UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

RECONNAISSANCE ENGINEERING GEOLOGY OF SITKA AND VICINITY, ALASKA, WITH EMPHASIS ON EVALUATION OF EARTHQUAKE AND OTHER GEOLOGIC HAZARDS

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Open-file report 74-53

1974

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

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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 following the 1964 Alaska earthquake; this report about Sitka and vicinity is a product of that program. Field-study methods were of a reconnaissance nature, and thus the interpretations in the report are subject to revision as further information becomes available. This report can provide broad geologic guidelines for planners and engineers during preparation of land-use plans. The use of this information should lead to minimizing future loss of life and property due to geologic hazards, especially during very large earthquakes.

Landscape of Sitka and surrounding area is characterized by numerous islands and a narrow strip of gently rolling ground adjacent to rugged mountains; steep valleys and some fiords cut sharply into the mountains. A few valley floors are wide and flat and grade into moderate-sized deltas.

Glaciers throughout southeastern Alaska and elsewhere became vastly enlarged during the Pleistocene Epoch. The Sitka area presumably was covered by ice several times; glaciers deeply eroded some valleys and removed fractured bedrock along some faults. The last major deglaciation occurred sometime before 10,000 years ago. Crustal rebound believed to be related to glacial melting caused land emergence at Sitka of at least 35 feet (10.7 m) relative to present sea level.

Bedrock at Sitka and vicinity is composed mostly of bedded, hard, dense graywacke and some argillite. Beds strike predominantly northwest and are vertical or steeply dipping. Locally, bedded rocks are cut by dikes of fine-grained igneous rock. Most bedrock is of Jurassic and Cretaceous age.

Eight types of surficial deposits of Quaternary age were recognized. Below altitudes of 35 feet (10.7 m), the dominant deposits are those of modern and elevated shores and deltas; at higher altitudes, widespread muskeg overlies a mantle of volcanic ash which commonly overlies glacial drift. Alluvial deposits are minor. Man-emplaced embankment fill, chiefly sandy gravel, covers many muskeg and former offshore areas; quarried blocks of graywacke are placed to form breakwaters and to edge large areas of embankment fill and modified ground.

The geologic structure of the area is known only in general outlines. Most bedded Mesozoic rocks probably are part of broad northwest-trending complexes of anticlines and synclines. Intrusion of large bodies of plutonic igneous rocks occurred in Tertiary and Cretaceous time. Extensive faulting is suggested by the numerous linear to gently curving patterns of some fiords, lakes, and valleys, and by a group of Holocene volcanoes and cinder cones. Two major northwest-striking fault zones are most prominent: (1) the apparently inactive Chichagof-Sitka fault, about 2.5 miles (4.0 km) northeast of Sitka, and (2) part of the active 800-mile- (1,200-km-) long Fairweather-Queen Charlotte Islands fault system, lying about 30 miles (48 km) southwest of the city.

Many earthquakes have been reported as felt at Sitka since 1832, when good records were first maintained; several shocks were very strong, but none of them caused severe damage. The closest major earthquake (magnitude about 7.3) causing some damage to the city occurred July 30, 1972, and had an epicenter about 30 miles (48 km) to the southwest. Movement along the Fairweather-Queen Charlotte Islands fault system apparently caused most of the earthquakes felt at Sitka.

The probability of destructive earthquakes at Sitka is unknown. The tectonics of the region and the seismic record suggest that sometime in the future an earthquake of a magnitude of about 8 and related to the Fairweather-Queen Charlotte Islands fault system probably will occur in or near the area.

Effects from some nearby major earthquakes could cause substantial damage at Sitka. Eight possible effects are as follows:

1. Sudden displacement of ground caused by movement along any of the faults at Sitka would directly affect only a small area and structures built across the fault. However, sudden tectonic uplift or subsidence of even a few feet would affect larger areas.

2. Intensity of ground shaking during earthquakes depends largely upon factors of water content, and the looseness and type of geologic material. Based upon these factors, geologic map units are divided into three categories of relative susceptibility to shaking.

3. Compaction of some medium-grained sediments during shaking accompanying certain strong earthquakes could cause local settling of surfaces of some alluvial and delta deposits. Likewise, the sand-filled core of the southeast part of the Sitka Airport runway might undergo some differential settling.

4. Liquefaction of saturated beds of loose, uniform, fine sand commonly occurs during strong earthquakes. At Sitka and vicinity, only a few such beds probably exist in alluvial and delta deposits. However, large quantities of excavated volcanic ash and muskeg are present that may liquefy during certain types of shaking. Liquefaction may induce landsliding.

5. Ejection of water-sediment mixtures from earthquake-induced fractures or from point sources is common during major earthquakes where saturated beds of sand and fine gravel are confined at shallow depth beneath generally impermeable beds. Ground subsidence is commonly associated with such activity. At Sitka, some of the alluvial and delta deposits might be susceptible to these processes.

6. Subaerial and subaqueous landsliding frequently occurs during earthquakes. Loose sediments with high water content on steep slopes are especially prone to sliding. At Sitka and vicinity, some embankment fill, refuse fill, and delta and volcanic ash deposits might slide during certain strong earthquakes. Subaqueous landsliding of the Indian River delta probably would be of only minor importance because of thinness and coarseness of the deposits. Elsewhere in the Sitka area, extensive avalanching, landsliding (mainly of the rockfall and mudflow type), and subaqueous landsliding of parts of deltas in Katlian Bay, Silver Bay, and Blue Lake should be expected, especially if shaking were to continue for several minutes.

7. Ground-water levels and surface-water levels often are affected during and after earthquake shaking of long duration. At Sitka, ground-water flow is restricted, and thus no earthquake-induced permanent change in flow is anticipated. Earthquake-triggered landslides could dam streams in the area; sudden failure of the dams might cause severe flooding of downstream areas.

8. Waves generated by earthquakes include: tsunamis, seiches, and local waves produced by subaerial and subaqueous sliding and tectonic displacement of land. Damage in the Sitka area would depend on wave height, tidal stage, warning time, and the possibility of wave focusing and reinforcement. The highest earthquake-generated wave recorded at Sitka was 14.3 feet (4.4 m). Many coastal localities along the Pacific Ocean have experienced waves as much as 40 feet (12.2 m) high.

Geologic hazards not necessarily associated with earthquakes include: subaerial and subaqueous landsliding, stream flooding, high water waves, and volcanic activity. Subaerial landslides of several types have occurred in the area during heavy rains or rapid snowmelt; subaqueous landslides happen intermittently during the normal growth of most active deltas. Recurrent stream flooding reflects heavy fall rains. High water waves generated by the impulse of landslides into bodies of water may from time to time be large enough to cause damage along some shores. Storm waves from the Pacific Ocean are estimated to have a 100-year maximum height of about 32 feet (9.8 m). Renewed volcanism might result in ash falls as one of several possible phenomena; a heavy fall of ash might collapse roofs, disrupt fishing and shipping, and clog intakes for filtration of water.

Recommended future geologic studies in the Sitka area could provide additional information needed for land-use planning. Detailed geologic mapping and collection of data on geologic materials, joints, faults, and stability of slopes are strongly recommended. Extensive offshore marine geophysical studies are needed to determine the position of nearby branches of the Fairweather fault; sensitive seismometers are needed to detect very small earthquakes in order to obtain an indication of activity along the fault branches. Naturally occurring volcanic ash apparently will not liquefy during earthquakes, but the ability of excavated ash to liquefy within a range of vibrational conditions suggests the need for further study. The program of volcanic surveillance being conducted on selected volcanoes elsewhere in Alaska should be expanded to include the volcanoes on Kruzof Island. Determination of the natural periods of oscillation of large lakes, fiords, bays, and sounds would assist in the prediction of heights of water waves caused by earthquake ground shaking.

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, Sitka and eight other communities in southeastern Alaska were selected for reconnaissance investigation. Reports were previously completed for the communities of Haines (Lemke and Yehle, 1972a), Juneau (Miller, 1972), Skagway (Yehle and Lemke, 1972), and Wrangell (Lemke, 1974). This report on the engineering geology of Sitka and vicinity emphasizes the evaluation of potential damage from major earthquakes and describes and appraises other geologic hazards, including subaerial landsliding, subaqueous landsliding, stream flooding, high waves, and volcanic activity. These geologic descriptions and hazard evaluations 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.

Extensive background information on southeastern Alaska and earthquake hazards is not included in the report. Instead, the reader is referred to the references listed near the end of this report or to the open-file report, "Regional and other general factors bearing on evaluation of earthquake and other geologic hazards to coastal communities of southeastern Alaska," by Lemke and Yehle (1972b).

Methods of study and acknowledgments

Collection of geologic data in Sitka and vicinity was limited to a total of 1 man-month during parts of 1965, 1968, and 1971. These data were supplemented by interpretation of airphotos and were used to prepare a reconnaissance geologic map, an integral part of this report. A list of airphotos examined during preparation of the map and report is given in table 1.

Several U.S. Geological Survey colleagues gave valuable assistance during different phases of the study: R. W. Lemke gathered extensive data during the initial phase of geologic data collecting and was senior author of a special preliminary report prepared in 1966 for the Alaska State Housing Authority on the geology of part of the Sitka area; Ernest Dobrovolny and H. R. Schmoll collected samples and provided data on volcanic ash; A. F. Chleborad, E. E. McGregor, P. S. Powers, H. C. Starkey, R. C. Trumbly, and R. E. Wilcox analyzed samples; H. W. Olsen interpreted analyses of volcanic ash and prepared figure 15; Meyer Rubin dated wood by radiocarbon methods; G. A. Rusnak, leader, and S. C. Wolf, on the *R/V Polaris* cruise POP 1967, contributed offshore geophysical information; M. J. Burchell, C. F. Knudsen, and R. P. Maley furnished information on recent earthquakes; and V. K. Berwick provided data on test wells. Information also was obtained through interviews and

Table 1.--Vertical airphotos of Sitka area examined during preparation of report[1]

Areal coverage	Scale	Date flown	Designation of photos	Organizations responsible for photography
Entire area--	1:40,000	Aug. 1948	SEA 124, SEA 128, SEA 140.	U.S. Navy and U.S. Geological Survey, Washington, D.C.
Do-------	1:11,000	May 1957	ALP 7-------	H. G. Chickering and Alaska Lumber and Pulp Co., Sitka, Alaska.
City of Sitka and part of Japonski Island.	1:4,800	Aug. 1959	1-2 Sitka, Alaska Harbor Lines.	Photronix Inc., and U.S. Army Corps Engineers, Anchorage, Alaska.
Do-------	1:12,000	July 1965	Sitka 1965--	U.S. Bureau of Land Management, Anchorage, Alaska.

[1]More recent photos which were not examined are available from the U.S. National Ocean Survey and the Alaska Department of Highways. Scale, date flown, and designation are as follows: U.S. National Ocean Survey - (1) 1:30,000, May 1967, 67L; (2) 1:30,000, June 1971, 71E; (3) 1:10,000, July 1972, 72-E (C). Alaska Department of Highways - (1) 1:9,600, May 1968, Sitka; (2) 1:7,200, 1971, Sitka.

correspondence with Federal, State, and city-borough officials, private citizens, and personnel of engineering and construction companies that have worked at Sitka. Especially acknowledged is the help of Fermin (Rocky) Gutierrez, Administrator of the City and Borough of Sitka, and personnel of Associated Engineers and Contractors, Inc., Alaska Lumber and Pulp Co., Alaska Department of Highways, Alaska Division of Aviation, U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, U.S. Forest Service, U.S. National Park Service, U.S. National Oceanic and Atmospheric Administration, and the Sitka Observatory.

It is emphasized that because of the short period of field study and the reconnaissance nature of the geologic mapping this 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 and discussions of related subjects, readers are referred to general textbooks on geology, engineering, soil mechanics, and seismology.

GEOGRAPHY

Location and extent of area

Sitka is on Baranof Island in southeastern Alaska, 95 miles (152 km) southwest of Juneau (fig. 1), at lat 57°03' N. and long 135°20' W. The Sitka area is considered in this report as the entire area shown on figure 2. It includes not only the Municipality of Sitka and immediate vicinity, as shown on figures 3 and 5, but also the surrounding area of Baranof Island and areas of Kruzof Island that lie within about 10 miles (16 km) of Sitka Sound.

Topographic and hydrographic setting

The Sitka area is here described in three parts: Baranof Island, Kruzof Island, and Sitka Sound:

1. Baranof Island is characterized by steep bedrock slopes that rise to rugged mountains and include summits as high as 3,300 feet (1,000 m) within a few miles of the shoreline. Several steep-walled fiords, such as Katlian Bay and Silver Bay, cut sharply into Baranof Island. The few gentle slopes are restricted to areas such as the floors of major river valleys, associated deltas, and to a 1/4- to 1/2-mile- (0.4- to 0.8-km-) wide strip of land along the shores of Sitka Sound which generally lies below an altitude of about 200 feet (60 m). Sitka is situated on such terrane between the deltas of Cascade Creek (loc. 2, fig. 2) and Indian River (fig. 3, in pocket). Topographic relief is about 120 feet (37 m) in Sitka and 80 feet (24 m) near the airport on Japonski Island. Several valley glaciers and small icefields head streams draining to Katlian Bay and Silver Bay. River discharge measurements are available for only Sawmill Creek (loc. 3, fig. 2), the drainage basin of which is about twice as large as that of Indian River. Discharge values average 485 ft^3/s ($13.7\ m^3/s$) and vary from 9.1 to 7,100 ft^3/s (0.26-$200\ m^3/s$) (U.S. Geol. Survey, 1960). Flooding of Indian River is discussed on page 78.

2. Kruzof Island and its line of major dormant volcanoes oriented N. 30° E. dominates the skyline west of Sitka. The altitude of Mount Edgecumbe, the tallest volcano, is 3,200 feet (975 m).

3. Sitka Sound, with its wide entrance, connects Sitka to the Pacific Ocean. The sound is fringed by a myriad of reefs and islands; Japonski Island is one of the larger ones. Bottom depths over wide areas average 150 feet (46 m), although depths to the floor vary greatly from place to place. A major feature is a channel that heads to Silver Bay and is cut as much as 600 feet (183 m) below the general level of the floor of the sound (fig. 4; U.S. Natl. Ocean Survey, 1971, 1972, 1973a). Tidal levels, read at Middle Anchorage (fig. 3) by personnel of the Sitka Observatory and reported by the U.S. Coast and Geodetic Survey (written commun., 1969), are as follows:

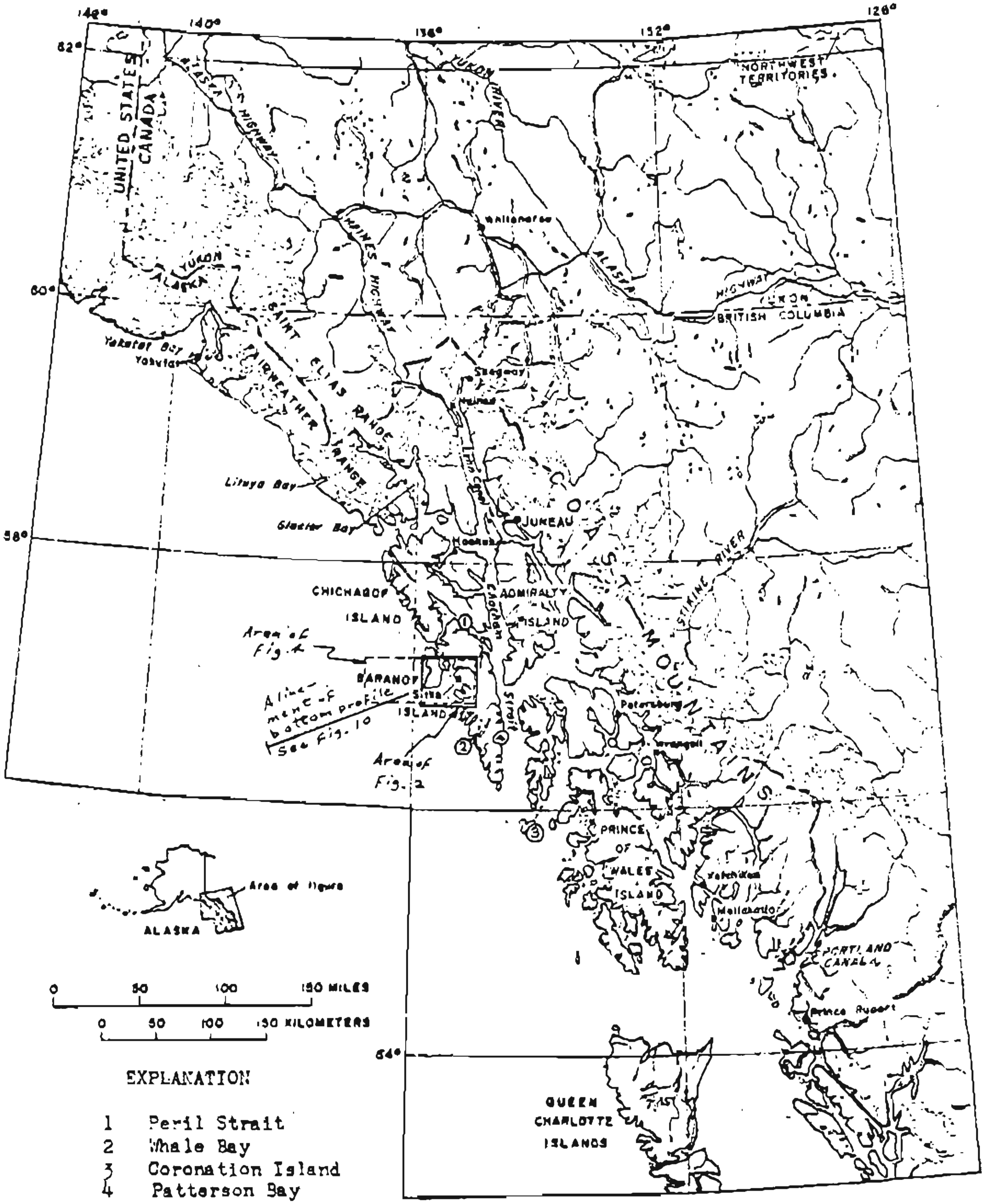
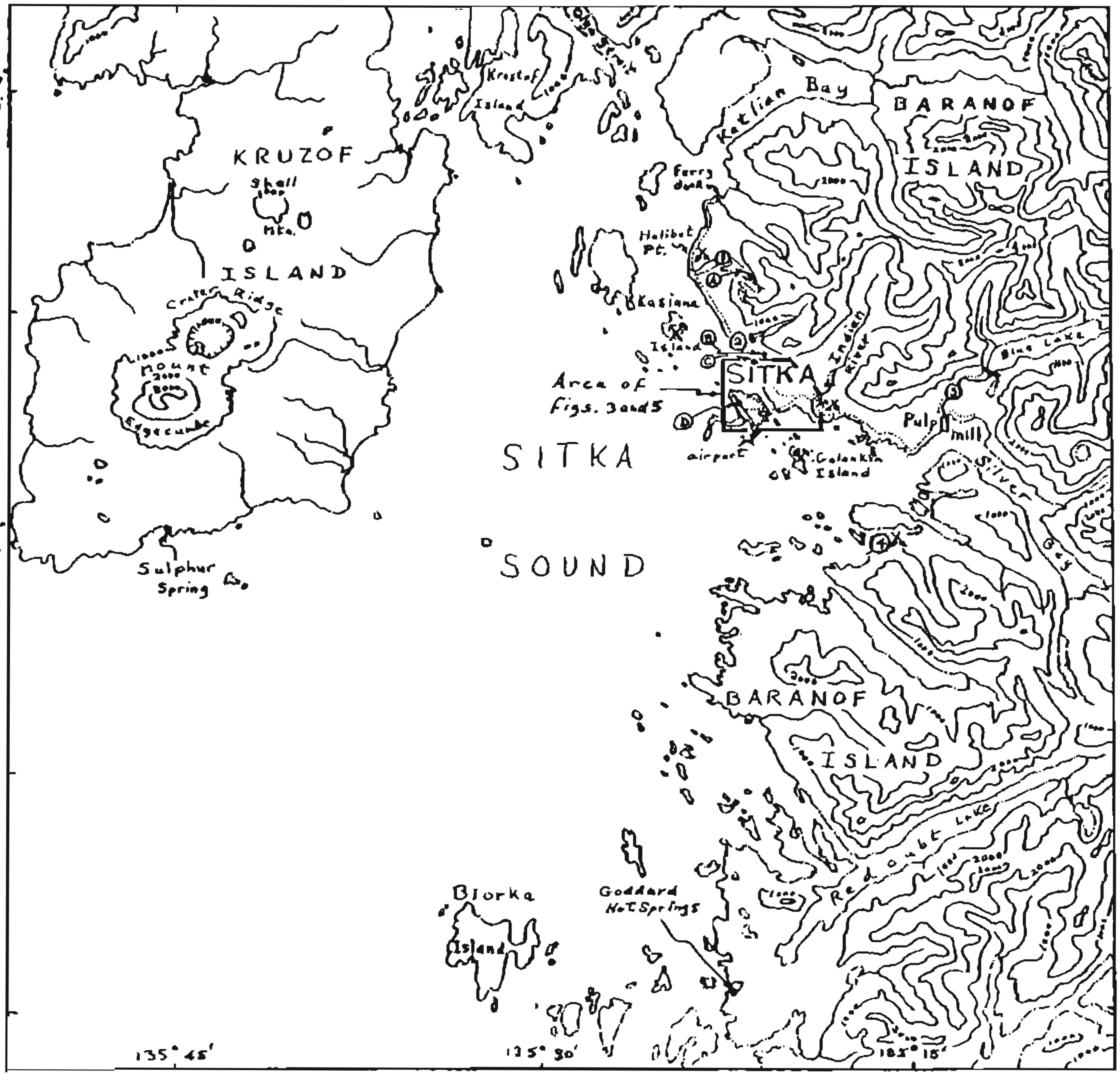


Figure 1.--Southeastern Alaska and adjacent part of Canada showing selected geographic features.



EXPLANATION

① Granite Creek

② Cascade Creek

③ Sawmill Creek

④ Leesoffskaia Bay

Ⓐ Ⓑ Ⓒ Ⓓ Location of selected samples (table 2)

Shoreline

Principal road

Large gravel and sand pit

Quarry

Dam

Base from U.S. Geological Survey topographic maps, Sitka, Alaska, 1951, and Port Alexander, Alaska, 1951.

SCALE 1:250,000

0 5 MILES

0 5 KILOMETERS

Contour interval 1,000 ft (305 m); datum mean sea level.

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

	Feet	Meters
Highest tide observed (Nov. 2, 1948)----	14.6	4.4
Mean higher high water-----------------	9.9	3.0
Mean high water------------------------	9.1	2.8
Half tide level------------------------	5.3	1.6
Mean low water-------------------------	1.4	4.3
Mean lower low water-------------------	0.0	0.0
Lowest tide observed (Jan. 16, 1957)----	-3.8	-1.2

Mean sea level is 5.2 feet (1.6 m), and the daily tidal range averages 9.9 feet (3.0 m). At Middle Anchorage (fig. 3) the tidal current flows southeastward on the ebb and flows northwestward on the flood; velocities of 0.5 knot have been recorded (U.S. Coast and Geod. Survey, 1962).

Climate and vegetation

Sitka's climate is characterized by abundant rainfall, cool summers, and winter temperatures that average near freezing. At the Sitka Observatory (fig. 3), between 1931 and 1960, the U.S. National Weather Service (1969) reported the mean temperature in January, the coldest month, as 32.3° F (0.8° C), and the mean temperature in August, the warmest month, as 55.5° F (13.1° C). Annual precipitation averages 96.57 inches (2,450 mm), most of which falls as rain; the greatest 24-hour falls recorded were 6.42 inches (163 mm), on September 9, 1948, and 8.50 inches (216 mm) at Japonski Island, on September 1, 1967 (U.S. Natl. Weather Service, written commun., 1973). Higher parts of the city, farther from tidewater, receive more precipitation, a greater percentage of which is snow. For central Baranof Island, a maximum 24-hour rainfall of 12 inches (300 mm) is indicated as a theoretical 100-year probability (Miller, 1963). Prevailing winds from July through September are from the west, and during most of the rest of the year are generally from the east or southeast. The extreme wind speed during a 6-year period was 48 miles (77 km) per hour on Japonski Island.

Vegetation on most slopes from shoreline up to timberline (about 2,250 feet (685 m)) consists of thick stands of coniferous trees and scattered shrubs. Some very gentle to flat slopes are treeless, and support thick muskeg vegetation characterized by moss and low shrubs. Within the area shown on figure 2, lumbering is intensive in many localities in order to supply the pulp mill at Silver Bay.

Historical background and population

The first permanent European settlement was established by the Russians at Sitka in 1804, but long before that time Tlingit Indian groups lived within part of the present townsite (U.S. Natl. Park Service, 1959). Sitka developed as a trading center and capital of Russian America until 1867, when the United States purchased Alaska. Subsequent growth was slow and mainly related to the fishing industry until the 1950's, when a large pulp mill was constructed by the Alaska Lumber and Pulp Company at Silver Bay. The 1970 population of Japonski Island and the incorporated city of Sitka was 4,205 (U.S. Bur. Census, 1971). However, by including the residents in adjoining built-up areas the total population was about 6,000.

Transportation and municipal facilities

Ships of the Alaska State Ferry System and several cruise lines, as well as freighters and barges, serve the Sitka area. Major docks are at Middle Anchorage, at the ferry dock 5 1/2 miles (8.8 km) northwest of the city, and at the pulp mill. Large numbers of fishing and pleasure boats are accommodated at small-boat harbors near Middle Anchorage and at Crescent Bay (fig. 3).

The Sitka Airport, on Japonski Island, serves scheduled and nonscheduled aircraft. Float planes use Middle Anchorage and near-shore areas east of the mouth of Indian River.

A road network of about 20 miles (32 km) connects Sitka with the ferry dock, airport, pulp mill, and the dam at Blue Lake.

The water supply for most of Sitka and Japonski Island is derived from Cascade Creek and Indian River through a system of low dams, small reservoirs, storage tanks, and pipelines. One of the tanks is located about 0.75 mile (1.2 km) south-southeast of Cascade Creek dam at an altitude of 200 feet (60 m). Water- and fuel-storage tanks on Japonski Island are symbolized on figure 3; buried and partially buried tanks are separately identified. The altitude of the highest tank is about 90 feet (27 m). At Sitka, fuel tanks are located northeast of Middle Anchorage and near the Post Office, at altitudes of about 60 feet (18 m) and 20 feet (6 m), respectively.

