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

By

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This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey standards or nomenclature.

CONTENTS

ILLUSTRATIONS

TABLES

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ABSTRACT

A program to study the engineering geology of most of the larger Alaska coastal communities and to evaluate their earthquake and other geologic hazards was started promptly after the 1964 Alaska earthquake; this report is a product of that program. Field-study methods were largely reconnaissance, and thus the interpretations in the report are subject to revision as further information becomes available. The report provides broad guidelines for planners and engineers when considering geologic factors during preparation of land-use plans. The use of this information should lead to minimizing future loss of life and property, especially during major earthquakes.

Skagway was established in 1897 as a seaport near the head of Taiya Inlet fiord in the northern part of southeastern Alaska. Rugged mountains, steep-walled valleys, fiords, and numerous glaciers and icefields characterize the landscape of the area. Valley floors are narrow and most carry large streams, which end in tidewater deltas. Skagway is situated on the delta and lower valley floor of the Skagway River.

Glaciers became vastly enlarged during the Pleistocene Epoch and presumably covered the area at least several times. The last major deglaciation probably occurred about 10,000 years ago. Subsequently, there was minor expansion and then partial retreat of glaciers; land rebound because of glacial melting is still going on today.

Bedrock is composed predominantly of plutonic intrusive rocks, chiefly quartz diorite and granodiorite; some metamorphic rocks and a few dikes are present. Most bedrock is of Jurassic and Cretaceous age.

An assortment of surficial deposits of Quaternary age form the valley bottoms and locally part of the valley walls. Thick deposits of sand and gravel have accumulated as deltas at the heads of fiords and as alluvium in the main stream valleys; deposits may be as much as 585 feet thick at Skagway. Locally, thin deposits mantle some of the steep bedrock slopes and also form some moderately to gently sloping ground. Manmade fill covers much of the top of the delta and floor of the Skagway valley. The fill is composed chiefly of gravel and sand. Quarried blocks of granodiorite are used as riprap to face

river dikes and on fill areas exposed to waves of Taiya Inlet.

The geologic structure of the area is imperfectly known. However, it appears that plutonic rocks intruded metamorphic rocks in Jurassic and Cretaceous time. Extensive faulting is strongly indicated by the strikingly linear or curvilinear pattern of fiords and many large and small valleys, but no major faults have been positively identified because of concealment by water or surficial deposits. Inferred faults include those coincident with the lower Skagway valley, Taiya Inlet-Taiya valley, and the Katzehin River delta-Upper Dewey Lake. Principal fault movements probably occurred in middle Tertiary time but some movement might have been in late Tertiary or possibly early Quaternary time. Local faults appear to join the Chilkat River fault, a segment of the important Denali fault system, one of the major tectonic elements of southeastern Alaska. One fault segment of this system shows evidence of movement within the last several hundred years. Southeastern Alaska's other major fault system is the active Fairweather-Queen Charlotte Islands fault system near the coast of the Pacific Ocean. This fault system passes to within about 100 miles of Skagway. At its northwest end the fault system merges with the Chugach-St. Elias fault.

One hundred twenty-two earthquakes, some of them strong, have been felt or possibly felt at Skagway during the years 1898 through 1969. The closest large earthquake (magnitude about 8) causing some damage at Skagway occurred July 10, 1958. Its epicenter was about 100 miles to the southwest. Other earthquakes, as much as 150 miles away, also have caused slight to moderate damage. The closest instrumentally recorded earthquake (magnitude 6) had its epicenter about 30 miles to the west of Skagway.

Most earthquakes in southeastern Alaska have occurred southwest, west, or northwest of Skagway, near the coast of the Pacific Ocean. They appear to be related to movement along the Fairweather-Queen Charlotte Islands fault system or the Chugach-St. Elias fault. Most have had their epicenters offshore. Some earthquakes may be related to movement at depth along the Denali fault system.

The probability of destructive earthquakes at Skagway is unknown because the tectonics of the region have not been studied in detail. However, on the basis of the seismic record and limited tectonic evidence, we suggest that sometime in the future an earthquake of at least magnitude 6 probably will occur very close to the city, a magnitude 7 earthquake might occur in the general area, and an earthquake of magnitude 8 probably will occur at some distance to the southwest, west, or northwest.

Effects from nearby large earthquakes could cause extensive damage at Skagway. Nine principal effects are considered.

1. Surface displacement. Displacement of ground caused by fault movement would affect only structures built athwart the fault. However, a sudden tectonic uplift of land of as much as a few feet might affect a wide area and necessitate extensive dredging and wharf rebuilding. On the other hand, a subsidence of several feet would allow tidewater to reach inland and flood part of the harbor facilities and the business district.

2. Ground shaking. Because intensity of ground shaking during earthquakes largely depends on type and water content of the geologic material being shaken, the geologic materials are separated into three categories. Those considered susceptible to strongest shaking are grouped into category 1 (containing materials that are saturated, loose, and of medium- to fine-grain sizes); those of intermediate susceptibility in category 2; and those least susceptible to shaking in category 3.

3. Compaction of some medium-grained sediments during strong earthquake shaking could cause local settling of alluvial and deltaic surfaces. Also, some manmade fills near the harbor might undergo marked differential settling.

4. Liquefaction of saturated beds of uniform, fine sand commonly occurs during strong earthquakes. Few such beds, however, are positively identified at Skagway; some may occur within deltaic and alluvial deposits. If present, these beds might liquefy and cause local settling or trigger landslides.

5. Ejection of water-sediment mixtures from earthquake-induced fractures or from point sources, plus some associated ground subsidence, is common during major earthquakes where saturated sand and fine gravel deposits are confined beneath generally impermeable beds. Some alluvial and deltaic deposits at Skagway probably are susceptible to these processes. Locally, ejecta might cover roads and areas between buildings and fill low-lying areas. Associated ground fracturing might damage roadways, foundations of buildings, and other facilities.

6. Subaerial and subaqueous slides occur frequently during earthquakes. Saturated loose sediments on steep slopes are especially susceptible to sliding. During a major earthquake, surficial deposits forming such slopes along the southeast side of the Skagway valley probably would be subject to sliding or earthflowing on an extensive scale. Some sliding might extend onto the valley floor and damage or destroy buildings and part of the railroad. Rockfalls would be numerous and locally very large rockslides might occur.

Subaqueous sliding of the Skagway delta is potentially the most damaging of earthquake effects. Sliding may have occurred there during the earthquake of September 16, 1899; any future major earthquake close to the city would cause extensive sliding, possibly triggered in part by liquefaction. If shaking continued for several minutes, successive slides might progressively remove large portions of the delta and allow extensive land spreading and fracturing of Skagway River alluvium as much as several thousand feet landward from the shoreline.

7. Glacier surfaces commonly receive extensive snow avalanches and rockslides during seismic shaking. In the Skagway area, glaciers may be disrupted at their margins, and resulting blocked streams might form lakes in a few places. If these lakes drained suddenly, downstream areas would be flooded. No long-term effects, such as glacier expansion, are expected.

8. Ground- and surface-water levels often are affected during and after strong earthquake shaking. At Skagway, ground-water levels probably would be lowered, but there would be no permanent change in water quality. Earthquake-triggered landslides could dam the Skagway River; the sudden failure of the dams might cause severe flooding.

9. Waves generated by earthquakes include tsunamis, seiche waves, and waves caused by subaerial and submarine sliding and tectonic displacement of land. Damage in the Skagway area would depend on wave height, tidal stage, and warning time. Some waves triggered by subaerial and subaqueous slides have a strong possibility of reaching heights of as much as 60 feet--or possibly even higher. Tsunamis from the open ocean must travel 160 miles of fiords before reaching Skagway, which allows sufficient time for appraisal of expectable wave height and, if necessary, evacuation of the harbor area and other low-lying ground.

Geologic hazards other than those hazards associated with earthquakes include nonearthquake-induced subaerial and subaqueous slides, floods, and slow uplift (rebound) of land. Landslides of moderate size are known to have occurred from time to time during heavy rains such as those of September 1967. Subaqueous slides happen intermittently during the normal growth of deltas. Submarine cables on the floor of northern Taiya Inlet presumably were broken by such slides on September 10, 1927. Flooding by the Skagway River has inundated parts of the city many times, usually during heavy rains in the fall. Two floods were reported to have been caused by the sudden draining of glacier-dammed lakes. Dikes protect the city from many smaller floods, but heightening and broadening is needed to give full protection. Slow land uplift at Skagway, because of regional glacioisostatic rebound, averages 0.059 foot per year. On this basis, the shoreline theoretically shifted seaward 500 feet and the harbor shoaled 4.4 feet between 1897 and 1972.

It is recommended that future geologic study of the Skagway area include: detailed geologic mapping and collection of data on geologic materials, joints, faults, and slope stability; complete evaluation of earthquake probability and response of materials to shaking; and collection and evaluation of periodic soundings and sediment data from Skagway and Taiya deltas to assist in forecasting the stability of the delta front.

INTRODUCTION

Purpose and scope of study

Promptly 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 those near tidewater. As a result, Skagway and eight other communities were selected in southeastern Alaska for reconnaissance investigation. The following report on the engineering geology of Skagway and vicinity emphasizes the evaluation of potential earthquake damage for the area, and describes and assesses other geologic hazards, including landslides, subaqueous sliding, flooding, and land uplift. The geologic descriptions and hazard evaluations presented are intended only as preliminary generalizations and as tentative appraisals, but they should be helpful in land-use planning, not only to government officials, engineers, planners, and architects, but to the general public as well.

Because this study is essentially confined to descriptions and appraisals of Skagway and vicinity, extensive background information is not included in the report. Instead, the reader is referred to "References cited" or to a report by Lemke and Yehle (1972b) entitled "Regional and other general factors bearing on evaluation of earthquake and other geologic hazards to coastal communities of southeastern Alaska." That report provides much of the regional and background information necessary to evaluate the earthquake probability of the region. In addition, it cites examples of effects of large earthquakes in different parts of the world in relation to possible future effects in cities of southeastern Alaska.

The reader also is referred to a report on the Haines area, a community 16 miles south-southwest of Skagway (Lemke and Yehle, 1972a). Additional information is furnished in that report on the evaluation of earthquakes and other geologic hazards in a somewhat different geologic environment than that of Skagway.

Methods of study and acknowledgments

Fieldwork in Skagway and vicinity was limited to two man-weeks during parts of July 1965 and 1968. The reconnaissance geologic map of Skagway and vicinity (fig. 5) is based on field studies by us, information obtained from others, and interpretations of geologic relationships from airphotos. The airphotos examined during preparation of our report are listed in table 1. Other members of the U.S. Geological Survey gave us much valuable assistance: W. O. Addicott identified marine shells, Meyer Rubin dated some of the marine shells by radiocarbon methods, R. A. Sheppard assisted in the identification

Table 1.--Airphotos of Skagway area, Alaska examined during preparation of report[1]

Areal coverage	Scale	Date flown	Designation of photo group	Available from:
Part of East Fork Skagway River and a few miles northwest (oblique and vertical photos)	1:40,000	Sept. 1942	35,2-2010	U.S. Geol. Survey, Wash., D.C. (taken by U.S. Army)
Most of area out to several miles beyond Skagway (vertical photos)	1:40,000	Summer 1948	SEA 75,80,32 125	U.S. Geol. Survey, Wash., D.C. (taken by U.S. Navy)
City of Skagway (vertical photos)	1:4,800	Sept. 1959	VAHL	U.S. Army, Corps Engineers, Anchorage, AK
Skagway, sides of lower Skagway valley, and sides of Taiya Inlet (vertical photos)	1:15,840	July 1962	EKX	U.S. Forest Service, Wash., D.C.
Skagway and sides of lower Skagway valley (vertical photos)	1:6,000	June 1965	Skagway	U.S. Bureau Land Mgt., Anchorage, AK

[1]More recent photos which were not examined are available from the U.S. National Ocean Survey; these cover only the immediate vicinity of Skagway except for item 3 below, which includes areas several miles beyond the edges of the city. Scale, date flown, and designation are as follows:
(1) 1:20,000, June 1966, 66L; (2) 1:10,000, August 1969, 69E(C);
(3) 1:30,000, June 1971, 71E.

of some bedrock, E. E. McGregor analyzed several samples of surficial deposits, G. A. Rusnak contributed offshore geophysical information, E. E. McGregor and R. A. Farrow conducted onshore geophysical studies, D. A. Morris and A. J. Feulner provided sample information from cooperative augering work in Skagway, and J. A. McConaghy provided data on city water wells. We also obtained other information through interviews and correspondence with Federal, State, and city officials, private citizens, and personnel of engineering and construction companies that have worked at Skagway. Especially, we would like to acknowledge the help of E. C. Hanousek, 1965 Mayor of Skagway, and personnel of: Cole and Paddock, Contractors; Golder, Brawner, and Associates, Limited; Tippetts-Abbett-McCarthy-Stratton, Consulting Engineers; Pacific Arctic Railway and Navigation Co. (White Pass and Yukon R.R.); Toner and Nordling, Registered Engineers; Alaska Department of Highways; U.S. Army Corps of Engineers; and U.S. National Ocean Survey, formerly U.S. Coast and Geodetic Survey.

It should be emphasized that because of our short period of field study and the reconnaissance nature of the geologic mapping our report discusses subjects only in general terms.

A glossary is included near the end of the report to assist readers who may be unfamiliar with some of the technical terms used. For more complete definitions of terms, readers are referred to general textbooks on geology, engineering, soil mechanics, and seismology.

GEOGRAPHY

Location and extent of area

Skagway is in southeastern Alaska, about 85 miles northwest of Juneau and 16 miles north-northeast of Haines (figs. 1, 2), at lat 59°27' N. and long 135°19' W. The Skagway area, as considered in this report, includes not only the city of Skagway and immediate vicinity, which was geologically mapped (fig. 5), but also other areas in the vicinity that were not mapped geologically. These include Taiya Inlet fiord and areas that extend beyond the city to the boundary of Haines Borough, west and south about 12 and 8 miles, respectively, and to the Canadian border, north and east about 24 and 12 miles, respectively.

Topographic setting

Skagway is situated on parts of the delta and lower valley floor of the Skagway River near the north end of Taiya Inlet (fig. 3). The inlet is a fiord or drowned glacial valley that has been cut deeply into the Coast Mountains. These mountains are very rugged and dominate the landscape near Skagway, rising steeply to altitudes of about 6,000 feet only a few miles from the city. Icefields in the mountains are extensive and, together with glaciers, cover about 25 percent of the area.

A striking feature of the Skagway area is the linearity of fiords and some valleys in northerly and northeasterly directions. Both fiords and valleys are steep-walled; most valleys have narrow floors, and many contain glaciers near their heads. The two principal valleys are the Skagway and Taiya valleys, named after their respective rivers.

Slopes in the vicinity of Skagway generally are steep, and level ground is restricted to the lower reaches of the floors of Taiya and Skagway valleys. Rivers flow in braided channels 5-10 feet below the level of the floors. Moderately sloping to hummocky ground comprises part of a topographic bench southeast of and about 500-900 feet above the floor of lower Skagway valley (figs. 4 and 15, both in pocket). Other moderately sloping ground forms parts of the lower spurs of the mountains separating Skagway and Taiya valleys. These areas lie below altitudes of about 2,000 feet. Elsewhere slopes are steep to very steep.

The Skagway River drains an area of 145 square miles northeast of Skagway; its discharge during 1963-70 varied between 9.2 and 13,600 cubic feet of water per second (U.S. Geol. Survey, 1971). Melting of glaciers provides much of the total waterflow and also the suspended sediment load of the river. Variation in daily rate of melting during the summer causes large fluctuations in day-to-day flow of the river. Extensive underflow occurs within the alluvial deposits of the Skagway River. At Skagway this underflow is indicated by a high water table,

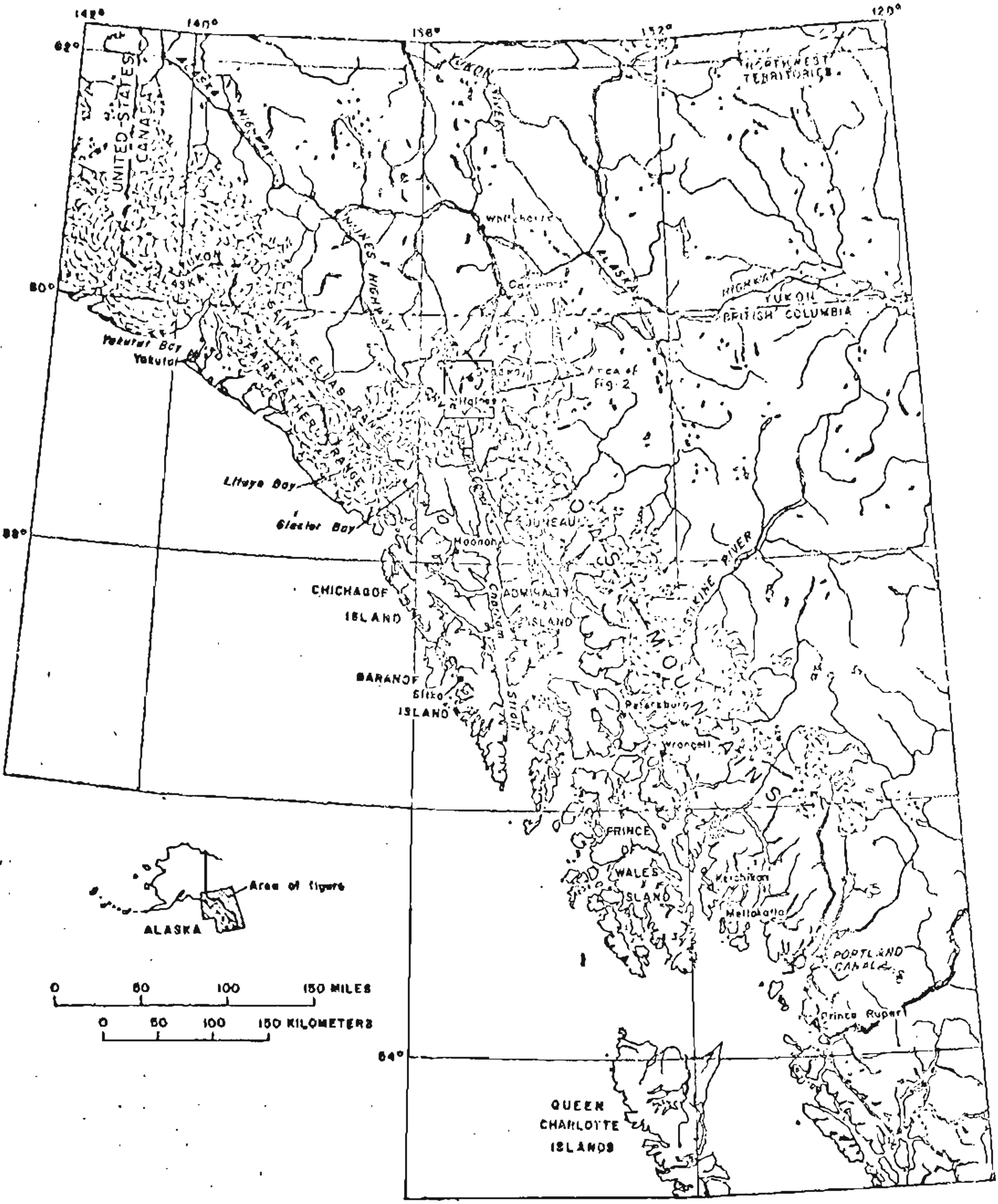

Figure 1.--Map of southeastern Alaska and adjacent Canada showing pertinent geographic features. CRV, Chilkat River valley.

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Figure 2.--Location map of Skagway and part of surrounding area, Alaska.

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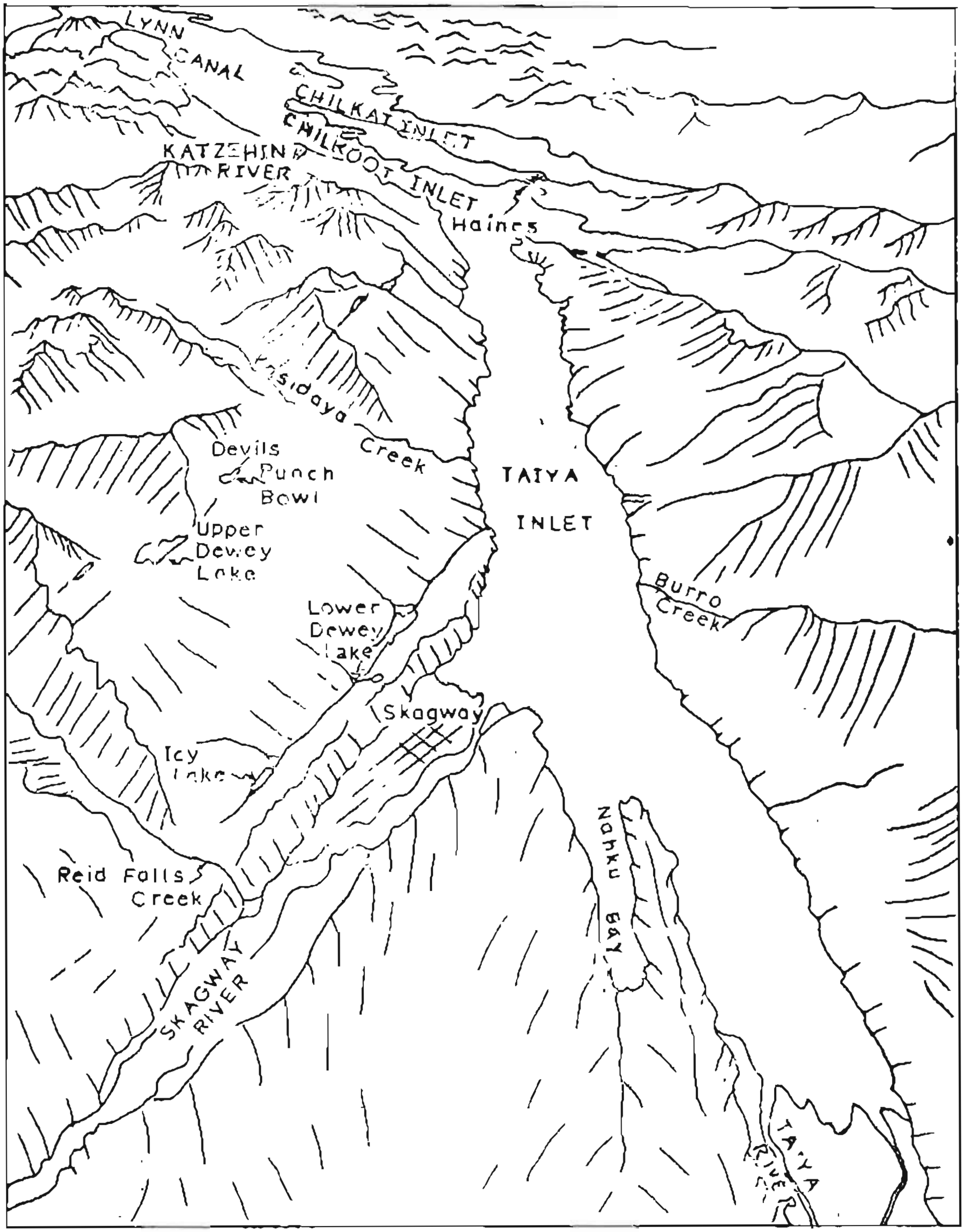


Figure 3.--Sketch of part of area showing Skagway and Taiya Inlet, Alaska. From oblique airphoto by U.S. Army, Sept 3, 1942 (35, 2-2010: 1 left 115); flying height about 20,000 feet.

local areas of wet ground, and several springs (fig. 4). Most springs drain into Pullen Creek, which flows along an abandoned channel of the Skagway River parallel to and near the southeast wall of Skagway valley. Flooding of the Skagway River is discussed in the section "Inferred future effects from geologic hazards other than those caused by earthquakes."

Bathymetry and tides

Taiya Inlet was first sounded in the 1890's. It has a maximum depth of 1,440 feet (U.S. Natl. Ocean Survey, 1971), and several miles along its axis are close to this depth. Detailed soundings of part of the short Skagway branch of Taiya Inlet at Skagway harbor were made in 1943 (U.S. Coast and Geod. Survey, 1943). Bathymetry shown on figures 4 and 5 generally follows these 1943 data; however, some 1971 sounding data (U.S. Natl. Ocean Survey, 1971) were used near the ore-handling terminal. Bottom depths over much of Skagway harbor undoubtedly are somewhat different than in 1943 because of current effects and owing to changes in the deposition of sediments that have been brought about by removal or construction of docks and by emplacement of manmade fill. In addition, underwater slides probably have occurred since the 1943 survey. Tidal and current measurements plus geodetic control have been undertaken in the Skagway area by the U.S. Coast and Geodetic Survey since the 1890's. The latest determination of the mean lower low water datum is based on 6 years of record, 1954-59; other tidal planes are as follows (U.S. Coast and Geod. Survey, 1960a):

	Feet
Highest tide observed (Oct. 22, 1945)	23.4
Mean higher high water (MHHW)	16.70
Mean high water (MHW)	15.70
Half tide level	8.65
Mean low water (MLW)	1.60
Mean lower low water (MLLW)	0.00
Lowest tide observed (Jan. 16, 1957)	-6.0

Mean sea level for the same period was 8.75 feet, as determined by Pierce (1961, p. 54). Land uplift is causing tidal planes to lower, and between 1909 and 1959 lowering of mean sea level averaged 0.059 foot per year (Hicks and Shofnos, 1965; see discussion under "Glaciation and associated land- and sea-level changes").

At Skagway harbor the tidal current on the ebb flows S. 15° W. at a maximum of 0.7 knot; at maximum flood, the current flows N. 15° E. at 0.3 knots (U.S. Coast and Geod. Survey, 1962, 1964).

Climate and vegetation

Skagway's climate is largely controlled by maritime influences; summers are cool, but winters lack the bitter cold characterizing weather northeast of the Coast Mountains (U.S. Weather Bur., 1959). Mean maximum temperature in January is 29.7° F. and in July it is 66.4° F., whereas mean minimum temperature in January is 19.4° F. and in July it is 48.4° F. (U.S. Weather Bur., 1958).

Mean total precipitation at Skagway is 27.76 inches per year, with precipitation generally lowest in May or June and highest in October. The heaviest recorded 24-hour rainfall was 4.21 inches on October 22, 1937. Greatest snowfall normally occurs during January and December; the mean fall for each of these months is 9.7 inches. Depth of frost in winter is probably several feet.

