EROSION OF DEPOSITS BY RUNNING WATER

Extensive marshland and a locally well developed and integrated system of small and large streams easily accommodate or adequately carry most rainfall and melting snows in the Yakutat area; only occasionally will stream flooding occur. In a like manner, because vegetation covers most of the ground, sheet flooding will probably occur only locally during exceptionally heavy rainfall. The susceptibility of the various mapped geologic materials to erosion by running water and sheet floods is given in table 6.

HIGH WATER WAVES

Non-earthquake-related water waves high enough to damage some harbor structures occasionally might strike shores in the Yakutat area. Three types of waves are possible: (1) waves generated by underwater landslides or subaerial landslides into bays and fiords (noted above, in relation to landslides themselves), (2) glacier-related waves, and (3) storm and other waves originating in the Pacific Ocean. The susceptibility of parts of the Yakutat area to high water waves is given in table 6.

Glacier-related high water waves in upper Yakutat Bay and connecting fiords have been caused by (1) breakage and falling of huge pieces of ice from hanging glaciers perched along steep walls of fiords and (2) possibly by breakout of glacier-dammed lakes (table 5). Resulting waves probably would dissipate to a large extent as they traveled into the wide, lower part of Yakutat Bay. Breakage and sudden falling of glacier ice into the deep waters of the fiords connecting to upper Yakutat Bay caused locally high waves in 1905 and 1845(?) (table 5). In many places in the region, glaciers dam ice-free or partly ice-free tributary valleys. If drainage becomes blocked in the tributary valleys, large lakes can form and break out suddenly at regular or irregular intervals. This situation presumably has occurred in the past in several places in the region, notably in Russell Fiord.

Glacial advances, development of glacier-dammed lakes, and large-scale cracking of hanging glaciers probably could be detected by monitoring of selected glaciers in the Yakutat region (Post and Mayo, 1971). A very generalized surveillance of glaciers could be accomplished by inspection of periodic imagery provided by orbiting satellites (Krimmel and Meier, 1975, p. 397).

Waves from most storms in the Pacific Ocean weaken after moving into Yakutat Bay. Even after being weakened, however, storm waves could be very large and cause damage to the more exposed shore areas. One set of destructive storm waves occurred November 18, 1907, as noted by Tarr and Martin (1912, p. 47).

The height of the probable maximum 100-year storm waves in the Pacific Ocean west of British Columbia, as determined by Watts and Faulkner (1968), is 23 m, which may be valid as a possible maximum wave height for some areas of the Gulf of Alaska near Yakutat Bay. Specific heights of waves in the Gulf of Alaska were studied and reported by McLeod, Adams, and Hamilton (1975).

The origins of other types of Pacific Ocean waves that rarely may affect the Yakutat area are unknown, and time of occurrence or wave height cannot be predicted. Waves reached heights of about 5 m above mean high water on March 30–31, 1963, along the north coast of the Queen Charlotte Islands and near Prince Rupert, British Columbia (fig. 1; U.S. Coast and Geodetic Survey, 1965, p. 46). The waves may have been caused by a massive submarine landslide along part of the continental slope or by some special long-period ocean wave similar to waves described by Munk (1962) and Rossiter (1971). A wave of unknown origin, though described as a tidal wave, removed at least a part of the beach at the southern end of Khantaak Island in 1889 (Tarr and Butler, 1909, p. 165). A submarine landslide may have generated the waves.

Whether the few low-lying areas at Yakutat could be damaged by slide-generated waves or special long-period ocean waves is unknown. It seems plausible to expect, however, that sometime in the future such waves will reach Yakutat without warning.

RECOMMENDATIONS FOR ADDITIONAL STUDIES

The reconnaissance nature of this geologic investigation did not permit more than a brief evaluation of the general geology, potential geologic hazards, and other geologic factors that would be helpful to land-use planning in the Yakutat area. Therefore, the following recommendations for additional investigations are listed in a generalized order of importance.

1. Additional geologic mapping and field study of the Yakutat region, utilizing current aerial photographs and updated topographic maps and nautical charts, should be performed, including collection of data on the distribution and physical properties of geologic materials and the plotting of data concerning joints and faults. Such work might lead to discovery of economic mineral deposits, a better understanding of geologic structure of potential gas- and oil-bearing areas, the locating of generalized zones of potentially unstable slopes and zones of geologic materials subject to liquefaction, and the identifying of areas most suitable for construction.

2. In order to help indicate the possible location of future large earthquakes, the type of movement along known faults and inferred faults in the region should be determined. To accomplish this work, and to delineate any unknown active faults, records of earthquake events detected by seismological instruments in the region will have to be analyzed for a period of at least a few years. Also important are measurements of the slow, very small vertical changes in ground levels in the region; these measurements assist in determining the rate of rebound of land following glacial retreat and may provide an indication of possible future earthquakes.

3. Offshore geophysical studies should be continued and expanded. These studies should help determine the configuration of the sea floor, the nature of faults, and their relationship to the stability of geologic materials on the sea floor. Such work might result in the location of potential submarine landslides that could be triggered by movement along the faults.

4. Because of the potential for extensive wave damge in the Yakutat area, there should be a study of the natural oscillation periods of basins enclosing or related to large bodies of water in the region, to assist in prediction of possible wave heights. Basin areas include Yakutat Bay, adjoining fiords, and the Continental Shelf and associated sea-floor valleys of the Gulf of Alaska near Yakutat. In conjunction with the study, a probability analysis of tsunami frequency should be undertaken, similar to the previously described analysis that was developed by Dames and Moore (1971) for the airport at Sitka, Alaska.

5. Stability of steep subaerial slopes, especially along upper Yakutat Bay and adjoining fiords, should be analyzed to determine the areas of greatest probability of landslides and any associated high waves. Although initial detection of the most unstable slopes should be accomplished during areal geologic mapping, a separate analysis of slopes would permit a more thorough evaluation of those factors considered most responsible for the instability.

6. The advance and retreat of glaciers in the region should be monitored because of the potential for (a) large local waves from massive breakage of ice or from breakout of glacier-dammed lakes; and (b) blockage of navigation by glacier advances or greatly increased calving of tidal glaciers.

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