The Blue Lake dam, a 155-foot- (47-m-) high, thin-arch concrete structure, and associated hydroelectricity-generating equipment near the mouth of Sawmill Creek furnish most of the power for Sitka and adjacent built-up areas. Standby diesel generators, as well as generators serving the pulp mill, are all situated at low altitude near shoreline.

The Sitka Observatory, at an altitude of 62 feet (19 m), is an important scientific station with a long tradition of data collection beginning in 1832. Today, in addition to a continuing role as a data-gathering base, some initial interpretations of meteorologic, magnetic, tidal, and earthquake data are performed. With its telecommunication ties to control centers elsewhere in Alaska, the Sitka Observatory serves an important part in the alerting of communities along the Pacific coast to threats of potentially destructive earthquake-generated water waves (Butler, 1971).

GLACIATION AND ASSOCIATED LAND- AND SEA-LEVEL CHANGES

The Sitka area probably was covered by glacier ice several times in the Pleistocene Epoch. During the culmination of the last major glacial interval, ice overlying the site of Sitka may have been as much as 2,750 feet (838 m) thick (Coulter and others, 1965). Ice was much thinner on the Continental Shelf; on the deeper part of the shelf it probably was afloat. Near the close of the Pleistocene Epoch, valley glaciers, ice shelves, and icefields melted drastically because of major climatic warming; most ice probably disappeared before 10,000 years ago (as considered in the Juneau area by Miller, 1972, 1973). Following major deglaciation, numerous erosional landforms of glacial origin were exposed in the Sitka area. Characteristic landforms include large rounded knobs of bedrock and U-shaped valleys and fiords. Some fiords have bottoms eroded several hundreds of feet deeper than the adjacent sea floor. Examples are the deep erosional channels that extend seaward from Katlian Bay and Silver Bay (fig. 4). Large-scale constructional landforms of Pleistocene glacial origin were not observed in Sitka and vicinity, possibly because of the limited time for observation and the concealing effects of thick vegetation, volcanic ash, and muskeg. However, airphoto interpretation of some areas near Sitka suggests a possible lateral moraine along the south side of the east fork of Indian River. In addition, at least some of the arcuate ridges and other features forming the floor of Sitka Sound (U.S. Natl. Ocean Survey, 1971, 1972) probably are moraines or other types of glacial drift.

During the Holocene Epoch (about the last 10,000 years), minor fluctuations of climate caused advances and retreats of glaciers, as documented in southeastern Alaska at Glacier Bay (Lawrence, 1958; Goldthwait, 1963, 1966; McKenzie, 1970) and Juneau (Heusser, 1960; Barnwell and Boning, 1968; Miller, 1972). Glaciers of Baranof Island probably advanced and retreated in similar manner. My interpretation of 1948 airphotos of glaciers and associated fresh-appearing moraines near Sitka indicates that modern glaciers are slowly retreating.

The position of land in relation to sea level in the Sitka area has changed greatly within the past tens of thousands of years, and apparently is continuing to change today. The primary cause of change has been the expansion and contraction of glaciers during the Pleistocene and Holocene Epochs; other causes are considered below. The weight of thick glacier ice depresses land; Gutenberg (1951, p. 172) considered 1,000 feet (305 m) of ice capable of causing a depression of 275 feet (84 m). Melting of ice during the last major deglaciation in the Sitka area caused the land to rebound. However, because of a time lag between melting and rebound, marine waters temporarily occupied many low areas that now are above sea level.

The minimum amount of relative land emergence at Sitka is 35 feet (10.7 m), based on the altitude of some landforms and elevated deposits that, although lacking marine fossils, clearly show that they formed at the shore or as part of a delta. Locations of elevated beach ridges, elevated offshore bars, and elevated lagoons are symbolized on figure 3.

Other landforms and the general topographic pattern of the area suggest a land emergence of 50 feet (15.2 m). Supportive evidence for a somewhat greater emergence is provided by the discovery in 1951 of a whale vertebra in a sand deposit at about 65 feet (20 m) (M. M. Miller, Michigan State Univ., written commun., 1971). The approximate age of marine shells from similar deposits along the outer coast of the Queen Charlotte Islands, British Columbia (fig. 1), is about 8,000 years (Brown, 1968, p. 36, sample GSC 292).

In the Sitka area there is also a suggestion for a possibly greater relative emergence to an altitude of about 250 feet (76 m), as evidenced by a widespread abrupt change in steepness of slopes. Reed and Coates (1941, p. 75) made a similar suggestion for the height of emergence along the outer coast of Chichagof and adjacent islands northwest of Sitka (fig. 1). It should be noted that along the fiords of the inner coast of southeastern Alaska, marine deposits at altitudes of as much as 750 feet (230 m) (Twenhofel, 1952; Ives and others, 1967, p. 523-524; Miller, 1972, 1973; Lemke, 1974) indicate an even more pronounced rebound of land than along the outer coast.

In modern time, land at Sitka is thought to be emerging relative to sea level at a rate of 0.0076 foot (0.00231 m) per year, on the basis of tidal gage readings between 1938 and 1972 (Hicks and Crosby, 1974). Northward from Sitka, rates of emergence are progressively greater with increasing closeness to Glacier Bay and its rapidly melting glaciers (fig. 1; Hicks and Shofnos, 1965).

Other possible causes for the relative emergence of land at Sitka are not related to deglaciation and melting of ice loads. One possible cause is related to the tectonic movement resulting from release of stresses deep within the western part of the North American Continent and the adjacent Pacific Ocean. Sitka is situated in this active tectonic region, as evidenced by numerous earthquakes along the Fairweather fault (fig. 4) southwest of the city. Another possible cause of land-level changes at Sitka relates to lava flows and ash eruptions resulting from the postglacial volcanic activity on Kruzof Island. Outpourings of these materials can cause large changes in the volume of molten rock in magma chambers beneath the island and adjacent areas, and may result in differential movement of the land surface in the region.

The above discussion of relative land- and sea-level changes treats mean sea level as a long-term fixed level. This is only an approximation, for many factors may combine to slowly change the level of water in the oceans. A major factor is the worldwide relationship of sea level to the melting and nourishment of glaciers. This factor and related topics were discussed by Higgins (1965) and Shepard and Curray (1967).

DESCRIPTIVE GEOLOGY

Regional setting

Several reconnaissance studies and detailed site studies have been completed on various aspects of the geology of the Sitka area since the turn of the century (see Knopf, 1912; Buddington and Chapin, 1929; Twenhofel, 1951; Berg and Hinckley, 1963; Loney and others, 1963, 1964; Brew and others, 1969). However, much work remains to be done.

Many types of bedrock and surficial deposits were recognized in the Sitka area. Using data from the published studies, I grouped bedrock types into four generalized categories. These are: volcanic rocks, intrusive igneous rocks, chiefly metamorphic rocks, and chiefly sedimentary rocks; distribution is shown on figure 4 (in pocket). At Sitka and immediate vicinity the sedimentary rocks predominantly are of the graywacke type (fig. 5, in pocket). Surficial deposits, though not shown on figure 4 because of thinness, scattered distribution, and lack of detailed observations, are shown on figures 5 and 6 along with the spatial relationships between the bedrock and the map units containing surficial deposits. Surficial deposits are fully described on pages 18-30.

A complex geologic history is indicated for the Sitka area. Small to large sedimentation basins were formed and filled with deposits of graywacke, fine-grained sedimentary rocks, and outpourings of lava and other volcanic products during late Paleozoic and most of late Mesozoic time (Brew and others, 1966; Loney and others, 1967; Berg and others, 1972). During late Mesozoic and Tertiary time, dominant processes were intrusion of igneous bodies, metamorphism of some rocks, and extensive deformation of preexisting rocks. Deformation included folding, breaking and moving of rocks by uplifting along vertical faults, strike-slip faulting, and possible thrust faulting. The Cenozoic era has been marked by glaciation, sea-level changes, volcanism on Kruzof Island, and extensive strike-slip faulting at least on the Continental Shelf.

Bedrock at Sitka and vicinity; Sitka Group (KJs)

At Sitka and vicinity, dark-gray graywacke of fine to medium grain is the predominant rock type (Berg and Hinckley, 1963) (fig. 5, in pocket). It is interbedded generally with a subordinate amount of very fine grained argillite; some beds are conglomeratic and contain subrounded to subangular rock fragments of gravel size. These various sedimentary rock types are not differentiated on figure 5. Thicknesses of beds generally range from 1 to 10 feet (0.3-3.0 m), and may be as much as 50 feet (15.2 m); conglomeratic graywacke beds are the least continuous.

Beds generally strike northwest, and are vertical or dip steeply; some beds strike more northerly or westerly, and, locally, beds are overturned (Berg and Hinckley, 1963; Loney and others, 1964). Prominent joints generally trend northeast (see p. 38 for discussion of jointing).

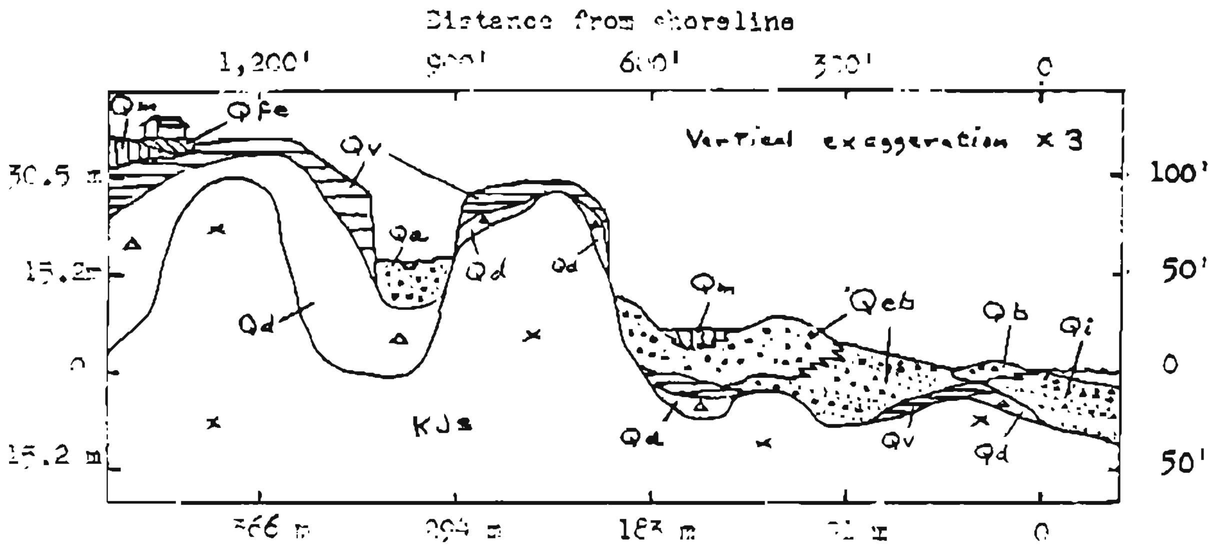


Figure 6.--Diagrammatic cross section perpendicular to shoreline at Sitka showing relations between geologic map units (fig. 5).

EXPLANATION

Qfe Manmade embankment fill

Qa Alluvial deposits

Qb Modern beach deposits

Qi Modern delta deposits of the intertidal zone

Qm Muskeg and other organic deposits

Qeb Elevated shore and delta deposits

Qv Volcanic ash deposits

Qd Glacial drift deposits

KJs Sitka Group: chiefly graywacke

Physical properties of graywacke at Sitka have been determined by the Alaska Department of Highways from samples obtained from the quarry about 600 feet (180 m) east of Indian River (fig. 5) and from preconstruction core drilling for the bridge from Sitka to Japonski Island. Graywacke at the quarry is hard and durable, with good resistance to chemical and physical weathering; specific gravity is 2.74 (Franklet, 1965, p. 27). Samples of cores from the bridge locality were reported by Slater and Utermohle (1969) to have a similar specific gravity and an unconfined compressive strength averaging 11,600 lb/in^2 (815 kg/cm^2) and ranging from 7,745 to 18,825 lb/in^2 (542-1,319 kg/cm^2). They sampled cores of the graywacke taken from a depth of 30 feet (9.8 m) and observed fractures in samples even from the maximum depth. Most of the graywacke was typically moderately fractured, although some was highly fractured. Several cores exhibited veins of calcite or quartz.

Distribution of bedrock outcrops is widespread (fig. 5). Graywacke is especially abundant along tidal shores where waves have removed the generally thin mantle of surficial deposits. There are also a few outcrops (1) between Swan Lake and Crescent Bay, (2) near the delta of Indian River, and (3) locally on and near Japonski Island. Small low exposures of argillite were observed only on Fruit Island (figs. 3, 5) and northeast of the large pond created by construction of the airport runway.

Graywacke from the quarry east of Indian River was used in 1965 and 1966 as riprap for (1) the breakwater protecting the small-boat harbor at Crescent Bay (fig. 5), and (2) the outer part of the large fill southeast of Castle Hill (fig. 3). The rock was noted as having good drilling and blasting properties (Franklet, 1965). Graywacke from a quarry on Kasiana Island, 4 miles (6.4 km) northwest of Sitka (fig. 2), was used in 1965, 1966, and 1971 as riprap for the Sitka Airport runway and the approaches to the Sitka-Japonski Island bridge (A. W. O'Shea, Associated Engineers and Contractors, Inc., oral commun., 1971). Some riprap has been quarried from Galankin Island, 2 miles (3.2 km) southeast of Japonski Island (fig. 2). Other wave-exposed fill areas on Japonski and connected islands are protected by riprap derived from hills removed during extensive blasting and excavation during the early 1940's. In 1965 several other hills with cores of graywacke were completely removed and used for construction of the airport runway. Large amounts of graywacke usable for riprap probably remain in quarries in the Sitka area.

The graywacke and other sedimentary rocks described above are included in the Sitka Group, and are probably of Early and Late Cretaceous age; some other rocks of the group may be partly Middle to Late Jurassic in age (Berg and Hinckley, 1963; Berg and others, 1972, p. D18).

Dikes of fine-grained igneous rock, though not observed, probably cut the sedimentary rocks here and there within the area shown on figure 5, because elsewhere in the Sitka area dikes are widespread. A short distance northwest of the area of figure 5 and about 0.6 mile (1 km) northeast of the bridge over Granite Creek (fig. 2), one 8-foot- (2.4-m-) thick dike was observed. Berg and Hinckley (1963, p. 19) reported felsic and other dikes to be abundant around Katlian Bay and on the south side of Krestof Island (fig. 2); some dikes are as much as 50 feet (15.2 m) thick. Emplacement of felsic dikes followed the extensive deformation of rocks of the Sitka Group, and thus dikes probably are post-Early Cretaceous and pre-late Pleistocene in age (Berg and Hinckley, 1963).

Surficial deposits at Sitka and vicinity

Eight types of surficial deposits at Sitka and vicinity were differentiated on the basis of grain size, origin, and time of deposition. These types include: glacial drift deposits, volcanic ash deposits, elevated shore and delta deposits, muskeg and other organic deposits, modern delta deposits of the intertidal zone, modern beach deposits, alluvial deposits, and manmade fill. Distribution of deposits is shown by means of geologic map units on the reconnaissance geologic map (fig. 5). Mapping is most accurate near roads and the developed parts of Sitka, where it is based upon numerous observations of good outcrops. Elsewhere, mapping is based largely on interpretation of airphotos and is less accurate. Boundaries between map units containing deposits that are more or less contemporaneous in origin have gradational contacts; boundaries between some units, especially drift and volcanic ash deposits, largely are inferred. Interpretation of relations of deposits to each other at depth is shown diagrammatically on figure 6. Grain-size classification of sediments composing the deposits is based on terminology of the National Research Council (1947): clay, less than 0.00015 inch (0.0039 mm); silt, 0.00015-0.0025 inch (0.0039-0.0625 mm); sand, 0.0025-0.079 inch (0.0625-2 mm); gravel, 0.079-2.5 inches (2-64 mm); cobbles, 2.5-10.1 inches (64-256 mm); boulders, greater than 10.1 inches (256 mm).

The probable sequence of events which resulted in the present distribution of surficial deposits in Sitka and vicinity is as follows. After melting of the last major Pleistocene glaciers and deposition of drift at many localities, volcanoes on Kruzof Island developed, and large quantities of erupted ash and lapilli fell over the Sitka area and northeastward in the early Holocene. The next clearly evident events are the deposition of delta, beach, and other shore and lagoonal deposits that are now at levels at least 35 feet (10.7 m) above sea level. Since then, natural modifications of the land have been minor, and include growth of large muskegs, stream downcutting and deposition, land emergence, and a seaward shift of delta- and shore-related processes. After 1940 large areas of ground were excavated or covered by manmade fill.

Glacial drift deposits (Qd)

Almost all glacial drift exposed in the area shown on figure 5 apparently consists of till, a nonsorted mixture of gravel, cobbles, and some boulders, in a matrix of sand, silt, and clay. The size of particles varies in any one outcrop, and cobbles and boulders are concentrated locally. Figure 7 shows four mechanical analyses of till. Most of these deposits are characterized by a lack of stratification and by stones that vary in shape from subangular to subrounded. The till is

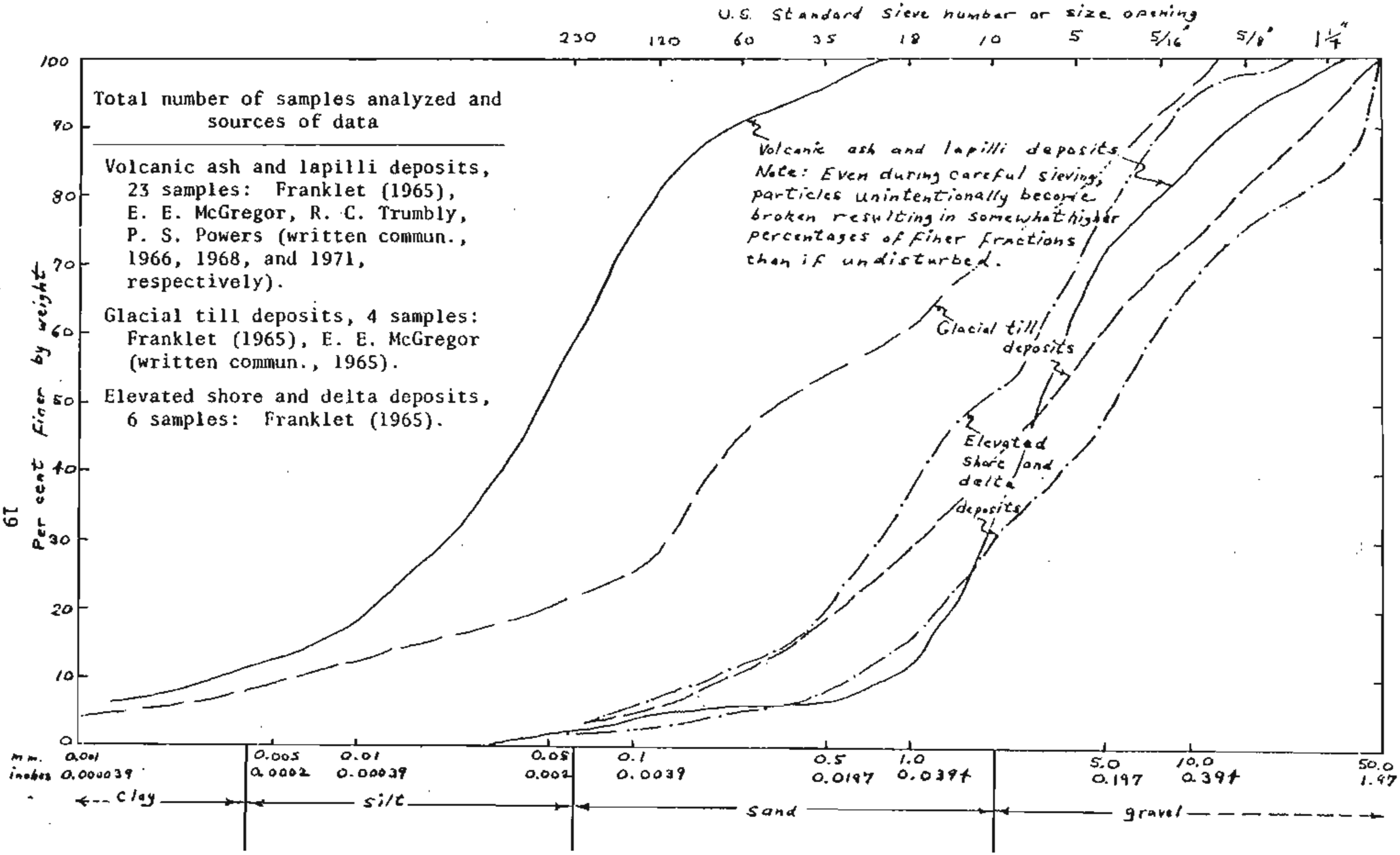


Figure 7.--Diagram showing ranges of particle-size distribution curves of some deposits in part of the Sitka area, Alaska.

compact; an average shear-wave velocity of compact till from elsewhere which is probably applicable is 2,300 feet (700 m)/s (fig. 15; Clark, 1966, p. 204; Seed and Idriss, 1970, p. 126). Near the Sitka Airport, a deep excavation revealed oxidized till to a depth of 6 feet (1.8 m) underlain by 11 feet (3.4 m) of unoxidized medium- to dark-gray till.

Thickness of the drift probably averages 10 feet (3.0 m), but the maximum may be as much as 50 feet (15.2 m). Distribution is sporadic but generally widespread inland from modern and emerged shores. Good examples of till may be seen in roadcuts along Lake Street, northeast of Swan Lake (fig. 5). Drift overlies bedrock, but at some places it is absent from the crest and margin of small bedrock hills (fig. 6). Overlying the drift are deposits of volcanic ash, muskeg, manmade fill, and sandy gravel that conceal drift deposits over large areas. These overlying deposits may conceal possibly thin lenses of fine sand or silt in the upper part of the drift.

Some exposures of drift deposits show moderately sorted and stratified sand and gravel or gravelly silt; lateral relations to till deposits are not clear. An example of sorted material is exposed at the abandoned pit near the northwesternmost part of Halibut Point Road (figs. 3, 5).

Drift originates in several ways. Most drift at Sitka formed chiefly at the base of thick glacier ice by being plastered on the underlying bedrock. The sorted drift probably was deposited by glacial meltwater streams. Because none of the analyzed drift samples contained marine fossils (table 2), it is unlikely that any large part of the drift exposed at Sitka was deposited in marine waters.

Till has been used extensively for fill at many localities, especially on Japonski Island in the early 1940's and mid-1960's. The several abandoned pits and large areas of leveled-off ground on the island attest to its use. As a foundation for manmade structures, drift generally should be well suited.

Volcanic ash deposits (Qv)

The deposits consist primarily of tan to reddish-yellow bedded ash consisting of silt, sand, and some clay-size particles, and, subordinately, of lapilli of fine gravel-size particles. The size ranges of 23 samples of the deposit near Sitka are shown on figure 7. There is no pronounced progressive decrease in grain sizes of the material with increasing distance from the volcanoes on Kruzof Island.

Some microscopic and X-ray examinations of the ash have been made. Ten samples from the deposit (locs. B and C, fig. 2) were described by R. E. Wilcox (written commun., 1971; app. I) as consisting generally of angular to subrounded fragments of pumiceous glass and fragments of basalt and andesite. An X-ray diffraction analysis of five samples (locs. B and C, fig. 2) by H. C. Starkey (written commun., 1971) indicated the following estimated relative percentages of minerals and

Table 2.--Analyses of selected samples of volcanic ash and lapilli and glacial till deposits near Sitka, Alaska

[Data for 5a from U.S. Bureau of Reclamation (Willard Ellis and P. C. Knodel, written commun., 1973); all other data from U.S. Geological Survey (written commun.: E. E. McGregor, 1965, 1966; R. C. Trombly, 1968; P. S. Powers, 1971, 1972). Samples from following lettered locations (fig. 2): 1, 9, 12, 13 = A; 3-8, 10, 11 = B; 2 = C; 14 = D][1]

Sample No.	Laboratory No.	Type of material	Size distribution curve in group on fig. 7	Natural moisture (percent)	Saturation (percent)	Atterberg limits L.L.[2]	Atterberg limits P.L.[3]	Atterberg limits P.I.[4]	Shrinkage limit	Water-absorption capacity (percent)	Swell capacity	Porosity (percent)	Harvard compaction	Saturated bulk density (g/cc)	Dry bulk density (g/cc)	Grain density (g/cc)	Dilatancy[5]	Microfossils[6]
1	5-235, D801-625	Volc. ash	Yes	([10])	([10])	([7])	([7])	([7])	([7])	57	None	66.1	([10])	1.564	0.802	2.56	([10])	([10])
2	5-239	Volc. ash and lapilli	--do----	([10])	([10])	([7])	([7])	([7])	([7])	68	--do--	58.1	([10])	[8] 1.691	[8] 1.11	[8] 2.65	([10])	([10])
3	8-146	---do----	--do----	65	([10])	([7])	([7])	([7])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	Rapid [8]	([10])
4	D801-709	Volc. ash	--do----	72	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	--do---	([10])
5a	SSH-1	---do----	--do----	[9] 80	[9] 93	([10])	([10])	([10])	([10])	([10])	([10])	[9] 71.4	([10])	[9] 1.684	[9] 0.820	2.82	([10])	([10])
5b	D801-706	---do----	--do----	57	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([7])	([10])	([10])	([10])	Rapid [8]	([10])
6	D801-707	---do----	--do----	56	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	--do---	([10])
7	D801-708	Volc. lapilli	Yes	78	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	Rapid [8]	([10])
8	8-147	Volc. lapilli and ash	--do----	96	([10])	([7])	([7])	([7])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	--do---	([10])
9	5-236	Volc. lapilli	--do----	([10])	([10])	([7])	([7])	([7])	([7])	53	None	70.7	([10])	[8] 1.383	[8] 0.676	([7])	([10])	([10])
10	8-148	Volc. lapilli and ash	Yes	95	([10])	([7])	([7])	([7])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	Rapid [8]	([10])
11	D801-945	---do----	No	52	([10])	([10])	([10])	([10])	([10])	([10])	([10])	64.4	([10])	[8] 1.61	[8] 0.97	[8] 2.72	([10])	([10])
12	5-225	Glacial till	Yes	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	None
13	5-226	---do----	--do----	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	Do.
14	5-227	---do----	--do----	([10])	([10])	14	11	3	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	([10])	Do.

[1]Analytical procedures follow American Society for Testing and Materials (1964) unless otherwise noted. Informal stratigraphic grouping of volcanic ash and lapilli as follows: 1-6, lower unit; 7-9, middle unit; 10-11, upper unit.

[2]Liquid limit.

[3]Plastic limit.

[4]Plasticity index.

[5]Procedure follows U.S. Bureau Reclamation (1960, p. 382).