Strong winds in winter blow from the northeast down Skagway valley and may continue for many days, and wind velocities of more than 100 m.p.h. may occur for several hours. At such times Skagway lives up to its Tlingit Indian name, "home of the north wind."

Thick stands of trees and some tall brush clothe most of the landscape below altitudes of 2,500-3,000 feet. Lumbering is done only on a small scale, and no large tracts of clear-cutting on steep slopes were apparent in 1968.

Historical background and population

Skagway and the abandoned town of Dyea in lower Taiya valley (fig. 2) both originated in 1897 as ship off-loading points for men and supplies destined for the goldfields of the Yukon, Canada. Dominance of early-day Skagway as a port was assured in 1900 with completion of the White Pass and Yukon Railroad across the Coast Mountains to Whitehorse, Yukon (Skagway Planning Comm., 1964). Skagway's dominance as a port lasted until 1943, when the tidewater community of Haines was linked by road across another part of the Coast Mountains to the Alaska Highway and Whitehorse (fig. 1).

The population of the city of Skagway in 1970 was 677 (U.S. Bur. Census, 1971). Future growth of Skagway is dependent primarily upon the city's maintaining adequate port and cross-mountain transportation facilities and secondarily upon increased tourism. Completion of road links to through highways at Haines, or at Carcross, Yukon (fig. 1), and development of a proposed U.S. National Historical Park probably would help expand Skagway's tourist economy.

Proposed industrial projects that would greatly expand population in the Skagway area include the Yukon-Taiya project, which is a complex of dams on the Yukon River near Whitehorse, and tunnels to the Taiya valley, where a hydroelectric plant and smelter would be located (Eng. News-Rec., 1952, p. 21; Johnson and Twenhofel, 1953). A second proposed major project is a dam and power plant on West Creek, a tributary of the lower Taiya River (fig. 2; Callahan and Wayland, 1965).

Transportation and other facilities

The narrow-gage White Pass and Yukon Railroad provides the only scheduled overland transportation to and from Skagway. It follows various branches of the Skagway River and terminates at Whitehorse. Two roads extend beyond the city (fig. 2), but only for short distances. One leads several miles northeast along the Skagway valley; the other, called the Dyea road, leads northwest to the lower Taiya valley and the abandoned townsite of Dyea.

The Skagway airfield (fig. 4) serves scheduled and nonscheduled aircraft. Because extension of the field may be impractical, future air-traffic needs probably will be met by construction of a runway in lower Taiya valley or southeast of Skagway on the topographic bench near Lower Dewey Lake.

Ships of the Alaska Ferry System and several cruise lines, as well as freighters, ore carriers, and tankers, regularly stop at Skagway. Main terminal facilities for the ferryboats and ore carriers are situated on tracts of manmade fill emplaced in 1959 and 1968, respectively. Other large vessels are served at the White Pass and Yukon Railroad's wooden wharf, which was rebuilt in 1965. A small-boat harbor protected by a breakwater was constructed in 1958.

Flood-control dikes were built in 1940 along the Skagway River by the U.S. Army Corps of Engineers (1964). Emergency repairs of the dikes have been required several times, however, because of erosion of dikes during floods, the latest in 1967.

Most of Skagway's water supply in 1965 was furnished through a system of stream-diversion dams, and by small lakes and a reservoir on the topographic bench southeast of the city. In addition, two wooden storage tanks (fig. 4, No. 9a) were used. Lakes used for water storage, and shown on figure 4, are Icy Lake, Lower Dewey Lake, and a reservoir between Lower Dewey Lake and Skagway; storage lakes shown only on figure 2 are Upper Dewey Lake and Devils Punch Bowl. In 1966 the city partially developed a new water supply from ground water supplied through wells (fig. 4, No. 9b). At least one of the wells is 75 feet deep (J. M. McConaghy, U.S. Geol. Survey, written commun., 1966). Some of Skagway's electricity is hydrogenerated. The water is furnished through the system of stream diversions described above.

Storage tanks for petroleum products are sited on the floor of the Skagway valley or on the Skagway River delta. Except for the two storage tanks labeled 9a on figure 4, all storage tanks are thought to contain or be capable of containing petroleum products. Another five tanks, not shown on figure 4, are present about a quarter of a mile up the Skagway valley from the group shown at the edge of the figure. Some of the pipelines which connect tanks with the harbor area are as large as 12 inches in diameter; most are buried to a depth of several feet. The group of tanks on the northwest side of Skagway valley and most of the pipelines were constructed in the early 1940's. Physical condition of the tanks and connecting lines is not known to us. An 8-inch pipeline extending to Whitehorse was being used for petroleum products in 1966 (Hilker, 1967).

GLACIATION AND ASSOCIATED LAND- AND SEA-LEVEL CHANGES

The Skagway area was covered by thick glacier ice several times in the Pleistocene Epoch. During the culmination of the last major glacial interval, ice over the site of Skagway may have been as much as 5,000 feet thick (Coulter and others, 1965). Today, numerous erosional landforms of glacial origin bear evidence of this glaciation. These include smooth rounded knobs of bedrock and U-shaped valleys and fiords, some showing marks of former levels of glacier ice on their walls. We have identified a few such levels here and there along the Skagway valley sides, at altitudes of 2,500 and 2,000 feet, and extensively along Taiya Inlet fiord, at 1,600 to 1,500 feet.

Although large-scale constructional landforms of Pleistocene glacial origin are not evident near Skagway, some are present several miles west of southern Taiya Inlet, where a partly concealed moraine holds back Chilkoot Lake (fig. 2; Johnson and Twenhofel, 1953, p. 11) and a moraine almost closes off Taiyasanka Harbor. In addition, shallow water at the mouth of Taiya Inlet may indicate another moraine (Davidson, 1900). During a part of the time of morainal development the termini of the glaciers may have been floating.

Major climatic changes caused extensive melting of glacier ice in the Skagway area and elsewhere after the moraines were developed. Icefields and valley glaciers shrank drastically, and probably many disappeared before 10,000 years ago. This assumption is based largely on radiocarbon age determinations on samples from the Juneau area (R. D. Miller, U.S. Geol. Survey, oral commun., 1967; R. D. Miller, 1972), which is geologically similar to the Skagway area.

During the Holocene Epoch, or about the last 10,000 years, minor advances and retreats of glaciers occurred in several regions in the northern part of southeastern Alaska, such as Juneau (Heusser, 1960; Barnwell and Boning, 1968; R. D. Miller, 1972), Glacier Bay (Lawrence, 1958; Goldthwait, 1963, 1966; McKenzie, 1970), and Yakutat Bay (Plafker and Miller, 1958) (see fig. 1 for locations). Evidence of similar glacier activity is clearly shown 4 miles east of Skagway, on 1948 airphotos, by a sharp change in vegetation 1.1 miles beyond the 1948 glacier front of the Denver Glacier (fig. 2). Downvalley 0.13 mile farther, an arcuate cross-valley feature probably marks another somewhat older glacier position. Closer to Skagway, a glacier, which is the source of Reid Falls Creek (fig. 6), left an end moraine 0.4 mile downvalley from the 1948 ice front. At similar distances downvalley from Upper Dewey Lake and Devils Punch Bowl (fig. 2), moraines also are present; second moraines lie slightly farther downvalley. Other glaciers in the Skagway area had shown similar advances in the not too distant past, and similar retreats in 1948. The date of the maximum Holocene glacial advance and the beginning of glacier retreat are unknown in the Skagway area. However, in the Glacier Bay region, about 60 miles southwest of Skagway, a major ice advance apparently culminated about 1750 A.D. and was succeeded soon thereafter by a well-documented retreat, which is still continuing.

The position of land in relation to sea level in the Skagway area not only has changed greatly within the past tens of thousands of years, but it is continuing to change. The primary causes of these changes are the expansions and contractions of glaciers in the Pleistocene and Holocene Epochs; secondary causes are considered below. The weight of thick glacier ice tends to depress the land and cause inundation by the sea of coastal areas. A theoretical land depression of about 275 feet could occur from the weight of a glacier 1,000 feet thick (Gutenberg, 1951, p. 172). Melting of the ice in the Skagway area during periods of deglaciation allowed the land to rebound slowly. However, because of a lag between glacier melting and the rebounding of the land, marine water probably occupied many of the low areas that now are above sea level.

The amount of land emergence related to the last major deglaciation at Skagway is unknown, because there are few deposits of assured marine, shore, or emerged deltaic origin. However, at altitudes of 200-300 feet along the northwest side of Skagway valley some of the glacial drift might be elevated shore or delta deposits. Also, at approximately similar altitudes, elevated deltas are interpreted to be present near the mouths of Burro and Kasidaya creeks along Taiya Inlet (fig. 2). Some marine deposits probably underlie the floor of lower Skagway valley (see "Alluvial deposits of the Skagway River"). In the Haines area several types of elevated deposits are present (Lemke and Yehle, 1972a). The closest dated sample to Skagway from an elevated fine-grained marine deposit was collected 13 miles to the south-southwest. Radiocarbon dating of marine shells indicated an age of 11,020±400 years BP (before the present) (U.S. Geol. Survey W-2294; Meyer Rubin, written commun., 1969). Elsewhere in the northern part of southeastern Alaska, emerged marine deposits are present in many areas and have been described by Twenhofel (1952), Goldthwait (1963, 1966), Haselton (1966), McKenzie (1970), and R. D. Miller (1972). The highest known deposits related to emergence since the last major glaciation are in the Juneau area, at an altitude of 750 feet (R. D. Miller, 1972).

The small-scale expansion and subsequent partial melting or complete melting of glaciers during the Holocene Epoch may have reversed or at least slowed land emergence in the Skagway area. Two features at Skagway indicate that sea level was higher than at present during part of the Holocene. One is an accumulation of marine shells that form part of a very small elevated beach deposit, 32 feet above mean sea level near the mouth of the Skagway River (fig. 5). The radiocarbon age of these shells is 2,880±250 years BP (U.S. Geol. Survey, W-2292; Meyer Rubin, written commun., 1969). The other feature, which is more speculative, consists of a possible emerged beach trending across the Skagway valley floor between 33.5 and 37.5 feet above mean sea level (fig. 5). This part of the valley floor has a relatively steeper gradient than the valley floor immediately upvalley or downvalley (see "Alluvial deposits of Skagway River").

The land at Skagway is being uplifted relative to sea level at an average rate of 0.059 foot per year based upon tidal observations and bench-mark measurements made during the period 1909-1959 (Hicks and Shofnos, 1965). Progressively higher rates of emergence were measured southwest from Skagway, with highest rates near Glacier Bay (see Lemke and Yehle, 1972b), whereas northeast from Skagway, progressively lower rates of emergence were recorded to about Carcross (Montgomery, 1948; Small, 1967). The effects of future land uplift in the Skagway area are discussed under "Inferred future effects from geologic hazards other than those caused by earthquakes."

All of the land uplift may not be attributable to rebound as a result of deglaciation. Some may be due to tectonic movements caused by stresses deep within the earth. Skagway is situated in an active tectonic region, lying only about 100 miles northeast of the active Fairweather fault. Numerous faults are inferred in the intervening area (fig. 12), and many earthquakes are recorded in the same general region (fig. 16).

Although mean sea level is treated as a fixed level in determining relative land and sea-level changes, this assumption is only an approximation, for many factors may combine to slowly change the level of water in the oceans. A major factor probably is the result of general worldwide relationship of glacial melting to glacial nourishment. This and other factors are discussed from a worldwide view by Higgins (1965), Bloom (1967), and Shepard and Curray (1967). Shepard and Curray (1967, fig. 2 and p. 286) selectively considered the small number of radiocarbon data available from stable shore areas in the world and showed that about 9,500 to 10,000 years BP sea level may have been about 65 to 185 feet (average approx. 100 ft) lower than at present.

The amount of land emergence discussed in the preceding paragraphs considers only the relative difference in altitude between an emerged deposit and present mean sea level. To obtain absolute values the differences between sea level at the time of formation of the deposit and today must be added or subtracted from the present altitude of the deposit.

DESCRIPTIVE GEOLOGY

Bedrock

Regional setting

The Skagway area lies within a very rugged part of an extensive linear belt of plutonic intrusive and some metamorphic rocks called the Coast crystalline belt (Roddick, 1966, p. 73). The belt, which extends over 1,000 miles, roughly parallels the coast of the Pacific Ocean from northern Washington to the north-south Alaska-Yukon border and includes the Coast Mountains of Alaska and British Columbia (fig. 1). Intrusive plutonic rocks predominate; these consist chiefly of quartz diorite, quartz monzonite, and granodiorite. Metamorphic rocks are minor and consist chiefly of schist, phyllite, and gneiss.

Types of bedrock

Geologic investigations of bedrock within the Skagway area have been made principally along the Skagway valley, the west side of Taiya Inlet, lower West Creek, along roadways, and at scattered mineral prospects by numerous geologists (Buddington and Chapin, 1929; Barker, 1952; C. L. Sainsbury, U.S. Geol. Survey, written commun., 1953; Christie, 1958; E. C. Robertson, U.S. Geol. Survey, written commun., 1959; Freeman, 1963; Callahan and Wayland, 1965; Herbert and Race, 1965). The following description of bedrock near Skagway is based on work by these geologists, especially Barker (1952) and Christie (1958).

Hornblende-biotite-quartz diorite is the predominant rock type exposed along the southeast side of lower Skagway valley, as shown on the reconnaissance geologic map of Skagway and vicinity (fig. 5, in pocket). The rock is well exposed along the southeast side of the valley from the Skagway River delta northeastward for 5 1/2 miles. Foliation strikes northwest and dips steeply northeast. The rock is generally medium grained and medium gray, but Barker (1952, p. 21) noted some lighter and darker tabular zones of the rock that are as much as several tens of feet thick; the darker zones are much richer in biotite and hornblende.

Small masses of metamorphic rocks are scattered within the quartz diorite exposed along the southeast side of Skagway valley. They consist largely of hornblende-mica-quartz-feldspar schist, phyllite, and gneiss, but include some marble and quartzite (Buddington and Chapin, 1929; Barker, 1952; Christie, 1958; R. A. Sheppard, U.S. Geol. Survey, written commun., 1966). Thickness is highly variable, but a maximum of 60 feet is given by Barker. Contacts with the quartz diorite generally are sharp, but some are brecciated. Metamorphic rock masses tend to parallel foliation of the quartz diorite. Continuity of individual masses of metamorphic rock apparently has not been established across the Skagway valley. Because only limited amounts of these rocks crop out in the geologic map area (fig. 5), they are not differentiated on the map. Directly northeast of the map area, however, and extending northeastward for about 2 miles, metamorphic rocks comprise roughly 40 percent of the bedrock (Christie, 1958, p. 46). Buddington and Chapin (1929, pls. 1, 2) show the same general area as being part of a northwest-southeast belt of metamorphic rocks.

Several igneous dikes cut the quartz diorite and metamorphic rocks (Barker, 1952, p. 34), but are not shown on our geologic map because of their small size. Mostly they are between 2 and 8 feet thick and consist of rhyolite, rhyolite porphyry, and basalt.

The area between lower Skagway valley and lower Taiya valley, shown in part on our geologic map, consists largely of granodiorite and quartz diorite. The rocks are variably foliated, generally light gray, and medium to coarse grained. In addition, numerous dikes of rhyolite and basalt up to several feet in thickness occur, as well as some small masses of metamorphic rocks.

Bedrock exposed along the west side of upper Taiya Inlet (fig. 2) consists of granodiorite and quartz diorite (Barker, 1952, p. 18). These rocks contain less hornblende than the quartz diorite along the southeast side of Skagway valley. Similar granodiorite was studied by Callahan and Wayland (1965) at the West Creek damsite (fig. 2). Barker (1952, p. 35) also noted several small dikes of basic composition that are characterized by vesicles.

Physical characteristics

Granodiorite and quartz diorite have been studied on a limited scale in a few places in the Skagway area for their physical characteristics. Callahan and Wayland (1965, p. A8), at the West Creek damsite, noted the granodiorite to be massive, unweathered, and homogeneous. Munson (1965, p. 4) observed granodiorite and quartz diorite along the road traversing the northwest side of Skagway valley (fig. 2) as having moderate to good hardness, durability, and toughness. Jointing of bedrock is discussed briefly under "Local structure."

Natural granular disintegration of granodiorite and quartz diorite locally has taken place within the geologic map area. The disintegration has resulted in formation of irregular zones consisting of: (1) mostly fine gravel and sand-sized particles of mineral constituents of the rock, and (2) some partly disintegrated bedrock fragments. Though grus is a term generally restricted to describing disintegrated granite, the term will be extended here to include the rock and mineral fragments from disintegration of all types of coarse- and medium-grained intrusive rocks in the Skagway area. Areas of grus are not differentiated on the geologic map, but they occur along the northwest side of Skagway valley in scattered patches possibly as much as 20 feet deep. Grus also constitutes at least part of the surficial deposits that form the base of the slope along the southeast wall of Skagway valley upstream from the railroad yard (Munson, 1961, p. 10).

Uses

Bedrock has been exploited for several uses near Skagway. Granodiorite used for riprap (armor rock) has been obtained from quarries along the northwest side of Skagway valley near the mouth of Skagway River and from a quarter of a mile northeast of the edge of the map area. The riprap has been used as protection against waves for exposed harbor works, and as protective diking against floods from the Skagway River.

Grus, from borrow pits along the northwest side of Skagway valley, has been used for road surfacing; however, some of the pits were exhausted by 1968. Grus along the southeast wall of Skagway valley upstream from the railroad yard has been used as fill along the railroad. Potentially usable grus zones probably occur elsewhere in the Skagway area.

Most bedrock in the Skagway area probably is well suited to support foundations for manmade structures. The proposed site for a dam on West Creek (Callahan and Wayland, 1965) is underlain by granodiorite. Preconstruction studies for major structures with deep foundations, however, should be detailed enough to define depths of weathering and to delineate zones of weakness, such as areas of closely spaced joints or possible faults.

No commercial production of minerals from Skagway and vicinity is known. However, several lead sulfide and molybdenum prospects have been reported (Herbert and Race, 1965, p. 13), and one uranium prospect (Freeman, 1963, p. 30).

Geologic age

Most of the rocks in the Skagway area are believed to be of Mesozoic age. The intrusive plutonic rocks were considered to be Jurassic and Cretaceous by Dutro and Payne (1957). Two radiometric age determinations by the Geological Survey of Canada on biotite from intrusive plutonic rocks near Skagway gave Late Cretaceous ages of 65±8 and 70±8 million years (Lowdon, 1963, p. 29). Although most dikes also may be of these ages or possibly of Tertiary age, vesicular dikes along the west side of Taiya Inlet are probably of Quaternary age (Barker, 1952, p. 35).

Surficial deposits

General description

The Skagway area contains only a few types of surficial deposits, mainly because deep erosion by a succession of Pleistocene glaciers not only removed preglacial deposits but also produced slopes too steep to retain much of the glacial deposits. Consequently, today most steep slopes are nearly devoid of glacial drift deposits, because the small amounts of drift that had been deposited slid or were washed downslope soon after melting of the valley glaciers. This material plus the other solid products of geologic weathering that move downslope under the influence of gravity is called colluvium and forms deposits at the bases of slopes. Elevated marine and beach deposits may be admixed and constitute a minor part of the colluvium. On gentler slopes, small patches of drift deposits are interspersed between bedrock exposures. In places drift and bedrock are mantled by minor stream or colluvial deposits or by patches of elevated marine and beach deposits too small to map.

The delineation of surficial deposits shown on the geologic map (fig. 5) is most accurate on the floor of Skagway valley and along the railroad and roads. Elsewhere, airphoto interpretation was relied on to a great extent because of the limited field time available and because of an abundance of steep and thickly vegetated slopes.

Deposits on the map have been divided on the basis of grain size, origin, and relative time of deposition into the following units: glacial drift deposits (Qd), colluvial deposits (Qca and Qci), alluvial fan deposits (Qaf), deltaic deposits of the intertidal zone (Qi), beach deposits (Qb), alluvial deposits of the Skagway River (Qam and Qat), and manmade fill (Qf). Boundaries between map units deposited more or less contemporaneously have gradational contacts. Boundaries of some units, especially drift and colluvial deposits, largely are inferred. Grain-size classification of sediments is based on National Research Council terminology (1947): clay, less than .00015 in.; silt, .00015-.0025 in.; sand, .0025-.079 in.; gravel, .079 to about 2 1/2 in.; cobbles, about 2 1/2-10 in.; and boulders, greater than 10 in.

The floor of the lower reach of Skagway valley is formed of floodplain and terrace alluvial deposits of the Skagway River. These deposits probably interfinger at depth with deltaic and marine sediments which are underlain by glacial and glaciomarine deposits. The total thickness of surficial deposits, as determined from a geophysical traverse at Skagway near First Avenue, is about 585 feet (fig. 8; E. E. McGregor and R. A. Farrow, U.S. Geol. Survey, written commun., 1967; Johnson and Twenhofel, 1953, p. 8). Fill has been emplaced along the waterfront and at several locations elsewhere in Skagway.

The age of the surficial deposits exposed in the mapped area is Pleistocene and Holocene. Drift deposits are exclusively Pleistocene; all others are Holocene.

Glacial drift deposits (Qd)

Two types of glacial drift are exposed, but these are not differentiated on the geologic map. One is an unsorted mixture called till, which consists of gravelly silt, sand, and some clay, cobbles, and boulders. The deposits are loose to compact, unstratified, and the larger fragments vary in shape from subangular to subrounded. The second type is generally sorted and composed of gravelly sand, sand, and minor amounts of cobbles; deposits are loose, variably stratified, and the larger fragments are subrounded.

Drift in most places is probably less than 20 feet thick. Contact of the drift with the underlying bedrock is irregular, and therefore isolated bedrock outcrops may be present within some areas of drift. In places, other deposits thinly cover the drift. Alluvial fan deposits mantle the edge of some drift deposits on the bench near Lower Dewey Lake and Icy Lake. Locally, small elevated marine and beach deposits, up to several hundred feet above sea level, may obscure drift on slopes.

Drift is distributed sparsely over slopes along the northwest side of Skagway valley and on the topographic bench southeast of the valley. It is concentrated particularly in bedrock depressions and along the southwest side of bedrock outcrops, which was the leeward side of glacier advance. Most of the drift on the topographic bench near Lower Dewey Lake and Icy Lake is thought to consist of till. Along the northwest side of Skagway valley, outcrops of sorted drift, chiefly gravelly sand, were noted.

Drift probably also extends to considerable depth beneath alluvial deposits forming the floor of the Skagway River, according to interpretations of geophysical data near First Avenue (fig. 8). No drift deposits were observed along the steep slopes forming the southeast side of Skagway valley. Any drift originally deposited there either was removed by landsliding or was thoroughly mixed with other geologic materials to form colluvium.

Drift originates in several ways. Till in the Skagway area was formed chiefly by a "plastering-on" process at the base of glacier ice. Part of the till, however, may be a type of glacial deposit that is formed when glaciers are not in basal contact with the land but are floating. Sediment from floating glaciers and from icebergs settles to the bottom of fiords, where it mixes with material from the normal "rain" of fine-grained marine sediment. The resulting glaciomarine deposit commonly resembles till and in many places merges with fine-grained marine deposits. Deposits of this type are well exposed in the Haines area (Lemke and Yehle, 1972a). Sorted drift near Skagway probably originated chiefly from deposition by glacial melt-water streams, some of which were in contact with glacier ice. Part of the sorted deposits, on the other hand, may be elevated beach deposits (see "Glaciation and associated land- and sea-level changes").

The sorted drift deposits along the northwest side of Skagway valley have been used extensively as material for road surfacing, but some of the borrow pits opened in this material were exhausted by 1968. No drift deposits elsewhere in the map area have been utilized. The deposits should be well suited as a foundation for most manmade structures.

Colluvial deposits (Qca and Qci)

The colluvial deposits mapped (fig. 5) consist of mixed accumulations of bedrock rubble, organic material, and other surficial deposits, especially drift, that have moved downslope either slowly or rapidly under the influence of gravity. They generally are a loose mixture of cobble- to boulder-sized rubble in a sandy to gravelly silt matrix, or they consist of a mixture of gravel, cobbles, sand, and some silt and clay. Silt or organic material locally may constitute a high percentage of colluvium; included stones generally are angular, but some are subrounded. Colluvium forms a thin mantle on many valley slopes in the area but is shown on the map only where it is thought to be at least 5 feet thick; locally, deposits may be as much as 50 feet thick. Mostly the deposits are unsorted, but some poor sorting and indistinct bedding does occur.

Mapped colluvial deposits chiefly are scattered along the southeast side of Skagway valley. They consist of talus and deposits of various types of landslides, probably including rockfalls, rockslides, earthflows, and avalanches, but none are differentiated on the map. A separation is made, however, between two types of colluvial deposits: (1) those mostly unvegetated (Qca), which are considered to be actively accumulating and probably creeping downslope and which locally are composed of boulder-size rubble so large that trees have difficulty becoming established; and (2) those that are thickly covered by vegetation (Qci) and are presumed to be inactive, though in part they may be creeping slowly downslope. Colluvial deposits grade into alluvial fan deposits on lower slopes. Bedrock directly underlies colluvium in most places, but locally drift or elevated marine and beach deposits may underlie the colluvium.

The deposits have been used from only one site, which is near the railroad yard, and probably were used for fill along the railroad near Skagway. Most of the deposits near Skagway are located on steep slopes and would be unsuited or poorly suited as foundations for manmade structures.

Alluvial fan deposits (Qaf)

The alluvial fan deposits are loose, poorly sorted, and poorly stratified materials that have been deposited by small streams where they leave steep slopes and cross gentler slopes. They generally consist of sandy gravel, cobbles, and some boulders. Stones are chiefly subangular to angular. Locally, the dominant constituent is sand and some silt and organic material. Maximum thickness of the deposits is thought to be about 50 feet. Bedrock generally underlies the alluvial fans, but on the topographic bench southeast of Skagway the fans may be underlain by drift. Along the lineament marked by Lower Dewey Lake and Icy Lake (fig. 15), fan deposits may be underlain by broken rock along a shear zone of a major fault. Some fans grade into colluvial deposits. Alluvial fans are scattered throughout the mapped area, forming a small part of the margin of the Skagway valley and part of the topographic bench southeast of the valley. The lakes on the bench owe their origin to single or coalescing fans that blocked drainage parallel to the bench.