[6]Microscopic inspection only of medium-sand-size fraction.

[7]Test attempted but results inconclusive.

[8]Test performed on remolded or disturbed sample.

[9]Average of seven determinations.

[10]Not run.

other materials: 40 to 60 percent amorphous matter, 20 to 50 percent plagioclase feldspar, none to slightly more than 20 percent chlorite, and none to a trace of quartz, mica, and mixed-layer chlorite-mica. No clay minerals were apparent.

Thickness of the ash deposits on level or gently sloping ground probably averages 5 feet (1.5 m), but may be as much as 11 feet (3.4 m), while on moderate to steep slopes deposits are thin or eroded away. At the base of some slopes a thickening of the deposit has occurred, probably because of erosion and redeposition by running water and small landslides, assisted by repeated freezing and thawing.

Distribution of volcanic ash deposits near Sitka varies with altitude and terrain. Above an altitude of about 40 feet (12.2 m) the ash is widespread (fig. 5), while at lower altitudes waves have eroded most of the deposit. Volcanic ash and lapilli deposits overlie glacial drift and bedrock. They generally are overlain by muskeg, manmade fill, and rarely by alluvial and elevated shore deposits. Three good examples of the deposit are located (1) near the abandoned pit near the north part of Halibut Point Road (figs. 3, 5), (2) on Japonski Island a few hundred feet southeast of the easternmost abandoned pit (fig. 5), and (3) near a steel water tank (loc. B, fig. 2), 0.75 mile (1.2 km) southeast of the mouth of Cascade Creek.

Three stratigraphic units, informally termed lower, middle, and upper, were recognized near Sitka and southeastward to Silver Bay (fig. 2). Table 3 is a detailed description of these units as they are exposed at the water tank. The lower and middle units can readily be identified near Sitka, but the upper unit is absent from some places or appears to be redeposited, probably by rainwater or small landslides. All three units are part of the group of air-fall volcanic debris that is widely distributed in central southeastern Alaska. The material also is classified as part of the Edgecumbe Volcanics as described by Berg and Hinckley (1963) and Brew, Muffler, and Loney (1969).

The ash probably fell about 10,000 years ago. Radiocarbon age determinations indicate that the ash was deposited sometime before 8,570±300 years ago (U.S. Geol. Survey sample W-1739; Ives and others, 1967, p. 525), but sometime after 10,300±400 years ago, according to Heusser (1960, p. 97, 104), or after 11,000 years ago, according to McKenzie (1970, p. 45).

Physical-property tests, summarized in part in table 2, were performed on several samples of the deposit. From these tests it is apparent that the deposit is characterized by a dry bulk density that is less than that of water because of the high percentage of pores (vesicles). Almost all pores and interparticle spaces are filled with water, and natural moisture content is high. The deposit is firm where undisturbed, but when worked by shovel or power tools the deposit readily breaks down into its constituent particles. In addition, the particles are easily crushed because of the low strength of the very thin glass walls of the myriad small pores within the particles. The firmness of the undisturbed volcanic ash is indicated by a shear-wave velocity of

Table 3.--Stratigraphic sections of volcanic ash and lapilli deposits exposed 0.75 mile (1.2 km) southeast of the mouth of Cascade Creek, Sitka area, Alaska (loc. A, fig. 2)

[Modified from descriptions by Ernest Dobrovolny and H. R. Schmoll (written commun., 1971). Sections in excavation behind steel water tank with base about 175 ft (53.3 m) above mean sea level. Exposure is in two sections separated by about 80 ft (24.4 m); section A is east of tank, section B is northeast of tank]

Overlying material: mixture of volcanic ash and lapilli, organic material, and some subangular gravel and cobbles

Subunit	Thickness (ft)	Thickness (m)	Description
Upper unit of deposit (measured at section B, top to bottom)			
U-6	1.08	0.33	Mostly ash, silt-clay size, tan, probably one fine lapilli bed in middle part; upper 0.08 ft (0.02 m) is fine sand size and gray.
5	1.50	.46	Fine lapilli grading upward to clay-size ash at top, probably single graded bed, gray-orange to orange-tan to orange, reddish-brown at top.
4	.17	.05	Ash, silt- to clay-size, tan.
3	.42	.13	Lapilli, somewhat graded bedding, orange; upper 0.02 ft (0.006 m) has dark-brown stain.
2	.42	.13	Mostly ash, with some interbedded fine lapilli, orange to gray, similar in color to most of U-1.
1	1.00	.30	Lapilli and ash, several thin graded beds, tan to grayish-orange; upper 0.08 ft (0.02 m) is light-brown ash.
Subtotal--	4.59	1.40	
Middle unit of deposit (measured at section B, top to bottom)			
M-2	2.42	0.74	Fine lapilli and ash, several beds; upper bed, 0.55 ft (0.15 m) thick, is coarser graded lapilli; various colors from gray to brown to orange, depending largely on grain size.
1	2.34	.71	Lapilli, two graded beds; lower is 1.75 ft (0.53 m) thick and upper is 0.58 ft (0.18 m) thick; upper bed is somewhat finer; orange to grayish orange.
Subtotal--	4.76	1.45	
Lower unit of deposit (measured at section A, top to bottom)			
L-10	0.15	0.04	Ash, fine, brownish-gray.
9	.19	.06	Fine lapilli and ash, graded bed, orange to orange-gray.
8	.08	.02	Ash, fine, grayish-brown.
7	.54	.16	Fine lapilli and ash, single graded bed, reddish-orange.
6	.12	.04	Ash, probably several beds, brown (below) to brownish-gray; generally, browner beds are finer and grayer beds are coarser.
5	.08	.02	Fine lapilli, single graded bed, orange.
4	.04	.01	Ash, fine-grained, brown to gray-brown.
3	.06	.02	Fine lapilli, single graded bed, orange.
2	.33	.10	Fine lapilli and ash, graded bed, tan.
1	.12	.04	Ash, silt- to clay-size, grayish-brown.
Subtotal--	1.71	0.5	
Total------	11.06	3.3	

Underlying material: glacial till containing high percentage of stones

590 feet (180 m)/s inferred from a compressional wave velocity determined by A. F. Chleborad (written commun., 1973) (fig. 15); the value lies within the range of values reported for at least one type of ash from Japan (Yoshizumi, 1972). Triaxial-compression laboratory strength tests on two undisturbed samples from the deposit (subunit L7, table 3) by Willard Ellis and P. C. Knodel (U.S. Bur. Reclamation, written commun., 1973) suggest that the ash has an undrained shear strength on the order of 20 lb/in^2 (1.4 kg/cm^2).

After initial excavation and physical breakdown of the deposit, if the water content remains high and working of the ash continues, the material commonly loses firmness and flows like a viscous liquid. (See "Liquefaction," p. 68.) This behavioral characteristic is readily demonstrated by laboratory tests of dilatancy (table 2). In the Sitka area this characteristic is well known to construction specialists (Franklet, 1965; Fermin Gutierrez, Administrator, City and Borough of Sitka, oral commun., 1971; Marc Petty, U.S. Forest Service, oral commun., 1971; J. C. Moores, Jr., Alaska Div. Aviation, written commun., 1972). However, in undisturbed volcanic ash and lapilli deposits in Sitka and vicinity, the potential for liquefaction and related landsliding appears to be low because of the scarcity of landforms clearly related to volcanic ash and lapilli deposits as observed from 1948 airphotos. On the other hand, on Kruzof Island, where deposits are as much as 50 feet (15.2 m) thick (according to Marc Petty), a large number of landforms indicative of landslides of several types were observed on the airphotos. The landslides may have been triggered by heavy rains or by liquefaction of volcanic ash and lapilli deposits.

Other physical-property tests (table 2) provided negative results because of particle breakdown that resulted in changes in the material during running of tests. Similar negative test results have been reported from Italy (Penta and others, 1961; Pellegrino, 1970) and Japan (Yamanouchi and Haruyama, 1969; Yamanouchi and others, 1970).

The ash and lapilli deposits originated from airfall of highly vesicular volcanic material that was ejected explosively from one or more of the volcanoes on Kruzof Island. Other ejected materials include fragments of dense volcanic glass, mineral crystals, and dense preexisting rocks. After a large eruption, air-carried fragments may cover wide areas. Heavier fragments fall faster than lighter fragments. Unless the deposit from an eruption is very thick, subsequent erosion and redeposition soon obliterate most traces of the individual deposits. The three stratigraphic subunits of volcanic ash and lapilli seen near Sitka probably are products of three different eruptions occurring within short intervals. Either subsequent eruptions were very much smaller or winds were substantially different in direction, because younger volcanic ash layers noted in peat beds by Heusser (1952, p. 341; 1960, p. 104) were extremely thin.

Use of volcanic ash and lapilli deposits for engineering purposes is limited. No use can be made of excavated ash and lapilli because of the dilatant, liquefiable nature of the moisture-laden mass after initial working. However, as foundation material the undisturbed deposits are moderately suitable if bearing loads are kept low to moderate. This appraisal of suitability is believed to be more realistic than previous ones that inferred a complete unsuitability of the deposits for foundation uses (Alaska State Housing Authority, 1966, p. 26, 27). Relatively larger loads tend progressively to break down the internal structure of ash particles by crushing the thin glass walls of the pores within the particles. It is not known whether chemical stabilization of volcanic ash to increase its strength has been attempted at Sitka.

Elevated shore and delta deposits (Qeb)

Deposits of former shore and near-shore areas that comprise the elevated shore deposits and deltas are locally well exposed near Sitka above present-day storm beaches and below altitudes of 35 feet (10.7 m) above mean sea level. Materials consist of loose, well-bedded sandy gravel, and some cobbles. Stones generally are subrounded, but some are subangular. Most beds are moderately well sorted, as illustrated on figure 7 by the relatively steep slope of the six size-distribution curves.

Thicknesses of the deposits may average 10 feet (3.0 m) and range from 5 feet (1.5 m) to at least 20 feet (6.1 m).

The distribution of the deposits is concentrated principally between Swan Lake and the east side of the mouth of Indian River (fig. 5). Elsewhere, scattered deposits are more or less parallel to the present shore. The cobble-rich parts of the deposit extend northwestward from the area of figure 5 to near Halibut Point (fig. 2). Best examples of the deposits are exposed in borrow pits (fig. 2) that are directly east of the area encompassed by figure 5. Another example is northeast of Harbor Rock, Middle Anchorage (figs. 3, 5), along the flank of the hill enclosed by the 100-foot contour line.

The deposits overlie bedrock, glacial drift, and, locally, volcanic ash and lapilli. Younger materials that overlie the deposits and that are in patches too small to map separately include muskeg and manmade fill.

The well-formed, very low ridges (fig. 3) marking the crest of some of the deposits may be either ancient beach berms deposited when sea level was near 35 feet (10.7 m) or, alternatively, ancient offshore bars deposited when sea level was much higher.

Deposition of the deposits started after the beginning of the last major deglaciation, at a time when marine waters still covered land up to an altitude of at least 35 feet (10.7 m) relative to present mean sea level. A relative land emergence, continuing over many years, caused a gradual seaward shift of principal places of delta deposition and of wave and long-shore current action. The loads of gravel and sand transported by streams settled at tidewater, where the streams lost carrying capacity and formed deltas. Tidal currents and waves--which, because of deeper water and fewer islands to slow waves, were more powerful than today--spread delta sediments along shores and directly eroded, winnowed, and redeposited geologic materials. Coarsest deposits formed near the most exposed reaches of the shore.

The elevated shore and delta deposits are extensively used as aggregate. Most of the developed sources lie directly east of the area of figure 5. As a natural foundation, the deposits are well suited because of firmness and generally good drainage; much of the city southeast of Swan Lake is built upon these deposits.

Muskeg and other organic deposits (Qm)

Much of the terrain of Sitka and vicinity is underlain by wet, boggy, organic material with scattered pools of water. Such organic terrain, commonly called muskeg, consists predominantly of mosses, and some sedges and heath plants, and, at depth in this area, interstratified similar material, plus wood fragments--all in varying states of decay and fragmentation. When describing these materials together, as a three-dimensional entity, they usually are called peat. The geologic map unit (Qm) also includes organic material that nearly fills sites of former lagoons developed inland from ancient beach ridges (fig. 3). At depth, beneath these former lagoons, it seems likely that the deposits include some fine sand and silt. The mapped muskeg deposits form the Kogish, Kina, and Staney Soil Series described from the Sitka area and elsewhere in southeastern Alaska by the U.S. Forest Service (Stephens and others, 1970). These soils are classified by type of peat and stage of decomposition.

Thicknesses of the deposits are variable and may average 7 feet (2.1 m). The average maximum thickness probably is about 30 feet (9 m), although a thickness of 75 feet (22.9 m) was reported at a locality (asterisk symbol, fig. 5) west of the large cove on Swan Lake. That locality and others marked by asterisks on figure 5 are places where deposits may be thicker than 30 feet. All of these localities appear to be crests of broad, very gently sloping domes of muskeg as much as several hundreds of feet in average hosizontal dimension.

Distribution of the deposits is widespread (fig. 5); good examples of the deposits are on north-central Japonski Island and in the area west of the north end of Swan Lake. The mapped deposits overlie mainly volcanic ash, glacial drift, and elevated shore and delta deposits. They are overlain by small areas of manmade fill too small or thin to show on the geologic map. Large mapped areas of fill, if known to overlie muskeg or other organic deposits, bear a stipple-overprint pattern on figure 5.

Physical properties of peats have been investigated by many individuals. Work by the Alaska Department of Highways at Sitka has been summarized by Franklet (1965), who noted the porous, loose nature of the materials, and the variable moisture contents, which range from 120 to 860 percent of dry weight of solid matter. Beneath a load, peat can compress to 75 to 95 percent of its original thickness, depending upon the proportion of fibrous moss relative to wood fragments in the deposit. Shear strength of peat is usually very low; sample-in-place values for peat at depths of less than 6 feet (1.8 m) were reported by MacFarlane (1969, p. 96) to vary from 0.69 to 2.8 lb/in^2 (0.049-0.20 kg/cm^2). The estimated average shear-wave velocity from this and other peat (Seed and Idriss, 1970, p. 126) is a quite low value of 130 feet (40 m)/s (fig. 15). Liquefaction of peat may occur during times of heavy construction activity because of the generation of certain types of vibrations by power equipment.

Muskegs and peat deposits develop where the climate is cool and moist and subsurface drainage is poor (Stephens and others, 1970). An average rate of peat accumulation for nondomed muskegs, using estimates from elsewhere, is 2.9 feet (0.88 m) per 1,000 years (Cameron, 1970, p. A23). Domed muskegs mark areas of faster accumulation.

No commercial use has been made of the peat in the Sitka area as a marketable commodity, despite an apparently high content of moss.

Road and building construction in areas of thick muskeg must employ various techniques to partially alleviate the problem of the softness and ease of consolidation of the material. It is a desirable practice to remove most of the peat at a construction site, but, except where peat is less than about 10 feet (3 m) thick, removal generally is impractical. Where peat is thicker, foundations for buildings usually are set on piles placed within the geologic material underlying the peat. Gravel pads adjacent to buildings are placed directly upon the muskeg. Road construction over thick peat can be designed to consolidate peat uniformly by correctly placing fill specified for the type and thickness of peat to be overlaid. MacFarlane (1969, p. 106) noted the desirability of using no more than 8 feet (2.4 m) of fill over peat deposits more than 15 feet (4.6 m) thick to achieve uniform flotation of the fill without failure of the peat. Controlled failure of peat has been used as an excavation method near Prince Rupert, British Columbia (fig. 1; Stanwood, 1958). There, in areas where slopes were gentle and underlying materials were firm, large bulldozers pushed and liquefied masses of peat up to a few hundreds of feet long.

Modern delta deposits of the intertidal zone (Qi)

The intertidal (upper) parts of modern deltas near Sitka consist chiefly of sandy gravel and some small cobbles. Materials characteristically are loose, well stratified, and well sorted within beds; most stones are subrounded. At depth within the deposit, beds of sand or sandy silt probably exist.

Thickness of delta deposits is uncertain; it is roughly estimated that the Indian River delta is about 30 feet (9 m) thick and that smaller deltas near Western Anchorage (fig. 5) are about 15 feet (5 m) thick.

The distribution of deposits as mapped and shown on figure 5 is at and near deltas along the intertidal zone; the line of mean lower low water is the lower limit of mapping, as for all deposits, although deposits continue beyond the line of mean lower low water.

In a seaward direction, the delta deposits merge with contemporaneous, finer grained delta deposits of sand and silt size. Landward and along the shore, the mapped deposits merge with modern beach, alluvial, and some elevated older shore and delta deposits. An irregular bedrock surface generally underlies the deltas, although locally they probably are underlain by glacial drift. Some very small areas of manmade fill overlying the deposits are too thin and small to map separately.

The origin of the modern delta deposits, like the origin of the previously described elevated delta deposits, is related to deposition from sediment-laden streams. However, the present streams carry much less sediment than their predecessors. Thus, less sediment is available today for movement by long-shore currents and waves from the deltas to adjacent shore areas.

Excavation and use of modern delta deposits as fill or aggregate were extensive during the early 1940's. All excavation sites visible on 1965 and earlier airphotos are symbolized on the geologic map (fig. 5). The part of the Indian River delta east of the mapped area apparently was the only part of the delta being exploited in 1971. The lack of infilling into the excavations by new sediments from stream and long-shore currents indicates limited renewability of the Indian River and other deltas. Thus, the Indian River delta should be considered as a limited source of fill and aggregate.

Delta deposits are well suited as foundations for manmade fills and building construction, except where exposed to very high waves.

Modern beach deposits (Qb)

Various mixtures or concentrations of gravel, cobbles, sand, and boulders characterize the modern beach deposits at Sitka and vicinity. Stones are mostly subrounded, but range from rounded to subangular. The coarsest part of the deposit is the upper limit, which is marked by the storm-wave accumulation several feet above mean higher high water. Near mean lower low water and the lower limit of the deposit as mapped, sand may predominate. Locally, small patches of manmade fill, including refuse, are partly incorporated into modern beaches, especially along the Sitka side of the channel northeast of Japonski Island. At many places within the area of the deposits, but at some distance from deltas, bedrock crops out in exposures too small to map. Some of these outcrops and conspicuous concentrations of boulders and cobbles are symbolized on figure 5.

Thickness of the deposits may vary from 5 to 15 feet (1.5-4.6 m) and averages 7.5 feet (2.3 m).

Distribution of the modern beach deposits is widespread at Sitka and vicinity except along the southwestern side of Japonski Island and adjacent islands. A good example of a beach predominantly of gravel and some cobbles is the deposit along the eastern part of the mapped area. Examples of beaches containing mostly cobbles and some boulders are those near Western Anchorage (fig. 5). Beaches merge along the shore with delta deposits. Bedrock commonly underlies modern beaches, although in some places glacial drift or volcanic ash and lapilli underlie the beaches. Manmade fills cover many areas of formerly exposed beaches at Sitka and vicinity. The extent of coverage is indicated by the position of the 1893 mean high water line (fig. 3).

The accumulation of modern beach deposits, like that of their predecessors, the elevated shore deposits, was effected by the action of waves and long-shore currents eroding, moving, and redepositing materials along shores. Highest storm waves arrive from the southwest, and those beaches facing southwest and at some distance from deltas or unprotected by reefs and islands display a high percentage of large boulders near their uppermost or storm level.

Use of beach deposits as fill or aggregate apparently was extensive in the early 1940's and has been sporadic since then. Areas of exploitation as seen on 1965 and earlier airphotos are symbolized on figure 5. Reserves probably are of limited extent. Modern beaches are well suited as foundations except for their exposure to very high waves.

Alluvial deposits (Qa)

Alluvium consists chiefly of loose sandy gravel and some cobbles. Stones are mostly subrounded. Bedding is moderately well developed, and sorting is good within individual beds. Locally, lenses of sand and organic silt probably are present in the upper parts of deposits, especially east of the dump near the north end of Kimsham Street (figs. 3, 5).

Thickness of alluvium may average 8 feet (2.4 m) within most of the mapped area. However, east of the dump the maximum thickness may be 15 feet (4.6 m), and along lower Indian River the maximum thickness may be about 20 feet (6 m).

Distribution of deposits is concentrated along some of the streams in the mapped area. Best exposed deposits are along Indian River. Some alluvial deposits merge, or formerly merged, with delta deposits. Bedrock, glacial drift, and some volcanic ash are the principal geologic materials beneath alluvial deposits. Muskeg locally is encroaching upon alluvium along small streams. Thus, in some places mapped alluvial deposits include accumulations of organic material. Manmade fill covers some alluvium near Peterson Avenue (figs. 3, 5).

Alluvium originates by the deposition of stream-transported preexisting geologic materials. As the quantity of water in a stream changes, the velocity and erosional capacity of the stream change. The velocity of small streams near Sitka is low most of the year. On the other hand, Indian River is capable of eroding, transporting, and depositing some material during much of the year, especially in the fall. (See discussion of floods on p. 78.)

Alluvium near Sitka is not used for fill or aggregate. Except for the risk from flooding, the deposits probably are well suited as foundations where lenses of organic material are sparse.

Manmade fill (Qfe, Qfm, Qfr)

Many varieties of geologic materials are included in manmade fill. The predominant materials are (1) sandy gravel or sand, (2) till, and (3) blocks of graywacke bedrock; subordinately, the materials are (4) muskeg and volcanic ash, and (5) garbage, scrap metal, and trash. Although most small fills are loose, some of the larger ones are firm, because of engineered consolidation developed during construction. As depicted on the geologic map, manmade fill is grouped into three general types on the basis of predominant material, construction method, and use. The first type is the ordinary embankment fill (Qfe) at Sitka and vicinity. It consists of sandy gravel or sand, till, and some blocks of rock as much as 4 feet (1.2 m) in diameter that serve as riprap or armor rock to protect shores from high waves. Riprap near Castle Hill, Crescent Harbor, and along the southwest side of Japonski Island is especially extensive (figs. 3, 5). A thick fill of sand was used as the core for the part of the Sitka Airport runway between Fruit Island and Japonski Island. The second type of fill is modified ground (Qfm), developed by refilling with embankment fill (apparently less than 4 feet (1.2 m) thick) in areas where large volumes of preexisting geologic materials were removed. A good example of this type of fill is south of the airport terminal building. The third type of fill is refuse fill (Qfr), composed of several varieties of materials. Northeast of the middle of the long axis of the airport runway, the fill is chiefly muskeg and volcanic ash, and along the north end of Kimsham Street, chiefly garbage, scrap metal, and trash.

Thickness of deposits of manmade fill is highly variable, although many of the deposits probably are about 7 feet (2 m) thick, and the maximum thickness may be as much as 65 feet (19.8 m). If an area of fill is known to be thicker than 25 feet (7.6 m), the area is symbolized on figure 5.

Distribution of fill is widespread, and covers many types of geologic materials. Where fill is known to overlie muskeg or other organic deposits, the area is symbolized on figure 5. The large amount of fill emplaced over historic offshore areas is indicated by the position of the 1893 mean high water line (fig. 3) relative to the present shoreline. This fill covered mostly sand, gravel, and bedrock.

Offshore features and surficial deposits

As here used, offshore refers to areas below mean lower low water. Such areas cover a large part of the map of Sitka and vicinity. Bottom-surface features and geologic materials include delta fronts, linear channels and ridges, a sediment layer of variable thickness, and numerous bedrock outcrops that are probably chiefly graywacke. Bottom-sediment data shown on U.S. National Ocean Survey charts (1972, 1973b) are numerous and were collected over a span of many years, but the charts lack information on thickness of sediments. However, data on thickness have been determined in a few areas during investigations for construction material for the Sitka Airport by J. D. Ballard (consulting engineer, written commun., 1965), Adams, Corthell, Lee, Wince, and Associates (1966), and Dames and Moore (1971). Other indications of subbottom geologic relationships were determined by S. C. Wolf (written commun., 1967) from a seismic-reflection profiling and sampling cruise headed by G. A. Rusnak of the U.S. Geological Survey.

The steep slope of the upper part of the Indian River delta front is one of the more prominent bottom-surface features near Sitka. About one-fourth of this delta front is shown in the southeast corner of figure 5. Slopes of about 27 percent typify the upper part of the delta front; materials probably are mostly sand in the upper part and sandy silt at depth. A bottom sample apparently collected a short distance beyond the steeper part of the delta front by S. C. Wolf is reported to consist of "very fine sand, mud, silt, some shells, and a few hard-packed clumps of sediment." The lower or outer part of the delta front has a slope of several percent; bottom sediments generally are described as "mud" (U.S. Natl. Ocean Survey, 1973b) or as a combination of mud, silt, shells, or organic matter by S. C. Wolf. According to interpretation of Wolf's data, thickness of sediments near the lower part of the Indian River delta front is variable, and at a few places graywacke(?) bedrock is at the sea floor or within several feet of the floor. These areas of higher bedrock are separated by pockets of sediment which are about 30-80 feet (9-24 m) thick.

The offshore parts of the other smaller deltas near Sitka are poorly developed.

The northwest-southeast linearity of several groups of islands, reefs, and channels in the Sitka area is especially striking. The linearity may be the result of differential glacial erosion of sheared, broken-up rocks that are part of fault zones. The channel between Sitka and Japonski Island is a good example of a linear channel that might be interpreted as being controlled by faulting. However, seismic-reflection profiles that cross the deepest part of the channel to the southeast are interpreted from Wolf's data to permit, but not require, the presence of a fault.

Bottom sediments of different kinds and of variable thicknesses are present between the scattered bedrock islands and reefs near Sitka (areas numbered below). They have been studied briefly by several organizations using several different methods. Adams, Corthell, Lee, Wince, and Associates (1966) worked mainly in three areas: (1) west of Japonski Island, (2) north of the northwestern part of Japonski Island, and (3) south of Alice and Aleutski Islands (figs. 3, 5). In general, they noted that between the several bedrock outcrops bottom sediments consisted of sandy gravel or gravelly sand, with local concentrations of shells, cobbles, or boulders. Here and there a thin covering of silt was present. Thickness of sediments was determined in several places, and it averaged 22 feet (6.7 m); no volcanic ash was mentioned as being present at depth. In the same three areas, data on bottom sediments by the

U.S. Coast and Geodetic Survey (U.S. Natl. Ocean Survey, 1973b), though much less extensive, are in general agreement. Several seismic profiles by the U.S. Geological Survey (S. C. Wolf, written commun., 1967) in area (4), south and southwest of Japonski Island, a short distance beyond the area of figures 3 and 5, indicate the presence of unconsolidated material with thicknesses varying from 6 feet (1.8 m) to as much as 60 feet (18.3 m). Seismic data by Dames and Moore (1971) from area (5), directly southeast of the Sitka Airport runway, indicated a similar variation in thickness of sediments. Area (6), the floors of Western Anchorage and the channel between Sitka and Japonski Island, was described (U.S. Natl. Ocean Survey, 1973b) as "rocky" or "mud" between the bedrock islets and reefs. In the channel near Middle Anchorage, at least two bedrock outcrops, symbolized on figure 5, have been altered by partial removal through blasting. Within area (7), the harbor at Crescent Bay, siphoning work reported by C. L. Fenn (U.S. Army Corps Engineers, oral commun., 1965) indicated 15-20 feet (4.6-6.1 m) of sandy gravel with some cobbles and boulders. Within area (8), the Sitka to Japonski Island bridge site, preconstruction investigations and bridge-tower construction revealed that sand, silt, shells, some boulders, and patches of volcanic ash and glacial drift overlie bedrock at depths of 8 feet (2.4 m) or less (Slater and Utermohle, 1969; A. W. O'Shea, Associated Engineers and Contractors, Inc., oral commun., 1971).