No extensive use has been made of the deposits as construction materials. The deposits constitute part of the dams for Lower Dewey Lake and Icy Lake, and thus, in combination with small artificial dams, they indirectly control water levels for hydroelectric power generation. Alluvial fans are poorly to moderately suited as foundation sites for manmade structures. Generally they are located in areas of potential flooding, and, locally, they are known to have a high organic content.

Deltaic deposits of the intertidal zone (Qi)

The delta of the Skagway River is discussed in two parts: (1) the very gently sloping top of the delta, which is exposed at low tide, and which constitutes the mapped unit (Qi) on figure 5; and (2) the steep to gently sloping front of the delta, which extends seaward from the line of mean lower low water as a separate sediment wedge of decreasing thickness. The delta top is discussed below, and the delta front is discussed under "Offshore deposits."

The mapped deltaic deposits generally are composed of sandy gravel, gravelly sand, and cobbles, and minor amounts of small boulders, shell fragments, and lenses of sand and silt. Stones generally are subrounded. The deposits are loose to dense, and sorting is generally good. The deposits form the intertidal flats, the surface of which dips seaward at about 0.88 percent (0°30') (figs. 6 and 7, in pocket; U.S. Coast and Geod. Survey, 1943). The deposits, at their landward margin, are either covered by manmade fill or are being covered slowly by alluvial deposits of the Skagway River. The seaward margin of the mapped deposits is approximately the mean lower low waterline. Much of the delta top is now covered by manmade fill.

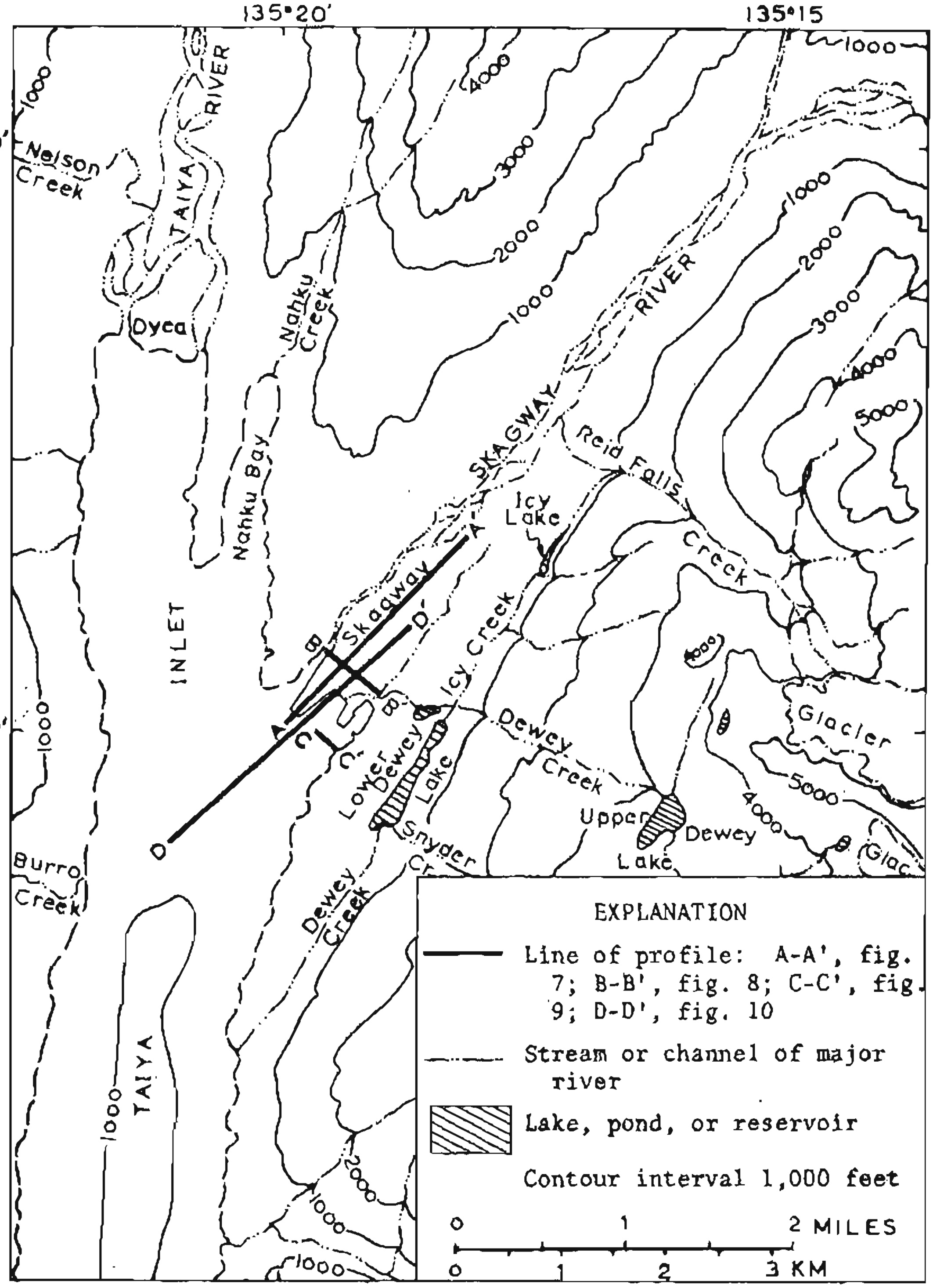


Figure 6.--Map of part of Skagway area, Alaska, showing location of profiles and major drainage features. Base from U.S. Geological Survey B-1 and C-1, 1963, U.S. National Ocean Survey Chart 8303, 1971.

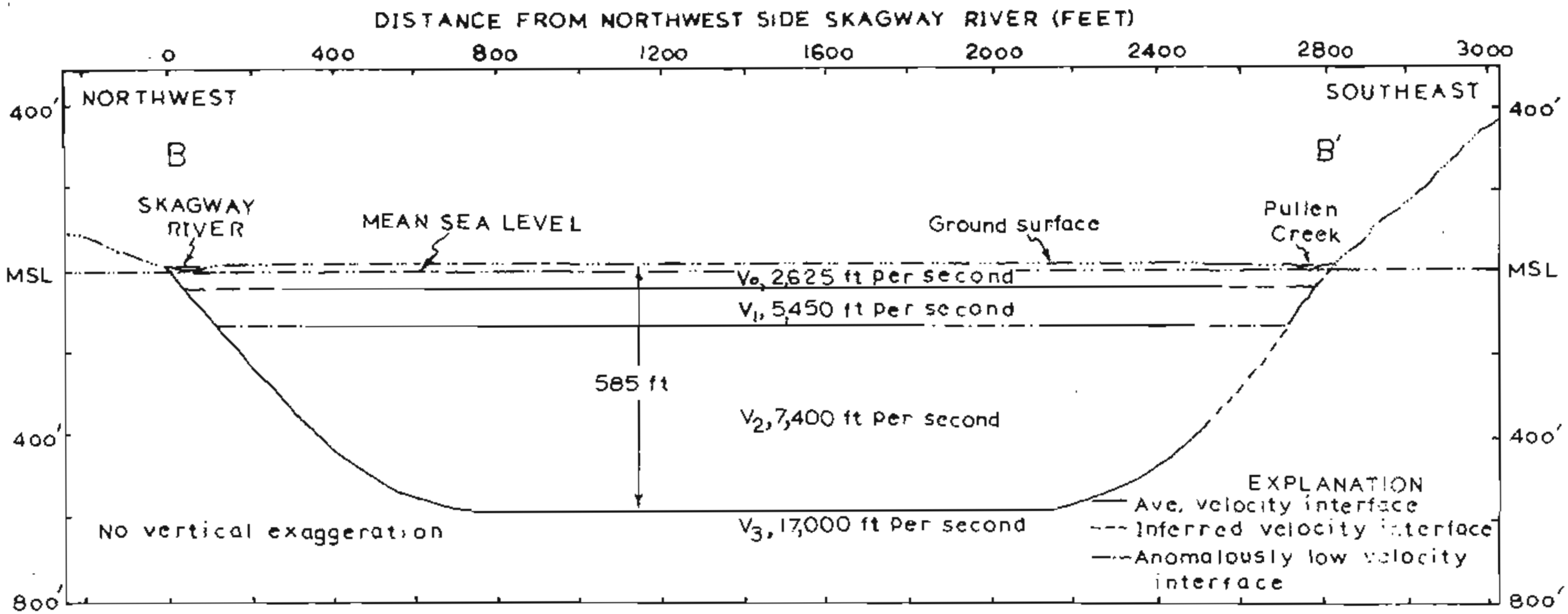
The thickness of the mapped deposits varies widely. In the central part of the intertidal flats it averages 30 feet and ranges from about 10 to 50 feet. These values are based upon our interpretation of logs from holes by Golder, Brawner, and Associates (written commun., 1967) for Pacific and Arctic Railway and Navigation Co., through Tippets-Abbett-McCarthy-Stratton, Consulting Engineers. Thicknesses of the southeast part of the deposits cannot be determined with much certainty, but we interpret the deposits to range between 8 and 17 feet thick based on driving rates of probes by the U.S. Army Corps of Engineers (written commun., 1958) at the small-boat harbor. The underlying material is thought to be sand, which probably was deposited as part of an earlier delta front.

Underlying the mapped deposits in the central part of the tidal flats are beds of sand or sand and some gravel 5-25 feet thick (Golder, Brawner, and Associates, written commun., 1967). A few silt lenses less than 2 feet thick, reported by C. J. Brown (Pacific and Arctic Railway and Navigation Co., written commun., 1968), probably occur within these beds. Beneath the sandy deposits are beds of gravelly sand or sand and gravel as much as 50 feet thick. These sediments underlying the mapped deltaic deposits probably were deposited as part of an earlier delta and may extend to a depth of about 145 feet (fig. 8).

Geophysical data indicate a change in type of sediments at a depth of about 145 feet (fig. 8); the underlying sediments are presumed to be compact glacial and glaciemarine deposits. They extend to a depth of about 585 feet, where an abrupt seismic velocity change is interpreted to be the contact of unconsolidated deposits with the underlying bedrock. The configuration of the buried bedrock surface in figure 8 is broadly U-shaped, probably due to glacial erosion.

The Skagway River delta is an active geologic feature, and most natural processes promote extension of the delta. The principal growth factor is the nearly continual addition of sediment to the outer margin of the delta from the Skagway River. Another factor helping to extend the delta seaward is the slow emergence of land in the area (see "Glaciation and associated land- and sea-level changes"). Factors that theoretically can reduce the extension of the Skagway River delta are: sediment compaction, reduction in amount or type of sediment carried to the delta, dredging, accumulation of sediment in increasingly deeper water offshore, subaqueous sliding, and eustatic (worldwide) rise of sea level.

Man's modification of the surface of the delta and of the Skagway River channel has altered the flow characteristics of Skagway River and its distributaries and of the longshore currents of the harbor area. These alterations may have caused unpredictable changes in patterns of deposition on the front of the delta, such as occurred at a locality in coastal British Columbia prior to a major subaqueous



DESCRIPTION OF VELOCITY UNITS

Seismic velocity unit	Depth to underlying velocity interface from ground surface (ft)	Depth to underlying velocity interface below mean sea level (ft)	Approx. maximum thickness (ft)	Possible geologic units (in part after Bush and Schwarz, 1964)
V_0	25	1	25	Saturated(?) loose alluvial and beach deposits and manmade fill
V_1	145	129	120	Fairly compact deltaic, marine, and (or) alluvial deposits
V_2	585	569	440	Compact glacial and glaciomarine deposits
V_3	-	-	-	Bedrock: intrusive or metamorphic rock types

Figure 8.--Seismic refraction profile B-B' and description of velocity units near First Avenue, Skagway, Alaska. From E. E. McGregor and R. A. Farrow, U.S. Geological Survey (written commun., 1967). See figures 4 and 6 for location.

slide (Terzaghi, 1956).

The deltaic deposits have been used extensively for large fills on the floor of lower Skagway valley and on the surface of the delta itself. Despite this extensive use, large quantities of material are still available. As a foundation, the mapped deltaic deposits are suited only for structures with limited occupancy uses. (See "Earthquake-induced subaqueous slides.")

Beach deposits (Qb)

Beach deposits are scarce in the vicinity of Skagway chiefly because only a very limited amount of gently sloping land exists for their development. The few deposits shown on the geologic map (fig. 5) are adjacent to sea cliffs near Yakutania Point, where they occur near mean high tide level and the inland limit of storm waves. The deposits are composed of loose mixtures of cobbles, gravel, sand, and boulders; shell fragments and driftwood are minor constituents. Gravel- and cobble-sized materials are generally subrounded, and boulders are angular to subangular. Deposits probably average 5 feet in thickness, with a maximum of 10 feet. The underlying bedrock surface is thought to be irregular.

Before Skagway was built, a high tide and storm beach of sandy gravel and cobbles with some shell fragments and driftwood probably existed near the landward margin of the Skagway delta. By 1968, however, the shore at Skagway was so greatly modified that all evidence for such a beach has been obscured.

Remnants of elevated beach deposits probably exist up to heights of several hundred feet above mean sea level in the vicinity of Skagway, as they do elsewhere in coastal southeastern Alaska, but they are too small to map and, hence, none are shown on figure 5. The closest known extensive deposits are 13 miles to the south-southwest, near Haines (Lemke and Yehle, 1972a). One small elevated beach deposit, predominantly of shell fragments, lies about 32 feet above mean sea level near the mouth of the Skagway River. The following shells from this locality (U.S. Geol. Survey Cenozoic loc. M3943) were identified by W. O. Addicott (U.S. Geol. Survey, written commun., 1969):

Gastropoda:

Buccinum? fragments, *Littorina*? fragments, and *Neptunea*? fragments

Pelecypoda:

Mytilus sp. fragments (principal component of the total of shells identified)

Cirrepedia (barnacles):

Balanus fragments

Some remnants of possible elevated beach deposits may constitute part of the surficial deposits mapped as drift along the northwest side of Skagway valley between 200 and 300 feet in altitude. Another possible deposit is on the floor of Skagway valley between altitudes of 33.5 and 37.5 feet. (See "Alluvial deposits of Skagway River.")

Because of their locations and small size the mapped beach deposits have only limited use either for construction materials or as foundation sites for manmade structures.

Alluvial deposits of the Skagway River (Qam and Qat)

The floor of Skagway valley is formed of sediment deposited by running water both from the modern and the ancestral Skagway River. These alluvial deposits consist of gravel, sand, and some cobbles, boulders, and silt. Thin beds of silt and sand make up the near-surface part of the deposit at Skagway, upvalley from about 14th Avenue. Gravel- and cobble-sized rock fragments generally are subrounded. The deposits are loose, generally well bedded, and locally well sorted within an individual bed; however, the grain size of adjacent beds may vary abruptly.

The deposits, although similar in composition, are differentiated into two units on the geologic map, based on their topographic position relative to the modern flood plain of Skagway River. One unit (Qam) consists of deposits forming the modern flood plain of the river; the other unit (Qat) includes deposits forming a terrace, whose surface is 5-10 feet above the modern flood plain. This terrace is a remnant of a higher and older flood plain of the Skagway River. A shallow former channel of Skagway River is evident on the terrace adjacent to the southeast side of the valley. Before the ground surface was modified by construction near the shoreline, alluvial deposits extended to tidewater, where they merged with deltaic deposits. Now, however, manmade fill extensively overlies alluvial deposits near shore and forms the surface map unit.

The alluvial deposits average 25 feet in thickness and are underlain at depths of 15-35 feet below the ground surface by deposits ranging in composition from sand to sand mixed with minor fine gravel. These underlying deposits, which we interpret to be of deltaic origin, have been penetrated by several test holes drilled in the terrace at Skagway by the U.S. Geological Survey (A. J. Feulner and D. A. Morris, written commun., 1966) and by the city of Skagway (J. A. McConaghy, U.S. Geol. Survey, written commun., 1966). Test-hole data and relations between deposits and the ground surface are shown in profile A-A' on figure 7. The interpretation of lateral continuity of the sandy deposits is made with some confidence, for the following reasons. First, logs of all the deep holes, except the city well, show a sequence of gravelly alluvium overlying sandy deposits. Second, a change in type of sediment occurs at a depth of 25 feet, as determined by a geophysical investigation near First Avenue (fig. 8). Third, sandy deposits also are present at similar depths in holes penetrating the upper part of the present Skagway River delta (see "Deltaic deposits of the intertidal zone"). Although test holes in the Skagway River alluvium do not extend through the predominantly sandy deposits, the geophysical profile, B-B', near First Avenue shows a change in seismic velocity at a depth of about 145 feet (fig. 8). These more compact sediments, which are presumed to be glacial and glaciomarine deposits, extend to a depth of about 585 feet, where the seismic velocity interface with bedrock is well defined.

Locally, some beds of clay underlie the terrace alluvial deposits in the central and north-central areas of the city. C. L. Sainsbury (U.S. Geol. Survey, written commun., 1953) reported that several shallow water wells in these areas penetrated a thin blue marine(?) clay that was described to him as plastic and impervious when wet but very hard when dry (for example, unit 1, Maki well, fig. 7). He also noted that wells that extended to about 20 feet, and below the clay, contained water fairly high in hydrogen sulfide. Neither the composition of the reported clay nor its areal extent, unfortunately, is known, because no samples were preserved and none of the test holes drilled nearby in 1966 by the U.S. Geological Survey intersected any clay beds (A. J. Feulner and D. A. Morris, written commun., 1966). Another deposit high in clay-sized particles may be present along the southeast side of the Skagway branch of Taiya Inlet below at least a part of the White Pass and Yukon Railroad wharf (fig. 4; see "Offshore deposits").

A remnant of a possible beach buried by younger alluvium may be present on the terrace at an altitude of 33.5-37.5 feet (fig. 5). Although no characteristic landform is present, ground-surface gradients here are anomalous in that they are relatively much steeper than gradients either downvalley or upvalley (fig. 7). In addition, the course of Pullen Creek is naturally diverted parallel to this relatively steeper gradient. Another possible origin for the relatively steeper gradient is that it reflects an eroded landslide from the southeast side of Skagway valley. Unfortunately, there are no subsurface data available to explain the anomalous gradients.

Use of alluvial deposits for construction material has been extensive from the modern flood plain of Skagway River and from scattered borrow pits in the adjacent terraces. Deposits forming the terraces are well suited as foundation sites for manmade structures, except locally, where the ground-water table is high. Dikes protect the terrace on which Skagway is situated from most Skagway River floods.

The floor of lower Taiya valley is formed of alluvium deposited by the Taiya River, but the alluvium there seems to be much finer grained than in the lower Skagway valley, despite similar bedrock in the two areas. Taiya valley deposits probably are finer grained because of a more gentle gradient of the valley floor (0.3 percent slope, or 0°10', for the lower 6.5 miles), which results in a lower stream-carrying capacity for coarse sediments. In contrast, the gradient of the lower 6.5 miles of Skagway valley is seven times steeper. Sediments forming the floor of lower Taiya valley are predominantly sand to a depth of at least 8 feet, as observed in exposures several hundred feet south of the Taiya River bridge (fig. 2). Sand, and probably some silt, seems to extend southward to at least the mean high waterline. A small exposure at the highway bridge shows a mixture of sand and gravel overlying fine to coarse gravel. The coarser nature of the exposure at the bridge may be attributed to sediments carried onto the valley floor by West Creek, which enters Taiya River about 1 mile upstream from the bridge.

Manmade fill (Qf)

Manmade fill includes all fill materials either purposely placed or indiscriminately dumped by man. On the geologic map we have differentiated two types of fill: ordinary fill, composed generally of loose mixtures of gravel, sand, cobbles, some boulders, and organic material plus riprap; and refuse fill.

Ordinary fill is distributed widely over the floor of lower Skagway valley and over the top of the Skagway River delta (fig. 5). This type of fill is believed to be at least 5 feet thick and to have a maximum thickness of probably 30 feet along the seaward edge of the tidal flats. Not shown on the map are numerous small areas of fill, mostly less than 5 feet thick, which include roads, embankments, areas around and under buildings, and other man-modified ground.

The five largest areas of fill are described below.

1. The foundation pad of the ore-handling terminal (fig. 4, No. 1) is composed of an hydraulically emplaced mixture of gravel and sand from Skagway River delta dredged from depths of as much as 50 feet below mean sea level. The fill was placed directly upon the top of the delta and then riprap was placed along the wave-exposed margins.

2. The vehicle-holding area of the Alaska ferry terminal (fig. 4, No. 2) and approach road consists of gravel, cobbles, and sand obtained from the adjacent deltaic deposits (Munson, 1961, p. 5). The fill is confined by piles, and its wave-exposed margin is protected by riprap. Munson reports that the fill has poor compaction properties because of a lack of suitable binder.

3. The breakwater, built to protect the small-boat harbor (fig. 4, No. 3; U.S. Army Corps Engineers, 1964), has a riprap exterior and a core of sandy gravel and cobbles.

4. The Skagway airport runway (fig. 4) is composed of sandy gravel and some cobbles beneath a paved surface.

5. The Skagway River dikes (fig. 4, Nos. 6a-6d) have a core of sandy gravel, cobbles, and some brush, overlain by a veneer of variable-sized riprap (U.S. Army Corps Engineers, 1964). Dikes near the railroad yard include abandoned railway equipment as part of their core. The dike along the northwest edge of the airport runway has a 12-inch pipeline for petroleum products partly embedded within it.

Most fill is obtained from the modern flood plain of the Skagway River or from the top of the Skagway River delta. Lesser amounts have been taken from borrow pits in Skagway River terraces, and from drift deposits and grus accumulations along the northwest side of Skagway valley. Except for the latter two sources, which mostly are exhausted, large quantities of fill material are still available.

Most riprap used at Skagway consists of angular pieces of granodiorite between 1 and 4 feet in average dimension; riprap averaging 2 feet was utilized for dikes along the Skagway River. One source of riprap is a quarry along the northwest side of Skagway valley about a quarter of a mile northeast of the northeastern boundary of the geologic map. Another source is the same side of the valley, near the mouth of the Skagway River.

Refuse fill constitutes a very small part of the fill deposits at Skagway. It is mapped only at the city dump (fig. 4, No. 7) near the southwest end of the Skagway airport, and consists chiefly of loose refuse and garbage.

Offshore deposits

A knowledge of the nature and distribution of the offshore unconsolidated deposits of Taiya Inlet is important for understanding the geologic setting and for appraising geologic hazards in lowland parts of the Skagway area. Important elements of the offshore environment below the water of Taiya Inlet are: (1) fiord margins, (2) sediments of the offshore parts of the Skagway River delta and the Taiya River delta, and (3) other sediments of the fiord margin and floor not directly related to these deltas; this element, however, will not be discussed in this report.

Fiord margins

The underwater slopes of the margins of Taiya Inlet fiord extend to depths of at least several hundred feet at gradients nearly identical to subaerial slopes, which average 84 percent (40°) and vary from 62 to 148 percent (32°-56°). Configuration of the underwater portion of fiord margins shown on figure 5 is based on detailed soundings by the U.S. Coast and Geodetic Survey (1943).

Southeast margin of the Skagway branch of Taiya Inlet.--Underwater profile C-C' (fig. 9), prepared from the 1943 soundings, shows part of the fiord margin near the White Pass and Yukon Railroad wharf (fig. 4). Average slope of the profile is 45 percent (24°15'), and the steepest segment of the profile has a slope of 200 percent (63°30'). Very close to the line of profile, the U.S. Coast and Geodetic Survey (1943) noted the bottom as "rocky" at a depth of 160 feet below mean sea level, which might be either bedrock, or coarse unconsolidated material of a landslide or drift deposit. Other limited data on bottom conditions along the southeast margin of the fiord show the bottom to be "mud" or "mud and sand." Unpublished data by G. A. Rusnak (U.S. Geol. Survey, written commun., 1967) from a preliminary evaluation of continuous seismic profiles of the inlet reveal that a surface sediment unit thins from a much greater thickness closer to the axis of the fiord to only a few tens of feet near the fiord margin.

Some deposits with a high clay content may be present near the railroad wharf. During reconstruction of the wharf in 1965, pile-driving penetration in the initial 20 feet was reported to be easy to very easy; the lower 15 feet, however, was harder, but bouncy or spongy, a behavior thought to indicate a clayey material at depth (G. Veres, Cole and Paddock, Contractors, oral commun., 1965). If the lower deposits are clayey, they may be of marine or glaciomarine origin. Some deposits with a high clay content also may underlie part of Skagway (see "Alluvial deposits of the Skagway River").

West side of geologic-map area.--Very steep underwater slopes characterize the northwestern part of the mapped area (fig. 5). Here, the east side of Taiya Inlet fiord extends down to depths of 400 feet, with an average slope of 73 percent (36°). Because of the steepness of these slopes, surficial deposits probably are not present.