Offshore deposits originate either by growth of a delta or as the result of both wave action and tide-generated long-shore and other currents. Such currents have eroded, transported, and redeposited preexisting geologic materials. Local areas of abundant cobbles and boulders probably are lag concentrations of material produced by wave erosion; finer grained material was washed into topographically low, slack-current areas, including the deep glacier-gouged channels in Sitka Sound.

The delta of Sawmill Creek at Silver Bay (fig. 2) is a feature of special interest in the Sitka area, because of the large pulp mill built partly upon it. Scattered data for the offshore part of the delta were obtained from the U.S. National Ocean Survey (1972), S. C. Wolf (written commun., 1967), the University of Washington (Barnes and others, 1956; McAllister and others, 1959), and Dames and Moore (1957), and from topographic mapping by Hubbell and Waller (written commun., 1957, to Dames and Moore). These data, most of which were collected before mill construction in 1957, indicate that slopes of the steep part of the delta front then averaged 28 percent (depth 15-150 feet (4.6-45.7 m)). The outer part of the delta had a very gentle slope of about 3 percent. Slope data were not sufficiently detailed to show irregularities of the bottom that might indicate the presence or absence of submarine landslides.

Generally, information on sediments indicates the presence of a variety of materials. Bottom sediments from depths of about 60 to 200 feet (18-61 m) are thought to consist, in general, of organic-laden sand and silt. In shallow water close to the intertidal zone and near the mill, sand and gravel were present. The only available stratigraphic information on geologic materials is from the mill area, where numerous borings indicated, in general, that gravel and sand or sand overlie sandy silt. Several borings along the west side of the delta, including the intertidal zone, revealed beds of peat-laden sand or peat-laden sandy silt many feet thick both near the surface and at depth. Dames and Moore (1957) recommended that before mill construction some of this material be removed and that the rest of it be consolidated by an engineered loading by manmade fill and buildings.

Data on the thickness of sediments overlying bedrock have been derived by geophysical means by Dames and Moore (1957) and S. C. Wolf (written commun., 1967). Near the former mean sea level line, the maximum thickness of sediments was determined as 160 feet (48.8 m). Thickness of sediments beyond the steep delta front and beneath water depths of about 200 feet (61 m) was suggested by seismic-reflection profiling to be 300 to 350 feet (91.4-106.7 m). At about the same water depth, the seismic velocity of the uppermost unit resulted in its being tentatively identified as an undisturbed, horizontally bedded material about 50 feet (15 m) thick.

The pulp mill and the dam at Blue Lake (fig. 2) together have modified several geologic processes at the Sawmill Creek delta. The natural supply of stream sediment to the delta has diminished, and the principal areas of deposition have shifted because of diversion of the mouth of the stream entirely to the east edge of the delta top. In addition, the presence of docking facilities and large fills has altered the local orientation of long-shore currents and the relatively weak waves.

STRUCTURAL GEOLOGY

Summary of regional structure

Southeastern Alaska is part of an active tectonic belt that rims the North Pacific Ocean. From time to time since the early Paleozoic, profound tectonic deformation, plutonic intrusions, and widespread metamorphism have occurred in the region (Buddington and Chapin, 1929; Brew and others, 1966; Plafker, 1971; Jones and others, 1970; Berg and others, 1972). The latest major events occurred in late Mesozoic and Tertiary time with some minor activity continuing into the Quaternary that further set a pattern of mostly northwest-, some north-, and a few northeast-trending structural features (Twenhofel and Sainsbury, 1958; Brew and others, 1963). Prominent among these features are high-angle faults along which extensive movement is suggested. Some of the major faults in southeastern Alaska and adjacent regions are shown on figures 8 and 9. The most important faults, some of which are active, include: segments of the Denali fault system, Fairweather and Queen Charlotte Islands faults (here called the Fairweather-Queen Charlotte Islands fault system), Chugach-St. Elias fault, Totschunda fault system, and some of the faults that cross Chichagof and Baranof Islands.

The Denali fault system comprises a series of fault-zone segments that extends over 1,000 miles (1,600 km) subparallel to the Gulf of Alaska (St. Amand, 1957; Twenhofel and Sainsbury, 1958; Grantz, 1966; Berg and others, 1972; Berg and Plafker, 1973). Four segments of the system are shown on figure 9 (designations 3 through 7). Along the Chatham Strait segment, right-lateral fault movement of 50 miles (80 km) was considered likely by Brew, Loney, and Muffler (1966, p. 158), while a different analysis (Ovenshine and Brew, 1972) indicated 120 miles (200 km) of separation. Differential vertical movement of at least 1.5 miles (2.4 km) is hypothesized (Loney and others, 1967, p. 524). The Chatham Strait fault was active at least after the Miocene (Loney and others, 1967), and possibly as long ago as the Silurian (Ovenshine and Brew, 1972).

The Fairweather-Queen Charlotte Islands fault system is an active tectonic feature that probably consists of a nearly continuous linear zone of vertical to steeply dipping fault segments and branches (St. Amand, 1957; Wilson, 1965; Brown, 1968; Tobin and Sykes, 1968). From south to north, the zone follows the continental slope and Outer Continental Shelf along British Columbia and most of southeastern Alaska, crosses the inner Continental Shelf, reaches shore southeast of Lituya Bay, and continues on land through a wide valley to the head of Yakutat Bay (fig. 9). Near the bay, the zone merges with thrust faults of the Chugach-St. Elias group of faults (figs. 8, 9; Plafker, 1969, 1971). Northwestward from Yakutat Bay, a hypothesized continuation of the Fairweather fault zone that might connect with the active Totschunda fault system (figs. 8, 9) has been speculated upon by Richter and Matson (1971). The onland segment of the Fairweather fault has been described by Tocher (1960), Plafker (1967), and Page and Lahr (1971); the offshore segment (Page, 1973; Page and Gawthrop, 1973) extends as the named fault southeastward to about 55°30' N. lat. Southeastward from this latitude,

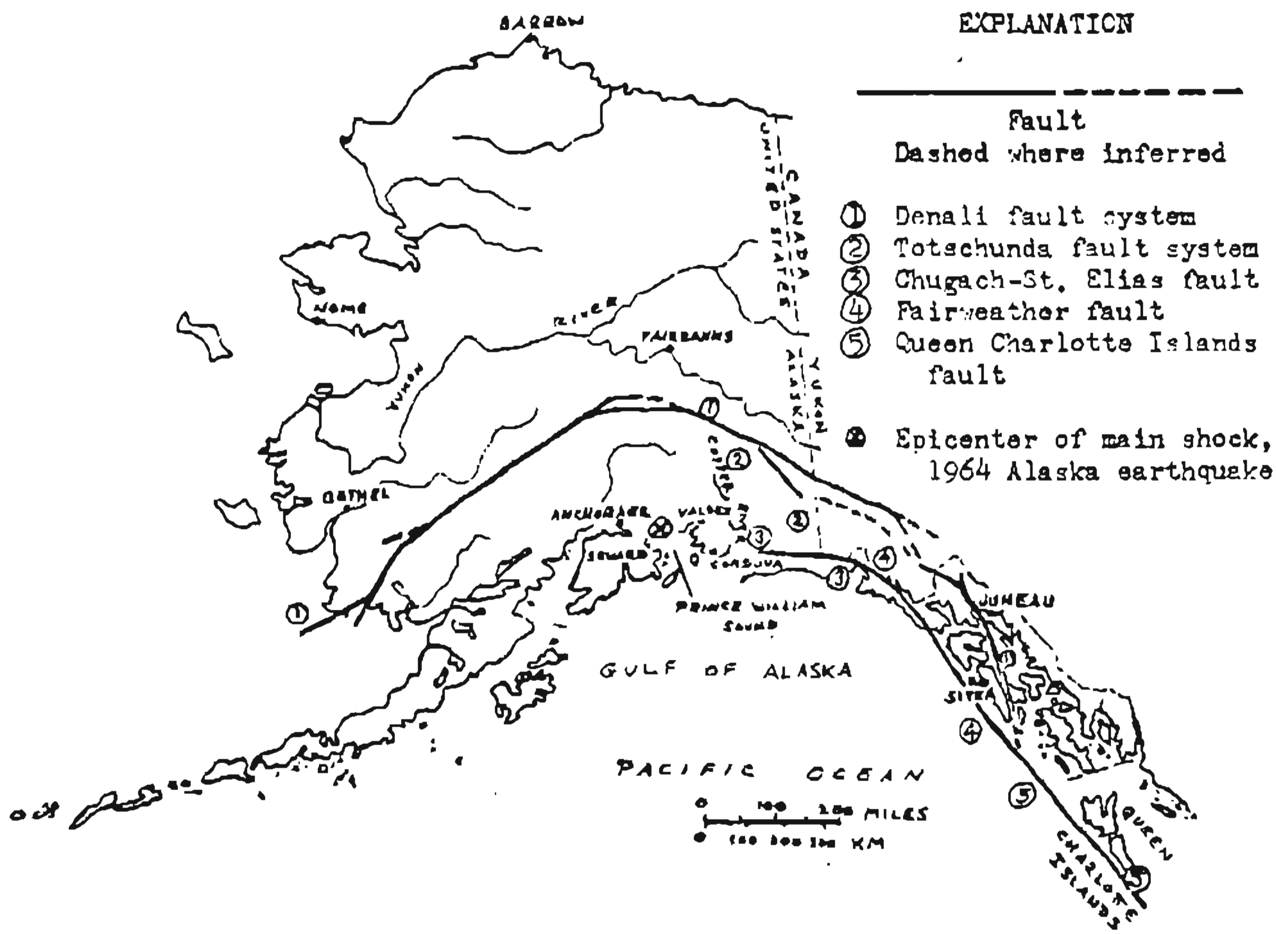


Figure 8.--Major elements of the Denali and Fairweather-Queen Charlotte Islands fault systems, Alaska and adjacent Canada. Modified from Grantz (1966), Tobin and Sykes (1968), Plafker (1969; 1971), Richter and Matson (1971), Berg, Jones, and Richter (1972), Berg and Plafker (1973), and Page and Gawthrop (1973).

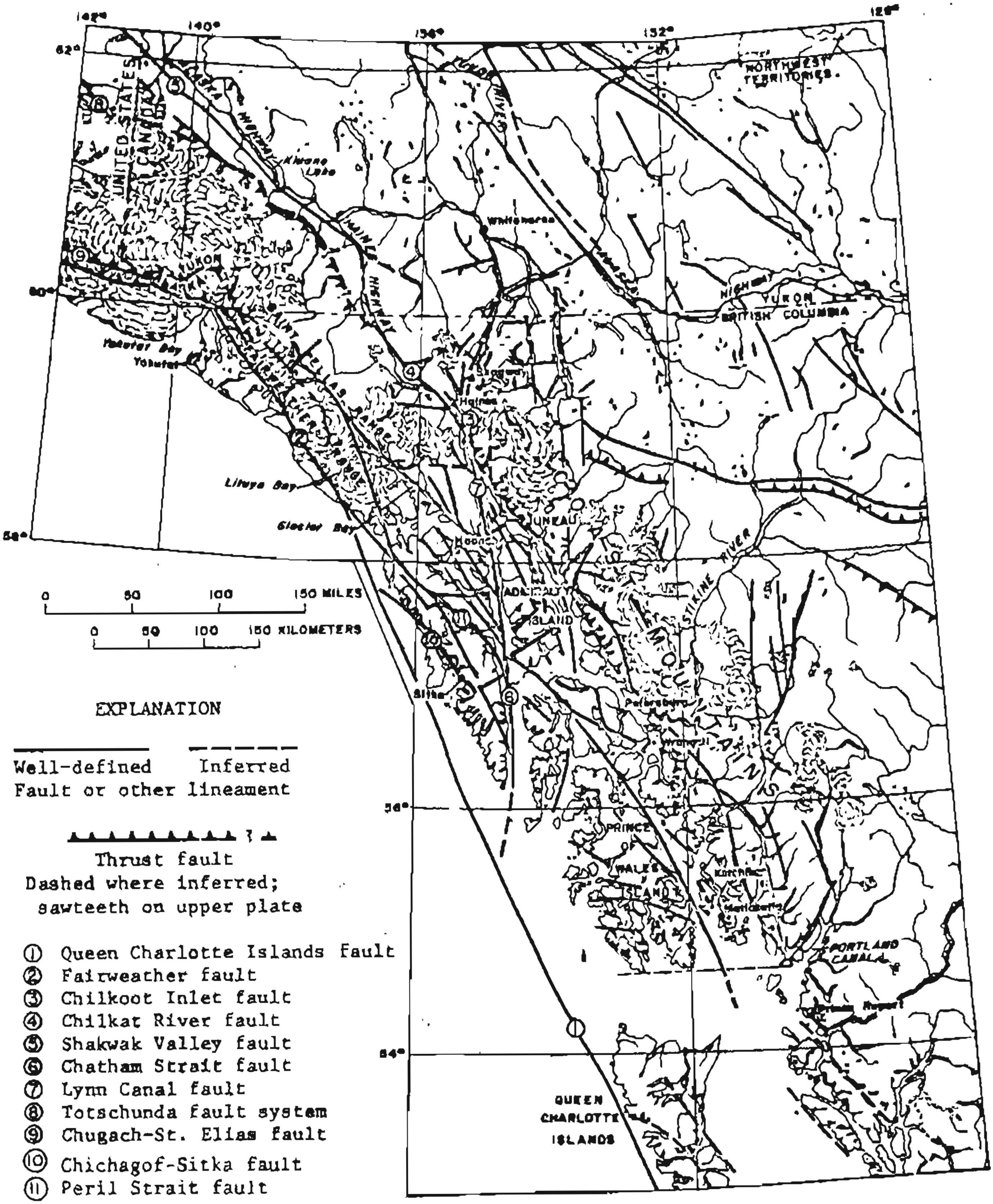


Figure 9.--Map of southeastern Alaska and adjacent Canada showing major faults and selected other lineaments interpreted to be probable or possible faults, shear zones, or joints. Taken from St. Amand (1957), Twenhofel and Sainsbury (1958), Gabrielse and Wheeler (1961), Brew, Loney, and Muffler (1966), Tobin and Sykes (1968), Canada Geological Survey (1969a, b), King (1969), Plafker (1969, 1971), Souther (1970), Richter and Matson (1971), and Berg, Jones, and Richter (1972), with additions and modifications by the writer.

the fault is called the Queen Charlotte Islands fault. The position of offshore segments of faults shown on figures 8 and 9 is generalized, and is based upon (1) the location of detectable earthquakes caused by the recurrent faulting, (2) limited geophysical data, (3) limited sounding data, and (4) theoretical considerations.

Movement along faults in the Fairweather-Queen Charlotte Islands fault system is thought to be similar to movement along the San Andreas fault system in California, a dominantly horizontal, northwestward movement of the earth's crust lying southwest of the fault relative to fixed points across the fault. Both fault systems are manifestations of the same apparent tectonic movement of a large block of the earth, termed the Pacific plate, past an adjacent plate, termed the North American plate (Isacks and others, 1968; LePichon, 1968; Morgan, 1968; Atwater, 1970). Theoretical calculations indicate that motion may average 2.25 inches (5.8 cm) per year. The total relative right-lateral horizontal slip along the Fairweather fault may be as much as 150 miles (240 km) (Plafker, 1972, 1973; Berg and others, 1972, p. D18). After the earthquake of July 10, 1958, u.t.,[1] which was caused at depth by activity along the fault, 21.5 feet (6.6 m) of right-lateral movement was measured at one place along the onland segment of the fault (Tocher, 1960, p. 280). Total horizontal movement along the offshore segment of the Fairweather fault and the Queen Charlotte Islands fault is unknown, but probably is large. Calculations from a few offshore earthquakes indicate right-lateral strike-slip motion along steeply inclined fault surfaces (Tobin and Sykes, 1968, p. 3840). (Further information about the Fairweather fault zone near Sitka is given on page 39.) Vertical movements along the Fairweather fault zone, although of subordinate importance, probably have been locally extensive. Grantz (1966) suggested that along the northeast side of the onland part of the fault zone relative uplift might total 3 miles (4.8 km) or more. An area of active thrust faulting at depth is indicated by the July 1, 1973, earthquake about 35 miles (56 km) offshore from the northwestern part of Chichagof Island (fig. 11; Gawthrop and others, 1973). The zone of faulting is coincident with the continental slope. The fault probably merges with the Fairweather fault in a manner similar to that of the Chugach-St. Elias fault.

Movement along faults that are part of the Fairweather-Queen Charlotte Islands fault zone may have begun sometime after the middle Eocene (Plafker, 1972, 1973).

Several major faults are known to cross Chichagof and Baranof Islands in a northwest-southeast direction, following linear to gently curving valleys and fiords; numerous minor faults are also present (fig. 9; Loney and others, 1963, 1964). Among the major faults, the most prominent are the Peril Strait fault and the Chichagof-Sitka fault.

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[1]The dates of all earthquakes in this report are given in universal time whenever possible; for the Sitka area, universal time is local standard time plus 8 hours.

The Peril Strait fault is a concealed feature about 110 miles (180 km) long which appears to join the Fairweather fault with the Chatham Strait fault. Brew, Loney, and Muffler (1966, p. 154) suggested that movement along the Peril Strait fault has been dominantly in a right-lateral direction, and near the northwestern end of the fault may total 18 miles (29 km) (Rossman, 1959). Elsewhere, right-lateral movement of about 1.5 miles (2.4 km) is indicated (Loney and others, 1967, p. 515). Some vertical uplift of the land northeast of the fault has occurred, possibly amounting to less than 1 mile (1.6 km) (Loney and others, 1967, p. 524). Major movements probably took place sometime after the Miocene; minor movement may have continued into the Holocene.

The Chichagof-Sitka fault zone (fig. 9) consists of several segments, including a likely southeastern extension, the Patterson Bay (fig. 1) fault, as considered by Grantz (1966). The fault zone is about 120 miles (200 km) long and, like the Peril Strait fault, it appears to join the Fairweather fault with the Chatham Strait fault. (The segment near Sitka is discussed on page 41.) The fault segments have steep dips, but few other data are available. Near the northwest end of the fault zone, right-lateral offsets of as much as 0.95 mile (1.5 km) are evident on presumably related faults (Berg and Hinckley, 1963, p. 020). Near its southeast end, along the Patterson Bay fault, about 3 miles (5 km) of right-lateral offset is evident (Loney and others, 1967, p. 520); movement occurred sometime in post-Eocene and pre-Miocene time. High-angle thrust faulting is another type of movement that may have taken place along the Chichagof-Sitka fault (Berg and others, 1972, fig. 1). The faulting might be associated with the vertical uplift of Baranof Island relative to land east of Chatham Strait that amounted to at least 1.5 miles (2.4 km) and occurred sometime after the Miocene (Loney and others, 1967, p. 524).

Local structure

Geologic reconnaissance work has outlined the major structural relationships of bedrock in the area shown on figure 4 (see Berg and Hinckley, 1963; Brew and others, 1963, 1969; Loney and others, 1963, 1964; Berg and others, 1972). Bedded rocks of Mesozoic and Permian(?) age appear to be part of a broad complex of anticlines trending northwest. These rocks have been intensely deformed during possibly two intervals of time, and today generally strike northwest and dip steeply southwest or are vertical; locally, beds dip northeast or are overturned. Large bodies of Tertiary and Cretaceous igneous rocks are intrusive into the older bedded rocks and are only slightly foliated; dips are variable. Quaternary volcanic rocks exhibit their original dips and thus have not been deformed.

Jointing of rocks is well developed, and the most conspicuous joints strike northeast and usually dip steeply; in places they are vertical. A second joint set strikes northwest, and a third strikes east (Berg and Hinckley, 1963, p. 022; Brew and others, 1963). On Japonski Island, a zone of fractures, presumably joints, extends northward from the north edge of the lagoon (fig. 5). The zone was reported by J. C. Reed (written commun., 1942) to be 250 feet (76.2 m) wide and to dip steeply westward.

Two major faults and a myriad of small faults and other types of lineaments cut bedrock (fig. 4). Most of these features attest to intense deformation of the Sitka area.

Fairweather fault zone

A 32-mile (51-km) segment of the major Fairweather fault zone trends through the offshore area shown on figure 4; it is depicted in only a generalized position (R. A. Page and W. H. Gawthrop, written commun., 1973), because the specific location of individual faults comprising the zone is unknown. It is very likely, however, that the southwest and northeast limits of the zone extend over parts of the continental slope and Continental Shelf (fig. 10) at least several miles beyond the position shown. Several types of steeply dipping faults probably are present--some that are active and others that are inactive. A few of these faults are believed to be present as shown on a subbottom acoustical profile run by the U.S. National Oceanic and Atmospheric Administration in 1971 southwest of Sitka and partly reproduced by Page (1973, p. 8). The profile crosses part of the area of the Fairweather fault zone, and includes several features shown on figure 4 that are inferred to be faults or other lineaments. At least one of the features is located in the general vicinity of the epicenter of the main shock of the July 30, 1972, earthquake; Page believes that the feature is the surface expression of one of the faults active at depth during the earthquake's main shock and aftershocks. To locate other faults, extensive seismic and other surveys are needed that cover large offshore areas near Sitka. Such surveys along the similar Queen Charlotte Islands fault zone have been conducted by the Canada Geological Survey and several universities (Srivastava and others, 1971; Chase and Tiffin, 1972). The surveys indicate that the zone of faulting, at least in that area, is at least 25 miles (40 km) wide.

The total amount and rate of movement along the offshore segment of the Fairweather fault zone nearest Sitka can only be speculated upon, but applicable data are available from other segments of the fault zone: (1) A right-lateral offset of about 10 feet (3 m) was measured after the earthquake of July 10, 1958 (Tocher, 1960, p. 287), at the onland segment of the fault nearest Sitka, 115 miles (184 km) to the northwest. (2) Predominantly right-lateral movement also has been calculated from data on the earthquakes of October 24, 1927, and August 22, 1949, both of which occurred along offshore segments of the Fairweather-Queen Charlotte Islands fault zone (Tobin and Sykes, 1968, p. 3840). Theoretically, the amount of right-lateral motion might average 2.25 inches (5.8 cm) per year along the Fairweather-Queen Charlotte Islands fault system (see p. 37).

A volcanic fissure zone on Kruzof Island and southwestward may be related to the Fairweather fault zone (Loney and others, 1967, p. 515), but details are speculative. The major volcanic vents have an

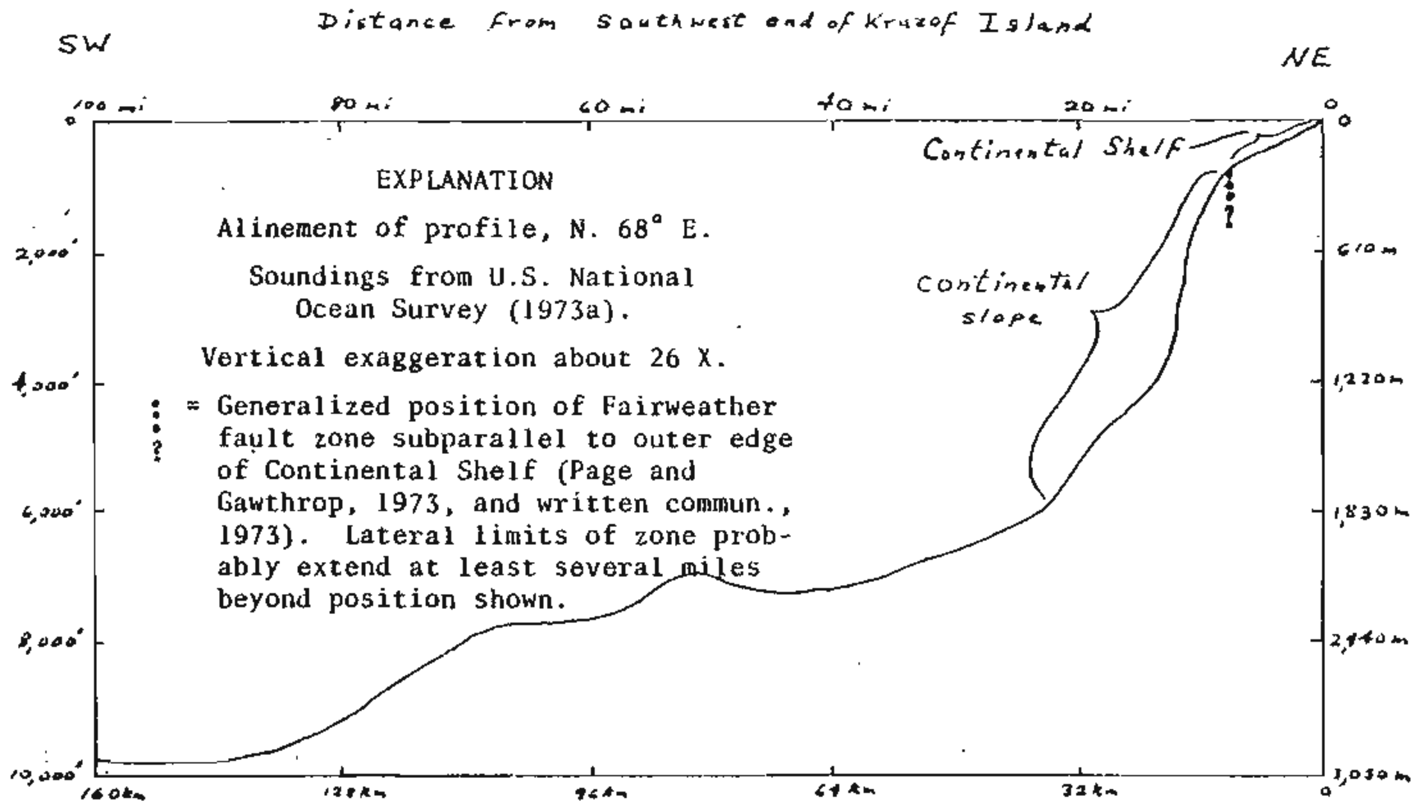


Figure 10.--Bottom profile offshore from Kruzof Island, Alaska, showing Continental Shelf, continental slope, and generalized position of Fairweather fault zone. For location of entire profile, see figure 1; for location of shoreward one-third of profile only, see figure 4.

alinement of N. 30° E. (fig. 4) and form an echelon-pattern relation to the fault zone. It is speculated that a large regional-scale resistance developed to the right-lateral motion along the fault zone and there evolved an echelon group of fissures or faults that served as conduits for magma and volcanism at the surface. The lack of offset of the line of vents suggests that of the possible branches of the Fairweather fault zone that are more than 5 miles (8 km) northeast of the position shown on figure 4, none have been active at the surface during the past about 10,000 years, on the basis of the suggested date for the extensive volcanic ash (p. 22).