The front of the Skagway River delta

The Skagway River delta consists of two recognizable parts: (1) the intertidal part (top of the delta), which has already been described; and (2) the delta front, whose upper limit is the approximate line of mean lower low water, and which received the bulk of its sediment from distributaries of the Skagway River flowing or formerly flowing across the delta top. The front extends seaward as a

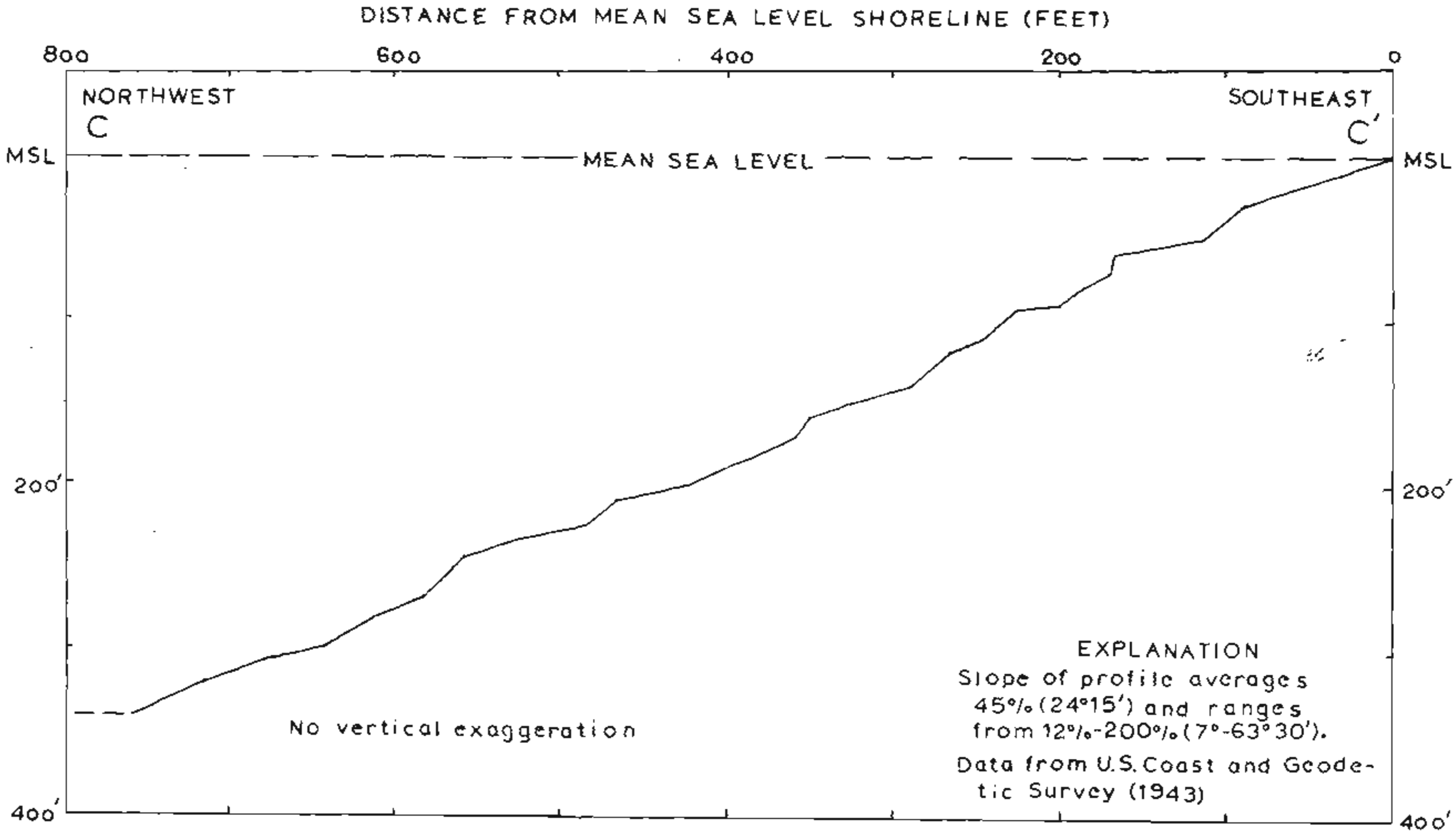


Figure 9.--Underwater profile C-C' showing part of southeast margin of Skagway branch of Taiya Inlet, Skagway, Alaska. See figures 4 and 6 for location.

decreasingly thick wedge of sediments.

The actual surface configuration of the front of the Skagway River delta is apparently fairly irregular and locally hummocky, as shown by bathymetric contours in figure 5, which are based on detailed sounding data by the U.S. Coast and Geodetic Survey (1943). Part of profile D-D' (fig. 10, in pocket) is constructed along a representative portion of the delta front. The profile indicates that the average slope of this part of the delta front is 15.8 percent (9°). Slopes of the upper 270 feet of the delta front along the profile are steeper and average 23 percent (13°).

The different kinds of deposits forming the surface of the Skagway delta front are known only sketchily from scattered points. The U.S. Coast and Geodetic Survey (1943) used the designation "rocky" for an area at the center of the delta front, although, as discussed later, it is unlikely that this term was intended to convey the presence of bedrock. Near the active distributaries of Skagway River, bottom sediments were designated as predominantly "sand," while other parts of the delta front, where water was less than 230 feet deep, were "mud" or "mud and sand." In deeper water near the center of the delta front, sandy silt was sampled in 1965 by G. A. Rusnak (written commun., 1967). Close to the Alaska ferry terminal (fig. 4), preconstruction investigations by Toner and Nordling, Engineers (written commun., 1962), revealed 2-3 feet of fine sand and silt overlying a sandy gravel with small boulders (cobbles?) that extended to a depth of 24 feet.

The types of deposits at depth beneath the surface of the delta front must be inferred, because no test holes penetrate this part of the delta. Data from borings in the delta top probably are applicable, however, because some of these holes penetrate through delta top sediments and enter older delta front deposits. These older deposits are presumed to be similar to deposits at depth within the present-day delta front. The four deepest holes, ranging in depth from 55 to 103 feet near the outer margin of the delta top, all bottomed in what may be generalized as gravelly sand, or sand and gravel (Golder, Brawner, and Associates, written commun., 1967). Therefore, sediments at depth within the present delta front probably are similar, though they may include some lenses of sandy silt or silt.

The thickness of deposits forming the delta front is inferred to be as much as several hundreds of feet. This estimate is based upon both the onshore seismic profile, B-B' (fig. 8), which indicates glacial and glaciomarine deposits at a depth of about 145 feet, and the offshore preliminary seismic profiling by G. A. Rusnak (written commun., 1967), which was interpreted by him as showing an intermediate seismic unit, possibly till, at a depth of 600-800 feet beneath marine deposits.

Subaqueous slides thought to be present on the delta front are generalized in figure 5. Slide locations, as we have shown them, are based on irregularities of the surface of the delta front and on limited data on bottom sediments (U.S. Coast and Geod. Survey, 1943). The bottom area, noted as "rocky" by the U.S. Coast and Geodetic Survey, is confined to part of the irregular surface on the central part of the delta front. This "rocky" area may be exposed drift. Although it is rather unlikely that the area could be bedrock, because of the evidence for deep glacial erosion elsewhere in the area, and because the onshore seismic profile B-B' (fig. 8) indicates a thickness of 585 feet of surficial deposits, a knob of bedrock might be present, similar in topographic setting to Indian Rock near the mouth of Taiya Inlet (fig. 2). Other submarine slides were inferred by G. A. Rusnak (written commun., 1967) to be present several hundreds of feet seaward from the steeper part of the delta front, based on some preliminary interpretations of seismic profiles.

Historical submarine slides may have occurred several times on or near the Skagway delta front. One possibly occurred prior to sinking of part of a wharf into the water during the earthquake of September 16, 1899[1] (Tarr and Martin, 1912, p. 86). Other underwater slides are believed to have caused at least five breaks in submarine communication cables in the northern part of Taiya Inlet between 1901 and 1968 (D. Alford, Alaska Commun. System, written commun., 1966, 1968; Heezen and Johnson, 1969). Some of these breaks were associated with earthquakes (see "Inferred effects from future earthquakes").

The front of the Taiya River delta

The north end of Taiya Inlet near the Taiya River delta (fig. 2) has been sounded only in a reconnaissance manner, and thus only a few scattered soundings are available (U.S. Natl. Ocean Survey, 1971). These soundings show the gradient of the delta front between depths of 80 and 250 feet to be about 11 percent (about 6°), and therefore only about one-half the gradient of the Skagway delta between similar depths (fig. 10). Gradients cannot be calculated for shallower depths because of insufficient soundings.

Deposits of the Taiya delta probably have a higher content of silt and fine sand-sized material than those of the Skagway delta, as indicated by the dominantly sandy nature of deposits exposed in the farthest downstream banks of the Taiya River. The delta of the Taiya River is gradually extending into the head of Taiya Inlet as sediment continues to be deposited at the front of the delta. During this extension process, subaqueous slides undoubtedly occur similar to those along the front of the delta of Skagway River.

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[1]The dates of all earthquakes are given in u.t. (universal time) in this report.

STRUCTURE

Summary of regional structure

Southeastern Alaska lies within an active tectonic belt that parallels the coast of the North Pacific Ocean (Buddington and Chapin, 1929; St. Amand, 1957; Twenhofel and Sainsbury, 1958; Brew and others, 1966; Grantz, 1966; Isacks and others, 1968; Atwater, 1970; Plafker, 1971). This tectonic belt has been active since at least the late Paleozoic, and the last major deformation occurred during the late Mesozoic and Tertiary, with some minor activity continuing into the Quaternary. The last major deformation included emplacement of intrusive rocks, and extensive crustal movements, ranging from compressional folding and regional uplift to faulting of various types. Many of the major elements of the structural setting of southeastern Alaska, especially faults, are discussed in our regional report (Lemke and Yehle, 1972b), and only those elements considered necessary for the discussion of the Skagway area are summarized here.

Faulting is extensive in southeastern Alaska. The Fairweather and Queen Charlotte Islands faults (here called the Fairweather-Queen Charlotte Islands fault system) and the Denali fault system comprise the most prominent fault elements (fig. 11). Both systems are tectonically active along at least parts of their lengths; major faults of the systems generally include several branching and subparallel faults in zones as much as several miles wide.

The Fairweather-Queen Charlotte Islands fault system apparently consists of a continuous belt of faults (fig. 12) that follows the continental slope along British Columbia and most of southeastern Alaska and then crosses the Continental Shelf near the northwest end of Chichagof Island, and continues on land through a broad valley to near the head of Yakutat Bay (St. Amand, 1957; Tocher, 1960; Wilson, 1965; Plafker, 1967, 1971; Tobin and Sykes, 1968). The Fairweather fault has moved in historic time, the motion of which was dominantly right-lateral strike-slip; data from a few earthquakes along the offshore Fairweather fault extension and along the Queen Charlotte Islands fault indicate similar movements. Earliest movement may have occurred in the Pliocene, and movement has continued to the present (Grantz, 1966; Tobin and Sykes, 1968, p. 3839). At its northwest end the Fairweather fault merges with the eastern end of the Chugach-St. Elias thrust fault (figs. 11, 12). Movement along this thrust fault and associated faults probably began in the Miocene and has continued intermittently since that time (Plafker, 1969, 1971).

The Denali fault system in southeastern Alaska and adjacent Canada includes, from northwest to southeast, the Shakwak valley, Chilkat River, Lynn Canal, and Chatham Strait faults (fig. 12). Segments of some faults are so prominently marked by linear fiords and valleys, and other topographic depressions, that geologists for some

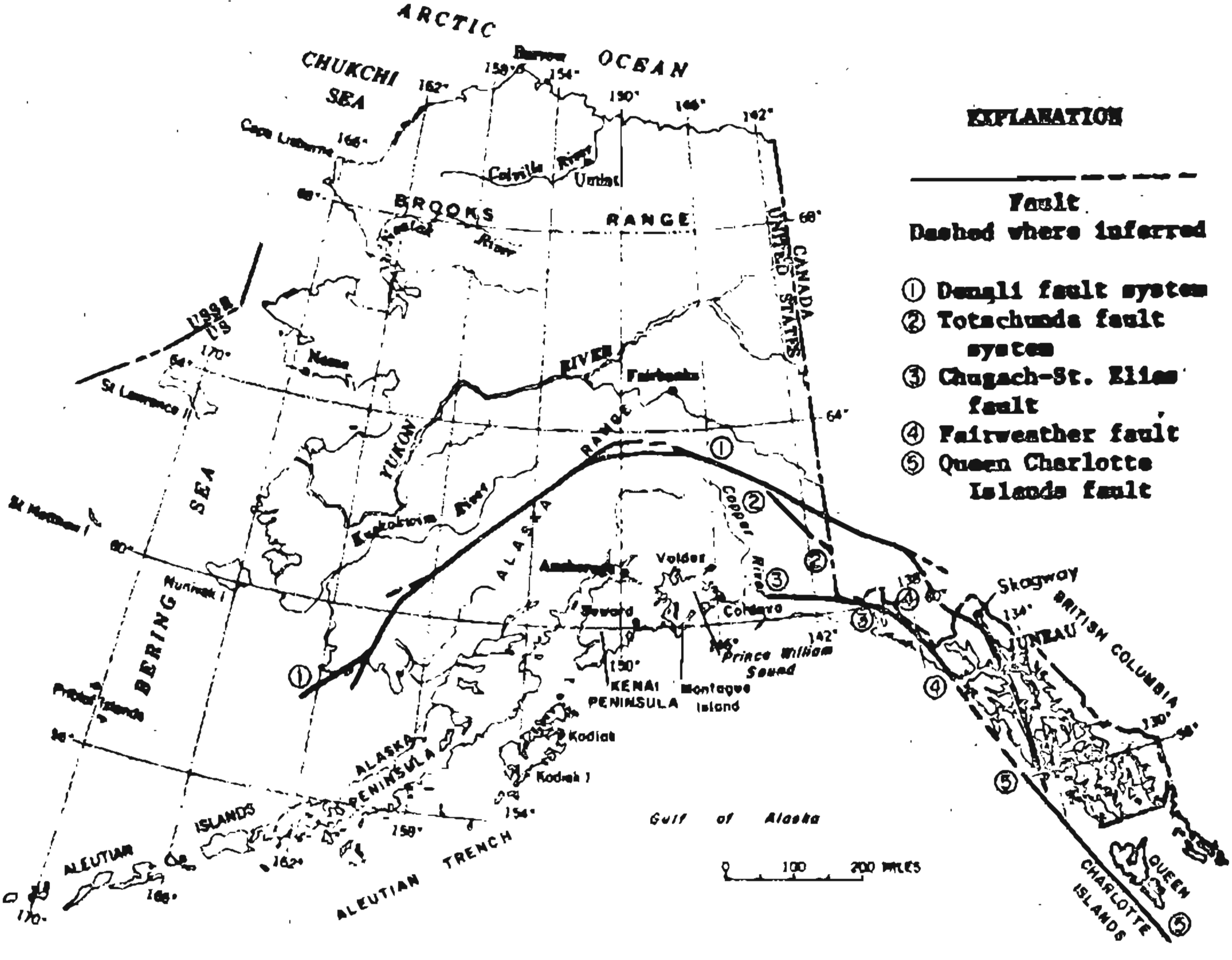

Figure 11.—Map of Alaska showing major elements of the Denali and Fairweather-Queen Charlotte Islands fault systems. Modified from Grantz (1966), Tobin and Sykes (1968), Plafker (1969; 1971), Richter and Matson (1971).

time have considered the probability of major faulting to account for the origin of these features (Wright and Wright, 1908, p. 40; St. Amand, 1957; Twenhofel and Sainsbury, 1958; Lathram, 1964; Grantz, 1966). Studies show that dominantly right-lateral strike-slip movement has occurred along most of the system, and that some of the faulting probably started before the Miocene (Grantz, 1966), and locally it continued into the Holocene (Bostock, 1952; Muller, 1967). Present activity along individual segments of the Denali fault system is considered under "Relation of earthquakes to known or inferred faults and recency of fault movement." Estimates of displacement along the Chatham Strait fault range from 50 miles (Brew and others, 1966) to 120 miles (Lathram, 1964). A probable major element of the Denali fault system in eastern Alaska is the Totschunda fault system (figs. 11, 12). Richter and Matson (1971) report fault offsets dominantly in a right-lateral direction; movement probably began in late Pleistocene and Holocene time. They speculate, along with Hamilton and Myers (1966), that the fault system might extend southeast and connect with the Fairweather and associated faults. George Plafker (written commun., 1971), however, does not believe that the Totschunda fault system is a continuation of the Fairweather fault.

Most major faults in southeastern Alaska exhibit offsets that are dominantly right-lateral strike-slip, although subordinate vertical offsets have been recorded or inferred along some faults. Uplift is reported of the Coast Mountains (Brew and others, 1966), of eastern Baranof and Chichagof Islands along the Chatham Strait fault (Loney and others, 1967), and of mountain areas along parts of the Shakwak valley fault (Muller, 1967) and Fairweather fault (Grantz, 1966).

Another type of fault motion--gravity faulting--may be locally important. Theoretical considerations by Bostrom (1967) and by Souther (1970) suggest that the earth's crust beneath northwestern British Columbia and southeastern Alaska presently may be spreading slowly westward under tension along north-south lines. They infer that this motion is partly a result of the active northwestward movement of the earth's crust along the oceanward side of the Fairweather-Queen Charlotte Islands fault system (Isacks and others, 1968; Atwater, 1970). Thus, north-trending inferred faults or lineaments in parts of southeastern Alaska might be rifts, grabens, or tear faults in the process of development because of this spreading.

Local structure

Introduction

Some data on general attitudes of bedrock, faults, and joints in the Skagway area are available from limited geologic studies and air-photo interpretation. The work by Christie (1957, 1959) on the major bodies of plutonic intrusive rocks along the Skagway valley revealed that planes of foliation of the quartz diorite strike northwest and

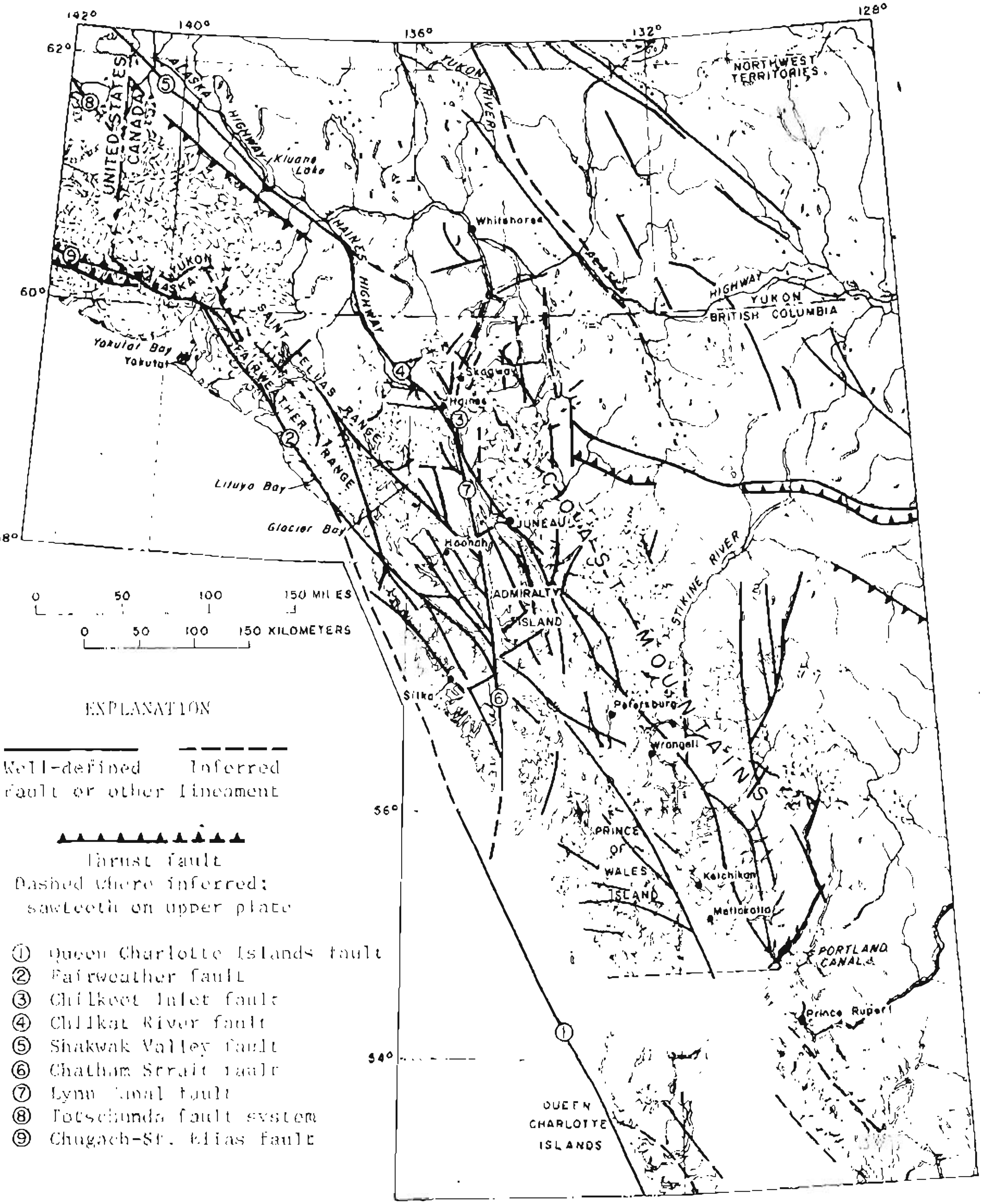

Figure 12.--Map of southeastern Alaska and adjacent Canada showing major faults and selected other lineaments interpreted to be probable or possible faults, shear zones, or joints. Taken from St. Amand (1957), Twenhofel and Sainsbury (1958), Gabrielse and Wheeler (1961), Brew and others (1966), Tobin and Sykes (1968), Geological Survey of Canada (1969a; 1969b), King (1969), Plafker (1969), Souther (1970), Plafker (1971), and Richter and Matson (1971); and with additions and modifications by the writers.

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dip steeply northeast; the granodiorite generally is not foliated. The relationships of different bodies of plutonic intrusive rocks on either side of lower Skagway and Taiya valleys to inferred faults has not been established. Detailed analyses of structural relations between bedrock units in the Juneau area, which is part of the same belt of rocks as in the Skagway area, are reported by Forbes and Engels (1970). These show a generally northwest strike to the bedrock. Most bedrock units grade into one another; locally, however, units are in sharp contact.

Jointing and sheeting are well developed in the plutonic intrusive rocks near Skagway. The joints principally strike N. 30° E. to N. 45° E. and dip very steeply or are vertical (fig. 13), approximating the orientation of the lower Skagway valley group of inferred faults. Jointing may be related in part, or wholly, to faulting or to release of regional bedrock stresses during erosion. Joints at the West Creek damsite, northwest of Skagway (fig. 2), were observed by Callahan and Wayland (1965) to consist of two principal sets of steeply dipping or vertical joints, one striking N. 40° E. to N. 50° E. and the other N. 60° E. to N. 80° E. (fig. 13). Sheeting is characteristic of the glacially rounded knobs of bedrock common in the Skagway area. The surfaces of the sheeting fracture generally are curved slightly; their strike and dip are controlled by the inclination of the surface of the bedrock. Thickness of sheets near the bedrock surface may range from 3 to 5 feet.

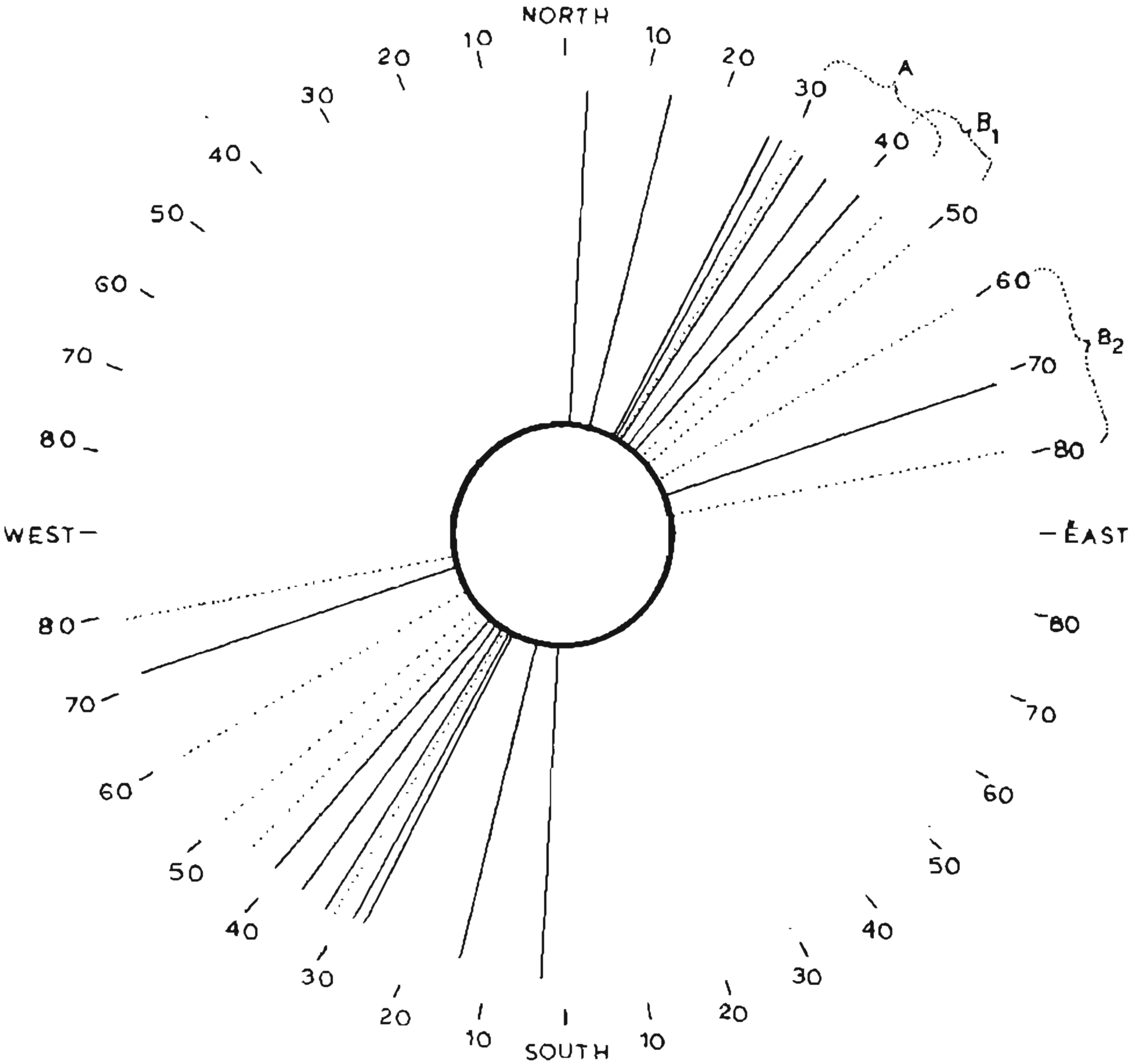
Faults

Faults or other lineaments are numerous in the Skagway area. Although no major faults have been identified by direct observations, several faults have been inferred by indirect methods, chiefly from topographic evidence as interpreted from airphotos (fig. 14; fig. 15, in pocket).

The age of faults in the Skagway area is not precisely known. The faults probably are no older than middle Tertiary and probably are no younger than the last major Quaternary glaciation. These ages are based largely on studies in adjoining areas and are summarized by Grantz (1966) for areas to the south and southwest of Skagway and by the Geological Survey of Canada (1962) for areas northeast of Skagway in Canada. No faults in surficial Quaternary deposits were observed during our limited studies near Skagway, nor have any been reported by others.

Three groups of inferred faults have been differentiated.

Lower Skagway valley group of inferred faults.--Three nearly parallel northeast-trending lineaments in and near the lower Skagway valley area are inferred to be major vertical or near-vertical faults (figs. 14, 15). They are marked by pronounced linear topographic depressions. The southeasternmost inferred fault extends through



.... Prominent joint--measured on ground:

A — Range of strikes of prominent joints near Skagway

B_1 and B_2 — Range of strikes of prominent joints, West Creek damsite

—— Major fault or other lineament. See figure 14.