Chichagof-Sitka fault zone

Figure 4 shows about 20 miles (32 km) of the northwest-southeast-trending Chichagof-Sitka fault zone between Olga Strait in the northeast and Silver Bay near the east edge of the figure. At its closest point, the fault is about 2.5 miles (4 km) northeast of Sitka. The exposed part of the fault zone forms a conspicuous linear depression of sheared bedrock that may be as much as half a mile (0.8 km) wide (Berg and Hinckley, 1963, p. 020). Glaciers and past and present streams have eroded the sheared rocks in the fault zone, thus developing some prominent linear waterways and valleys. The short, approximately parallel faults nearby (fig. 4) probably are branches of the main fault.

The amount and direction of movement along the branches of the fault near Sitka are unknown, but information on movement elsewhere along the fault is given on page 38.

Fault striking northeastward from Silver Bay

A 2-mile (3.2-km) length of an unnamed fault about 10 miles (16 km) long (fig. 9) is shown on the east edge of figure 4 as striking northeastward along a valley whose mouth is at Silver Bay. The valley is along the route of a proposed highway from Sitka to Chatham Strait (Alaska State Housing Authority, 1966, p. 120). The fault is the only one reported near Sitka for which estimates of a substantial offset have been determined. Movement along the fault caused a left-lateral offset of about 0.6 mile (1 km), and probably occurred in post-Eocene and pre-Miocene time (Loney and others, 1967, p. 520). The relation of the fault at Silver Bay to the Chichagof-Sitka fault is unknown.

Other faults and lineaments

Only a few of the myriad of other faults, zones of sheared bedrock, and other types of lineaments in the area are shown on figure 4; many other faults exist but are too small to map or are concealed by thick vegetation, surficial deposits, or bodies of water. Some of the concealed faults might contain deep narrow zones of sheared rock. Most known faults are probably high-angle faults, according to Berg and Hinckley (1963, p. 022). They also noted the difficulty in determining the amount and direction of fault movements, because most faults strike northwest, paralleling the strike of bedding and foliation, and marker beds are rare. A few faults strike north, northeast, or east. Movement along the faults probably occurred in post-Eocene and pre-Miocene time, concurrent with faulting along the Chichagof-Sitka fault, its branches, and likely extensions.

Lineaments are linear or gently curved geologic features that are prominent enough topographically to be expressed on airphotos and maps. Study of the ground surface can usually determine the origin of lineaments, but in the Sitka area the reconnaissance nature of investigations leaves much detailed geologic work to be done; consequently, the origins of lineaments are largely speculative. It is probable that most lineaments shown on figure 4 are faults, but many of the lineaments that trend northwest may be the intersections of the ground surface with planes of bedding or foliation (Brew and others, 1963, p. B112). Some lineaments may be joints, especially those lineaments striking northeast, which is the trend of the most conspicuous joints. This direction is also the trend of the volcanic fissure zone marked by the belt of major volcanic vents on Kruzof Island. In many places deep erosion by former glaciers along the direction of strike of faults, joints, bedding, or foliation now emphasizes these features. Some lineaments probably were formed by glacial erosion independent of bedrock structure.

EARTHQUAKE PROBABILITY

Accurate prediction of the place and 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 coast of the Pacific Ocean. For the Sitka area, the evaluation of earthquake probability is based on two factors: (1) the local seismicity as determined from historic records, and (2) the local geologic and tectonic setting. The regional aspects of the two factors, and other information on earthquake probability for southeastern Alaska, were considered by Lemke and Yehle (1972b).

Seismicity

The Sitka area lies within the broad region of earthquake activity that includes much of southeastern Alaska, southwestern Yukon, and northwestern and coastal British Columbia. Unfortunately, the written record of earthquakes in this region is meager. There are three reasons: (1) the relatively short time that written records have been kept, (2) the very low population, and (3) the sparsity of permanent seismologic stations in the region.

The earthquakes that have been instrumentally recorded and located by permanent stations during the period 1899 through 1972 are shown on figure 11. Except in rare cases, these earthquakes were shallow (less than about 18 miles (30 km)), and probably behaved like earthquakes originating at similar depths elsewhere in the world; table 5 shows data from similar shallow earthquakes in southern California which have been studied and related to each other. Figure 11 shows that in the region of southeastern Alaska nine earthquakes of magnitude 7 or greater have occurred near the coastline of the Pacific Ocean, and that earthquakes of lesser or unknown magnitudes are widespread (1) in the northern part of the region shown on figure 11 and (2) near the outer coast of the central and southern areas of southeastern Alaska. Microearthquakes are not shown on figure 11 because of a lack of detection owing to their very small size. However, they have been reported from central and southern areas of southeastern Alaska by Tobin and Sykes (1968, p. 3839), Johnson (1972), and Rogers (1972, 1973). Most microearthquakes probably are the result of very small movements along faults at depth; Rogers (1973) believes that many of them are caused by movements of glaciers near tidewater. Some microearthquakes, especially in the Glacier Bay area (fig. 1), may be caused by isostatic rebound of land following the intensive melting and retreat of large glaciers that started a few hundred years ago.

On figure 11 the following large- and moderate-sized earthquakes are located within 100 miles (160 km) of Sitka: three of magnitude 7 or greater (designations "P," "H," and "Q," respectively, fig. 11), two of magnitude 6 or greater but less than 7 (designations "M" and "R"), and six of magnitude 5 or greater but less than 6 (not designated by letter).

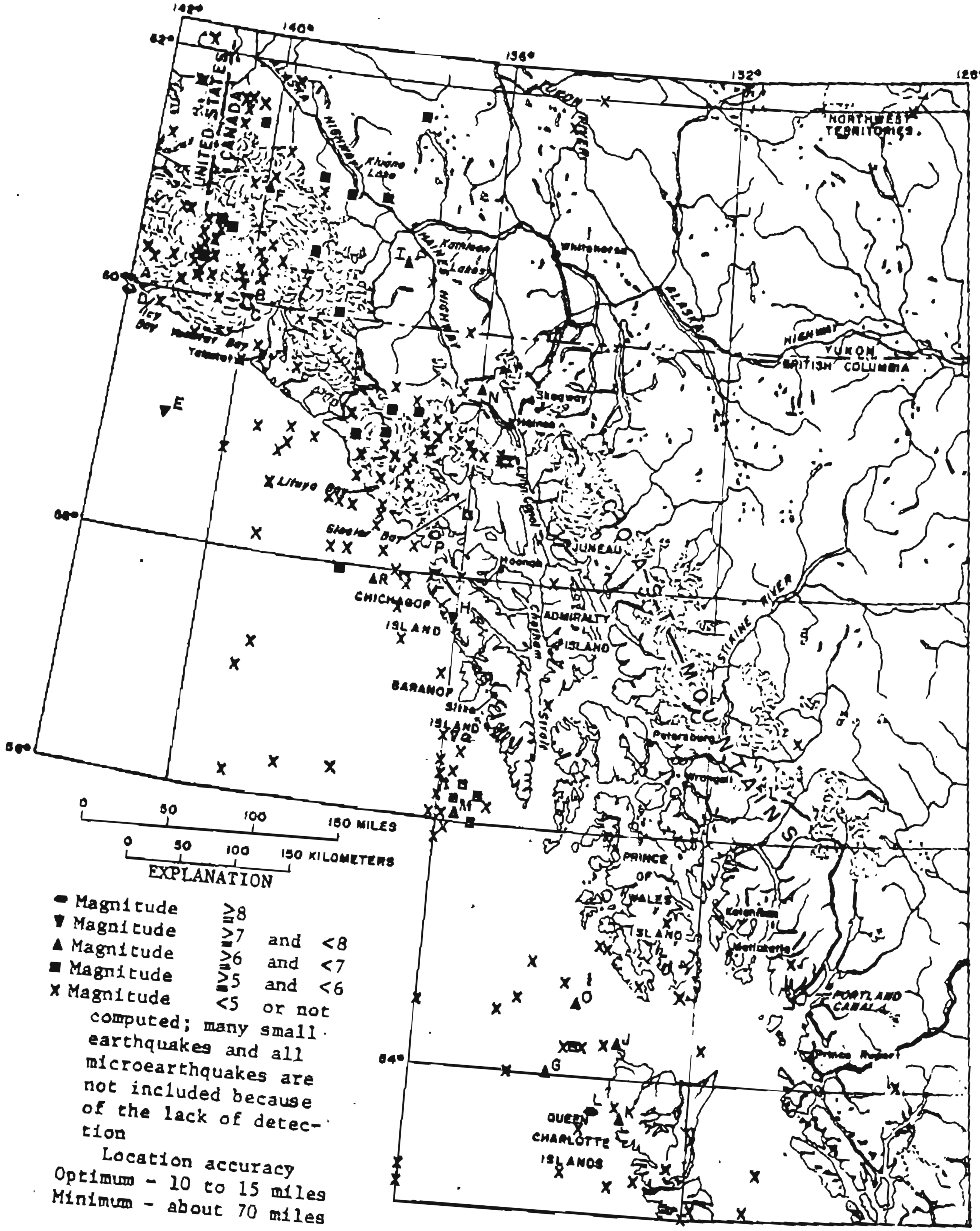


Figure 11.--(See facing page for caption.)

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
Q	July 30, 1972	7.1-7.6
R	July 1, 1973	6.7

Figure 11.--Map showing locations of epicenters and approximate magnitude of earthquakes in southeastern Alaska and adjacent areas, 1899-1972, and July 1, 1973. Data from Canada Dept. Energy, Mines and Resources, Seismological Service (1953, 1955, 1956, 1961-1963, 1966, 1969-1973), Davis and Echols (1962), Internat. Seismological Centre (1967-1972), Milne (1963), Tobin and Sykes (1968), U.S. Coast and Geodetic Survey (1930-1970, 1964-1970, 1969), Wood (1966), U.S. Natl. Oceanic and Atmospheric Adm. (1971, 1972, 1973a, b), Lander (1973), and Page and Gawthrop (1973; written commun., 1973).

Table 4.--Partial list of earthquakes felt and possibly felt at Sitka, Alaska,

1832 through 1972, and July 1, 1973

Date[1]	Comment[2]	Reference[3]	Distance, miles (and km), and direction to epicenter shown on fig. 11	Magnitude	Possible radius of perceptibility, miles (and km) (Gutenberg and Richter, 1956)	Distance, miles (and km), direction, and place nearest Sitka at which felt
Dec. 1832	Quite strong----------	1	?	?	----------	----------
Dec. 15, 1843	Two light shocks----------	2	?	?	----------	----------
Dec. 16, 1843	Strong shock 3 sec. long, and a feeble shock.	2	?	?	----------	----------
Apr. 6, 1847	Very severe; seven shocks; ground crack, "Lincoln St."	2, 3	?	?	----------	----------
Apr. 21, 1861	Shaking----------	2	?	?	----------	----------
Oct. 26, 1880	Severe shock 18 sec., ground-surface waves, three later slight shocks (see description, table 6).	4	?	?	----------	----------
Oct. 27, 1880	Five slight to sharp shocks-	4	?	?	----------	----------
Oct. 29, 1880	Five shocks----------	4	?	?	----------	----------
Nov. 13, 1880	Shock----------	4	?	?	----------	----------
Nov. 14, 1880	Two shocks, first 6 sec. long.	4	?	?	----------	----------
Sept. 4, 1899	Felt?----------	2	320 (510) NW	~8.3	>360 (>575)	95 (150) NE Juneau.
Sept. 10, 1899	Very slight shock----------	2	270 (430) NW	~8.6	>360 (>575)	----------
Sept. 23, 1899	Felt? (Possibly felt, according to Tarr and Martin, 1912.)	2	?	?	----------	----------
Oct. 9, 1900	Felt?----------	2	320 (510) NW	8.3	>360 (>575)	170 (270) N Skagway.
Sept. 24, 1907	Very pronounced shock----------	5	?	?	----------	----------
Oct. 5, 1907	Felt?----------	2	?	?	----------	35 (55) NE near Angoon.
May 15, 1908	Slight shock----------	2	250 (400) NW	7	240 (380)	----------
Feb. 16, 1909	----do----------	2	?	?	----------	----------
July 11, 1909	Distinct shock, III----------	2	?	?	----------	----------
Mar. 14, 1910	Felt----------	6	?	?	----------	----------
July 7, 1910	----do----------	6	?	?	----------	----------
Nov. 21, 1912	Moderate shock----------	6	?	?	----------	----------
Dec. 15, 1917	Heaviest shock in years-----	6	?	?	----------	----------
Mar. 18, 1919	Felt?----------	7	80 (130) SW	?	----------	----------
Dec. 15, 1919	Felt----------	8	?	?	----------	----------
May 8, 1920	Felt?----------	7	80 (130) SW	?	----------	----------
Apr. 25, 1923	----do----------	8	170 (270) NW	5.75	125 (200)	95 (150) NE Juneau.
June 22, 1923	----do----------	7	75 (120) SW	?	?	----------
Oct. 25, 1925	----do----------	7	75 (120) SW	?	?	----------
Oct. 24, 1927	Felt; cracks in some buildings.	6	55 (90) NW	7.1	260 (415)	----------
Nov. 13, 1927	Generally felt----------	6	75 (120) SW	?	----------	----------
Nov. 21, 1927	Felt----------	6	75 (120) SW	?	----------	----------
Dec. 31, 1927	----do----------	6	75 (120) SW	?	----------	----------
Mar. 3, 1929	Two shocks----------	6	?	?	----------	----------
Sept. 1, 1929	Felt----------	6	?	?	----------	----------
Dec. 10, 1932	Felt by a few----------	6	?	?	----------	----------
May 4, 1934	Felt----------	6	?	?	----------	----------
May 29, 1936	----do----------	6	?	?	----------	----------
Sept. 28, 1937	Felt?----------	6	?	?	----------	75 (115) N Hoonah.
Oct. 15, 1945	Felt----------	8	210 (335) NW	?	----------	----------
Nov. 16, 1945	----do----------	9	75 (120) NW	~5.6	120 (190)	----------
Apr. 30, 1947	----do----------	8	195 (310) NW	?	?	----------
Nov. 30, 1948	Felt?----------	8	?	?	----------	55 (90) SSW Little Port Walter.
Aug. 22, 1949	Felt----------	3	250 (400) SSE	8.1	>360 (>575)	----------
Oct. 31, 1949	Felt and felt?----------	10 10	75 (120) SW	6.5 and ~6.	180 (290), and 132 (210).	----------

Table 4.--Partial list of earthquakes felt and possibly felt at Sitka, Alaska, 1832 through 1972, and July 1, 1973--Continued

Date[1]	Comment[2]	Reference[3]	Distance, miles (and km), and direction to epicenter shown on fig. 11	Magnitude	Possible radius of perceptibility, miles (and km) (Gutenberg and Richter, 1956)	Distance, miles (and km), direction, and place nearest Sitka at which felt
Mar. 9, 1952	Felt	6	175 (280) NNW	6	132 (210)	---
Sept. 28, 1952	----do	6	170 (270) NW	?	---	---
Oct. 28, 1955	----do	6	145 (230) NW	?	---	---
Apr. 27, 1956	Felt?	6	?	?	---	50 (80) NW Chichagof.
Nov. 17, 1956	----do	6	190 (300) SSE	6.5	180 (290)	95 (150) ESE Petersburg.
June 1, 1957	----do	10	100 (160) NW	?	---	---
June 5, 1957	----do	7	80 (130) NNW	?	---	---
June 23, 1957	Felt	6	115 (185) NW	~5.6	120 (190)	---
Apr. 9, 1958	----do	6	165 (265) SW	?	---	---
May 5, 1958	V, felt by nearly all, numerous alarmed.	6	60 (95) NW	?	---	---
July 10, 1958	VI, VII	11, 6	100 (160) NNW	~8	360 (575)	---
July 13, 1958	Felt	6	85 (135) NW	~5.6	120 (190)	---
July 17, 1958	----do	6	80 (130) NW	?	---	---
July 8, 1963	----do	6	30 (50) E	3.7	35 (55)	---
Mar. 28, 1964	II, not felt Japonski Island.	6	525 (840) NW	8.4	>360 (>575)	---
Mar. 29, 1964	Felt, at Japonski Island	6	?	?	---	---
Mar. 25, 1966	Felt	6	37 (60) SW	~4.7	80 (130)	---
Apr. 16, 1966	Felt?	6	37 (60) SW	4.1	52 (85)	---
Oct. 10, 1966	----do	6	30 (50) WNW	4.8	85 (135)	---
Apr. 12, 1967	Felt	6	65 (105) SSW	4.4	68 (110)	---
July 15, 1971	----do	6	210 (335) SSE	5.2	100 (160)	---
July 30, 1972	VI+, strong; felt for probably 40 sec.; many aftershocks felt.	6, 12	30 (48) SW	7.1-7.6	~250 (~450)	---
Aug. 4, 1972	II	6, 12	65 (105) SW	5.0	90 (145)	---
Aug. 4, 1972	V, probably several aftershocks felt.	6, 12	60 (95) S	5.8	125 (200)	---
Aug. 15, 1972	III	6, 12	55 (90) SSW	5.0T	90 (145)	---
Nov. 17, 1972	Felt	6	75 (120) S	5.0	90 (145)	---
Dec. 8, 1972	Felt?	6	57 (90) SW	4.2	58 (95)	---
July 1, 1973	Felt. Minor damage	6	90 (145) NW	6.7	200 (320)	---

[1]Dates are u.t. (universal time) except first 10 entries; among these, only entries of 1832, 1843, 1848, and 1861 might be Julian Calendar (12 days after Gregorian Calendar in 19th century); all other entries use Gregorian (present-day) Calendar.

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

Felt?, Earthquake possibly felt at Sitka but as far as can be determined there is no readily available published report of the event's being felt at Sitka. However, an earthquake did occur, known because of (1) a published report of its being felt elsewhere in the region, and (or) (2) an instrumental record and epicenter plot (fig. 11) of the earthquake by seismologists. (Tabulation based on (1) radius of average distance perceptibility of earthquakes as described by Gutenberg (1956, p. 141) if epicenter and magnitude are known, and (2) general evaluation of regional geologic structure.) Newspapers published at Sitka were not examined; these probably would provide many additional accounts of earthquakes.

III, Published report of earthquake intensity, Modified Mercalli intensity scale (see table 5).

[3] 1 Krause (1885).
2 Tarr and Martin (1912).
3 L. E. Thielke (Sitka Historical Soc., oral commun., 1965); M. Reid (Sitka Borough Office, oral commun., 1971).
4 Monthly Weather Review, U.S. War Department (1881).
5 Reported in the Fairbanks [Alaska] Daily News for September 24, 1907.
6 U.S. Coast and Geodetic Survey (1930-1970); Hock (1958); Eppley (1965); Wood (1966); U.S. National Oceanic and Atmospheric Administration (1973a, b); or Lander (1973).
7 Milne (1956 or 1963).
8 U.S. Weather Bureau (1918-1958).
9 Davis and Echols (1962).
10 Tobin and Sykes (1968); Sykes (1971).
11 Davis and Sanders (1960).
12 Page and Gawthrop (1973, written commun., 1973).

Table 5.--Approximate relations between earthquake magnitude, energy, ground acceleration, acceleration in relation to gravity, and intensity (modified from U.S. Atomic Energy Commission, 1963)[1]

M[2]	E[3]	a[4]	a/g[5]	I[6]	
	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

(For explanation of footnotes see facing page.)

Table 5.--(Explanation of footnotes)

[1]These relations are thought to be provisionally valid for many of the earthquakes of magnitude less than 7.7 that occur or may occur in the Sitka area. The relations, however, were developed chiefly from data on southern California earthquakes having depths of about 10 miles (16 km) and magnitudes less than about 7.7; for earthquakes of higher magnitude the relationships between some of the columns is largely theoretical (Gutenberg and Richter, 1956; Hodgson, 1966). The generalized nature of relationships is stressed because records even from the same earthquake may not relate to each other exactly as shown. Instead, there may be recordings of values that are higher or lower than shown. One example is the February 9, 1971, San Fernando, California, earthquake (magnitude 6.6) that locally developed very high ground accelerations of about 1.0 g, although in general the accelerations were between 0.2 g and 0.4 g (Maley and Cloud, 1971; Page and others, 1972). Another example is the July 30, 1972, Sitka, Alaska, earthquake (magnitude 7.1 to 7.6) that developed accelerations of 0.06 g to 0.09 g (Lander, 1973). These were lower values than relations shown.

[2]M, magnitude, scale according to Richter (1958).

[3]E, energy in ergs (10^{-7} m^2 kg/s^2).

[4]a, ground acceleration in cm/s^2.

[5]a/g, ground acceleration in relation to the acceleration of gravity, 32.2 ft/s^2 (981 cm/s^2), the approximate value at 45° lat (adopted as a standard by the Internat. Committee on Weights and Measures).

[6]I, Modified Mercalli intensity scale, abridged from Wood and Neumann (1931).

Table 4 gives a list of earthquakes felt and possibly felt at Sitka from 1832 through 1972 as compiled and interpreted from readily available published reports and instrumental records from permanent seismologic stations. Among the major earthquakes listed, the maximum intensities (Modified Mercalli scale, table 5) of shocks felt at Sitka were VI or VII during the July 10, 1958, earthquake (designation "P," fig. 11) and were in the upper range of VI during the July 30, 1972, earthquake (designation "Q," fig. 11). The October 26, 1880, earthquake also probably was major, but evaluation of data by eyewitnesses (table 6) is difficult. However, because of the duration of shaking (at least 18 seconds), the large number of aftershocks, and the large area of affect from Hoonah in central southeastern Alaska to coastal British Columbia (fig. 1; Rockwood, 1881; U.S. War Dept., 1881), it is presumed that the earthquake was major.

The July 10, 1958, earthquake was strongly felt, and lasted about 30 seconds at Sitka (K. Kravens, former Chief, Sitka Observatory, oral commun., 1965). Damage, however, was minor, with reports of bottles and store merchandise falling from shelves, one chimney toppling, and a concrete basement cracking (U.S. Coast and Geod. Survey, 1960). A small wave was recorded on the tidal gage (table 8).

The major earthquake of July 30, 1972, has been studied by several persons from different organizations. Lander (1973) reported an epicentral distance from Sitka of 25 miles (40 km), a shallow depth, and a magnitude value that varied from 7.1 to 7.6, on the basis of data from a group of permanent seismologic stations. R. A. Page (written commun., 1973) and R. A. Page and W. H. Gawthrop (written commun., 1973), using a slightly different set of data, reported a magnitude of 7.3 and an epicentral distance of 30 miles (48 km). The former Seismological Field Survey group (previously part of the U.S. Natl. Oceanic and Atmospheric Adm. and now part of the U.S. Geological Survey) noted on the strong-motion accelerograph at the Sitka Observatory that maximum acceleration values for the three mutually perpendicular motions of the instrument founded on bedrock (graywacke) varied from 6 to 9 percent of the acceleration of gravity and that periods of vibration varied from 0.1 to 0.2 seconds (Lander, 1973). Motion was felt for about 40 seconds.

Damage to Sitka was minor, and the Seismological Field Survey group reported only that some walls and plaster cracked, a few chimneys cracked (some of which were overturned), and that goods fell from shelves in grocery stores and some homes. There were some accounts of ground waves on muskeg and similar ground; at one place waves developed that were as high as 4 feet (1.2 m) (W. E. Osbakken, Chief, Sitka Observatory, oral commun., 1973; P. B. Trainer, Colorado Univ., written commun., 1973). The relative displacement of two other much firmer types of ground was registered on seismoscopes. Though less accurate than accelerographs, seismoscopes can provide relative values for ground motion that can be compared to data from more accurate instruments, like accelerographs (Hudson and Cloud, 1967). Maley and Silverstein (1973) reported that the average relative displacement registered on four seismoscopes in buildings founded on bedrock (graywacke) or on a few feet of surficial deposits over bedrock was 0.37 inch (0.94 cm), whereas the

Table 6.--Sequence of events at Sitka, Alaska, during the earthquakes of October 1880

[Part of eyewitness account, U.S. War Dept., 1881]

Local time	Description
Tues., Oct. 26	
1:20 p.m.	Within an interval of 18 sec the following sequence of events occurred: (1) rumbling noise, (2) regular upheaval of buildings in turn during passage of ground-surface wave traveling from true east to west, (3) severe upheaval with noise of splitting and cracking in and beneath the ground, (4) slight shock with apparent return ground-surface wave
2:14 p.m.	Slight shock with little vibration
8:46 p.m.	Two shocks coming from true east
Wed., Oct. 27	
5:35 a.m.	Two short and sharp shocks from magnetic east to west, rapid movements; however, oscillations north to south and very perceptible
9:15 p.m.	Sharp shock from southwest to northeast
11:04 1/3 p.m.	Slight shock from east to west, low rumbling noise for 1 min 8 sec
11:45 p.m.	Same
Thurs., Oct. 28	No perceptible upheaval, but during part of afternoon and night a few people sensed what might be called a quivering of the air. Nervous persons appeared to be very buoyant and restless while other persons complained of loss of appetite and nausea
Fri., Oct. 29	
1:05 a.m.	Shock of considerable duration
6:38 a.m.	Sharp shock with oscillation from southeast to northwest, long rumbling noise
11:58 1/2 a.m.	Three shocks, first two in rapid succession; the third evidently was the return or settling back of the crust of the earth. Direction from northeast to southwest
Late Fri.	For at least 15 min a sensation as if some kind of an enveloping electrical wave, current, or pressure were passing from east to west

value was 0.45 inch (1.24 cm) on a seismoscope installed in a building constructed partly on reworked and undisturbed volcanic ash at least 20 feet (6.1 m) thick overlying bedrock (graywacke). Thus, the mixture of volcanic ash appears to have displayed a motion response to the earthquake that was slightly greater than that of the bedrock.

There were numerous reports of effects of the earthquake on large bodies of water (Lander, 1973). Many such bodies had their surfaces rippled or agitated by the shock. Several persons on boats underway reported that at the onset of the earthquake it felt like hitting a rock or whale. Other persons reported a rapid, heavy hammering on their boat hulls. A group of earthquake-generated waves as much as 0.5 foot (0.15 m) high was recorded on the tidal gage (table 8).

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

In some earthquake regions of the world a close relation has been established between earthquakes and specific faults. In most of southeastern Alaska, earthquake epicenters are located at best within only 10 to 15 miles (16-24 km), and data on faults generally are lacking because of concealment by water or surficial deposits. Nevertheless, there appears to be a strong relation between some extensive groups of earthquakes and certain zones of faults. One example is the broad belt of epicenters of large earthquakes and many moderate and small earthquakes shown on figure 11 that very roughly parallels the coast of the Pacific Ocean. These earthquakes apparently are caused by subsurface movements along faults within the Fairweather-Queen Charlotte Islands fault zone and the connecting Chugach-St. Elias faults (figs. 8, 9). It must be pointed out, however, that movement along some faults may be a fault-creep type of motion unaccompanied by earthquakes.

The Fairweather and Queen Charlotte Islands faults and the Chugach-St. Elias fault are active at depth, as manifested by the great number of instrumentally recorded earthquakes that occur in the general region. Sometimes rupture (displacement) along faults extends up to the ground surface. Rupture at the surface occurred near the connection of the Fairweather and Chugach-St. Elias faults during the largest earthquake of September 10, 1899 (Tarr and Martin, 1912, p. 36), and at several locations along the Fairweather fault during the earthquake of July 10, 1958 (Tocher, 1960). Subsurface faulting is continuing along the onland part of the Fairweather fault, as interpreted from the microearthquakes detected by Page (1969) at a single locality along the surface trace of the fault during a 3-day period in 1968. Along the offshore part of the Fairweather fault nearest Sitka, current activity is indicated by the earthquakes (fig. 11) recorded by distant seismograph stations, and by a week of microearthquake detection in the Sitka area by Tobin and Sykes (1968, p. 3839). In addition, more than 100 aftershocks of the July 30, 1972, earthquake, some as small as microearthquakes, were located by Page and Gawthrop (1973; written commun., 1973) within a linear area about 119 miles (190 km) long and less than 6.2 miles (10 km) wide (Page, 1973). The area is considered to mark the approximate boundary of the fault, within the Fairweather fault zone, that was active during and after the July 30, 1972, earthquake event.

Movement along parts of the Fairweather-Queen Charlotte Islands fault system may have begun after the middle Eocene (Plafker, 1972, 1973), whereas the Chugach-St. Elias and associated faults have been active since at least the late Cenozoic (Plafker, 1969, 1971).

In the vicinity of the Chatham Strait fault (fig. 9), the segment of the Denali fault system nearest Sitka, felt or instrumented earthquakes are rare (fig. 11). In addition, no local microearthquakes from the Chatham Strait area were recorded during a microearthquake-detection study in July 1970 (Johnson, 1972; Johnson and others, 1972) nor during a total of about a year of intermittent recordings, from 1968 through 1971, by the Canada Geological Survey (Rogers, 1972).

On one basis of geologic consideration it is estimated that movement along the Chatham Strait fault segment of the Denali fault system occurred sometime after the Miocene (Loney and others, 1967, p. S24); on another basis, it is considered to have started in the latest Paleozoic to earliest Mesozoic (Jones and others, 1970) or the Silurian (Ovenshine and Brew, 1972). Because of concealment of the fault, evidence of most recent faulting probably can be determined only by seismic profiling methods. The only known indication of possible Holocene movement is along the south end of Chatham Strait fault west of Coronation Island (fig. 1), where deformation, including faulting of sediments, was interpreted from seismic investigations (Ovenshine and Berg, 1971; Ovenshine and Brew, 1972).

Of the numerous faults and inferred faults that cut Chichagof and Baranof Islands, none clearly relate to the very few earthquakes that have epicenters plotted on land. The northwest ends of the major faults crossing Chichagof Island appear to join the Fairweather fault and thus might be active themselves near these junctions and for short distances southeastward (Page and Gawthrop, 1973; written commun., 1973). That no fault movement is taking place at depth along the Chichagof-Sitka fault in the Sitka area was indicated by Tobin and Sykes (1968) following their short-term microearthquake study, and corroborated by the work of Page and Gawthrop (1973; written commun., 1973).

No historic movement along any of the faults on Chichagof and Baranof Islands has been reported. The most recent fault exposed at the surface is on northwest Chichagof Island, where Rossman (1959) noted minor vertical offset along a 3-mile- (4.8-km-) long fault considered to be of Holocene age. Most faulting on Chichagof, Baranof, and adjacent islands probably took place either in post-Eocene and pre-Miocene time or sometime after Miocene time (Loney and others, 1967, p. 524).

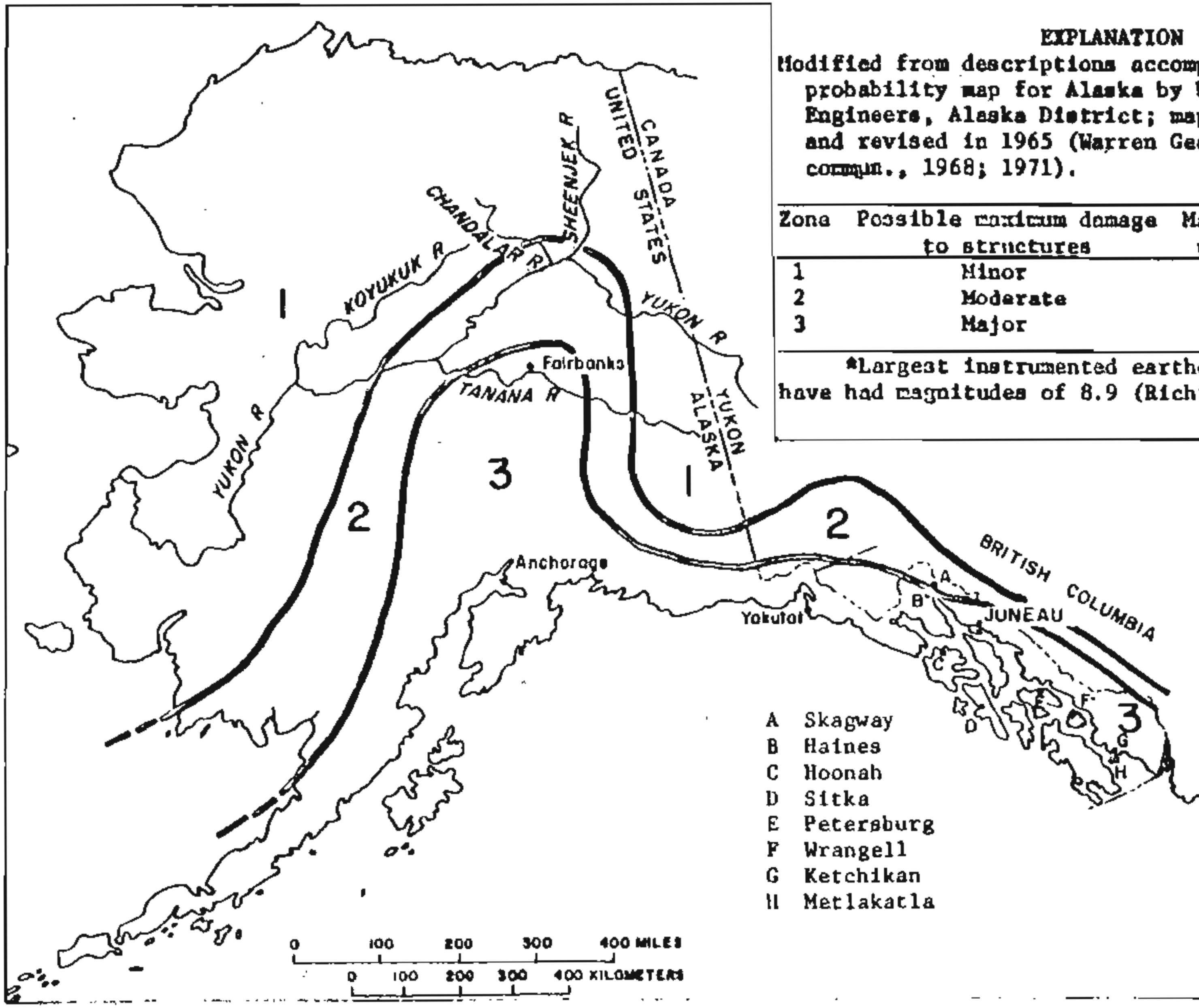
Assessment of earthquake probability in the Sitka area

Only a general assessment of earthquake probability can be made for the Sitka area, because information on seismicity, geologic structure, and tectonic framework of most of the area is limited. Two basic types of maps have been developed by seismologists, geologists, and engineers to portray the probability of earthquakes occurring in an area. One type considers only the likelihood that earthquakes of a certain size might occur sometime in the future; the second type presents the number of earthquakes of a certain size that are expected to occur during a specific period of time. Both types of maps are based upon the premise that future earthquakes are most likely to occur where past earthquakes have occurred. The longer the period of record, the greater is the total of known earthquakes, and thus the greater is the accuracy of prediction.

As noted, in southeastern Alaska the historic record is short, and geologic and tectonic background information is known only in general terms. As a result, the probability maps here described (figs. 12 through 14) are based solely on the seismic record of earthquakes that were instrumentally located.

The Sitka area is shown on two examples of the first type of earthquake probability map, both of which use earthquakes located through the year 1965. These maps lack prediction of the frequency of occurrence. The first example is the seismic probability map prepared by the U.S. Army Corps of Engineers (fig. 12; Warren George, written commun., 1968, 1971). Their map relates possible damage to earthquake magnitude, and shows the Sitka area in the highest zone, where maximum probable earthquakes are of magnitudes greater than 6.0. The second example is the map included in the 1970 edition of the Uniform Building Code (fig. 13; Internat. Conf. Building Officials, 1970). That map relates possible damage to Modified Mercalli intensities of earthquakes, and shows the Sitka area in the highest zone, where maximum probable earthquakes might have Modified Mercalli intensities of VIII or higher (or a magnitude of more than about 6.5, table 5). The Uniform Building Code portrayal of the Sitka area is identical to the portrayal on seismic probability maps in publications by the U.S. Departments of the Army, the Navy, and the Air Force (1966), and Johnson and Hartman (1969, pl. 49), and in Alaska Industry magazine (1970).

Sitka also is shown on the second, or frequency type of earthquake probability map, which uses earthquakes located through the year 1960. An example of such a map (fig. 14) shows probable peak acceleration of earthquakes as a percent of gravity per unit area per 100 years (Milne and Davenport, 1969; Klohn, 1972). For the Sitka area (fig. 2), the map indicates that a peak acceleration of about 50 to 100 percent gravity (magnitude about 7.2-7.6, table 5) might be expected within any 100-year period. Another example of a frequency map, though not included in this report, is a generalization of acceleration data shown on figure 14, plus equivalent data for the rest of Canada, to form the seismic zone map of Canada (Natl. Research Council Canada, 1970; Stevens and Milne, 1974, p. 148). That map indicates that the Sitka area is in zone 3 (Canada). Ferahian (1970, p. 590) estimated that a major earthquake in zone 3 (Canada) might have a maximum Modified Mercalli intensity of VIII to IX and a horizontal ground acceleration of 50 percent gravity (magnitude about 7.2, table 5) unless comprehensive local data indicate that lesser values are more likely.



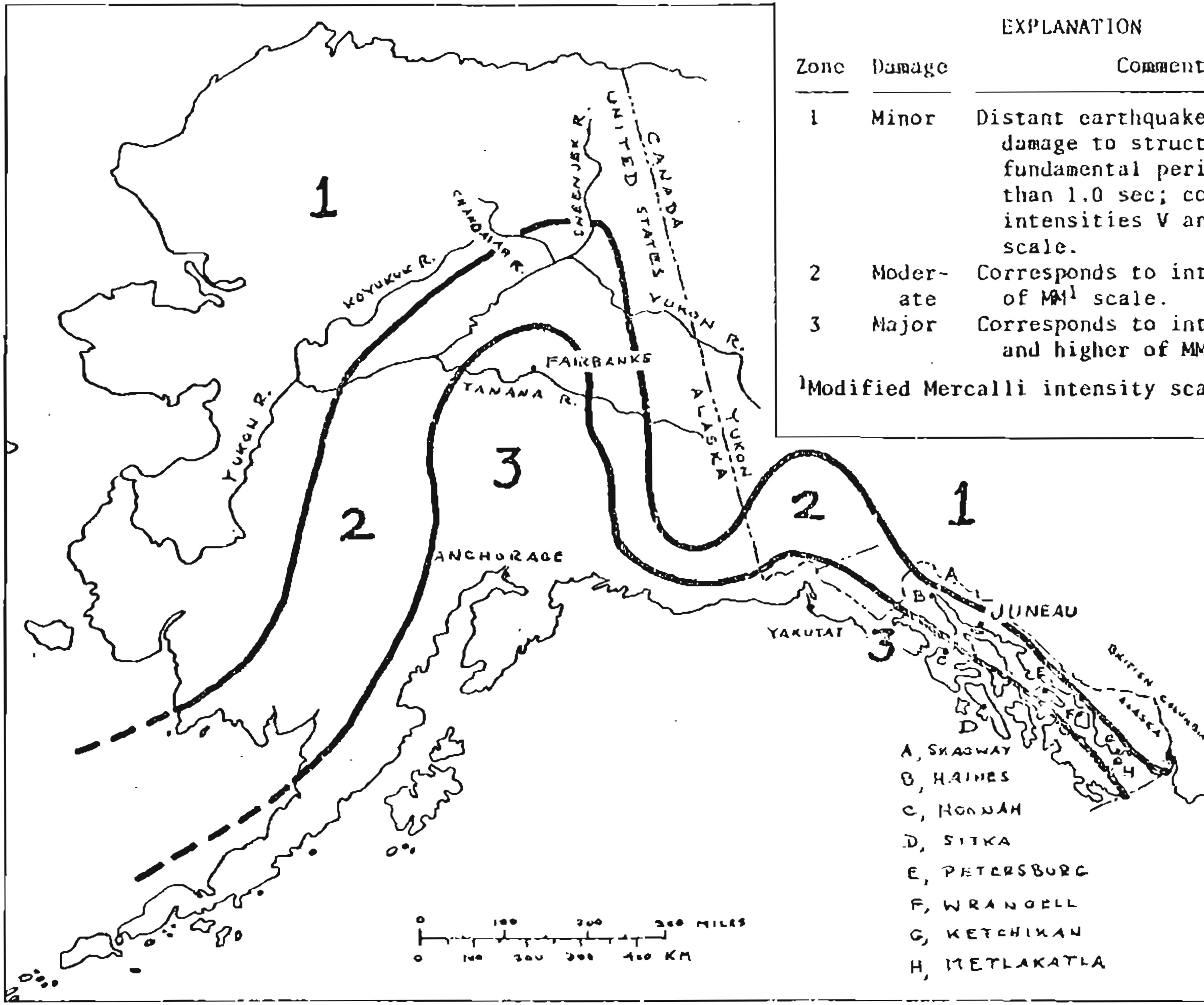
EXPLANATION

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 12.--Seismic probability map for most of Alaska as modified from U.S. Army Corps of Engineers, Alaska District.

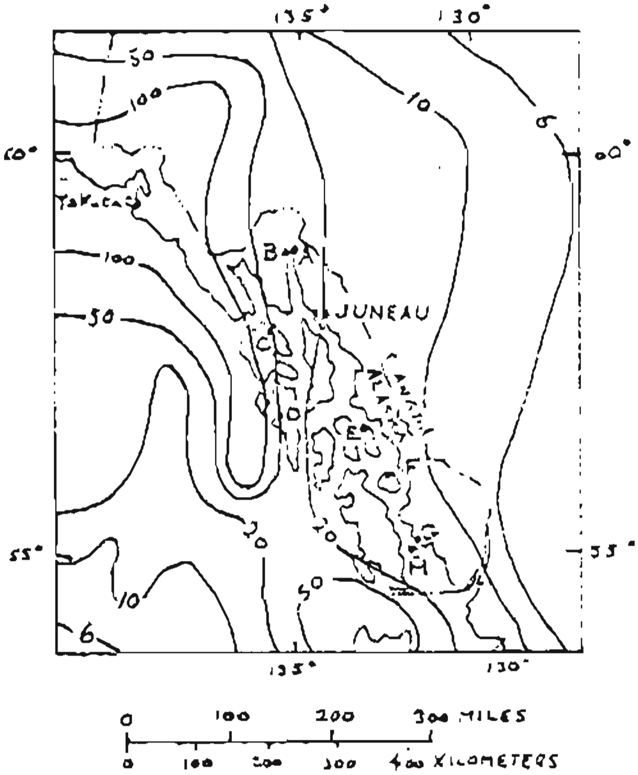


EXPLANATION

Zone	Damage	Comment
1	Minor	Distant earthquakes may cause damage to structures with fundamental periods greater than 1.0 sec; corresponds to intensities V and VI of MM[1] scale.
2	Moderate	Corresponds to intensity VII of MM[1] scale.
3	Major	Corresponds to intensity VIII and higher of MM[1] scale.

[1]Modified Mercalli intensity scale (table 5).

Figure 13.--Seismic zone map of Alaska. Modified from the 1970 edition of the Uniform Building Code (Internat. Conf. Building Officials, 1970).



EXPLANATION

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Contour, showing peak earthquake acceleration as a percent of gravity. See table 5 for approximate relations between earthquake acceleration, magnitude, energy, and intensity.

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

Map is based upon the amount of energy released by the largest earthquake (above magnitude 2.5) that occurred each year in a unit area of 3,860 mi^2 (10,000 km^2) during the period from 1898 through 1960, projected to a 100-year interval.

Figure 14.--One-hundred-year probability map showing distribution of peak earthquake accelerations as percents of gravity for southeastern Alaska and part of adjacent Canada. Modified from Milne and Davenport (1969).

Only general agreement exists between the different seismic probability maps. Absolute agreement probably is not possible because of varying procedures used to analyze limited data covering different periods of time; in addition, none of the maps are recent enough to include the nearby July 30, 1972, earthquake of magnitude about 7.3 or the July 1, 1973, earthquake of magnitude 6.7. These earthquakes might alter some input values to the probability maps.

In summary, it is possible to give only a generalized assessment of earthquake probability in the Sitka area. By considering only the values presented on the three probability maps, it is reasonable to assume that earthquakes of magnitudes as great as 7.6 will continue to occur in the Sitka area. On the other hand, by combining data from seismologic stations with historical earthquake records, and the limited information on geologic structure and tectonic activity, I conclude that an earthquake of magnitude about 8 will occur sometime in the future along a branch of the Fairweather fault in or near the Sitka area. This conclusion is in keeping with those conclusions drawn by Kelleher (1970), Sykes (1971), and Kelleher and Savino (1973), who predicted the location of future large earthquakes along major fault zones like the Fairweather-Queen Charlotte Islands fault zone at sites between earlier large earthquakes. Along the Chichagof-Sitka fault or adjacent faults, the possibility of movements causing large earthquakes is concluded to be very slight. The likelihood cannot be disregarded, however, until detailed geologic and other studies determine the nature of concealed fault zones, the long-term levels of microearthquake activity, and the presence or absence of tectonic fault creep.

INFERRED EFFECTS FROM FUTURE EARTHQUAKES

The following discussion and evaluation of the geologic effects of possible future large earthquakes at Sitka and vicinity are based on the assumption that an earthquake with a magnitude of about 8 will occur in or near the Sitka area sometime in the future. Large earthquakes elsewhere have caused many of the same geologic effects that probably would occur at Sitka and vicinity under similar circumstances. A general description of geologic effects has been given for southeastern Alaska by Lemke and Yehle (1972b).

Specific evaluation of geologic effects for Sitka and vicinity is based partly on observations by others during earthquakes felt at Sitka and partly on determination of the response of local geologic materials inferred from actual response of similar materials during earthquakes elsewhere.

The relation of geologic effects of earthquakes to land-use planning is beyond the scope of this report. An example of a report that does relate geologic effects to planning was prepared by Nichols and Buchanan-Banks (1974), in part for the California Legislature's Committee on Seismic Safety.

Effects from surface movements along faults and other tectonic land-level changes

In southeastern Alaska, movement (rupture) at the ground surface along faults has occurred during only a few earthquakes in historical times. Sudden movements are not common because most fault movements occur at considerable depth. Other tectonic changes, such as sudden uplift or subsidence of land, with or without surface rupture, also have happened only rarely during historic earthquakes.

It is not possible to state which faults in which locations at Sitka and vicinity might move during a future large earthquake. Numerous faults and inferred faults are present in the Sitka area, and many of them trend northwest, parallel or approximately parallel to the Chichagof-Sitka fault or the active Fairweather fault. There is probably only a slight likelihood that sudden tectonic movement will occur and rupture the ground surface along these faults during future earthquakes; sudden tectonic uplift or subsidence also has little likelihood of occurring.

Any sudden surface offset of several inches to several feet along a fault at Sitka and vicinity would cause some damage to buildings, pipelines, bridges, and manmade fills straddling the fault. If sudden tectonic uplift or subsidence of a few inches occurred, it would shake the city but not seriously affect it. However, an uplift or subsidence of several feet would greatly affect it. The most serious effect of a major uplift would be shoaling of harbor areas and attendant navigational difficulties. Conversely, a major subsidence would submerge harbor facilities and shift inland the zone of wave erosion.

Ground shaking

Ground shaking causes much of the damage to manmade structures during major earthquakes. At a given location, the severity of ground shaking is influenced by and varies with several factors:

1. Earthquake mechanism, magnitude, duration, and focal depth and distance of the location from the epicenter.

2. Type and structure of rock between the causative fault and the location.

3. Topography of the bedrock surface, and degree of fracturing and depth of weathering of the rock underlying that surface.

4. Physical characteristics, structure, and thickness of surficial deposits overlying bedrock.

For a given earthquake within a relatively small area like Sitka, the last factor is the most significant. Therefore, the following discussion and evaluation concentrate on the inferred response of the geologic map units, including bedrock, shown on figure 5.

The geologic map units are differentiated into three categories on the basis of generalized observations of their physical characteristics (table 2; fig. 15) and consideration of data on the response of similar geologic materials during major earthquakes elsewhere (table 7). It is well documented that shaking is most severe on geologic materials that are loose, soft, fine grained, water saturated, and thick (where materials are unconsolidated). Conversely, shaking is much less severe on geologic materials that are hard, firm, unfractured, and thin. Figure 15 illustrates how firmness and thickness affect the response of several geologic materials to ground shaking.

Although the observations and considerations on which the three categories were developed are consistent with most studies of ground shaking in many parts of the world, there are exceptions. One example is the unexpected severity of ground shaking sometimes reported in alluvial deposits adjacent to steep slopes formed of bedrock (Richter, 1959, p. 137); another example is the unexpectedly strong shaking recorded on the crests of bedrock ridges (Davis and West, 1973). Several other apparently anomalous responses of geologic materials were described by Hudson (1972, p. 1783).

As far as possible, the geologic map units are arranged within the three categories in a descending order of severity of response. However, the position of units must be regarded as tentative:

Table 7.--Relative shaking response of geologic materials in terms of ground acceleration, amplitude, or intensity

Reference	Locality	Direct comment by author(s) cited
Neumann and Cloud, 1955, p. 205.	General	As much as 10-15 times greater acceleration for unconsolidated soil than for basement rock.
Gutenberg and Richter, 1956, p. 111, 122.	Los Angeles, Calif.	About 2.5 times greater amplitude for alluvium than for weathered granitic bedrock.
Gutenberg, 1957, p. 222.	General	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- to 2.4-unit[2] increase for rather thickly bedded (>33 -ft (10-m)) unconsolidated deposits; water table at depth of <16 ft (5 m) but not at ground surface.
Modified from Barosh, 1969, p. 87, no. 9.	----do------	1.6- to 2.8-unit[2] increase for less thickly bedded (16 – to 33 -ft (5- to 10-m)) unconsolidated deposits; water table within 10 ft (3 m) of ground surface.
Modified from Barosh, 1969, p. 87, no. 11.	----do------	2.3- to 3.0-unit[2] increase near contacts between thin-bedded (<16 -ft (5-m)) unconsolidated deposits and other geologic materials of dissimilar physical properties, expecially density.
Modified from Barosh, 1969, p. 89, no. 14.	----do------	2.0- to 3.9-unit[2] increase for loose unconsolidated deposits overlying bedrock on steep slopes. Equivalent increase for colluvium and some landslides; greatest intensity increase near toe and head of slides.
Modified from Barosh, 1969, p. 88, no. 12, 13.	----do------	2.3- to 3.9-unit[2] increase for muddy and sandy unconsolidated deposits close to rivers and lakes; water table at ground surface. Equivalent increase for unconsolidated deposits with high organic content, peat, muskeg; water table at ground surface. Equivalent increase for manmade fill; greatest intensity increase where loose and water table very near ground surface.

[1]Modified Mercalli earthquake intensity scale (see table 5).