Figure 13.--Diagram showing strike of joints measured on ground and selected faults or other lineaments near Skagway and West Creek damsite, Alaska. In part after Callahan and Wayland (1965) and Christie (1957).

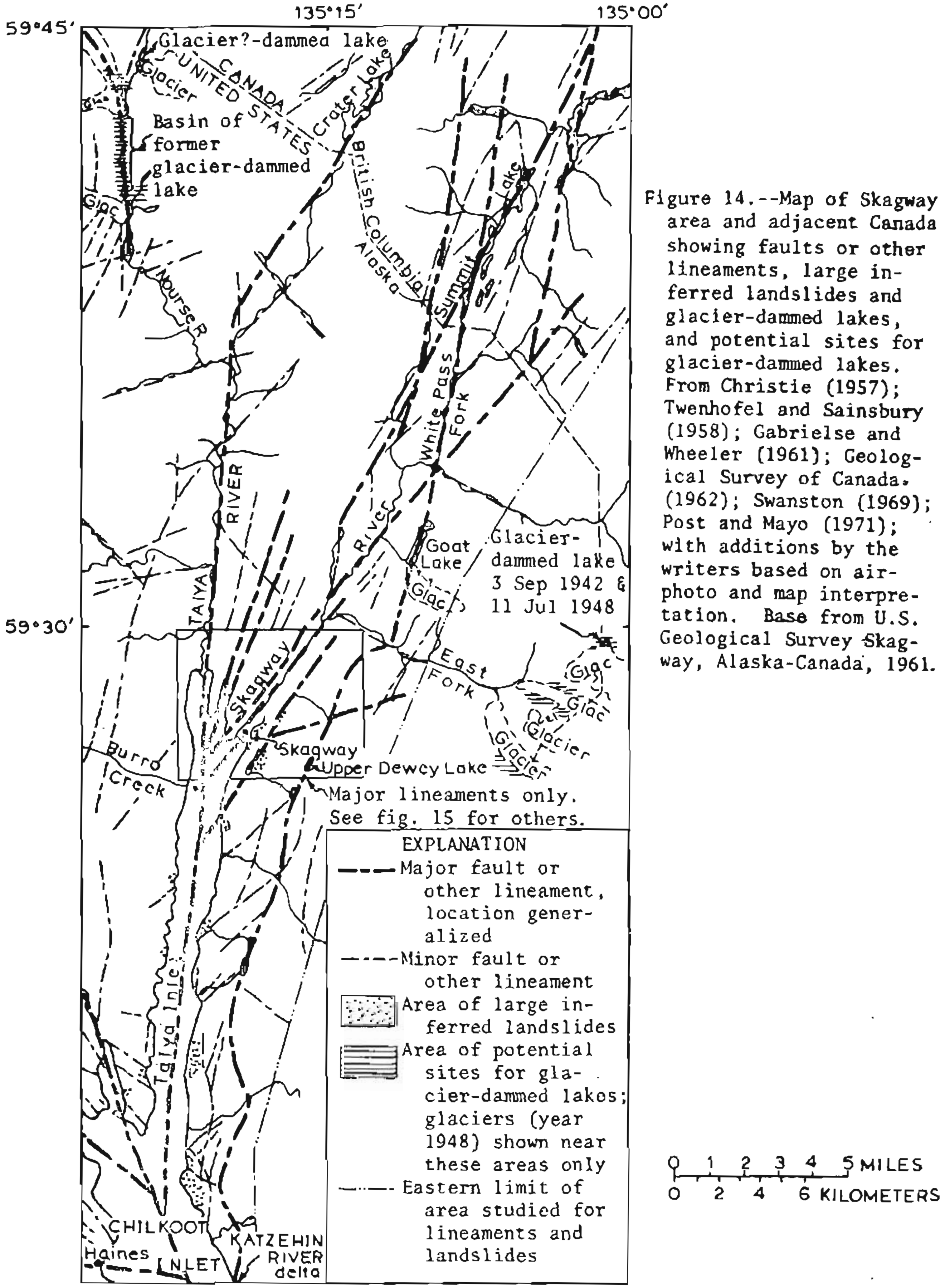


Figure 14.--Map of Skagway area and adjacent Canada showing faults or other lineaments, large inferred landslides and glacier-dammed lakes, and potential sites for glacier-dammed lakes. From Christie (1957); Twenhofel and Sainsbury (1958); Gabrielse and Wheeler (1961); Geological Survey of Canada. (1962); Swanston (1969); Post and Mayo (1971); with additions by the writers based on airphoto and map interpretation. Base from U.S. Geological Survey Skagway, Alaska-Canada, 1961.

Lower Dewey Lake and Icy Lake, a central inferred fault extends along the lower Skagway valley downstream from its junction with East Fork Skagway River, and the northwesternmost inferred fault extends along a depression that trends from near Yakutania Point to Black Lake and Skagway River Falls upstream from East Fork Skagway River, and then on northeasterly into Canada (figs. 14, 15). The orientation of the faults, at least near Skagway, approximates the principal strikes of joints (fig. 13). Conspicuous topographic benches characterize the ground surfaces between the faults in the vicinity of Skagway, and may be glacially eroded upper surfaces of fault blocks, as suggested by C. L. Sainsbury (written commun., 1953). Related(?) local faults, as much as 40 feet wide along the southeast side of lower Skagway valley, were observed by Sainsbury to cut quartz diorite in a N. 5° E. to N. 20° E. direction and to dip southeast. The three major inferred faults may merge to the southwest and be branches of a major lineament in Taiya Inlet. To the northeast they may merge with other more northerly trending faults that in Canada have been studied on the ground and mapped as definite faults (Gabrielse and Wheeler, 1961, fig. 4; Geol. Survey Canada, 1962). Major movement along all three faults of the Skagway valley group may have occurred during the middle or late Tertiary.

Taiya Inlet-Taiya valley group of inferred faults.--The straightness and combined lengths of Taiya Inlet and Taiya River valley (about 25 miles; fig. 14) are highly suggestive of a zone of major faulting. Unfortunately, however, no direct evidence of faulting is available. Numerous major and minor lineaments are present east of Taiya Inlet and many of them appear to merge with the Taiya lineament, but along the west side there are very few lineaments. On land, near Nahku Bay, several inferred faults appear to join the Taiya Inlet lineament, but none has been identified offshore (G. A. Rusnak, written commun., 1967). To the south, the Taiya Inlet fault appears to merge with the inferred Chilkoot Inlet fault (fig. 12, No. 3). No information on fault movement is available from Chilkoot Inlet. Major movement on the adjacent Chilkat River fault, a segment of the Denali fault system, however, may have occurred as late as middle Tertiary time (Grantz, 1966), and the Taiya Inlet-Taiya valley group of inferred faults also may have been active at that time.

Katzehin River delta-Upper Dewey Lake group of inferred faults.--Inferred faults of this group lie generally east of Taiya Inlet, as well as south and southeast of lower Skagway valley. Thus, they are subparallel to both of the previously discussed groups of inferred faults (fig. 14). The trace of the main fault is reflected by gently curving shallow depressions that contain several lakes and extend from the delta of the Katzehin River on the south to at least the East Fork Skagway River to the north. Numerous minor lineaments are present between the main fault and Taiya Inlet; some parallel the main fault whereas others appear to branch from it. Many of the minor lineaments are inferred to be faults; however, some may be joints or possibly headwall scarps of large landslides. To the south the main fault either merges with or is truncated by the Chilkoot Inlet fault, whereas to the north relations to other inferred faults are obscure. The main fault was noted by Twenhofel and Sainsbury (1958, p. 1433) and Gabrielse and Wheeler (1961, fig. 4), but they did not indicate the nature of the fault. Sinuosity of the fault trace, however, suggests an eastward dip for much of the fault's length. Major movement along the fault may have preceded or have been contemporaneous with activity along the Chilkat River fault in middle Tertiary time.

EARTHQUAKE PROBABILITY

Accurate prediction of exactly the place or time of occurrence of destructive earthquakes is not yet possible. However, broad regions can be outlined by geologists and seismologists where damaging earthquakes probably will occur in the future. One such region is the wide belt that roughly parallels the North Pacific Ocean. For the Skagway area, the evaluation of earthquake probability is based on two factors: (1) the seismicity or earthquake history of the area, as determined from the historic record, and (2) the local and regional geologic and tectonic setting of the area. The regional aspects of these two factors, and other pertinent information on earthquake probability, are considered in detail in our regional report (Lemke and Yehle, 1972b).

Seismicity

The Skagway area lies within a broad region of earthquake activity (fig. 16) which includes most of southeastern Alaska, plus some areas to the northwest, and adjoining areas in southwestern Yukon and coastal British Columbia. Unfortunately, the earthquake record of this region is meager. There are three reasons for this: (1) the brevity of the record--only about 70 years of written historic record of earthquakes in the region, (2) the low population density of the region throughout historic time, and (3) too few seismologic stations able to instrumentally record earthquakes in this region.

The earthquakes that have been instrumentally located in southeastern Alaska and nearby areas for the period 1899-1969 are shown on figure 16. During this period in the area of figure 16, eight earthquakes of magnitude 7 or greater occurred, all close to the coast of the Pacific Ocean. Earthquakes of lesser, or unknown, magnitudes that have been instrumentally located are widespread in the region, except eastward from the central and southern parts of southeastern Alaska. Even here, however, at least a few microearthquakes have been recorded (Whitham, 1969, p. 27).

Within 100 miles of Skagway, 34 earthquakes have been instrumentally located (fig. 16), most of which occurred northwest, west, or southwest of Skagway. They include one earthquake each of magnitudes 8, 6 1/2, and 6 (designations P, I, and N, respectively, fig. 16), plus 29 others of lesser or unknown magnitudes. The "N" event, which occurred March 9, 1952, was the closest instrumentally recorded earthquake to Skagway; the epicenter was about 30 miles to the west. Most earthquake epicentral locations shown on figure 16 are accurate, at best, within a radius of 10-15 miles, and many are accurate only to within 70 miles. The earlier historic earthquakes are the least accurately located. The depths of origin of earthquakes also are not accurately known. It is assumed, however, that they are shallow, except in rare cases (see discussion in our regional report, Lemke and Yehle, 1972b).

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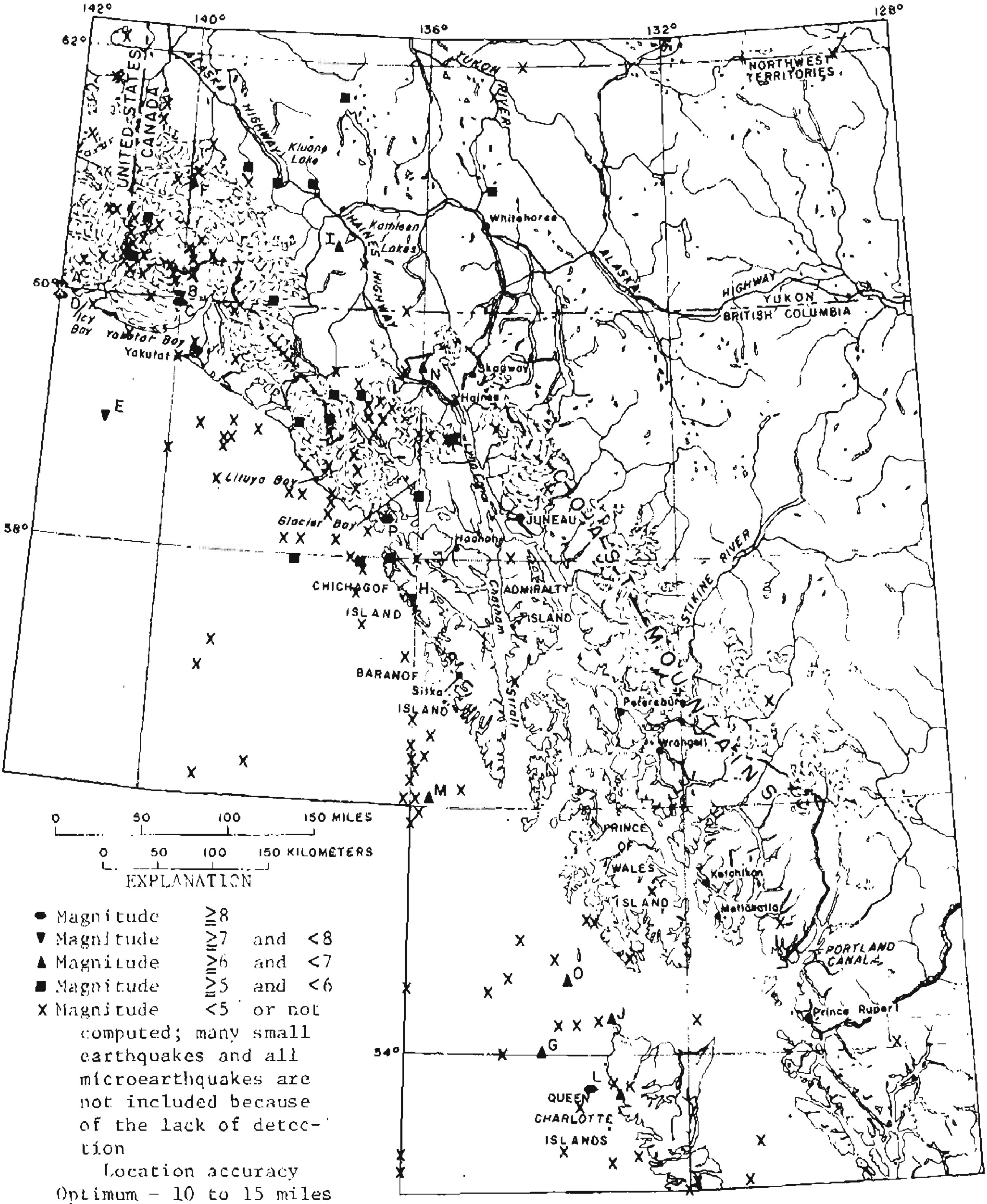

Figure 16.--Map showing locations of epicenters and approximate magnitude of earthquakes in southeastern Alaska and adjacent areas for period 1899-1969 inclusive. Data from Canada Dept. of Energy, Mines and Resources, Seismological Service (1953, 1955, 1956, 1961-63, 1966, 1969, 1970), Davis and Echols (1962), International Seismological Centre (1967-1970), Milne (1963), Tobin and Sykes (1968), U.S. Coast and Geodetic Survey (1930-1969, 1964-1970, 1969), and Wood (1966).

Dates and magnitudes of some earthquakes of magnitude ≥6

Designation on map	Date (Universal Time)	Magnitude
A	September 4, 1899	8.2-8.3
B	September 10, 1899	7.8
C	September 10, 1899	8.5-8.6
D	October 9, 1900	8.3
E	May 15, 1908	7
F	July 7, 1920	6
G	April 10, 1921	6.5
H	October 24, 1927	7.1
I	February 3, 1944	6 1/2
J	August 3, 1945	6 1/4
K	February 28, 1948	6 1/2
L	August 22, 1949	8.1
M	October 31, 1949	6 1/4
N	March 9, 1952	6
O	November 17, 1956	6 1/2
P	July 10, 1958	7.9-8.0

A list of earthquakes felt at Skagway according to written records is given in table 2, along with some other earthquakes that we think possibly were felt there but for which no written records are readily available. The maximum earthquake intensities (Modified Mercalli scale) experienced at Skagway were VI-VII, felt during the earthquake of October 9, 1900 (designation D, fig. 16); VI, during the earthquake of February 16, 1909; and another VI, during the earthquake of July 10, 1958 (designation P, fig. 16).

The series of major earthquakes near Yakutat during September 1899 also were strongly felt at Skagway, but intensity values for these are not available. However, from newspaper and eyewitness accounts given by Tarr and Martin (1912), it is estimated that intensities at Skagway probably were at least VII. The earthquake of September 4 (designation A, fig. 17), whose epicenter was about 240 miles distant, caused severe shaking at Skagway. Tarr and Martin (1912, p. 73, 74) include the following information in their report:

> "The quake was not a sudden jar, but a steady motion of the earth from north to south. So perceptible was the shaking-up that pools of water collected in the streets and sloshed about like water does in a bucket or basin when shaken violently."

Severe shaking also occurred in Skagway during the larger of two earthquakes of September 10, 1899 (designation C, fig. 16), which had an epicenter about 170 miles distant. The following account by B. F. Shelton is quoted by Tarr and Martin (1912, p. 82):

> "There were 'literal earth waves, both motion and feeling being exactly as if on board a vessel. * * * Severe shocks * * * resulting in many cracked chimneys and gaping walls. Only two buildings are said to have escaped injury.'"

Considerable shaking also was reported during the earthquake of September 16, 1899. Tarr and Martin (1912, p. 86) give an account by B. F. Shelton:

> "* * * rocking motion commenced violently again lasting it seemed, for a great length of time. * * * One of the long piers at Skagway sank into the water for a portion farthest out, but no very severe damage was done. * * * There is no doubt, however, that if Skagway had been a town of brick and stone buildings very much damage would have been done and possibly lives lost."

Two and a half miles northwest of Skagway, on the floor of lower Taiya valley, motion was described as resembling waves like the sea, travelling west to east (Tarr and Martin, 1912, p. 74). The same authors noted an account in the Seattle Weekly Times, October 4, 1899, of

T[illegible]

Oct. or Nov. 1898	felt[1]
Sept. 4, 1899	severe shaking 1/2 to 3 3/4 min.[1]
Sept. 10, 1899	severe shaking[1]
Sept. 16, 1899	consider-able shaking[1]
Sept. 17, 1899	rocking motion[1]
Sept. 23, 1899	felt?
Dec. 21, 1899	felt?
Feb. 16, 1900	felt?
Aug. 10, 1900	severe[2]
Oct. 9, 1900	VI-VII[2]
(1901-none)	
Aug. 17, 1902	felt?
(1903-1906-none)	
Sept. 24, 1907	3-4 second shock[1]
May 15, 1908	felt?
Feb. 16, 1909	VI[1]
Oct. 26, 1909	felt[1]
Mar. 14, 1910	V[2]
Jul. 7, 1910	28 seconds (?)IV-V[1]
(1911-1918-none)	
Dec. 15, 1919	felt[3]
Mar. 22, 1920	moderate intensity[3]

Dates are Universal Time
Felt Published report o[illegible]
Felt? Earthquake possibl[illegible] pretation based on scribed by Gutenbe[illegible]
IV Published report o[illegible]
* Published report o[illegible]

[1]Tarr and Martin (1912[illegible] (1918-58). [4]Davis and Sand[illegible] magnitude 8.4, epicenter of

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several buildings which had been moved a foot or two on their foundations, and of two small ones, which had toppled over.

The most recent earthquake to cause some damage at Skagway was the earthquake of July 10, 1958 (designation P, fig. 17), with an epicenter about 95 miles distant. It was felt by most people in Skagway; the shaking, which was in a north-south direction, caused some concrete foundations to crack (Davis and Sanders, 1960, p. 250). Many landslides occurred along valley sides, and although two abnormal waves reached Skagway, harbor works were not damaged (Manager, Alaska Power and Telephone Co., oral commun., 1965; see table 5). Offshore, however, underwater landslides broke submarine communication cables in four places (D. Alford, Alaska Commun. System, written commun., 1966, 1968; Heezen and Johnson, 1969).

The major Alaska earthquake of 1964 (March 28, u.t.), whose main epicenter was about 450 miles distant, was felt in Skagway. Ground motion consisted of a slow north-south rolling motion which lasted about 5 minutes, according to J. C. Lee, U.S. Postmaster (written commun., 1964; see also Plafker and others, 1969, and Eckel, 1970). Lee also reported four tsunamis or other abnormal waves, but none were damaging (table 5).

Relation of earthquakes to known or inferred faults and recency of fault movement

A sudden tectonic slippage between two parts of the earth's crust is believed to be the cause of most shallow-focus earthquakes. However, only in some earthquake regions can a close positive relation be established between earthquakes and specific zones of faulting. Unfortunately, in southeastern Alaska complete data on faults generally are lacking, and earthquake epicenters are, at best, located only to within 10-15 miles. Despite the limited data, there appears to be a strong relation between many earthquakes and certain zones of faults in some areas in southeastern Alaska.

Studies by Tobin and Sykes (1968) of earthquake data for the period 1954-63 in southeastern Alaska and adjacent areas strongly suggest that a belt of seismicity follows and defines the Fairweather-Queen Charlotte Islands fault system. As shown on figure 16, this belt is only roughly apparent, because earthquakes plotted thereon also include events that happened both before and after the period of study of Tobin and Sykes. Earlier events are located less accurately and, thus, tend to distort any definite linear pattern. The fault system probably does not consist of a single fault plane but rather it consists of a wide zone of faults.

Surface rupture occurred along onshore parts of the Fairweather fault segment of the Fairweather-Queen Charlotte Islands fault system during the earthquake of July 10, 1958 (designation P, fig. 16). The maximum movement noted was about 21 1/2 feet of right-lateral slip and about 3 1/2 feet of vertical slip (Tocher, 1960, p. 280). Offshore parts of the Fairweather and Queen Charlotte Islands fault system are concealed, but hypothetical movements, computed by Tobin and Sykes (1968, p. 3840) for this and two other major earthquakes (Oct. 24, 1927, and Aug. 22, 1949; designations H and L, respectively, fig. 16), all indicated right-lateral strike-slip motion on a steeply dipping fault plane. The same type of movement probably takes place at depth during most other earthquakes that occur along this broad belt of seismicity.

The only other surface faulting reported to have occurred in southeastern Alaska was at the time of the September 10, 1899, earthquake (designation C, fig. 16) in the vicinity of upper Yakutat Bay close to strands of what now are called the Fairweather and Chugach-St. Elias faults (Tarr and Martin, 1912). In addition to presumed surface breakage, the land apparently was uplifted over a substantial part of the same area.

Although there are no other examples known to us where surface faulting has occurred during historic earthquakes in southeastern Alaska and adjacent areas, several earthquake epicenters have been located (Nos. 4, 5, fig. 12; fig. 16) along strands of the Shakwak valley and Chilkat River segments of the Denali fault system. It is presumed that these earthquakes were caused by movements at depth along segments or branches of the fault system. The latest surface movement along at least part of the Shakwak valley fault may have been only a few hundred years ago, according to Bostock (1952, p. 9). Along the Chilkat River fault, such recent movements have not been recognized at the surface; Grantz (1966) noted that the fault was active before middle Tertiary time. The Chilkat River fault still may be tectonically active, however, because numerous small earthquakes have been felt in the area (table 2), and microearthquakes were recorded there during a short-term seismologic study by Boucher and Fitch (1969). The possibility of creep movement along the Chilkat River fault also was suggested by Boucher and Fitch. The possible relation between glacio-isostatic rebound and faulting in the area is considered by Lemke and Yehle (1972a).

No earthquakes have been recorded by instruments in the immediate Skagway vicinity, although some local shocks were felt on December 7, 1920, February 21, 1922, and November 24, 1924 (table 2). These shocks might be related to minor movement at depth along one of the nearby inferred faults (fig. 15), or they may be related to glacioisostatic rebound in the area. The apparent local nature of the earthquakes is emphasized by the fact that no records from Juneau or any community near the Chilkat River fault noted these events.

The latest surface faulting at Skagway is estimated to have occurred between post-middle Tertiary time and the last major

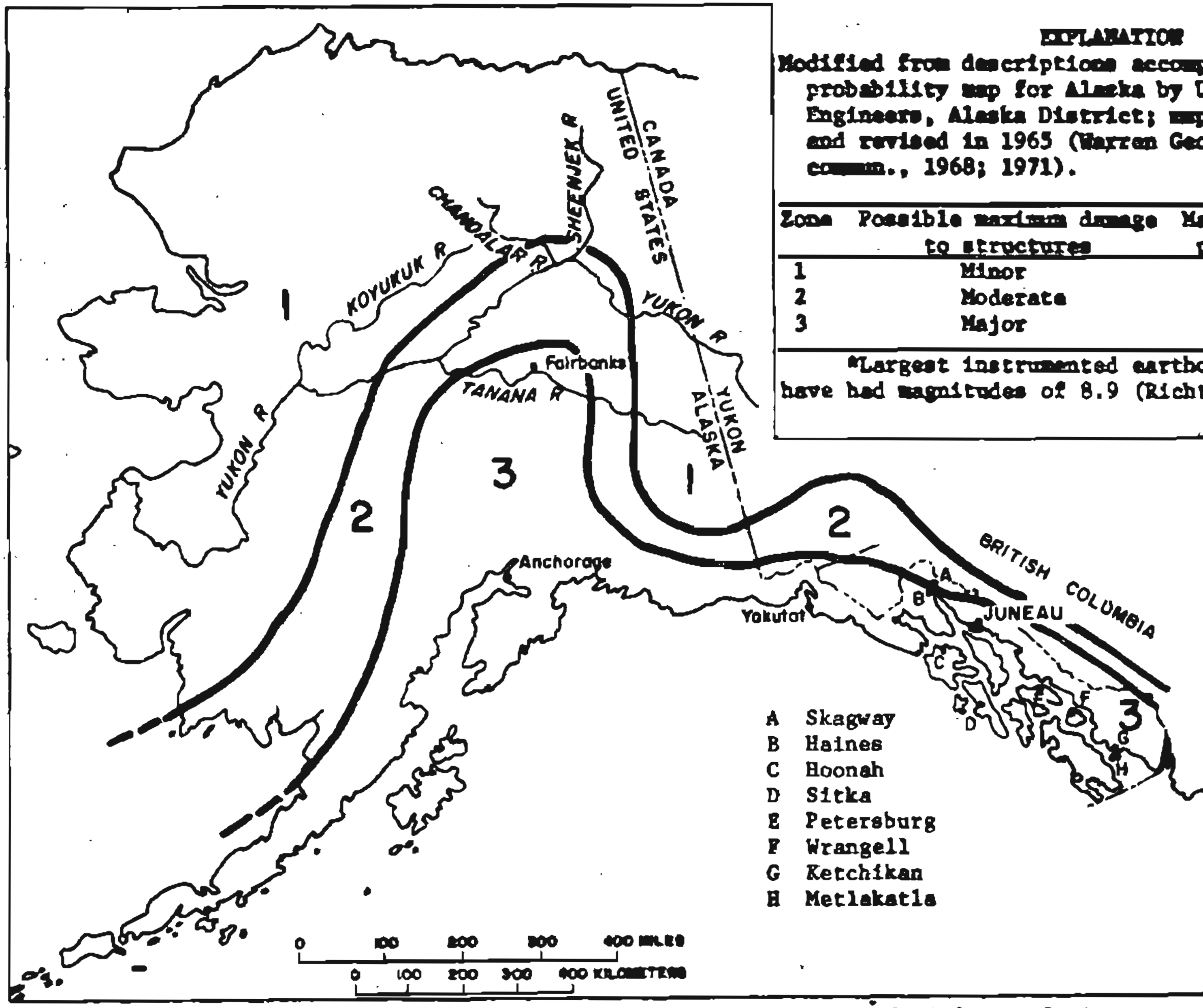
Quaternary glaciation. This estimate is based on geologic analysis by others in adjacent areas plus our own limited observations near Skagway, which indicated that there had been no faulting of surficial Quaternary deposits. Similarly, there is no evidence of faulting of Quaternary deposits offshore near Skagway (G. A. Rusnak, written commun., 1967).

Assessment of earthquake probability in Skagway and vicinity

Only a general assessment of earthquake probability can be made for the Skagway area, because the basic data on seismicity and on the tectonic framework of southeastern Alaska are so limited. Two basic types of maps have been developed by geologists, seismologists, and engineers to portray the probability of earthquakes in a region. One type considers only the probability that an earthquake might occur sometime in the future; the second type presents the expected frequency of earthquake occurrences during a specified future period of time. Both map types are based upon the premise that future earthquakes are most likely to occur where past ones have occurred. The longer the period of record, the greater is the number of earthquakes that have occurred during that period, and hence, the greater is the accuracy for predicting the number of future earthquakes in a given time. Unfortunately, in southeastern Alaska the historic record is short and the geologic and tectonic factors needed for evaluation are only poorly known. As a result, the probability maps described here are based solely on the seismic record of instrumentally located earthquakes.

The Skagway area is included on two examples of the first type of earthquake probability map, or those lacking prediction of timing. The first example is the U.S. Army Corps of Engineers seismic probability map (fig. 17; Warren George, written commun., 1968, 1971). It shows Skagway as being in zone 2 but closely adjacent to zone 3. Based on this map, a maximum probable earthquake of about magnitude 6.0 might be expected in the Skagway area. The second example is the Uniform Building Code map (fig. 18; Internat. Conf. Building Officials, 1970). It shows Skagway to be on the boundary between zones 1 and 2. On the basis of this second map, the maximum probable earthquake expected at Skagway might have an intensity of VI-VII (Modified Mercalli scale), or a magnitude of about 5.5 (table 3). The Uniform Building Code map portrayal of the Skagway area is identical to the seismic probability maps shown in publications by the U.S. Departments of the Army, Navy, and Air Force (1966), and by Johnson and Hartman (1969), and in Alaska Industry (1970).

Skagway is shown on three examples of the second, or frequency, type of earthquake probability map. One example shows seismic energy in strain release per unit area per 100 years (fig. 19; Milne, 1967). For the Skagway area, it indicates that a single earthquake of magnitude 6.2, or about eight earthquakes of magnitude 5, could account for the release of all the seismic energy. A second example (fig. 20)



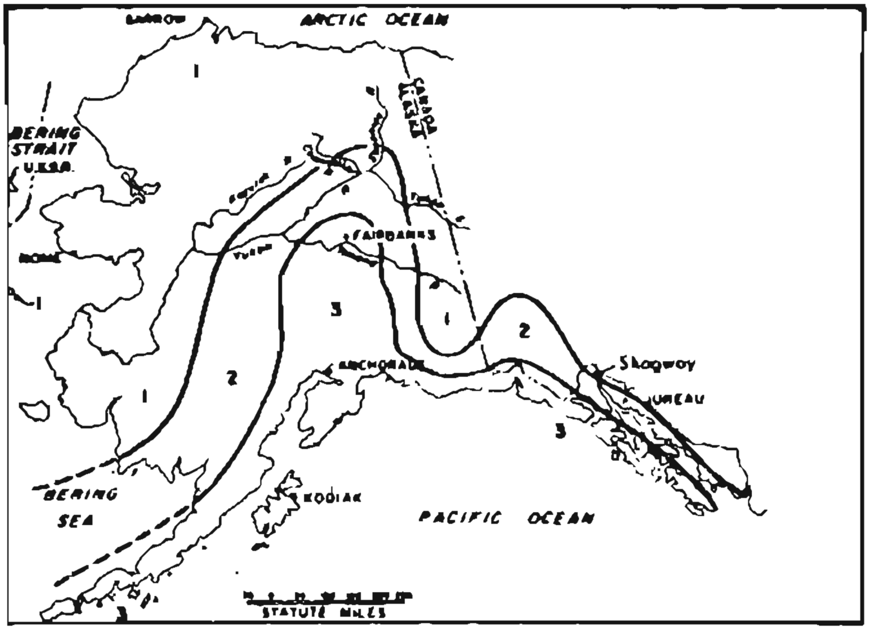
EXPLANATION

Modified from descriptions accompanying the seismic probability map for Alaska by U.S. Army, Corps of Engineers, Alaska District; map prepared in 1957 and revised in 1965 (Warren George, written commun., 1968; 1971).

Zone	Possible maximum damage to structures	Magnitude of largest probable earthquake
1	Minor	3.0-4.5
2	Moderate	4.5-6.0
3	Major	>6.0*

*Largest instrumented earthquakes of the world have had magnitudes of 8.9 (Richter, 1958)

Figure 17.—Seismic probability map for most of Alaska as modified from U.S. Army Corps of Engineers, Alaska District.



ZONE 1 - Minor damage: distant earthquakes may cause damage to structures with fundamental periods greater than 1.0second; corresponds to intensities V and VI of the MM* Scale

ZONE 2 - Moderate damage: corresponds to intensity VII of the MM* Scale

ZONE 3 - Major damage: corresponds to intensity VIII and higher of the MM* Scale

*Modified Mercalli Intensity Scale of 1931

Figure 18. Seismic zone map of Alaska. Modified from the 1970 edition of the Uniform Building Code (International Conference of Building Officials, 1970).

Table 3.--Approximate relations between earthquake magnitude, energy, ground acceleration, acceleration in relation to gravity, and intensity (modified from U.S. Atomic Energy Commission, 1963)

M[1]	E[2]	a[3]	a/g[4]	I[5]	
	10^{14}			I	Detected only by sensitive instruments
3	10^{15}			II	Felt by a few persons at rest, especially on upper floors; delicate suspended objects may swing
	10^{16}	5	.005g	III	Felt noticeably indoors, but not always recognized as a quake; standing autos rock slightly, vibration like passing truck
4	10^{17}	10	.01g	IV	Felt indoors by many, outdoors by a few; at night some awaken; dishes, windows, doors disturbed; motor cars rock noticeably
	10^{18}			V	Felt by most people; some breakage of dishes, windows, and plaster; disturbance of tall objects
5	10^{19}	50	.05g	VI	Felt by all; many frightened and run outdoors; falling plaster and chimneys; damage small
6	10^{20}	100	.1g	VII	Everybody runs outdoors; damage to buildings varies, depending on quality of construction; noticed by drivers of cars
	10^{21}			VIII	Panel walls thrown out of frames; fall of walls, monuments, chimneys; sand and mud ejected; drivers of autos disturbed
7	10^{22}	500	.5g	IX	Buildings shifted off foundations, cracked, thrown out of plumb; ground cracked; underground pipes broken
		1000	1g	X	Most masonry and frame structures destroyed; ground cracked; rails bent; landslides
8	10^{23}			XI	Few structures remain standing; bridges destroyed; fissures in ground; pipes broken; landslides; rails bent
	10^{24}	5000	5g	XII	Damage total; waves seen on ground surface; lines of sight and level distorted; objects thrown up into air

These relations until 1971 believed applicable fairly well in southern Calif. where average focal depth of earthquakes has been about 10 mi. (see Gutenberg and Richter, 1956; Hodgson, 1966). However, revisions may be necessary because of exceptionally high accelerations, as much as 1 g, during the San Fernando, Calif., earthquake of Feb. 9, 1971 (magnitude 6.6) (Maley and Cloud, 1971).

[1] M, magnitude scale, according to Richter (1958). [2] E, energy, in ergs. [3] a, ground acceleration, in centimeters per second^2. [4] a/g, ground acceleration as a percent of acceleration of gravity (about 981 cps^2 or about 32.2 fps^2, adopted as a standard by the International Committee on Weights and Measures). [5] I, Modified Mercalli intensity scale (abridged from Wood and Neumann, 1931), complete description given in Richter (1958).

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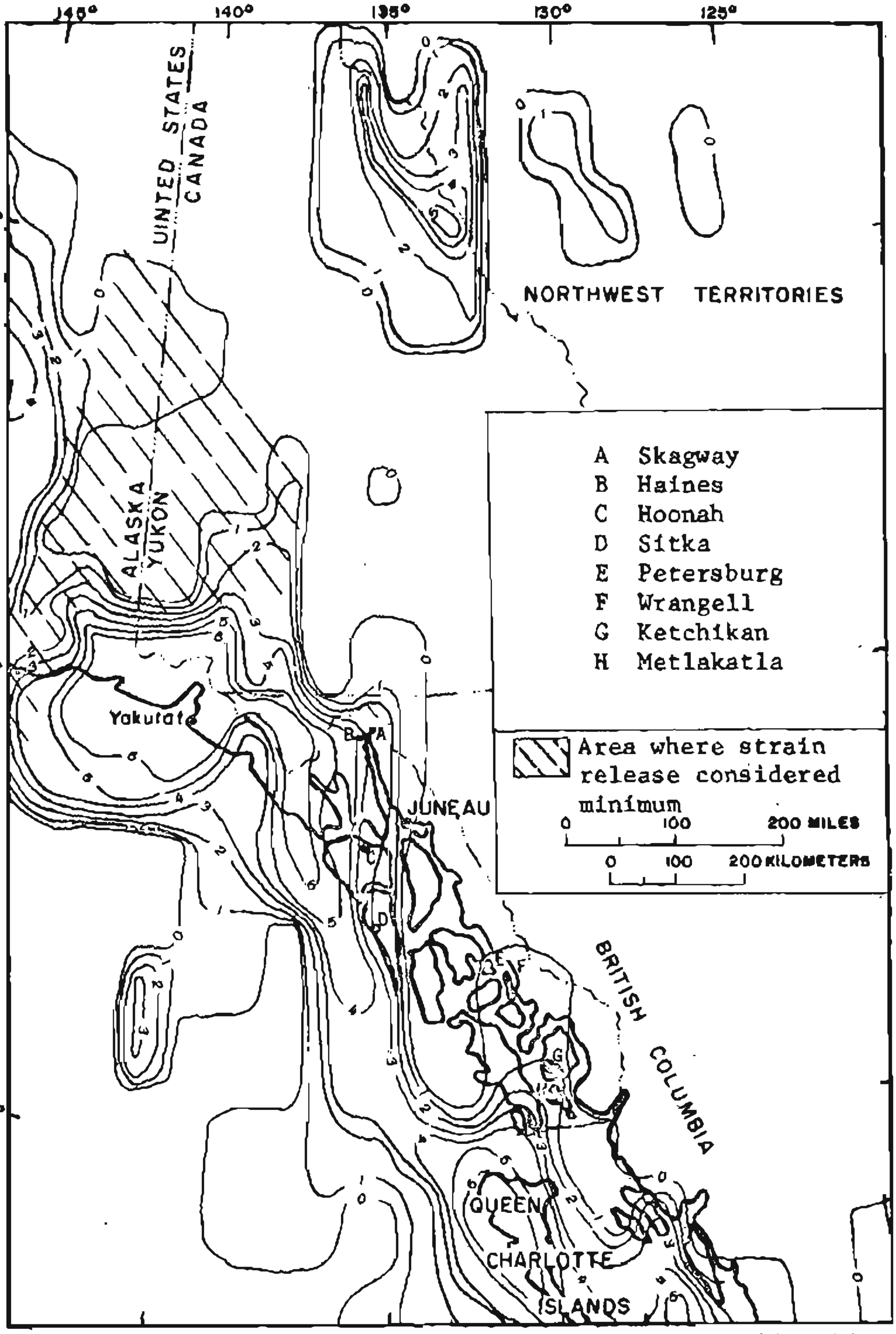


Figure 19.--Strain-release map of seismic energy 1898-1960, inclusive, in southeastern Alaska and part of adjacent Canada with explanation showing interpreted frequency of energy release. Modified from Milne (1967).

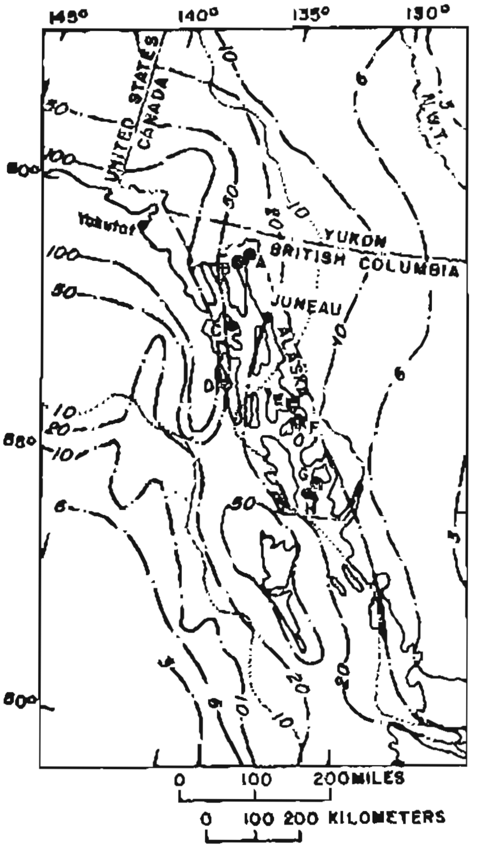
EXPLANATION FOR FIGURE 19

Map contour	Energy level in strain release units[1]	Interpreted frequency per 100 yrs of certain magnitudes (M)[2] necessary to release all of energy level				Interpreted magnitude necessary to release all of energy level in a single event per 100 yrs
		M 5	M 6	M 7	M 8	
0	0.1	----	----	----	----	3.7
1	1	1	----	----	----	5.0
2	5	5	----	----	----	5.9
3	10	10	1.8	----	----	6.3
4	20	20	3.5	----	----	6.7
5	50	50	8.9	1.6	----	7.3
6	100	100	17.8	3.1	----	7.7
[3] 7	200	200	36	6.5	1.03	8.1
8	500	500	90	15	2.5	8.6
9	700	700	120	21	3.5	8.7

[1]Energy level, strain-release (Benioff, 1951) unit here defined in terms of energy of a magnitude 5 earthquake ($10^{1.5(M-5)/2}$) per area (10^4 km^2) based on earthquakes 1898-1960 inclusive, extended to a 100-year base.

[2]A one-unit increase in magnitude is about a 30-fold increase in energy release and a two-unit increase is a 900-fold increase (Steinbrugge, 1968).

[3]Northern area of contour 6 has a maximum energy of 700 strain-release units; southern area of contour 6 has 236 units. Contours 7, 8, and 9 are not shown on map; tabular data for 7, 8, and 9 have been extended by the writers.



EXPLANATION

Average-value method		Extreme-value method
	3	
	6	
········10········ ←	10	— · — · —6
	20	
	50	
	100	

Contours showing peak earthquake acceleration as a percent of gravity (about 982 cm/sec^2 for southeastern Alaska at sea level*)

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

*See table 3 showing relations between acceleration units, energy, magnitude, and intensity.

Figure 20.--One-hundred-year probability map showing peak earthquake accelerations for southeastern Alaska and part of adjacent Canada. Modified from Milne and Davenport (1969). Based upon earthquake strain release from 1898-1960 (extended to a 100-year interval) as interpreted by an extreme-value method and using data from all instrumented earthquakes. For comparison of method, another interpretation is offered through an average-value method (dotted contour on map) which uses only earthquakes having an acceleration of 10 percent gravity.

shows probable peak acceleration of earthquakes per unit area per 100 years (Milne and Davenport, 1969). It indicates that a peak earthquake acceleration of 30 percent gravity (magnitude about 6.7, table 3) might be expected at Skagway. The third example is a generalization of acceleration data shown on figure 20 plus equivalent data for other areas of Canada and constitutes the seismic zone map of Canada (Natl. Research Council Canada, 1970). The map as described by Hasegawa (1971, p. 14) places the Skagway area in zone 3 (Canada). Ferahian (1970, p. 590) notes that, in lieu of more reliable data, a major earthquake in zone 3 (Canada) is estimated to have a maximum intensity of VIII-IX and a horizontal ground acceleration of 50 percent gravity (magnitude about 7, table 3).

Only general agreement, therefore, exists between values given by the different seismic probability maps, principally because of varying procedures used to analyze the rather limited amounts of available earthquake data. None of these maps, however, includes any consideration of either the regional geologic setting or the current tectonic activity. More confidence could be placed in the earthquake probability maps if these factors were considered. Specific factors that have proved important in the evaluation of earthquake probabilities elsewhere include: (1) the possibility that faults long inactive suddenly may become reactivated; (2) that faults active during Pleistocene and early Holocene time, but inactive during most of historical time, suddenly may become reactivated; (3) that certain presently inactive fault segments of otherwise active fault systems can be expected to become active again in the future; (4) that the occurrence of small earthquakes is not necessarily an indication of where large earthquakes will occur, or vice versa; and (5) that large earthquakes occasionally may occur in areas where there is little or no record of seismicity or of obvious tectonic structure that would indicate the likelihood of such a large earthquake. These five points are discussed in our regional report (Lemke and Yehle, 1972b) along with a number of earthquake examples from other parts of the world to illustrate the points.

In summary, it is possible to give only a generalized assessment of earthquake probability at Skagway. From the available seismic probability maps, derived from instrumented earthquake data, it appears that an earthquake of at least magnitude 6 may occur at or in the vicinity of Skagway sometime in the future. But, if the available data on geologic structure and probable tectonic activity of adjacent areas also are considered, it is concluded that an earthquake of magnitude 7 might occur. In addition, it is concluded that earthquakes of magnitude about 8 will occur again somewhere to the southwest, west and northwest of the city, on or near the Queen Charlotte Islands, Fairweather, and Chugach-St. Elias faults (fig. 11). The nearest parts of these faults are a minimum of about 100 miles from Skagway. Despite a decrease in energy of an earthquake with distance from its point of origin, especially across structural trends, the potential for damage at Skagway from the longer period motions of these earthquakes is important to consider. Inferred geologic effects of future earthquakes at Skagway are detailed in the following section.

INFERRED EFFECTS FROM FUTURE EARTHQUAKES

The following discussion and evaluation of the geologic effects of possible future large earthquakes in the Skagway area is based on the assumption that an earthquake of at least magnitude 6 will occur sometime in the near future. Possible effects include surface faulting, tectonic uplift, or subsidence; ground shaking; compaction and liquefaction of sediments; water-sediment ejection; subaerial and subaqueous sliding; changes to glaciers, to ground water, and to streams; and the possible effects of abnormal, earthquake-induced water waves. Because a knowledge of these effects at Skagway cannot be determined from past earthquakes, our evaluations are based on the physical setting and types of geologic materials at Skagway compared to the responses during large earthquakes of similar materials under similar conditions elsewhere. Descriptions of some of these large earthquakes, and the responses of materials during the earthquakes are given in our regional report (Lemke and Yehle, 1972b).

Surface displacement along faults and other tectonic land-level changes

Surface displacement along faults during earthquakes is rare because movements usually occur only at considerable depth. In southeastern Alaska, surface displacement along faults is known to have occurred only during a few earthquakes. Other tectonic land-level changes, such as sudden uplift or subsidence, also have occurred only rarely during historic earthquakes.

Active surface faults have not been identified at Skagway. However, numerous faults in the Skagway area are inferred to underlie fiords, lakes, and surficial deposits. These faults are described under "Structure." A sudden offset at the surface of several inches to several feet occurring along any of the inferred faults would damage manmade structures straddling the faults. Surface displacement along the inferred lower Skagway valley fault might damage some buildings, bridges, pipelines, and fills built directly across the faults. Surface displacement along other major inferred faults would be much less damaging because only a few manmade features exist near them. It should be re-emphasized that the zones of major faults near Skagway are generalized only and that no individual faults have been identified as yet within these zones.

Sudden tectonic uplift of a few inches at Skagway would not seriously affect the city, but an uplift of several feet would greatly affect it. Effects of such an uplift would include increased erosion by the Skagway River, shoaling of the harbor, and other problems along the waterfront where there is a critical relationship between height of land and water. Most of these problems could be overcome by strengthening of dikes, harbor dredging, and reconstruction of harbor facilities.

A tectonic subsidence of 10 feet would significantly affect harbor facilities and the seaward part of the city. It would require extensive additions to fills, rebuilding of harbor structures, moving of buildings and railroads, and replacement of waterlines and sewerlines. The 20-foot mean sea-level contour interval, as shown on figure 4, illustrates the amount of land that would be inundated at mean higher high water, if a submergence of about 10 feet occurred.

Ground shaking

Most of the damage to manmade structures during major earthquakes is caused by the shaking of the ground. The intensity of ground shaking at any point depends on many variables, including: earthquake magnitude; distance from the origin point; acceleration, period, duration and amplitude of seismic waves; nature of geologic materials; geologic structure; topography; and height of ground-water table (Barosh, 1969, p. 7). The variable most responsible for the range of shaking at any epicentral distance is the type of ground. Therefore, we will concentrate our discussion and evaluation of strong ground shaking at Skagway and vicinity on the inferred response of the mapped geologic units and of the materials of which they are composed.

Studies by geologists and earthquake engineers of the effects of many large earthquakes throughout the world have made it apparent that many of these effects are due to differences in the degree of ground shaking because of different types of geologic materials. It has been well documented, as shown in table 4, that earthquake shaking is greater on geologic materials that are loose, soft, unconsolidated, fine grained, and water saturated; conversely, shaking is much less on materials that are hard, firm, and unfractured, such as many kinds of bedrock.

The individual responses of geologic map units (fig. 5) to seismic shaking have not been studied at Skagway and vicinity. Nevertheless, limited observations on the physical characteristics of geologic materials permit development of a threefold classification of the probable responses of geologic map units to ground shaking. These are: category 1, strongest expectable shaking; category 2, intermediate expectable shaking; and category 3, least expectable shaking. The tentative placement of geologic map units within these categories is as follows:

Category 1: strongest expectable shaking

A. Manmade fill (Qf)
B. Deltaic deposits of the intertidal zone (Qi)
C. Alluvial deposits of the Skagway River (Qam and Qat)
D. Alluvial fan deposits (Qaf) (part of unit)
E. Colluvial deposits (Qca and Qci)
F. Beach deposits (Qb)

Table 4.--Relative values of earthquake intensity, acceleration, or amplitude on different geologic materials

Reference	Locality	Value versus geologic material
Neumann and Cloud, 1955, p. 205	General	As much as 10-15 times greater acceleration for unconsolidated soil than basement rock
Gutenberg and Richter, 1956, p. 111	Los Angeles, Calif.	2 1/2 times greater amplitude for terrace alluvium than for weathered granitic bedrock
Gutenberg, 1957, p. 221	General	May be 10 times greater amplitude for water-saturated soft ground than for granitic bedrock
Gutenberg, 1957, p. 222	--do--	If amplitude for rock is 1 unit, dry sand is about 3 1/2 units and marshy land is 12 units
Richter, 1959, p. 135	Los Angeles, Calif.	2-3 units[1] greater for Quaternary alluvium, terraces, and dunes than for igneous rocks
Milne, 1966, p. II-52	General	As much as 2 units[1] greater for very poor material than for igneous bedrock
Modified from Barosh, 1969, p. 87, no. 8	U.S.S.R.	1.6-2.4 unit[2] increase for rather thick-bedded (>32 1/2 ft) unconsolidated deposits; water table at depth of <16 1/4 ft but not at ground surface
Modified from Barosh, 1969, p. 87, no. 9	--do--	1.6-2.8 unit[2] increase for less thickly bedded (16 1/4-32 1/2 ft) unconsolidated deposits; water table within 9 3/4 ft of ground surface
Modified from Barosh, 1969, p. 87, no. 11	--do--	2.3-3.0 unit[2] increase near contacts between thin-bedded (<16 1/4 ft) unconsolidated deposits and other geologic materials of dissimilar physical properties, especially density
Modified from Barosh, 1969, p. 89, no. 14	--do--	2.0-3.9 unit[2] increase for loose unconsolidated deposits overlying bedrock on steep slopes
Modified from Barosh, 1969, p. 88, no. 12	--do--	2.3-3.9 unit[2] increase for muddy and sandy unconsolidated deposits close to rivers and lakes; water table at ground surface

Table 4.--Relative values of earthquake intensity, acceleration, or amplitude on different geologic materials--Continued

Reference	Locality	Value versus geologic material
Modified from Barosh, 1969, p. 88, no. 12	--do--	2.3-3.9 unit[2] increase for unconsolidated deposits with high organic content, peat, muskeg; water table at ground surface
Modified from Barosh, 1969, p. 88, no. 13	--do--	2.3-3.9 unit[2] increase for manmade fill; greatest intensity increase where loose and water table very near ground surface
Modified from Barosh, 1969, p. 89, no. 14	--do--	2.0-3.9 unit[2] increase for colluvium and some landslides; greatest intensity increase near toe and head of slides

[1]Modified Mercalli earthquake intensity scale (see table 3).

[2]U.S.S.R. GEOFIAN seismic intensity scale which somewhat equals the Modified Mercalli scale (Barosh, 1969, p. 7). (Increases in intensity are added to the intensity of granite.)

Category 2: intermediate expectable shaking
  A. Alluvial fan deposits (Qaf) (part of unit)
  B. Drift deposits (Qd)

Category 3: least expectable shaking
  Intrusive rocks (KJi)

The above categories and placement of geologic map units are generalized. Locally, shaking may be much stronger or weaker because of modification of earthquake energy waves by selective focusing, reflection, or refraction of the waves. Such modifications may be the reason for the higher than expected ground shaking often reported in alluvial deposits adjacent to bedrock (Richter, 1959, p. 137). Modification of seismic waves may have occurred during the earthquake of September 4, 1899, when shaking on alluvial deposits at Skagway was north-south in contrast to the lower Taiya valley, 2 1/2 miles northwest, where shaking was east-west (Tarr and Martin, 1912, p. 73, 74).