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

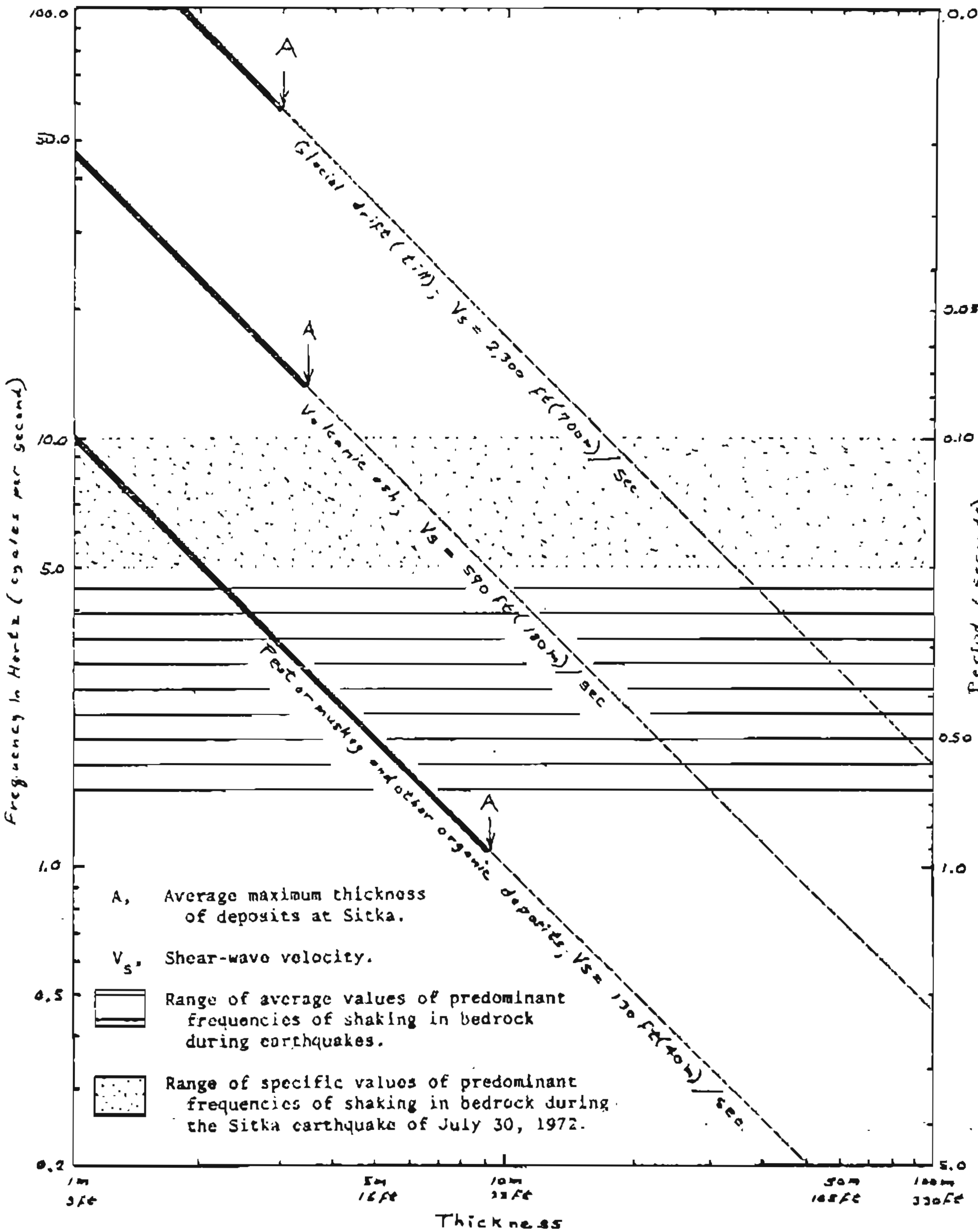

Figure 15.--(See facing page for caption and explanation.)

Figure 15.--Comparison of fundamental frequencies of several surficial deposits at Sitka, Alaska, with predominant frequencies of earthquake shaking in underlying bedrock. Prepared for this report by H. W. Olsen.

EXPLANATION

A surficial deposit amplifies the shaking of underlying bedrock when one or more of the natural vibrational frequencies of the deposit coincide with the predominant frequencies of bedrock shaking. Maximum amplification usually occurs when the fundamental, or lowest, vibrational frequency of a deposit coincides with the predominant frequency of bedrock shaking. On the other hand, no amplification occurs when all the natural vibrational frequencies of the deposit are appreciably higher than the predominant frequencies of bedrock shaking.

The figure shows the relation of fundamental frequency to thickness for three types of deposits, in increasing order of firmness: (1) peat or muskeg and other organic deposits, (2) undisturbed volcanic ash deposits, and (3) glacial drift (till) deposits; the thick-line segments of each relation correspond to the ranges of thickness of these deposits at Sitka. The frequency is also expressed by its reciprocal, the period, on the right-hand side of the figure. The relations are defined by $f = Vs/4H$, where f is the fundamental frequency, Vs is the shear-wave velocity, and H is the thickness of the deposit. The shear-wave velocity of the volcanic ash was inferred from compressional wave velocity data on an undisturbed sample of ash from Sitka, measured by A. F. Chleborad (written commun., 1973). Shear-wave velocities of the glacial drift (till) and peat or muskeg and other organic deposits were estimated from data by others on tills and peats collected elsewhere than Sitka (Clark, 1966, p. 204; MacFarlane, 1969, p. 96; Seed and Idriss, 1970, p. 126).

The figure also shows the range of values for predominant frequencies of bedrock shaking that may be expected at Sitka. The average values given are correlations by Seed, Idriss, and Kiefer (1969, p. 1204) for earthquakes from elsewhere having magnitudes 5.5 to 8.0 and an epicentral distance of 30 miles (48 km). The specific values for the Sitka earthquake of July 30, 1972, are preliminary results of strong-motion accelerograph records from the Sitka Observatory (Lander, 1973, p. 747).

Comparison of the fundamental and predominant frequencies on the figure shows the following: (1) No amplification is to be expected in the till and ash deposits because their fundamental frequencies, and hence also higher vibrational frequencies, exceed the range of expectable predominant frequencies of bedrock motions at Sitka. (2) Amplification is to be expected in the peat or muskeg and other organic deposits, because their range of fundamental frequencies coincides with, and extends below, the range of expectable frequencies in bedrock.

Category 1.--Strongest expectable shaking:

A. Muskeg and other organic deposits (Qm) and embankment fill (Qfe) overlying them.

B. Refuse fill (Qfr).

C. Modern delta deposits of the intertidal zone (Qi).

D. Alluvial deposits (Qa).

E. Embankment fill (Qfe) overlying alluvial deposits (Qa) and modern delta deposits of the intertidal zone (Qi).

F. Volcanic ash deposits (Qv).

Category 2.--Intermediate expectable shaking:

A. Modern beach deposits (Qb).

B. Embankment fill (Qfe) overlying modern beach deposits (Qb), elevated shore and delta deposits (Qeb), and glacial drift deposits (Qd).

C. Elevated shore and delta deposits (Qeb).

D. Modified ground (Qfm).

Category 3.--Least expectable shaking:

A. Glacial drift deposits (Qd).

B. Bedrock of the Sitka Group (KJs).

Geologic units in category 1 (strongest expectable shaking)

Muskeg and other organic deposits (Qm) and embankment fill (Qfe) overlying them.--The muskeg and other organic deposits at Sitka and vicinity should experience very strong shaking because of their high water table, substantial looseness, and average maximum thickness (fig. 15). The looseness of the deposits is indicated by an average shear-wave velocity of 130 feet (40 m)/s estimated from data on similar materials from other areas that probably are applicable to deposits at Sitka. The response of muskeg deposits at Sitka during earthquakes is further illustrated by the presence of ground waves as much as 4 feet (1.2 m) high in muskeg during the July 30, 1972, earthquake (p. 50) and by a felt report of the Alaska earthquake of 1964 (J. D. Ballard, oral commun., 1965) (main shock, magnitude 8.4; distance about 525 miles (840 km); fig. 8).

The degree of shaking at Sitka and vicinity where embankment fills overlie muskeg and other organic deposits (shown on the geologic map by a stippled overprint) should be almost as strong as on the muskeg deposits.

Piles driven through the muskeg and into firmer ground may partly reduce the degree of shaking in structures built on fill overlying muskeg or other organic deposits.

Refuse fill (Qfr).--This type of fill should experience very strong ground shaking during major earthquakes, because the deposit is very loose and generally water saturated. The degree of shaking of the deposit adjacent to the airport runway should be especially severe because of the large quantity of very loose excavated volcanic ash and muskeg and the submerged condition of much of the fill.

Modern delta deposits of the intertidal zone (Qi).--During some major earthquakes, most of these deposits probably will shake strongly because of their looseness, high water content, and, near Indian River, an appreciable thickness. The deposit is not as loose as refuse fill. However, if some modern delta deposits are found to contain numerous beds of loose sand and sandy silt, the deposits should be classified above refuse fill.

Alluvial deposits (Qa).--Most of these deposits probably would shake strongly during some major earthquakes because they are generally loose, have a high water table, and, locally, an appreciable thickness. These deposits are classified as less susceptible to shaking than modern delta deposits because of lesser thicknesses. An area of special consideration is east of the dump near the north end of Kimsham Street, where the upper part of the deposit may contain lenses of loose sand and organic silt. Such materials might shake much more severely than other areas of alluvial deposits.

Embankment fill (Qfe) overlying alluvial deposits (Qa) and modern delta deposits of the intertidal zone (Qi).--Most of these fills probably will shake strongly during some major earthquakes, but less strongly than deposits described above because of better drainage and, generally, a somewhat greater degree of firmness developed during construction. The most severe shaking should be anticipated on fills which are saturated and are probably at least 25 feet (7.6 m) thick. (Fills known to be more than 25 feet thick are symbolized on the geologic map (fig. 5) by a ruled overprint.)

Some fills contain geologic materials that may pose special problems during earthquake shaking. One such fill is the part of the Sitka Airport runway between Fruit Island and Japonski Island, where the fill core is mainly of sand capped by gravel and edged by blocks of riprap. Because of the presumed uniformity of the sand and the saturation and thickness of the fill, it is thought that the fill may shake very strongly during some major earthquakes. (See "Liquefaction," p. 68.) The other fills that may pose special problems are the group of fills containing a high percentage of excavated, dumped, and reworked volcanic ash. Ash deposits, especially where mostly broken down into constituent particles, have a very high porosity. This porosity and the very high water content characteristic of the ash promote a response to vibrations from power equipment that often results in liquefaction of the ash. Although dominant vibrations developed during earthquakes are not likely to be identical to vibrations from power equipment, it is possible that under certain conditions the ash contained in some fills may be shaken severely during some major earthquakes. The greater the percentage of ash in these fills, the greater could be the severity of ground shaking, and the greater the potential for liquefaction or some type of landsliding.

Volcanic ash deposits (Qv).--These deposits are placed in the category of strongest expectable ground shaking because of the ease of physical breakdown of the deposits. If breakdown were not so easy, they would be placed in the category of intermediate expectable shaking. Volcanic ash deposits are unique in that they are firm in the undisturbed state despite their very high porosity and very high water content, but if disturbed, so that they break down into constituent particles, the ash is dilatant (table 2) and often liquefies. The relative firmness of the undisturbed ash is indicated by a shear-wave velocity of 590 feet (180 m)/s, inferred from a compressional wave velocity determined by A. F. Chleborad (written commun., 1973) (fig. 15); the value lies within the range of values reported for at least one type of ash from Japan (Yoshizumi, 1972).

Limited laboratory testing and theoretical investigations were carried out to evaluate whether, during major earthquakes, the undisturbed deposits would remain stable and respond as relatively firm materials, or whether they would incur physical breakdown and respond as a soft, loose deposit. Dynamic laboratory testing of samples (loc. B, fig. 2) by Willard Ellis and P. C. Knodel (U.S. Bur. Reclamation, written commun., 1973) indicates that the material is stable provided that the sum of the static and earthquake-induced shear stresses is less than the static shear strength, which was previously noted (p. 24) to be about 20 lb/in^2 (1.4 kg/cm^2). Theoretical analysis by H. W. Olsen (fig. 15) indicates that earthquake-induced shear stresses are generally much smaller, although they vary with the thickness of the deposits and become substantial for ash deposits thicker than about 30 feet (9 m). High shear stresses occur when the deposit is sufficiently thick for it to amplify bedrock motions. Figure 15 shows that the ash deposits in Sitka and vicinity are generally too thin for significant amplification to take place.

Geologic units in category 2 (intermediate expectable shaking)

Modern beach deposits (Qb).--Shaking of these deposits probably will be less than on deposits described above, because of less thickness and less continuity of beds; shaking should be slightly more severe than on geologic units described below because of a higher water table, and greater looseness for modern beach deposits.

Embankment fill (Qfe) overlying modern beach deposits (Qb), elevated shore and delta deposits (Qeb), and glacial drift deposits (Qd).-- These combinations of deposits probably will shake at an intermediate level during some major earthquakes. The level of shaking is thought to be slightly greater than for units described below because of the possibility of locally slightly greater looseness and softness, and a higher water table, especially near the margins of the deposits.

Elevated shore and delta deposits (Qeb).--The level of shaking of these deposits is expected to be slightly higher than for the unit described below, because of greater thickness, and the possibility near the margins of the deposit of some areas of slightly poorer drainage than the usual well-drained character of the deposit and the presence of some finer grained geologic materials than the sandy gravel comprising most of the deposit.

Modified ground (Qfm).--This deposit should shake the least severely of any units in the intermediate category of ground shaking, because of its thinness, less than 4 feet (1 m), and the firmness of underlying geologic materials.

Geologic units in category 3 (least expectable shaking)

Glacial drift deposits (Qd).--These deposits will experience a low degree of ground shaking during major earthquakes because of their firmness and low moisture content. The average shear-wave velocity of firm tills from elsewhere is 2,300 feet (700 m)/s (fig. 15).

Bedrock of the Sitka Group (KJs).--Ground shaking on bedrock at Sitka and vicinity will be the least severe of any of the geologic units because of the hard, dense nature of the bedrock compared to all other geologic materials. However, along bedrock promontories, along zones of closely spaced joints, and along zones of sheared, broken rock near faults, somewhat stronger shaking should be anticipated.

Compaction

Strong shaking of loose geologic materials during major earthquakes may result in compaction (volume reduction) of some unconsolidated deposits. Compaction often is accompanied by ejection of water or water-sediment mixtures (see p. 69). As a result of such combined processes, the surface of the ground locally may settle as much as several feet (Waller, 1966a, 1968; Lemke, 1967, p. E34). Generally the greatest settlement will occur where (1) the ground-water table is high and some of the water can be expelled; (2) the deposits are loose, thick, and consist of silt- to fine gravel-sized materials; and (3) strong shaking persists for at least a few minutes.

At Sitka and vicinity, most surficial deposits generally are not susceptible to compaction during earthquakes, with the following exceptions: (1) Refuse fills probably are very susceptible to earthquake-induced compaction because of their substantial looseness and high water table. (2) Parts of some embankment fills may be susceptible to compaction because of the high water table and not being mechanically compacted to maximum density during emplacement. (3) The upper part of alluvial deposits east of the Kimsham Street dump locally may be subject to compaction during strong shaking because of a high water table and possible beds of loose sand and organic silt. (4) Some compaction of modern delta deposits near Indian River could be expected because of the likelihood that some beds of loose sand, sandy silt, or fine gravel are present at depth and water could be expelled from the beds.

Liquefaction

Ground shaking during major earthquakes in other areas is known to have caused liquefaction of certain types of saturated, unconsolidated deposits. Especially susceptible are deposits that contain materials with very low cohesion and uniform, well-sorted, fine- to medium-grained particles like coarse silt and fine sand (Seed and Idriss, 1971). A major consequence of liquefaction is that sediments that are not confined at the margin of the body of sediment will tend to flow or spread toward those unconfined margins and will continue to flow or spread as long as pore-water pressures remain high and shaking continues (Youd, 1973). Another major consequence of liquefaction is that it can trigger massive subaerial and subaqueous landslides, especially where slopes are steep and shaking is of long duration.

If liquefaction occurs in saturated sediments that are confined at the margin of the body of sediment, the result is the familiar quicksand condition.

Few geologic units at Sitka and vicinity contain large quantities of sorted material of particle sizes considered susceptible to liquefaction. The following are materials that might be susceptible to liquefaction during some major earthquakes, listed in what is thought to be a decreasing order of susceptibility:

1. Saturated muskeg and excavated, broken-up volcanic ash are common in some refuse fills and occasionally are present in a few embankment fills. Strong shaking associated with certain major earthquakes might liquefy these materials, as they have been seen to liquefy when being transported and shaken in trucks or while being shoved by bulldozers.

2. Some of the upper beds of the alluvial deposits east of the Kimsham Street dump and some of the deeper beds of the Indian River delta may consist of uniform sand or coarse silt that might liquefy during some major earthquakes.

3. The sand comprising most of that part of the large embankment fill forming the airport runway between Fruit Island and Japonski Island is a fill material of special interest because of the apparent uniformity of the sand and the high water table. Both the mechanical compaction of the sand that was developed during construction and the lateral confinement of the sand by the enclosing riprap dike serve to protect the sand from liquefaction during major earthquakes. However, if there were incompletely compacted parts of the sand fill or if the riprap were partly removed by waves, liquefaction might occur locally during ground shaking accompanying some earthquakes.

Reaction of sensitive and quick clays

Large-scale reactions of sensitive and quick clays are very unlikely at Sitka and vicinity because only glacial drift deposits which are dominantly till contain even minor amounts of clay-sized particles. The percentage of clay minerals within the clay-size range of particles is probably very low.

Water-sediment ejection and associated subsidence and ground fracturing

Ejection above the ground surface of water or slurries of water and sediments from certain deposits is common during strong shaking and ground fracturing accompanying some major earthquakes (Davis and Sanders, 1960, p. 227; Waller, 1966a, 1968). The ejection process has been called fountaining or spouting, and some fountains as high as 100 feet (30.5 m) have been reported (Waller, 1968, p. 100). Compaction processes (p. 67) often accompany ejection. Sand is the material most frequently ejected, although, locally, fine gravel and silt are common. Ejection takes place most often where loose sand-sized materials are dominant in a deposit and where the water table is shallow and restricted by a confining layer. Seismic shaking of confined ground water and sediment causes hydrostatic pressure to increase; then, if the confining layer ruptures, the water and sediment erupt from point sources or along ground fractures. Ejected material can cover extensive areas to depths of several feet. The withdrawal of sediments and water from depth, plus compaction processes, may result in differential subsidence of the ground surface, cratering, and additional fracturing of ground.

The only deposits at Sitka and vicinity that might be susceptible to water-sediment ejection are some of the alluvial deposits and modern delta deposits of the intertidal zone. The alluvial deposits east of the north end of Kimsham Street may contain lenses of water-bearing sand sufficiently confined by compact silt in a few places to allow buildup of hydrostatic pressure during earthquake shaking and cause ejection of water-sediment mixtures, local subsidence, and possibly additional fracturing of ground. Some of the possible lenses of sand in delta deposits also might be sufficiently confined by compact layers to react in a like manner.

Earthquake-induced subaerial landslides

Geologic materials may experience a variety of downslope mass movements, termed collectively "landslides," during earthquake-caused ground shaking. Movements may consist of single or multiple landsliding events, land spreading, small-scale slumping, earth flowage, minor creep, or rockfalls (Eckel, 1970). In season, snow avalanching would be common. Loose, water-saturated deposits on steep slopes are especially prone to downslope movement, as are deposits with high contents of clay-sized material. Liquefaction may trigger sliding and flowage of material on even very gentle slopes. Important additional effects are that landslides may block streams and may cause waves in standing bodies of water.

In the Sitka area, small landslides, including numerous rockfalls, occurred on steep slopes during the earthquake of July 30, 1972 (Lander, 1973; W. E. Osbakken, written commun., 1973). Fortunately, most slopes at Sitka and vicinity (figs. 3, 5) are not steep. Deposits that may contain materials susceptible in part to sliding and slumping during some earthquakes are (1) embankment and refuse fill, (2) modern delta deposits and adjacent alluvial deposits, and (3) volcanic ash deposits. Although the water table is high in most of these deposits, none of them contain large quantities of clay-sized material.

Fill areas not edged by riprap or piles probably would experience some slumping and opening of marginal cracks during strong shaking. Within these areas, damage would especially affect road embankments, refuse dumps, fills in water, and fills containing large quantities of excavated volcanic ash or muskeg. However, it must be noted that logging roads constructed on the thick volcanic ash of Kruzof Island were reported as undamaged by the ground shaking accompanying the July 30, 1972, earthquake (W. E. Osbakken, written commun., 1973). The lack of damage may be an indication that only a very limited range of seismic vibrations initiate landsliding in volcanic ash deposits.

The modern delta deposits of the intertidal zone locally might slide if shaking were of sufficiently long duration, because submarine landslides working progressively headward can involve the deposits above water. The large-scale landsliding and seaward spreading of alluvial deposits and subaerial parts of deltas such as occurred at several places during the Alaska earthquake of 1964 (Coulter and Migliaccio, 1966, p. C19; McCulloch, 1966, p. A34; Lemke, 1967, p. E28) are unlikely to occur at any of the deltas at Sitka because, here, deposits are much thinner, overlie bedrock at shallower depth, and seem to be formed of coarser grained sediments than at the other places. However, at Sawmill Creek delta on Silver Bay (fig. 2) the thickness of the delta and the grain size of the sediments apparently are similar to those of deltas that slid during the 1964 Alaska earthquake. Katlian River delta and other deltas, at the east end of Katlian Bay (fig. 2), may have similar characteristics.

The loosened, weathered volcanic ash along the margin of some deposits that lie on moderate to steep slopes locally might slump, slide, or flow during earthquake shaking of long duration.

Earthquake-induced subaqueous landslides

Delta fronts are particularly susceptible to sliding as a result of strong shaking during major earthquakes. Shaking during the 1964 Alaska earthquake triggered landsliding of delta fronts at numerous places in southern Alaska (Kachadoorian, 1965; Coulter and Migliaccio, 1966; McCulloch, 1966; Lemke, 1967). Liquefaction was thought to have triggered and accompanied many of the landslides. Some landslides, in turn, triggered large waves that swept back onto the land.

The fronts of active deltas are inherently unstable, and subaqueous landslides and attendant slurrylike bottom currents have been described as characteristic (Terzhagi, 1956; Mathews and Shepard, 1962; Dott, 1963; Tiffin and others, 1971). Small landslides of parts of delta fronts can occur even during normal sediment accumulation, because of the increasing weight and steepness of slope.

Subaqueous landsliding along part of the front of Indian River delta probably will occur during some major earthquakes; liquefaction of sediments within the delta would trigger additional landslides. The possibility of massive landslides occurring is thought to be limited because of the proximity of bedrock outcroppings, indicating a relatively restricted delta. Along the fronts of the other deltas at Sitka and vicinity (fig. 5), landsliding is rather unlikely. On the other hand, at the fronts of the large deltas near the mouths of Katlian River and Sawmill Creek, and at the several deltas along the shores of Blue Lake (fig. 2), massive subaqueous landslides are possible during shaking accompanying major earthquakes. Landslides in Blue Lake might generate high waves in the lake or clog the outlet works of the dam with sediments moving as slurry flows.

Effects on glaciers and related features

Strong ground shaking and tectonic changes of land level have caused short- and long-term changes in glaciers and related drainage features elsewhere in Alaska (Post, 1967). Only a few small glaciers exist in the Sitka area, so the effects of shaking on the glaciers or streams fed by them will be of very little importance to the area. If a snow cover were present, avalanching would be extensive during major earthquakes and might temporarily block some streams.

Effects on ground water and streamflow

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

At Sitka and vicinity, the ground-water table is near the surface only in alluvial and modern delta deposits, and these are the only deposits that may have more than a very small ground-water flow. Apparently very little use is made of ground water from these deposits. Earthquake effects that would alter ground-water flow include: water-sediment ejection, ground compaction, and sliding or seaward spreading of part of the Indian River delta.

Alterations to streamflow characteristically are an important consequence of major earthquakes. Streams flowing on alluvial deposits can experience a temporarily diminished flow because of water loss into fractures opened by ground shaking. The sediment load of streams often will be increased temporarily following a major earthquake. Streams may be dammed by earthquake-caused landslides, snow avalanches, or broken winter ice. Generally, such dams are destroyed by erosion in a short time, but some of them may persist long enough to form sizable lakes. If the dams break suddenly, severe downstream flooding can result.

Blockage of streamflow by earthquake-caused landslides at Sitka and vicinity (figs. 3, 5) is unlikely, but elsewhere in the Sitka area (fig. 2) the likelihood is high that streams will be dammed, at least temporarily, during some major earthquakes. Because of the possibility of such flooding, prompt aerial inspection of streams, especially those in the Granite, Cascade, and Sawmill Creeks and Indian River drainage basins, should be made after major earthquakes. Damage to manmade structures near these streams would be selective. Flooding because of sudden release of water from breached landslide dams might damage some bridges, roads, parts of hydroelectric-generating facilities, and detention dams used for the Sitka and Japonski Island water supply.

The several hot and mineral springs in the Sitka area (fig. 2) probably would be affected by geysering or surging, fluctuations in water temperature, and at least short-term changes in mineral content. During the earthquake of October 26, 1880, geysering occurred at the Goddard Hot Springs (U.S. War Dept., 1881).

Tsunamis, seiches, and other earthquake-induced water waves

Earthquake-induced water waves often develop during major earthquakes and continue to affect shorelines for some time thereafter. Types of waves include tsunamis, seiches, waves generated by subaqueous and subaerial landslides, and waves generated by local tectonic displacement of land. The following discussion considers each of these types of earthquake-induced waves and the likelihood that they would develop waves of heights that might affect Sitka.

Tsunamis are long-period water waves that occur in groups. They are caused by sudden displacements of water. The largest tsunamis originate where large displacements occur along major thrust faults on the sea floor; smaller displacements, such as apparently occur along strike-slip faults, result in correspondingly smaller waves. Large subaqueous landslides, some of which might be triggered by earthquakes, also are capable of generating large waves. In the deep ocean, groups of tsunami waves travel long distances at great speed and with low height, but as they approach shallow water and smooth-floored areas of the Continental Shelf, and V-shaped bays in particular, their speed decreases greatly, although the height of the waves increases many fold. Wiegel (1970) noted that many waves that strike Pacific Ocean coastal areas have been as high as 40 feet (12.2 m), and that a few waves have been as high as 100 feet (30.5 m). Wave height in shallow water, and whether the wave is of the breaking or nonbreaking type, are controlled largely by the initial size of the wave, configuration of the bottom and shoreline topography, the natural period of oscillation of the water along the shelf or in the bay, and the stage of the tide. These controls, as they applied to the generation of the large tsunami during the 1964 Alaska earthquake, have been discussed by Wilson and Tørum (1968).

At Sitka, several tsunamis and other earthquake-induced waves have been experienced. Some of these are listed in table 8 along with the heights as noted by eyewitnesses or as recorded from tidal gages by personnel of the Sitka Observatory. The maximum wave, crest to trough, was 14.3 feet (4.4 m) high, and arrived March 27, 1964, as one of the group of tsunami waves resulting from the 1964 Alaska earthquake. Much smaller waves occurred August 22, 1949, July 9, 1958, and July 30, 1972, from earthquakes designated "L," "P," and "Q," respectively, on figure 11.