In order to translate these categories of expectable ground shaking into equivalent terms of expectable damage to manmade structures, certain basic assumptions must be made; namely, that essentially identical structures are being compared, and that these structures are well built and conform to standard building codes and practices.

Geologic units in category 1 (strongest expectable shaking)

Manmade fill (Qf).--Numerous examples throughout the world attest to the much greater severity of earthquake shaking of manmade fills relative to other geologic materials (Duke, 1958; Richter, 1958; Barozzi and Lemke, 1966). The physical character of most fill is conducive to development of strong ground shaking because the fill generally is loose, and water saturated. Fills dominantly of refuse are especially subject to strong shaking, whereas earth fills that are well compacted during emplacement will shake substantially less.

The principal areas of manmade fill at Skagway are near the harbor, along the Skagway River, and at scattered locations elsewhere on the floor of lower Skagway valley. Except for the city dump, most fill (Qf) generally is composed of relatively loose mixtures of gravel, sand, cobbles, and some boulders. The two largest fills are the ore-handling terminal and the Alaska ferry terminal; both probably would be strongly shaken during a major earthquake. Emplacement of the ore terminal fill was by hydraulicking. Poor compaction of the ferry terminal fill was noted by Munson (1961, p. 5). Both fills were derived from and overlie saturated deltaic deposits. This underlying unit (Qi) undoubtedly also would shake severely during a major earthquake. Other earthquake effects, especially sliding of the delta front (described in the next section), may cause even greater damage to the fills than ground shaking.

Strong shaking also would occur in other areas underlain by fill, such as the city dump, the vicinity of First Avenue, and between Spring Street and the southeast side of Skagway valley. Locally, these fills may contain sizable amounts of refuse or organic material. The Spring Street area appears to have a high ground-water table, which would tend to increase the severity of ground shaking during a major earthquake.

The Skagway Airport fill probably also would experience strong ground shaking, although it should not be as severe as for those fills closer to the shoreline. The ground-water table is lower at the airport, the underlying geologic materials are coarser, and the fill is older and probably more compact.

Riprap, which forms the face of dikes along the Skagway River, harbor fills, and the breakwater for the small-boat harbor, also would be shaken strongly. Severity of the motion would largely depend upon motion of the underlying geologic materials.

Small areas and long linear areas of fill also probably would be strongly shaken. All small fill overlies loose alluvial deposits on the floor of lower Skagway valley. The ground-water table in these deposits generally is shallow or at the surface.

<u>Deltaic deposits of the intertidal zone (Qi)</u>.--Deltaic deposits, like alluvial deposits, also are subject to strong shaking during major earthquakes (table 4). In a physical setting such as at Skagway, however, sliding of the delta front may be the most important factor in considering the overall earthquake hazard to structures that are built on the top of the Skagway River delta.

The upper part of the deltaic deposits, which are exposed at mean lower low water, consists mostly of sandy gravel, gravelly sand, and cobbles. These materials are saturated and commonly loose. At depths averaging 30 feet, the deposits are underlain by somewhat finer grained material consisting of sand or sand and some fine gravel. Below them are beds of gravelly sand or sand and gravel. Total thickness of unconsolidated deposits near First Avenue, the former inland limit of the deposit, is interpreted to be 585 feet (fig. 8). All the factors probably would contribute to increasing the degree of shaking.

Massive areas of fill overlie a large part of the deltaic deposits seaward from the higher high waterline of 1897 (fig. 5). In addition to the weight of the fills themselves, piles of ore and a few large oil tanks load the delta top. Some compaction of deltaic deposits has therefore taken place beneath the largest fills. It has been suggested (C. L. Sainsbury, U.S. Geol. Survey, oral commun., 1967) that compaction of this type might restrict ground-water flow and raise the water table upvalley from the ore-handling and ferry terminals. Regardless of the amount of compaction or possible changes in the ground-water regime, it is believed that strong shaking and buildup of pore pressures might occur during a major earthquake, which could buoy deltaic deposits. Excess pore pressures and buoyancy of sediments have caused liquefaction and sliding of deltaic deposits and manmade structures elsewhere (Terzaghi, 1956, p. 22).

Alluvial deposits of the Skagway River (Qam and Qat).--Most of the city of Skagway is built on terrace alluvial deposits (Qat) of the Skagway River. Piers and abutments of the highway bridge are the only structures built on the modern flood-plain alluvial deposits (Qam); however, northeast of the map area the railroad embankment and pipeline occupy the margin of the modern flood plain.

Any major earthquake affecting Skagway probably will cause strong ground shaking in the underlying alluvial deposits, owing to the looseness of the deposits and the high water table. It can be anticipated that nearby large earthquakes will result in more damage than occurred during the distant large earthquakes of September 1899. These were the only earthquakes felt at Skagway for which effects have been described in some detail. This account, by Tarr and Martin (1912), notes that the predominant form of movement during the earthquakes of September 4 and 10, 1899, was rocking, which resembled waves on the sea and which caused large frame buildings to sway. Similar motion was described by them at the former town of Dyea, 2 1/2 miles northwest of Skagway, which also was situated on alluvial deposits. In addition, 6-inch-wide cracks formed in the alluvium at Dyea (Parnell, 1970, p. 9).

Strongest shaking probably will be experienced in alluvial deposits close to steep valley margins of bedrock. Neuman (1954, p. 74) indicates that an increase in acceleration may occur where earthquake vibrations pass from intrusive plutonic rocks into more easily vibrated materials--like alluvium. Other local increases or decreases in severity of ground shaking on the Skagway valley floor could result from modifications of seismic energy waves due to (1) discontinuous, somewhat compact beds within the alluvial deposits, (2) change in grain size at a depth of about 25 feet to sand and some fine gravel, and (3) variations in the depth to more compact glacial and glaciomarine deposits, tentatively interpreted to be present at a depth of about 145 feet near First Avenue (fig. 8).

Vibration damage to manmade structures by ground shaking during a major earthquake probably will take the form of severe cracking of foundations and extensive structural damage to many buildings. Damage would be especially severe in buildings one of whose resonant periods of vibration corresponds to a strong or prolonged seismic wave period of the earthquake.

Other important earthquake effects that might occur within the Skagway River alluvial deposits include ground settlement from compaction, water-sediment ejection and ground fracturing, and liquefaction.

Another potential hazard to structures built on these deposits is the strong possibility of landsliding from the adjacent valley walls, as well as subaqueous sliding of the Skagway River delta. These secondary effects will be discussed later under appropriate headings.

Alluvial fan deposits (Qaf) (part of unit).--Some of the alluvial fan deposits shown on the geologic map (fig. 5) are placed in category 1, strongest expectable shaking; others are placed in category 2, intermediate expectable shaking. Those in category 1 are restricted to fan deposits in the linear depression that also contains Lower Dewey Lake and Icy Lake. Manmade structures near the lakes consist of a low dam at the southwest end of Lower Dewey Lake and associated facilities for part of Skagway's water supply.

As described previously in more detail, most alluvial fan deposits consist of loose sandy gravel, cobbles, and some boulders, and, locally, lenses of sand, silt, and organic material. In most places fan deposits overlie bedrock. The linear depression that parallels Skagway valley on the southeast is partially occupied by Lower Dewey Lake and Icy Lake; the intervening areas are occupied by coalescing fans and ponded sediments, both characterized by a high water table. Total thickness of deposits may be 50 feet. Because of these physical relations, alluvial fan deposits near the lakes are thought to include a substantial amount of sand, silt, and organic material. As a consequence, a major earthquake near Skagway probably would cause strong shaking of these alluvial fan deposits. Other earthquake effects (described later under appropriate headings) might include differential settlement, water-sediment ejection, and rupture of the low dam at the southwest end of Lower Dewey Lake founded on these alluvial fan deposits, which would lower the lake level and somewhat reduce the water supply of Skagway.

Colluvial deposits (Qca and Qci).--Ground shaking of the colluvial deposits during a major earthquake probably would be strong because of their looseness, generally high water content, and position on steep bedrock slopes. The intensity of shaking within the two geologic subunits, Qca (generally active, and locally composed of very coarse rubble) and Qci (presumably inactive), may or may not be about the same, depending on the relative stability of the individual deposits. Near the margins of these deposits where they are thin, and especially if they are saturated, shaking might be especially strong during a major earthquake because of amplification of earthquake vibrations after their passage from intrusive plutonic bedrock into thin, loose deposits (table 4; Neuman, 1954, p. 74; Barosh, 1969, p. 89).

Damage to the two city's water tanks and nearby waterlines sited on the deposits might occur during strong ground shaking accompanying a major earthquake. Other earthquake effects (discussed later in more detail under appropriate headings) probably would include some rockfalls, landslides, slumps, and flowage along the southeast side of the valley and possibly out onto the floor of Skagway valley.

Beach deposits (Qb).--A few scattered beach deposits are present near Yakutania Point (fig. 5), but, to date, no manmade structures have been built upon them. During a major earthquake these deposits probably will shake strongly because of their thinness, looseness, and high water table.

Geologic units in category 2 (intermediate expectable shaking)

Alluvial fan deposits (Qaf) (part of unit).--As previously noted, some alluvial fan deposits are placed in category 1, strongest expectable shaking, and have already been discussed under that category; the remainder of the deposits shown on the geologic map are placed in category 2.

During a major earthquake, alluvial fan deposits in category 2 generally would be subject to intermediate ground shaking relative to the strong motion anticipated on geologic units in category 1. Locally, however, shaking may be strong, especially at margins of deposits where the geologic materials are thin, the water table is high, or interstratified sediments like silt and sand are present. Other seismic effects might include landslides, flowage, water-sediment ejections, and ground fractures.

Only a few manmade structures have been built on the deposits in category 2, such as a part of the railroad mainline and a few dwellings. Damage to the railroad might consist of displacement of ties and rails.

Drift deposits (Qd).--Mapped drift deposits occur only locally on bedrock slopes along the northwest side of Skagway valley and on the topographic bench to the southeast of the valley. As a group, the deposits are compact to loose, and include a broad range of particle sizes, from silt to some boulders. Maximum thickness may be 20 feet, and the ground-water table probably is deep.

Ground shaking during a major earthquake generally would be intermediate in severity, chiefly because of the greater compactness of many of the deposits compared to other surficial deposits. Locally, where the drift is thinner or looser, ground shaking might be somewhat stronger.

The only manmade structures built on these deposits are segments of unpaved roads along the northwest side of Skagway valley. Damage probably would be slight during a major earthquake.

Geologic unit in category 3 (least expectable shaking)

Intrusive rocks (KJi).--Ground shaking on bedrock during major earthquakes generally should be the least, relative to shaking of other geologic units in the area. However, intermediate shaking might result locally on zones of naturally fragmented bedrock, on sheared bedrock near faults, or in areas of closely spaced joints. None of these zones has been differentiated on our geologic map.

Manmade structures on bedrock are not extensive but include a small dam and reservoir on the topographic bench southeast of the Skagway valley and several dwellings along the northwest side of the Skagway valley. Damage to these structures should be minimal during ground shaking accompanying major earthquakes. Destruction of the dam is not considered likely, presuming that good building practices were used during construction.

Compaction

Strong ground shaking of loose geologic materials during major earthquakes may result in compaction, or volume reduction, of deposits, especially where the ground-water table is high and silt- to fine gravel-sized materials predominate. The compaction process often is accompanied by water-sediment ejection and associated ground fracturing and liquefaction. As a result, the surface of the ground may settle several feet (Waller, 1966a; Lemke, 1967, p. E34).

The amount of ground settlement, and whether it is uniform or differential, is a function of the local geologic conditions and position of the water table. Generally, the greatest settlement will occur where (1) the ground-water table is high and some of the water can be expelled, (2) loose, cohesionless, thick deposits are present, (3) strong ground shaking persists for at least 2 minutes, and (4) the incoming seismic energy wave frequency is similar to the natural frequency of the deposits.

At Skagway, the mapped geologic units considered the most susceptible to compaction during a major earthquake are the deltaic deposits of the intertidal zone (Qi), alluvial deposits of the Skagway River (Qam and Qat), manmade fills (Qf), and some alluvial fan deposits (Qaf). Compaction of other geologic units is unlikely to be a hazard during major earthquakes.

Both deltaic deposits (Qi) and alluvial deposits of Skagway River (Qam and Qat) have high water tables and generally contain sand- and gravel-sized geologic materials capable of being compacted during major earthquakes. Thickness of these deposits near First Avenue is interpreted to be approximately 145 feet (fig. 8). Settlement of the ground surface probably would not be uniform, because some parts of the deposit would compact more than others. A potential for differential settlement in the deltaic deposits is indicated by boring data (Golder, Brawner, and Associates, written commun., 1967), which revealed variations in grain size and in packing or relative density. Some materials in the deposits are loose, but the majority are compact or dense.

Differential compaction in alluvial deposits of the Skagway River apparently occurred during the earthquake of September 4, 1899. At that time shaking forced ground water up to the surface at Skagway, where it collected in pools on roads (Tarr and Martin, 1912, p. 74); however, no settlement of ground was reported. Strong ground shaking for probably at least a few minutes' duration is required to compact and settle coarser alluvial deposits. Minor earthquakes that were felt at Skagway during the period 1910 through 1944, with intensities of as much as V, produced no measurable settlement in these deposits at the city hall (J. O. Phillips, U.S. Coast and Geod. Survey, written commun., 1965).

Most manmade fill (Qf) probably would settle differentially during a major earthquake and might disrupt buildings, road and railroad embankments, water and sewerlines, and petroleum-product pipelines. Also, ground settlement of only a few feet would result in some inundation of shore areas at high tides.

Alluvial fan deposits (Qaf) are the only other deposits that might compact to any large extent. The amounts of compaction cannot be forecast because of lack of detailed information on the distribution of grain sizes within the deposits. Differential settlement of the surfaces of alluvial fans might occur. These fans dam lakes on the topographic bench southeast of Skagway and form the foundation for at least one manmade dam. If settlements were large, both natural and manmade dams might fail and lakes might drain.

Liquefaction in cohesionless materials

Ground shaking during major earthquakes elsewhere is known to have caused liquefaction of certain types of saturated geologic materials, especially those with very low cohesion and consisting of uniform, well-sorted, fine-grained materials. According to Seed and Idriss (1971, table 1), deposits of uniformly fine sand, which have been shaken for more than 30 seconds and are within 25 feet of the ground surface, are particularly susceptible to liquefaction. If liquefaction occurs in sediments that have no lateral restraint, such as along delta fronts, the material will tend to flow toward a free face and continue to flow as long as ground shaking continues. Movement of material in flowage of this type can occur on very low gradients.

Geologic units considered most susceptible to liquefaction during strong ground shaking are deltaic deposits of the intertidal zone (Qi) and alluvial deposits of Skagway River (Qam and Qat). Other geologic units which locally might contain beds susceptible to liquefaction include alluvial fan deposits (Qaf) and sorted drift deposits (Qd).

The ground-water table is high in both deltaic deposits and alluvial deposits, but the deposits apparently contain only a few beds of uniform fine sand. In the upper part of the alluvial deposits some beds of sand and silt occur (fig. 7) which may in part be sufficiently well sorted and loose enough to liquefy. The deltaic deposits also probably contain some layers or lenses of uniform fine sand, which may be subject to liquefaction, but fine sand was identified in only one of 14 test holes in these deposits (Golder, Brawner, and Associates, written commun., 1967). The differing rates of ground penetration during the boring operation (maximum depth about 95 feet) indicate that the original packing or relative density of deposits ranged from loose to very dense, regardless of material size or depth.

The most important effect accompanying liquefaction probably would be the triggering of subaqueous slides and landslides, possibly of the flow type. Other effects include differential ground compaction and water-sediment ejection (discussed later).

Liquefaction in beds of the deltaic deposits could promote extensive subaqueous and onshore sliding of the deltaic deposits and might result in catastrophic damage to port and other waterfront facilities. Other direct damage to manmade structures from liquefaction of sediments close to the ground surface probably would be selective. Though very light structures might float, most structures probably would sink, depending upon their weight relative to the specific gravity of the liquefied material and to its thickness and areal extent; taller structures might actually overturn.

Reaction of sensitive and quick clays

Only two geologic map units are thought to contain even minor amounts of clay-sized particles--unsorted drift deposits (Qd) and, locally, some colluvial deposits (Qci). In the colluvial deposits, some beds of uniform clay might be present as small concealed remnants of fine-grained marine deposits. If some of these clays are sensitive and become quick (liquefy) during strong shaking, landsliding would be greatly facilitated. It is unlikely, however, that sensitive clays constitute a major hazard in the Skagway area.

Water-sediment ejection and associated subsidence and ground fracturing

Upward ejection of slurries of ground water and sediments from certain deposits is common during strong ground shaking in major earthquakes (Davis and Sanders, 1960, p. 227; Waller, 1968). Sand is the sediment most commonly ejected, though the material may range from nearly pure water through varying mixtures of water and sediment of various sizes. The ejection process has been variously called fountaining or spouting and takes place especially where sand-sized materials are dominant in a deposit and where the water table is shallow and is confined by a restrictive layer. During winter, frozen ground can act as a restrictive layer. Seismic shaking of confined ground water and sediment causes the hydrostatic pressure in the sediment to increase;

then, if the impermeable material is ruptured, the water and sand will erupt from point sources or along associated ground fractures. Fountains have been reported to reach heights of 100 feet (Waller, 1968, p. 100), and ejected material has covered extensive areas to depths of a few feet. The accompanying withdrawal of geologic materials and water at depth frequently results in differential subsidence of the ground surface, cratering, or extensive fracturing of ground.

The geologic units most susceptible to water-sediment ejection are the deltaic deposits (Qi) and the alluvium of the Skagway River (Qam and Qat). Probably less susceptible are the alluvial fan deposits (Qaf). No other geologic map units are likely to be subject to this process.

Damage from water-sediment ejection to manmade structures built upon deltaic and alluvial deposits of the Skagway River would depend upon proximity of the source of fountaining as well as the sediment content of the ejecta. Layers of ejected sand as much as a few feet thick might cover roads and areas between buildings and fill basements and other low areas. Differential ground subsidence and craters several feet deep, and ground fractures as much as several feet wide and deep might damage roads, water and sewerlines, and some building foundations. Alluvial fan deposits that form natural dams for lakes or foundations for manmade dams might be subjected to so much water-sediment ejection, subsidence, and ground fracturing that the fans no longer could serve as effective natural dams or foundations.

Earthquake-induced subaerial slides and slumps

Downslope movement of surficial deposits on steep slopes is common during strong ground motion accompanying earthquakes. These movements may consist of single or multiple landsliding, small-scale slumping, earth flowage, minor creep, or land spreading. Steep subaerial slopes underlain by loose water-saturated deposits are especially prone to sliding. Liquefaction may cause sliding and flowage of material on even very gentle slopes.

The deltaic deposits (Qi) probably are the most susceptible of all the mapped geologic units to subaerial landsliding resulting from near offshore submarine sliding. Discussed here are the onshore effects of subaerial sliding. The contributing submarine sliding is discussed under "Earthquake-induced subaqueous slides." Other geologic units at Skagway that would be prone to slide are: colluvial deposits (Qca and Qci), local areas of bedrock on steep slopes, some alluvial fan deposits (Qaf), manmade fill (Qf), and some of the alluvial deposits of the Skagway River (Qam and Qat).

Deltaic deposits of the Skagway River and part of the alluvial deposits of the Skagway River might move seaward as successively huge blocks of fractured ground similar to that which occurred in several localities during the 1964 Alaska earthquake. At Valdez during the 1964 earthquake, a combination of major landsliding, land spreading, and extensive fracturing of ground extended landward as much as 3,400 feet from the delta front (Coulter and Migliaccio, 1966, p. C19). In the rather unlikely event that there were a comparable amount of movement at Skagway, the disrupted ground would extend to somewhere between 4th and 7th Avenues. Clearly, such activity would cripple Skagway's economy by destroying or seriously damaging the ore terminal, Alaska ferry terminal, storage tanks, pipelines, small-boat harbor and its breakwater, part of the railroad wharf, and much of the business district. At two other localities during the 1964 Alaska earthquake, sliding and ground breakage extended landward as much as 1,300 feet (McCullough, 1966, p. A34; Lemke, 1967, p. E28). If there were similar movement at Skagway, it would destroy or seriously damage most harbor terminal facilities.

Any major earthquake close to Skagway would trigger landslides of several types in colluvial deposits, as evidenced by local failure of the deposits during the earthquake of July 10, 1958 (U.S. Coast and Geod. Survey, 1960b, p. 32). Extensive ground fractures may occur along some of the valley slopes. Some earthflows and rockfalls probably will occur in the general vicinity of the scarps indicated on the geologic map (fig. 5), chiefly because of steep slopes, a high probability of moderately fractured bedrock, and numerous patches of very thin colluvium in these localities. In addition, landsliding might be initiated within the areas marked as large inferred landslides shown on figures 5, 14, and 15. Damage to manmade structures at Skagway from landslides in colluvial deposits might be moderate to severe. Slides could cover or destroy parts of the railroad mainline and wharf and the several buildings within a few hundred feet of the valley side.

Some alluvial fan deposits (Qaf) also probably will slide during strong ground shaking because of steep slopes, high water table, and locally the presence of a considerable content of fine-grained material. Some damage to manmade structures and some partial filling of lakes and the reservoir might occur if sliding took place in the fan deposits at Lower Dewey Lake and Icy Lake. Slide material entering the bodies of water could clog outlet works and create low waves. The railroad mainline near Reid Falls Creek might be covered by slide material.

The borders of relatively steep manmade fills (Qf), that are not edged by riprap or piles, probably would experience extensive slumping and opening of marginal cracks during strong ground shaking. Damage especially would affect road and railroad embankments, refuse dumps, embankments around petroleum-product storage tanks, and some segments of river dikes.

Earthquake-induced subaqueous slides

Delta fronts are particularly prone to sliding during strong shaking accompanying major earthquakes. Shaking during the 1964 Alaska earthquake triggered large-scale sliding of deltas and associated alluvium at numerous localities elsewhere (Kachadoorian, 1965; Coulter and Migliaccio, 1966; McCullough, 1966; Lemke, 1967). Liquefaction was thought to have accompanied many slides. Some subaqueous slides triggered large waves that swept back onto the land.

The inherent instability of fronts of active deltas has been well described by Terzaghi (1956), Moore (1961), Mathews and Shepard (1962), and Dott (1963). Subaqueous slides and slurrylike bottom currents are frequent, and breakage of communication cables is commonly attributed to these processes. The number of slides would be greatly increased during earthquakes. The northern part of Taiya Inlet between 1901, when the first cable was laid to Skagway, and 1968 had six instances of cable breakage (D. Alford, Alaska Commun. System, written commun., 1966, 1968; Heezen and Johnson, 1969). Breaks of August 1901 and September 10, 1927, apparently were caused by slides not triggered by earthquakes, but four breaks occurred soon after the earthquake of July 10, 1958. One of these apparently took place near the Skagway River delta and another took place near Burro Creek delta (fig. 6). A failure of part of the Skagway delta front is inferred during the earthquake of September 16, 1899, when the outer end of a former wharf (loc. 1, fig. 5) sank into the water (Tarr and Martin, 1912, p. 86). The event was preceded by intermittent earthquakes during the previous 12 days. The hummocky configuration of the delta front, as shown on figure 5, is interpreted as subaqueous slides (see "Offshore deposits").

The stability of underwater slopes along the margin of northern Taiya Inlet near Skagway and the railroad wharf was not investigated by us. That some of these slopes are unstable, however, is indicated by a slide that occurred along the southeast side of the Skagway branch of Taiya Inlet slightly southwest of the railroad wharf in the fall of 1966 during fill emplacement (loc. 2, fig. 5; C. O. Brawner, written commun., 1966). The slide may have been triggered by an unreported earthquake, manmade vibrations, or weight of the fill on the steep slope.

Subaqueous sliding in the vicinity of Skagway almost certainly will occur during any future major or minor earthquake, especially along the fronts of large deltas. Sliding of delta fronts can occur during normal sediment accumulation, owing to the increasing weight and steepness of the mass of sediment itself; however, earthquakes would start an even greater number of slides, especially if liquefaction also occurred. Strong ground shaking of several minutes could initiate a successive headward failure of ground that might partly destroy, or at least extensively fracture, ground landward from the Skagway delta front (previously described under "Earthquake-induced subaerial slides and slumps").

Future slides during major earthquakes also probably will occur along the margin of Taiya Inlet. Some subaqueous slides also might be triggered by subaerial slides moving over underwater deposits and overloading them.

Effects on glaciers and related features

Strong ground shaking and tectonic changes to land may cause short- and long-term changes to glaciers and related drainage features. The closest glacier to Skagway is 2 1/2 miles to the east, at the head of Reid Falls Creek (fig. 15). Glaciers and icefields probably cover 25 percent of the upland parts of the Skagway area, and glacier melt waters dominate the discharge of rivers. Some of the possible earthquake-induced changes to glaciers elsewhere in Alaska were studied by Post (1967), and these include: (1) thickening and advance of glaciers, (2) blockage of streams by rupture of glaciers, and (3) emptying of glacier-dammed lakes. Only the latter two will be considered as they might affect Skagway. Any thickening of glacier ice that might take place as a result of even several earthquakes is not considered to be a hazard to either the Skagway or Taiya valley areas.

A major earthquake near Skagway might result in icefalls or disruption of glaciers by shaking or tectonic displacement which could block or divert streams (Davis and Sanders, 1960, p. 247). Unless a blocked stream could remove the ice and any associated sediment in a relatively short time, a lake might form. Sudden release of the water due to failure of the dam could cause downstream flooding. Streams tributary to East Fork Skagway River and the Nourse River, a tributary to Taiya River (fig. 14), might be susceptible to such blockage.

Breakout of glacier-dammed lakes also may cause severe downstream flooding (Marcus, 1960; Stone, 1963). Three possible glacier-dammed lakes and several potential sites for glacier-dammed lakes are shown on figure 14. Others may be present, but they could not be identified from either the existing topographic maps or from aerial photos. Goat Lake, 7 miles northeast of Skagway, is the largest of the possible glacier-dammed lakes. Its outlet appears on airphotos to consist partly of drift-covered ice that might be susceptible to rupture during a major earthquake; however, no ground examination was made. Skagway could be seriously damaged by flooding if the lake drained suddenly. Previous floods, which damaged the city in 1901 and 1909, were attributed to breakout of unidentified glacier-dammed lakes (E. Larsen, Skagway resident, oral commun., 1965). It is not known if earthquakes occurred shortly before the floods.

Effects on ground water and streamflow

The occurrence of strong ground shaking and of any kind of permanent ground displacement during an earthquake may alter considerably the flow of ground water and surface streams. Examples reported by Waller (1966b) from south-central Alaska show that the 1964 Alaska earthquake strongly affected the partly confined ground water, especially in alluvial and deltaic deposits. Ground motion, which fractured confining beds, subsequently allowed the ejection of varying mixtures of water and sediment. After the earthquake, some ground-water levels were raised because of: (1) ground subsidence, (2) increase in hydrostatic pressure, or (3) compaction of sediments. Other ground-water levels were lowered because of: (1) pressure losses, (2) sediment grain rearrangement, (3) lateral spreading of sediments, or (4) more free discharge of ground water after sliding of delta fronts. Some changes in hydrostatic pressure and ground-water level were temporary, while others lasted for at least a year; some changes may be permanent.

Changes to streamflow frequently are an important result of many earthquakes. Most streams flowing on alluvium will experience a temporary diminished flow during major earthquakes because of water loss into fractures opened by ground shaking. The sediment load of streams often will be increased temporarily following a major earthquake. Dams may be formed by landslides, debris and snowslides, glacier ice, or broken winter ice. Though generally destroyed by erosion in a short time, dams may persist long enough to form sizable lakes. Severe flooding can result if such dams break suddenly.

It is likely that landslide-formed dams will block at least temporarily the Skagway River or some of its tributaries during a major earthquake near Skagway. Because of the strong possibility of severe flooding to the city, if such a dam broke, prompt aerial inspection should be made of the Skagway River drainage basin following a major earthquake, especially the valleys tributary to the East Fork Skagway River.

A nearby major earthquake probably would alter the level of the ground-water table at Skagway. Presently the water table is either at the surface or only a few feet below. Water-sediment ejection and ground compaction would occur within the city during ground shaking, and sliding of the Skagway River delta and seaward spreading of deltaic and alluvial deposits might occur. As a result, some parts of the city after the earthquake might have a higher water table due to ground subsidence, but, in general, the water table probably would be somewhat lowered because of an increased flow of ground water toward Taiya Inlet.

Damages to manmade structures and facilities, which utilize ground and surface water, would be highly variable. Flooding from sudden release of water from breached landslide dams might damage railroad embankments, Skagway River dikes, and parts of the city. Flooding on the topographic bench might rupture manmade dams and outlet works, which form parts of the hydroelectric facility and the city's water supply. The remainder of the city's water supply is provided from two wells on the Skagway valley floor (9b, fig. 4). These wells, springs, and the other wells in Skagway, during and shortly after a major earthquake, probably would surge and also become turbid. Silting- or sanding-up of the wells, and breakage of casings and distribution lines might occur, if the earthquake were of long duration, or if extensive seaward landsliding or land spreading took place. In addition, the level of water in the wells might lower.

Tsunamis, seiches, and other abnormal water waves

Earthquake-induced water waves commonly develop during and after major earthquakes. These waves include tsunamis, seiche waves, and abnormal waves generated by subaqueous and subaerial slides or by local tectonic displacement of land. The following discussion considers each of these types of abnormal waves, the risk to Skagway of waves of certain heights, and of probable damage to the city.

Tsunamis are a type of long water wave that generally is caused by earthquake-associated displacements of very large areas of the ocean floor. In deep ocean waters the tsunami waves travel at great speed and low height, but as they approach shallow water (shelves and V-shaped bays in particular) their speed decreases greatly but their height can increase many fold. Many waves as much as 40 feet high, and a few waves as much as 100 feet high, were reported by Wiegel (1970). Wave height in shallow water largely is controlled by the initial size of the wave, the configuration of the underwater and shoreline topography, the natural oscillation of the water along the shelf or in the bay, and the stage of the tide. These controls are discussed thoroughly by Wilson and Tørum (1968), as they applied to the tsunami generated by the 1964 Alaska earthquake.

Skagway experienced tsunamis on May 22, 1960, and March 27, 28, 1964, and a possible tsunami on July 9, 1958, despite being 160 miles by water from the Pacific Ocean, where the waves were generated by large earthquakes (table 5). The water route is marked by shallows and changes in direction which greatly alter the speeds and heights of waves. Apparently, none of the waves so far has caused damage at Skagway, probably because of low wave height or a low tidal stage at the time of wave arrival. The height and timing of some possible tsunamis at Skagway appear to be complicated by other abnormal waves generated in adjacent fiords. A case in point is the wave action reported on July 9, 1958, when a wave, probably generated by a subaqueous slide, may have preceded other waves of a tsunami (table 5). The tsunami of the 1964 Alaska earthquake had a height of 10 feet for the initial wave at Skagway. This height was forecast accurately by the U.S. Weather Bureau (J. P. Bauer, Sr., written commun., 1964). Warnings to southeastern Alaska of the approach of potentially damaging

Table 5.--Tsunamis and other abnormal waves which reached or possibly reached Skagway, Alaska

Date of arrival, local time	Description	Reference	Comment
Sept. 3, 1899	Waves 1-2 ft high along connecting fiord at least 30 miles south of Skagway	Tarr and Martin, 1912, p. 74	Possibly reached Skagway, but not reported; waves dissipated(?)
Apr. 1, 1946	Tsunami recorded along outer coast of southeastern Alaska	Cox and Pararas-Cayayannis 1969	Do.
Nov. 4, 1952	do	do	Do.
Mar. 9, 1957	do	do	Do.
July 9, 1958	A wave at Skagway rose 25 ft above tide level (low at the time); a later wave was lower. No wave damage reported	Mgr., Alaska Power and Telephone Co. (oral commun., 1965)	Probably caused by subaqueous slides in Taiya Inlet that also broke communication cables as close as 2 miles from Skagway; other slides broke cables in connecting fiord 18 miles to south (Heezen and Johnson, 1969). Later wave possibly a tsunami
May 22, 1960	Tsunami reached Skagway, wave rose 1.2 ft above tide level. No wave damage reported	Berkman and Symons, 1964, p. 20	-
Mar. 27-28, 1964	Tsunami reached Skagway. Initial wave occurred at 1/2 tide, and rose 10 ft above tide level; three later waves were lower, but one rose to 5 ft above tide level. No wave damage reported	J. C. Lee, <u>in</u> Cloud and Scott, 1969, p. 37	Possibly accompanied by locally generated waves caused by same earthquake. Subaqueous slides broke communication cable in connecting fiord 18 miles to south (D. Alford, Alaska Commun. System, written commun., 1966)

tsunamis are issued by personnel of the National and Alaska Regional Tsunami Warning System of the U.S. National Ocean Survey, which give estimated times of wave arrivals (Butler, 1971, p. 31). For Skagway, such warnings should allow sufficient time to evacuate low-lying ground and the harbor area and other low-lying areas.

Seiche waves are water waves that may be set in motion by sympathetic oscillation of closed or semiclosed bodies of water owing to passage of seismic waves, tilting of the enclosing basins, or the impact of large landslides into the bodies of water. The natural oscillation of a water body is controlled mostly by the configuration of the containing basin. Several examples of the extensive development of seiche waves or possible seiche waves between one-half foot and about 25 feet high, which occurred during the 1964 Alaska earthquake, are given for lakes and narrow tidal inlets by McCullough (1966) and McGarr and Vorhis (1968) and from U.S. Geological Survey unpublished data (1964). Generation of seiche waves in the Skagway area during the 1964 or other earthquakes is not known. Waves reported south of Skagway, on September 3, 1899, might have been seiche waves (table 5; Tarr and Martin, 1912, p. 74).

Massive sliding, both subaerial and subaqueous, has been documented by many authors as causing small to very large abnormal water waves in tidal inlets and lakes during seismic shaking. Delta fronts especially are prone to failure and to generation of such waves. Several failures, none of them close to Skagway, which occurred during the 1964 Alaska earthquake, generated waves as much as 30 feet high, and one wave had a maximum vertical runup of 170 feet (Kachadoorian, 1965; Coulter and Migliaccio, 1966; McCullough, 1966; Lemke, 1967; Plafker and others, 1969). Subaerial sliding triggered by seismic shaking also has generated abnormally high waves. Probably the world's record height of wave runup induced by landsliding occurred in parts of Lituya Bay, 100 miles southwest of Skagway, during the earthquake of July 10, 1958, when a wave attained a runup height of 1,740 feet (fig. 1; D. J. Miller, 1960). In the narrow fiords near Skagway neither distant nor nearby earthquakes in historic time have formed waves that are clearly attributed to local subaerial or subaqueous sliding. However, earthquake-triggered subaqueous slides are known to have happened in Taiya Inlet July 9, 1958 (local time), because communication cables were broken (table 5; Heezen and Johnson, 1969). The 25-foot-high wave at Skagway on July 9, 1958, possibly was triggered by such a slide. That large subaerial landslides may have occurred in the past along the sides of Taiya Inlet is shown by the presence of several inferred landslides along the inlet margins (fig. 14). Any of the slides could have been triggered by earthquakes, and in turn could have generated abnormal waves.

Some of the very local but damaging waves, which occurred in southern coastal Alaska during the 1964 Alaska earthquake, apparently were not triggered by earthquake-induced slides, seiches, or tsunamis.

Plafker (1969, p. 139) suggested that these local waves might have been generated by direct tectonic displacement of the land. However, it was not clear whether small-scale faulting, uplift, or subsidence occurred in the local areas. Wave height probably was controlled by the direction and amount of land displacement, as well as bottom configuration and shore orientation. In the Skagway area, earthquake-induced waves of this type have not been recognized.

In order to evaluate adequately the effects at Skagway of any type of abnormal water waves generated by future earthquakes, data are needed for several physical factors. One need is to refine data on attenuation of wave energy from tsunami waves arriving from distant sources and traveling up fiords to Skagway. Another need is to identify potential areas of sliding on delta fronts and on other steep subaqueous and subaerial slopes along Taiya Inlet. Still another need is to determine the resonance of major water bodies near Skagway.

We feel that abnormal waves constitute a substantial risk to Skagway, regardless of their origin. Damage potential will depend upon wave height, stage of tide, and slope of the shore. Selected contours are shown on figure 4 to give some idea of the parts of Skagway that would be flooded and possibly damaged by waves with runups of 20, 60, or 100 feet above mean sea level.

The probability of waves with heights of 100 feet or more seems very slight, but it cannot be ruled out. A wave triggered by a large nearby landslide, or by a wave caused by a massive local subaqueous slide, might possibly reach such a height in the Skagway area. Tsunami and seiche waves with heights of 100 feet or more at Skagway are considered highly unlikely. The U.S. Coast and Geodetic Survey (1965) considers that, directly after the generation of a local tsunami, all areas less than 100 feet above sea level and within 1 mile of the coast should be considered potential danger areas, unless determined otherwise by competent scientists. This consideration well might be extended to include fiords where large landslides might occur, during or shortly after earthquakes.

Whereas the probability of earthquake-induced waves 60-100 feet high occurring has only a slight likelihood, waves 20-60 feet high have a moderate likelihood of sometime occurring in the Skagway area. Elsewhere, during the 1964 Alaska earthquake, waves 30 feet high at several locations resulted from the widespread subaqueous sliding of deltaic deposits. In Taiya Inlet during a major earthquake, parts of the Skagway River delta, Taiya River delta, and Burro Creek delta almost surely would slide and generate waves. Other waves might be generated by subaerial sliding from steep fiord walls, by possible seiching, or by tectonic displacement of land. Tsunamis might be amplified by sympathetic oscillations and development of other waves within fiords to reach heights of 20-60 feet. Directly after the generation of distant tsunamis, the U.S. Coast and Geodetic Survey (1965) considers areas less than 50 feet above sea level and within 1 mile of the coast to be potential danger areas, unless otherwise determined by competent scientists.

The probability is moderate to strong that earthquake-induced waves as much as 20 feet high will wash onto low-lying ground in Skagway sometime in the future. The waves most likely will be generated by subaqueous sliding of delta fronts, although waves of other origins, especially those from subaerial slides, should be expected. As an example of wave height related to damage, a 10-foot-high wave occurring near the time of monthly high tides probably would cause severe damage to harbor facilities, oil tanks, boats, and most buildings below an altitude of about 20 feet (fig. 4). However, a 20-foot-high wave arriving at low tide would cause little or no damage.

Lakes and reservoirs near Skagway may experience some seiche waves during earthquakes as the result of subaerial sliding and subaqueous sliding of geologic materials, or tectonic displacement of land. The height of such waves probably would be low, but they might be sufficient to cause some damage. In certain combinations of earthquake ground shaking, or tectonic displacement and slide-induced waves, some segments of manmade structures might fail, and flooding could occur.

INFERRED FUTURE EFFECTS FROM OTHER GEOLOGIC HAZARDS THAN THOSE CAUSED BY EARTHQUAKES

In addition to the hazard from earthquakes, there is a potential for damage to Skagway from other geologic hazards, including: (1) nonearthquake-induced landsliding and subaqueous sliding, (2) flooding, and (3) slow uplift (rebound) of land. These processes and their possible effects upon Skagway are described below.

Landsliding and subaqueous sliding

Numerous slopes in the Skagway area are subject to failure by downslope, mass-wasting processes, such as landsliding and subaqueous sliding. Although many such failures are triggered by earthquakes, many also may occur from time to time as the result of normal delta development, heavy rainfall, rapid snowmelt, seasonal freezing and thawing, and man's alteration of slopes.

Specific examples of nonearthquake-induced sliding near Skagway have been recorded only infrequently--probably because of the small scale of sliding. One recorded example, though, is the breaking of submarine cables near the front of Skagway River delta on September 10, 1927, and possibly in August 1901 (D. Alford, Alaska Commun. System, written commun., 1966, 1968; Heezen and Johnson, 1969). Intermittent submarine slides and slurrylike bottom currents characterize all actively expanding delta fronts (Shepard, 1956; Mathews and Shepard, 1962; Coulter and Migliaccio, 1966, p. C16). Another example of apparently nonearthquake-induced sliding is the failure of manmade fill and fiord-margin sediments near the railroad wharf in 1966 (loc. 2, fig. 5; C. O. Brawner, written commun., 1966). Possibly the added weight of the fill triggered the slide, although vibrations from equipment or an unreported earthquake might have been the cause. Terzaghi (1956, p. 13) reported an example of a slide from another fiord region where construction altered submarine currents, interfered with sediment deposition, and caused premature sliding of part of a delta front. In none of the three examples were waves reported. On the other hand, numerous waves caused by nonearthquake-triggered landslides have been reported in Norwegian fiords and lakes by Jørstad (1968).

Small-scale slide events, including debris flows, rockfalls, talus and soil creep, soil flows, and subaqueous slides, undoubtedly have occurred at frequent intervals in the Skagway area. These probably were especially frequent during times of heavy rains, rapid snowmelt, frequent cycles of freezing and thawing, and oversteepening of delta fronts by rapid sedimentation.

There appears to be a moderate to high probability in the Skagway area for the occurrence from time to time of large landslides, moderate-size subaqueous slides, and associated waves. Moderate damage to Skagway can be expected because of these events. Types of damage from slides and waves are given under "Inferred effects from future earthquakes." Small slides, earthflows, and rockfalls have a very high probability of continuing at frequent intervals, but these will cause only limited damage.

Flooding

Most floods of rivers and streams in the Skagway area were caused by heavy rain, but a few may have been the result of the sudden release of waters from glacier-dammed lakes. A potential cause of floods would be a similar release of waters ponded behind landslide, alluvial fan, moraine, or manmade dams.

The Skagway River is known to have flooded and caused damage to Skagway in 1901, 1909, 1919, 1936, 1937, 1943, 1944, 1949, and 1967 (U.S. Army Corps Engineers, 1964; U.S. Weather Bur., Monthly Climatological Summaries; E. Larsen, Skagway resident, oral commun., 1965). Except for the floods of 1901 and 1909, which are thought to have been due to sudden outbreak of glacier-dammed lakes, all floods resulted from heavy rains occurring in September or October. Dikes built in 1940 by the U.S. Army Corps of Engineers have relieved to some extent the threat to Skagway from normal flooding of the Skagway River.

The most severe flood occurred on October 22, 1937, when part of the city was covered with water as much as 6 inches deep. Rainfall that day was 4.21 inches (U.S. Weather Bur., Monthly Climatological Summary). Floods of September 1967 also were fairly severe, because, in addition to a washout of part of the Skagway River dike near 20th Avenue, there were several large earthslides onto the railroad, numerous small slides throughout the area, and flooding of the low-lying ground near Spring Street (Kenneth Larsen, Alaska Dept. Highways, written commun., 1967).

In the future, flooding of Skagway by the Skagway River can be expected to continue at irregular intervals, similar to the past, unless dikes are raised and broadened (U.S. Army Corps Engineers, 1964). The 100-year statistical probability for maximum 24-hour rainfall, developed by the U.S. Weather Bureau, shows that within the Skagway River basin there is a 1-percent chance during any single year for a 24-hour rainfall of 10 inches (J. F. Miller, 1963). Dikes might be extensively breached by floodwater if such a rain occurred, and part of Skagway River probably would reoccupy a former channel that lies next to the southeast side of Skagway valley. Pullen Creek roughly follows this old channel.

Because at least two of the Skagway River floods are thought to have been caused by breakout of glacier-dammed lakes, we examined topographic maps and 1948 airphotos of Alaskan glaciers which are parts of the Skagway or Taiya River watersheds for possible glacier-dammed lakes and potential sites for glacier-dammed lakes. Two glacier-dammed lakes and several potential sites exist in the Skagway River drainage area, and one possible lake and several potential sites were found in the Nourse River valley, tributary to Taiya River valley (fig. 14; Post and Mayo, 1971). Other lakes and potential sites may be present for reasons given under "Effects on glaciers and related features." Our photograph and map analysis also included inspection of major valleys for evidence of debris-dammed lakes due to large landslides, alluvial fans, or moraines damming streams. No landslides were observed, but fans form the dams for Lower Dewey Lake, Icy Lake, and the primary dam for a lake in the Nourse River valley (fig. 14), whereas a moraine forms a secondary dam for the Nourse valley lake. Another lake that is partly moraine-dammed is Goat Lake, 7 miles northeast of Skagway. It is concluded that the potential for flooding in the Skagway area due to an outbreak of lakes dammed by glaciers, alluvial fans, or moraines probably is remote but cannot be ignored.

Land uplift

A different type of minor geologic hazard to Skagway--one that poses no threat to life and only a minor threat to property--is the slow uplift of land relative to sea level (see "Glaciation and associated land- and sea-level changes"). Emergence of land averaged 0.059 foot per year between 1909 and 1959, and a continuation of uplift at about this rate was suggested by Hicks and Shofnos (1965) following their preliminary analysis of 1962 tidal data from Skagway. The increment of uplift for a single year is small, but the aggregate from 1897 to 1972, the historical period of the city of Skagway, theoretically could have caused a seaward displacement of the shoreline of about 500 feet and a shoaling of the harbor of about 4.4 feet. An even more important contribution to the shoaling, however, might be from infill of fine sediments to harbor areas.

RECOMMENDATIONS FOR ADDITIONAL STUDIES

The reconnaissance nature and limited time for our geologic study did not permit a full evaluation of all aspects of potential geologic hazards or of other factors of possible benefit to land-use planning in the Skagway area. Therefore, the following recommendations are made for additional studies that are beyond the scope of our work; these are given in order of importance:

1. A detailed geologic field study of the Skagway area, utilizing current airphotos and updated topographic maps, should be made on a systematic areal basis. In addition to mapping, the study should include collection of data on distribution of geologic materials, joints, faults, and areas of potentially unstable slopes. Geophysical explorations should be made for possible fault zones beneath valley fills. Especially important would be a collection of data on the physical and engineering properties of surficial deposits forming the delta and floor of lower Skagway valley and the delta and floor of lower Taiya valley.

2. A long-term and more thorough evaluation should be made of the faulting potential in the area, and of the earthquake response of geologic materials in the Skagway area. The work should include: (a) installation and monitoring of seismometers in different types of geologic materials to detect very small as well as large earthquakes, (b) installation and monitoring of instruments to measure possible horizontal earth movements across and along fiords and major valleys, and (c) studies of the specific responses of geologic materials to earthquake shaking, especially with regard to liquefaction potential. The latter is especially important in the fine-grained deposits in the Skagway delta and in the saturated, uniform sand deposits forming the Taiya River delta and floor of lower Taiya valley.

3. Detailed soundings and bottom-sediment studies should be made of Taiya Inlet, especially of delta fronts. Potentially unstable areas, such as very steep slopes, and sectors of rapid sedimentation can be located. Periodic resoundings would permit changes in slopes to be identified and, thus, help to evaluate potential failures of these slopes. Preventive measures might be possible under some circumstances. A part of the sounding study should include analysis of the configuration of the basin of Taiya Inlet. The dissipation or amplification of waves caused by tsunamis or landslides is dependent upon the configuration and resonant characteristic of the inlet.

4. Stability analyses of inferred landslides should be undertaken. We noted by airphoto interpretation several areas of inferred landslides along Taiya Inlet and Skagway valley; other landslides undoubtedly exist. Positive identification of landslides probably can be accomplished during the field studies recommended in item 1. Subsequently, studies should be specifically oriented to determine the risk of future landsliding by evaluation of geologic materials and their contacts,

ground- and surface-water relationships, orientation of joints and faults, and slope steepness.

5. Margins and especially outlets of reservoirs and of natural and man-modified lakes should be inspected to determine their condition. Based on the results of the inspection, both static and dynamic stability analyses should be made of critical structures. Of special importance are studies of Goat Lake, the dam and reservoir between Lower Dewey Lake and Skagway, and alluvial fan- and glacier-dammed lakes in the Skagway River and Taiya River drainages. Periodic inspections of these features are advisable.

6. Relative land uplift at Skagway should be further analyzed. Continued measurements of tidal and other bench marks should be undertaken to determine if the rate of uplift remains stable. Sound judgments about dredging in Skagway harbor and planning of future construction on the lower Taiya valley may depend upon appraisal of such information.

GLOSSARY

Technical terms that are used extensively in this report are defined here for readers who may not be familiar with them.

Creep: The slow, generally imperceptible, downslope movement of earth material.

Dip: The angle which a bed, layer, dike, fault, fissure, or similar planar geologic feature forms with an imaginary horizontal surface when measured at right angle to the strike.

Drift: A general term for rock material of any kind that has been transported from one place to another by glacier ice or associated streams. Material may range in size from clay to boulders and may be sorted or unsorted. It includes till and all kinds of stratified deposits of glacial origin.

Epicenter: The point on the earth's surface directly above the origin point of an earthquake.

Fault: A fracture or fracture zone along which there has been displacement of the two sides relative to one another parallel to the fracture. There are several kinds of faults: A normal fault is one in which the hanging wall (the block above the fault plane) has moved downward in relation to the footwall (the block below the fault plane); on a vertical fault, one side has moved down in relation to the other side. A thrust fault is a low-angle fault on which the hanging wall has moved upward relative to the footwall. A strike-slip fault is a fault on which there has been lateral displacement approximately parallel to the strike of the fault. (If the movement is such that, when an observer looks across a fault, the block across the fault has moved relatively to the right, then the fault is a right-lateral strike-slip fault; if the displacement is such that the block across the fault has moved relatively to the left, then the fault is a left-lateral strike-slip fault.) The term active fault is in common usage in the literature, but there is no general agreement as to the meaning of the term in relation to time. In general, an active fault is one on which continuous or, more likely, intermittent movement is occurring. As used in this report, an active fault is defined as one that has displaced the ground surface during Holocene time.

Foliation: Banding or lamination of crystalline rock that resulted from segregation of minerals during metamorphism or lamellar flow.

Foundation: Natural or artificially emplaced earth material on which manmade structures are placed.

Graben: A fault block, generally long and narrow, that has been relatively downdropped along normal faults bounding each side of the block.

Holocene: The most recent epoch in geologic time; it includes the present. Used interchangeably with the term Recent. As used in this report, the Holocene Epoch consists of approximately the last 10,000 years of geologic time.

Intensity: Refers to the severity of ground motion (shaking) at a specific location during an earthquake and is based on the sensations of people and visible effects on natural and manmade objects. The most widely used intensity scale in the United States is the Modified Mercalli intensity scale. (See table 3.)

Joint: A fracture in bedrock along which there has been no movement parallel to the fracture. Movement at right angles to a fracture, however, may take place and produce an open joint.

Lineament: A linear feature of the landscape, such as alined valleys, streams, rivers, shorelines, fiords, scarps, and glacial grooves which may reflect faults, shear zones, joints, beds, or other structural geological features.

Magnitude: Refers to the total energy released at the source of an earthquake. It is based on seismic records of an earthquake as recorded on seismographs. Unlike intensity, there is only one magnitude associated with one earthquake. The scale is exponential in character and where applied to shallow earthquakes, an increase of 1 unit in magnitude signifies approximately a 32-fold increase in seismic energy released.

Microearthquake: An earthquake that generally is too small to be felt by man and can only be detected instrumentally. The lower limit of magnitude of felt earthquakes generally is between 2 and 3; many microearthquakes, on the other hand, have magnitudes of less than 1.

Moraine: An accumulation of material (mainly till) deposited by glacier ice which has a topographic expression of its own. It includes but is not restricted to ground moraine, end moraine, terminal moraine, medial moraine, and lateral moraine.

Pleistocene: An epoch of geologic time characterized by world-wide cooling and by major glaciations; also called the "glacial epoch" or Ice Age. The Pleistocene Epoch denotes the time from about 2 million to 10,000 years ago.

Seismicity: A term used to denote the historical frequency of earthquakes occurring in a certain area.

Seismic seiche: Waves set up in a body of water by the passage of seismic waves from an earthquake, or by sudden tilting of a water-filled basin.

Strike: The compass direction of a line formed by the intersection of a bed, bedding surface, fracture, fault, foliation, or other essentially planar geologic feature with a horizontal plane.

Till: An unstratified and unsorted mixture of clay, silt, sand, gravel, cobbles, and boulder-size material deposited by glacier ice on land.

Tsunami: A sea wave, otherwise known as a seismic sea wave, generated by sudden large-scale vertical displacement of the ocean bottom as a result of submarine earthquakes or of volcanic action. Tsunamis in the open ocean are long and low, and have speeds of 425-600 miles an hour. As they enter shallow coastal waters they can greatly increase in height and also in height and distance of runup onto land.

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