Seiches are water waves that are set in motion as sympathetic oscillations or sloshings of closed or semiclosed bodies of water, caused by the passage of air-pressure disturbances or seismic waves, by the tilting of enclosing basins, or by the impact of large landslides into bodies of water. Basically, the natural period of oscillation of a water body is controlled by the configuration of the containing basin. Examples of the extensive development of seiches or possible seiches between half a foot (0.15 m) and about 25 feet (7.6 m) high that occurred during the 1964 Alaska earthquake were given for lakes and tidal inlets by McCulloch (1966) and McGarr and Vorhis (1968, 1972), and by U.S. Geological Survey unpublished field data recorded in 1964. At Sitka, the seismic seiche developed about 4 minutes after the initial shock, and was 1.0 foot (0.3 m) high; it had a duration of 3.5 minutes (McGarr and Vorhis, 1972). One of the set of water oscillations which, as recorded on the Sitka tidal gage, developed at the time of the arrival of the group of tsunamis, had a height of 3.5 feet (1.1 m) and a period of 30 minutes (Wilson and Tørum, 1968, p. 100). Other earthquakes originating in different regions may generate different seismic waves and thus cause water oscillations of different heights. An example is the July 30, 1972, earthquake that developed a set of waves having a period of 7 to 10 minutes and a height of 0.5 foot (0.15 m) (Lander, 1973); it was not determined which part of the set of waves was due to seiching in Sitka Sound and (or) over the Continental Shelf and which part was due to the impulse tsunami wave. Seiches often are masked by other types of waves.

Massive landslides, both subaerial and subaqueous, have caused small to very large water waves in some tidal inlets and lakes in Alaska during seismic shaking. Delta fronts, especially, can respond to shaking by extensive landsliding and generation of such waves. Several failures that occurred during the 1964 Alaska earthquake generated waves as much as 30 feet (9.1 m) high, and one wave had a maximum vertical runup of 170 feet (51.8 m) (Kachadoorian, 1965; Coulter and Migliaccio, 1966; McCulloch, 1966; Lemke, 1967; Plafker and others, 1969; Von Huene and Cox, 1972). Subaerial landsliding triggered by earthquake shaking also has generated high waves. Probably the world's record height of wave runup was 1,740 feet (530 m), triggered by a landslide in Lituya Bay, 135 miles (215 km) northwest of Sitka (fig. 1) during the July 10, 1958,

Table 8.--Tsunamis and other possibly earthquake induced waves that reached or possibly reached Sitka, Alaska, 1880 through 1970, and July 30, 1972[1]

Date, local time	Max. runup height or amplitude[2], max. rise or fall of wave[3], or max. wave height[4] [ft (and m)]	General region of earthquake and area of generation of tsunami; comments
Oct. 26, 1880	Possible wave[5]--------------	Northeastern North Pacific Ocean(?). "Tidal" wave ran into Whale Bay 36 mi. (58 km) southeast of Sitka; wave also occurred along coast of British Columbia.
Nov. 10, 1938	[2] 0.6 (0.18)---------------	Western Gulf of Alaska near Alaska Peninsula.
Apr. 1, 1946	[2] 1.3 (0.40); [3] 2.6 (0.79)--	Northern North Pacific Ocean near Aleutian Islands.
Dec. 20, 1946	Possible wave, max. height 1.0 (0.30)[6]	Northwestern North Pacific Ocean near Japan.
Aug. 22, 1949	No wave discernible[2]; about 0.2 (0.06)[4]	Northeastern North Pacific Ocean, near Queen Charlotte Islands, British Columbia.
Mar. 4, 1952	[2] 0.3 (0.09)---------------	Northwestern North Pacific Ocean near Japan.
Nov. 4, 1952	[2] 1.0 (0.30); [3] 1.5 (0.46)--	Northwestern North Pacific Ocean near U.S.S.R.
Mar. 9, 1957	[2] 1.3 (0.40); [3] 2.6 (0.79)--	Northern North Pacific Ocean near Aleutian Islands.
July 9, 1958	[2] 0.3 (0.09); about 0.5 (0.15)[4]	Northeastern North Pacific Ocean near southeastern Alaska.
May 22, 1960	[2] 2.0 (0.61); [3] 3.0 (0.91)--	Southeastern South Pacific Ocean near Chile.
Mar. 27, 1964	[2] 7.8 (2.4); [3] 14.3 (4.4)---	Northwestern Gulf of Alaska along south coast of Alaska. Other waves, 1.0 ft (0.3 m)[7] and 3.5 ft (1.1 m)[8] high.
Feb. 3, 1965	[4] 0.5 (0.15)---------------	Northern North Pacific Ocean near Aleutian Islands.
May 16, 1968	[4] 0.2 (0.06)---------------	Northwestern North Pacific Ocean near Japan.
July 30, 1972	[9] 0.5 (0.15)---------------	North Pacific Ocean about 30 mi. (48 km) southwest of Sitka.

[1]Other tsunamis of low height probably have occurred, but detection on tidal records is very difficult. (Newspapers published at Sitka were not examined; these papers probably would provide accounts of additional moderate- to large-sized tsunamis or other abnormal waves.)

[2]Cox and Pararas-Carayannis (1969).

[3]Spaeth and Berkman (1967).

[4]U.S. Coast and Geodetic Survey (1951, 1960, 1967, 1970).

[5]National Weather Review, U.S. War Department (1881).

[6]Dames and Moore (1971).

[7]McGarr and Vorhis (1972).

[8]Wilson and Tørum (1968, p. 100).

[9]Maximum(?) height, from tide gage record (Lander, 1973).

earthquake (Miller, 1960). In the fiords near Sitka, neither distant nor nearby earthquakes in historic time are recorded to have formed waves clearly attributable to subaerial or subaqueous landsliding. However, the "huge" wave that entered Whale Bay, 36 miles (58 km) southeast of Sitka (fig. 1), during the October 26, 1880, earthquake (table 8; U.S. War Dept., 1881) may have been triggered by submarine landslides at the mouth of the bay. That subaerial landslides may have occurred along the slopes of Silver Bay is shown by the presence of topographic features indicative of landslide scars at several locations along the steep margins of the fiord. Such landslides could have been triggered by earthquakes and could have generated waves of substantial height.

Some of the very locally generated waves that caused damage in southern coastal Alaska during the 1964 Alaska earthquake apparently were not triggered by earthquake-induced landslides and were not seiches or tsunamis. Instead, Plafker (1969) and Von Huene and Cox (1972) suggested that these local waves were generated by direct tectonic displacement of the land; wave height probably was controlled by bottom configuration, shore orientation, and by the direction and amount of land displacement. In the Sitka area, earthquake-induced waves of this type have not been recognized.

Waves or other special water movements have occurred in the two largest lakes in the Sitka area during earthquakes. In Blue Lake during the August 22, 1949, earthquake (designation "P," fig. 11) there occurred a sequence of water movements that included a withdrawal and then a return rush of water at one shore location (M. Reid, Sitka Borough Office, oral commun., 1971). The other event happened during the October 26, 1880, earthquake, when the water in Redoubt Lake, 12 miles (19 km) southeast of Sitka (fig. 2), "rose 6 feet [1.8 m] instantly and fell as quick * * *" (U.S. War Dept., 1881). It is suggested that subaqueous landslides and seiche effects may have caused these water motions.

Damage to Sitka from tsunamis, possibly reinforced by seiching, is one of the most likely consequences from earthquakes and should be anticipated. Unfortunately, wave heights and amount of damage cannot be predicted with precision. If all tsunamis were of the nonbreaking type and of low height, and occurred at low tide, no damage would result. On the other hand, if a group of moderately high, breaking-type waves were to strike at highest high tide, extensive damage probably would be sustained by boats, harbors, other low-lying areas, and nearby above-ground fuel tanks (fig. 3).

One can speculate on several possible wave heights of tsunamis that might strike Sitka. When considering these heights, it must be borne in mind that wave focusing and sympathetic resonance of local waves in bays and inlets could increase wave heights by many feet. Analyses of wave heights that might affect the Sitka Airport were prepared by Dames and Moore (1971, p. B5, B6) on the basis of local tsunamis that occurred between 1900 and 1970. One of their analyses indicates a maximum wave height (crest to trough) of at least 20 feet (6.1 m) on the basis of a 100-year-probability interval. The other of their analyses indicates that "there is a 65-percent chance that a tsunami will hit Sitka in a

100-year interval with a maximum wave height of at least 20 feet * * * a 25-percent chance that such [a] wave will occur in 29 years, and a 10-percent [chance] that such a wave will hit * * * in 10 years."

Wiegel (1970) noted that many Pacific Ocean tsunamis have been about 40 feet (12 m) high. At Sitka, a 40-foot wave (amplitude or runup of 20 feet (6 m)) occurring at midtide could flood land below the 20-foot contour interval shown on figure 3. For comparison, a 57-foot (17.4-m) wave occurring at highest high tide and reinforced by a resonant wave of 3.5 feet (1.1 m) could flood most land below the 40-foot contour interval. An even more cautious approach was expressed by the U.S. Coast and Geodetic Survey (1965b), with the warning that all land less than 50 feet (15.2 m) above sea level and within 1 mile (1.6 km) of the coast should be considered potentially endangered after generation of distant tsunamis.

Warnings to southeastern Alaska regarding the arrival time of potentially damaging tsunamis are issued by the National and Alaska Regional Tsunami Warning System of the U.S. National Ocean Survey (Butler, 1971; Cox and Stewart, 1972). For Sitka and vicinity, such warnings of tsunamis that are generated at great distances should allow sufficient time to evacuate the harbor and other low-lying areas. However, it is doubtful that the warning time for tsunamis generated nearby and along the Fairweather-Queen Charlotte Islands fault zone is sufficient. The small waves generated along the fault zone by the nearby July 30, 1972, earthquake presumably arrived 7 minutes after the initial shock (Haas and Trainer, in press).

Wave damage to shore areas from earthquake-triggered subaerial and subaqueous landslides may occur at several places in the Sitka area. The potential for damage is higher along Katlian Bay, Silver Bay, and Blue Lake than at Sitka, because there is a greater possibility of landslides along these bodies of water--with their steep slopes, deep water, and large steep-fronted deltas. Special consideration should be given to the possibility of earthquake-generated waves overtopping Blue Lake dam, particularly when the level of the lake is high.

INFERRED FUTURE EFFECTS FROM GEOLOGICAL HAZARDS OTHER THAN EARTHQUAKES

In addition to the hazards from earthquakes, there is a potential for damage in the Sitka area from other geologic hazards. These include: (1) subaerial and subaqueous landslides, (2) stream floods, (3) high water waves, and (4) volcanic activity.

Subaerial and subaqueous landslides

Numerous slopes in the Sitka area (fig. 2), especially near Katlian Bay, Silver Bay, Blue Lake, and on Kruzof Island, are subject to various types of subaerial and subaqueous landsliding. Although many slope failures occur during earthquakes, as discussed previously, most occur at other times on steep subaerial slopes during seasonally heavy rainfall, rapid snowmelt, seasonal freezing and thawing, or as a result of man's alterations of slopes, or on subaqueous slopes of active deltas during normal oversteepening by deposition. Locations of many of the subaerial landslides in the area are shown on maps prepared by the U.S. Forest Service (Swanston, 1969).

Subaerial landslides at Sitka and vicinity (fig. 3) are rare, because most slopes are only moderate to gentle. Locally, where there are steep slopes, landslides should be considered as possible, especially if the ground surface is underlain by water-saturated material. Excess water probably triggered the landslide in the fall of 1970 that covered Halibut Point Road at a place directly northwest of the map edge of figure 3; the landslide was composed of fill, volcanic ash, and glacial drift.

Steep slopes are common along the mountain front near Sitka and along the valley sides of Granite and Cascade Creeks and Indian River; several narrow landslides along these slopes show on aerial photos taken in 1948. These landslides probably were triggered by heavy rainfall. Slopes along most of Katlian Bay, Silver Bay, and Blue Lake are very steep; consequently, there is a high potential for sliding. Several embayments along the walls of Silver Bay fiord and irregularities of the floor of the bay suggest that large-scale landsliding has occurred in the past (Barnes and others, 1956, p. 6). Examples of several types of landslides caused by man's alteration of slopes are in an area along the highway near the pulp mill and the mouth of Silver Bay fiord, where some of the slopes were oversteepened during initial road construction in the 1950's. Since then, slopes have failed many times. Failures in October 1972 (W. E. Osbakken, written commun., 1973) may have been initiated by a rock-loosening action, accompanied by some rockfalls, during the July 30, 1972, earthquake; the loosened rock finally broke away and descended the slope as a result of the heavy rainfall in September and October 1972. Near the same locality, an earlier landslide occurred in 1942 along the northwest side of the very steep Sawmill Creek valley; heavy rains in September of that year may have triggered the landslide. On the part of northern Kruzof Island included on figure 2, numerous landslides are evident on airphotos taken in 1948; most of them probably took place during periods of heavy rain.

Intermittent subaqueous landslides of various sizes and slurrylike bottom currents characterize actively expanding delta fronts (Shepard, 1956; Mathews and Shepard, 1962; Coulter and Migliaccio, 1966, p. C16). Some landslides possibly may be triggered prematurely by construction activity or by the presence of new fills and wharves because of the alteration of normal flow and movement of long-shore currents and sediments (Terzaghi, 1956, p. 13). In the Sitka area, subaqueous landslides undoubtedly will occur from time to time, thus removing parts of the fronts of active deltas that have become oversteepened.

Stream floods

Most stream flooding in the Sitka area is caused by heavy rains in the fall of the year or by rapid snowmelt. An additional but much less likely cause of flooding is the sudden release of waters impounded behind landslides, other natural obstructions, or manmade dams. Cursory examination of 1965 and earlier airphotos showing streams near Sitka revealed no large natural obstructions to streamflow.

Waterflow records of the Sawmill Creek drainage basin show floods in 1913, 1926, 1936, September 1942, November 1946(?), on September 8, 1948, and in October 1972 (U.S. Bur. Reclamation, 1954; Wells and Love, 1957; Childers, 1970; W. E. Osbakken, written commun., 1973). Indian River probably reflects a similar flood pattern; however, available records were not checked. The effects of extreme floods at Sitka such as might result from the 12-inch (0.3-m) rainfall in 24 hours predicted as a 100-year probability for central Baranof Island (Miller, 1963) would include washouts of some bridges, culverts, and water intakes. Only a few buildings or large fills intrude onto what appear to be prehistoric flood plains, except along "Moore" Creek near Halibut Point Road (fig. 3). As a result, only minor damage to buildings and fills is anticipated from stream flooding.

High water waves

Nonearthquake-caused water waves high enough to damage some harbor structures occasionally might strike shores in the Sitka area. Two types of waves are possible: (1) waves originating from landslides into bays, fiords, and steep-walled lake basins, and (2) storm and other waves originating in the Pacific Ocean.

Large waves could result from subaqueous landsliding of parts of steep deltas fronting in Katlian Bay, Silver Bay, and Blue Lake; however, the likelihood of such waves is probably slight. Waves could also result from subaerial landslides along the fiord or valley walls. Waves generated by these events might be simple impulses that cause backwashing waves and waves on opposing shores, or the wave action might be complex and perhaps include seiches. Although no waves in the Sitka area have been identified as having been caused by landslides, historical observations are limited. On the other hand, many landslide-induced waves have been reported as occurring along the steep-walled fiords and lake basins in Norway, where several hundreds of years of records are available (Jørstad, 1968).

Storm and other types of waves from the Pacific Ocean gradually weaken as they move into Sitka Sound because of the general shoaling of the water, extensive bottom irregularities, and the great number of islands. Even after being weakened, some sets of waves still are very large and could cause extensive damage to exposed shore areas. One illustration of how waves might theoretically weaken compares the height of the probable maximum 100-year storm waves in the Pacific Ocean west of British Columbia, which is 70 feet (21.3 m) (Watts and Faulkner, 1968), to the maximum height of the 100-year storm waves in Sitka Sound near the southeast end of the Sitka Airport runway, which is estimated as being only 32 feet (9.8 m) (Dames and Moore, 1971, p. B9-B13). Considering that the wave runup might have a height of 16 feet (4.9 m) at midtide, such a wave would partly flood shore areas lying at altitudes of 20 feet (6.1 m).

The origin of the other types of waves from the Pacific Ocean that may affect the Sitka area at rare intervals is unknown. They cannot be predicted as to time of occurrence or wave height. Waves of unknown origin reached heights of 18 feet (5.5 m) above mean high water on March 30-31, 1963, along the north coast of the Queen Charlotte Islands and near Prince Rupert, British Columbia (fig. 1; U.S. Coast and Geod. Survey, 1965a, p. 46). It is speculated that the waves were caused by a massive submarine slide along part of the continental slope or by some special long-period ocean wave similar to waves described by Munk (1962) and Rossiter (1971). Another type of long-period ocean wave may be the cause of the "freak" waves and heavy surf that struck part of the Oregon and Washington coast on November 25-26, 1972, as reported in the Denver [Colorado] Post for November 27, 1972. Whether or not low-lying areas at Sitka could be damaged by slide-generated or special long-period ocean waves is not known. It seems plausible to expect, however, that sometime in the future such waves will reach Sitka without warning.

Volcanic activity

Another geologic hazard to the Sitka area is the possibility of renewed volcanic activity on or near Kruzof Island. The closest volcanic vents on Kruzof Island are 7.5 miles (12 km) west of Halibut Point, 10.5 miles (17 km) west-northwest of the center of the city, and 15 miles (24 km) west of Blue Lake (figs. 2, 4). Though quiet outflow of lava would directly affect only a very few people on Kruzof Island itself, other processes associated with volcanic eruptions could cause damage to the works of man. Associated volcanic events, all of which have been experienced during eruptions in other volcanic areas (Crandell and Mullineaux, 1967; Chesterman, 1971), include the following, listed in what is thought to be a decreasing order of likelihood for the Sitka area: (1) ash falls and drifting clouds of gas; (2) earthquakes and all of their associated effects, including water waves; (3) floods, mudflows, and landslides caused by torrential rains; (4) waves generated by violent eruptions of new volcanoes on the sea floor or by impact of high-velocity masses of mud or other debris entering the sea; and (5) showers of fragmental volcanic rubble impelled by large steam explosions.

The probability of future large eruptions on Kruzof Island is unknown, but might be established by several methods (see item 6, p. 83). Nevertheless, in an effort to evaluate the volcanic hazard to Sitka, the evidence for prehistoric, historic, and present-day activity is here considered. In prehistoric times the last major period of eruption included the widespread deposition of airfall ash and lapilli that occurred about 10,000 years ago. These eruptive products overlie much of Chichagof, northern Baranof, and nearby islands (Brew and others, 1969). Volcanic activity on Kruzof Island did not end with the widespread fall of ash, because it is clear that some of the vents and lava flows on Kruzof Island are younger than the widespread ash (Brew and others, 1969) and constitute about 0.06 mile^3 (2.5 km^3) of volcanic deposits. In the Sitka area, two occurrences of a very thin ash deposit located by Heusser (1952, p. 341) may be contemporaneous with the younger vents and flows described on Kruzof Island. The thin ash lies within peat deposits about 3 feet (0.9 m) below the surface and is at least 7 feet (2.1 m) above the approximately 10,000-year-old ash and lapilli deposits. This thin ash suggests volcanic activity perhaps about 3,000 years ago. This date is estimated as the time required to develop 3 feet (0.9 m) of peat, although development time may be as short as 700 years, on the basis of data from other distant areas (Cameron, 1970, p. A23). Two other thin ash layers within peat deposits but at shallower depths were located by Heusser (1960, p. 104) on Kruzof Island, 12 and 30 miles (19 and 48 km) northwest of the city.

No substantiated historic records of volcanic eruptions on Kruzof Island are known, although Becker (1898, p. 13) listed possible eruptions in 1796 and 1841-1842, and Reed (1958, p. 14) noted eruptions mentioned in Tlingit Indian legends. Some indication of the level of volcanic activity on Kruzof Island during the 20th century is contained in the 1904 data of F. E. Wright (U.S. Geol. Survey, unpub. data). He described nonflammable gas as bubbling intermittently from the surface of the lowest lake on the floor of Crater Ridge volcano (fig. 2). Other possible indicators of the level of volcanic activity may be the character of the flow, temperature, and chemical constituents of the mineral and hot springs in the Sitka area and northward. These springs, studied briefly by Waring (1917, p. 32, 91), include (1) the sodium chloride-rich Goddard Hot Springs near the southeast margin of Sitka Sound (fig. 2), (2) a sulfur spring at the south shore of Kruzof Island (fig. 2), and (3) boron-rich hot springs 22 miles (35 km) northeast of Crater Ridge. No other studies of the springs are known. On the basis of research on mineral and hot springs in other volcanic areas, White (1957a, b) and White, Barnes, and O'Neil (1973) noted that local springs do not always reflect the volcanic characteristics of the area. The explanation for the Sitka area hot springs given by Twenhofel and Sainsbury (1958, p. 144) and preferred in this report is that the hot waters are recirculated ground water that moves upward along fault zones or joints cutting bodies of igneous intrusive rocks.

The most likely potential effects on Sitka from volcanic eruptions and associated processes include: (1) Airfall material that could load buildings, blanket the ground, and float on bodies of water. Some ash would settle to the bottom of bodies of water and some of it would be washed to shore. Floating ash might interfere with fishing and shipping operations, clog water intakes and filters, and abrade turbines. If the eruption were large, building roofs might collapse from the weight of accumulated ash and larger sized airfall material. In addition, gas clouds and ash might cause problems to breathing. (2) Volcanic earthquakes and water waves generated by the earthquakes could cause some shaking damage to buildings and wave damage to harbor areas. (3) Ash-laden torrential rains might fall during eruptions and cause stream flooding and mudflows that could endanger bridges, culverts, manmade fills, and water-supply intakes. Rains probably would trigger landslides on moderate and steep slopes in the area.

RECOMMENDATIONS FOR ADDITIONAL STUDIES

The reconnaissance nature and limited time for geologic investigation did not permit the full evaluation of the general geology, potential geologic hazards, or of other geologic factors which would be beneficial to land-use planning in Sitka and vicinity. Therefore, the following recommendations are made for additional investigations that were beyond the scope of this study. These are given in order of importance.

1. Detailed geologic mapping and field study of the Sitka area, utilizing current airphotos and updated topographic maps, should be conducted on a systematic areal basis. The work should include collection of data on distribution and properties of geologic materials, and on joints, faults, and areas of potentially unstable slopes.

2. Extensive offshore geophysical studies are recommended both in Sitka Sound and west of Kruzof, Chichagof, and Baranof Islands to (a) determine the location of faults within the Fairweather-Queen Charlotte Islands fault zone, as suggested similarly by Page (1973, p. 9); (b) determine the stability of geologic materials underlying the continental slope; and (c) determine the relation between faults and the continental slope.

3. The level of earthquake activity along faults and inferred faults in the area should be determined in order to help indicate the location of future large earthquakes. For best results, the study should be continued for at least several years. It will require the installation of seismological instruments of normal sensitivity, similar to those at the Sitka Observatory, and instruments of high sensitivity at several locations both offshore and onshore. Also important are determinations of horizontal and vertical changes in ground positions along faults. Changes might possibly indicate that an earthquake may occur in the very near future or that tectonic creep is occurring along the fault. For a thorough study of large earthquakes, it is very desirable to have groups of seismological instruments operating in the immediate vicinity before the actual event. Rarely is that desire fulfilled because of the great cost of instruments. Therefore, it is urged that, if there are indications of an imminent earthquake, groups of portable seismological instruments be ready for immediate use in the area of interest. Shortly after the July 30, 1972, earthquake, such portable instruments were set up, and valuable data regarding the general location of the active fault that apparently caused that earthquake are now available (Page, 1973; Page and Gawthrop, 1973).

4. Stability of steep subaerial and underwater slopes on Baranof Island near Sitka should be analyzed. Fiord and other valley walls and fronts of deltas need to be evaluated as to areas of greatest potential instability. Although initial detection of unstable subaerial slopes is possible during areal geologic mapping, a separate slope analysis would permit a more thorough evaluation of geologic materials, geologic contacts, ground-water relationships, vegetation, and orientation of joints and minor faults. Also recommended is periodic inspection of steep slopes.

5. Research on the response of excavated volcanic ash to shaking and changes in physical properties and behavior is urged. Although local experience and generalized data given in this report indicate that the material readily liquefies under some types of vibration, both the actual mechanism that causes liquefaction and the possible control are worthy of research.

6. The probability of future eruptions of volcanoes on Kruzof Island should be investigated, along with the relation of a possible offshore extension of the volcanic fissure to the Fairweather fault zone. Determination of future activity depends upon monitoring and interpreting changes in surface topography, microearthquake activity, and heat, gas, and water emissions. Such changes are being studied during the surveillance of Augustine Island volcano in southern coastal Alaska (Harlow and others, 1973; Mauk and Kienle, 1973) and during surveillance of volcanoes in parts of Oregon, Washington, and northern California (Friedman, 1972; Lange and Avent, 1973).

7. Because of the potential for wave damage, a study of the natural oscillation periods of major lakes, fiords, bays, and sounds near Sitka is recommended. The natural period controls the height of seiches and the likelihood of reinforcement of these waves (1) during passage of air-pressure disturbances, (2) during passage of seismic waves, and (3) during water surges developed by distant storms. The oscillation period of Blue Lake might be the most logical to determine first, because of the importance of the dam confining the lake.

GLOSSARY

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

Accelerograph: An instrument designed to permanently record the changes of velocity of bedrock or surficial deposits impelled by earthquake or other vibrations.

Argillite: A fine-grained rock derived from siltstone, claystone, or shale. It has undergone more hardening than these rocks and is intermediate between them and slate.

Dike: A tabular body of igneous intrusive rock that cuts across the structure of the enclosing rocks.

Dilatancy: The increase in bulk volume of a material during any process of nondestructive deformation. It is accompanied by an increase in the volume of interparticle spaces.

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 not complete 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.

Graywacke: A type of very hard fine- to medium-grained sandstone composed of fragments of principally quartz and feldspar and, locally, argillite, slate, and fine-grained rocks of volcanic origin; also may include some lenses of finer or coarser mineral or rock fragments.

Holocene: The most recent epoch in geologic time; it includes the present. Has generally replaced 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 on 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 5.)

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.

Lapilli: Air-ejected, volcanic debris of gravel size (0.079-2.5 in (2-64 mm)); coarser grained than volcanic ash.

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; also the representation of such a ground feature on topographic maps or on airphotos or other remote-sensing imagery.

Liquefaction: The transformation of a material having very low cohesion from a solid state to a liquid state by a process of shock or strain that increases pore-fluid pressure.

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 be detected only 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. A moraine has a topographic expression of its own and 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 worldwide cooling and by major glaciations; also called the "glacial epoch" or Ice Age. The Pleistocene Epoch denotes the time from about two million to ten thousand years ago.

Quick clay: A clay that has a very high sensitivity to disturbance. (See definition for sensitive clay.)

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.

Seismoscope: An instrument that indicates qualitatively the occurrence of strong ground motion developed during earthquakes.

Sensitive clay: A clay that upon being disturbed has its shear resistance substantially reduced.

Shear wave: A type of vibrational wave transmitted by a shearing of material that produces oscillation in a direction perpendicular to the direction of transmission.

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.

Tectonics: The part of geologic study dealing with origin, development, and structural relations of large-sized areas of the earth's crust.

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 (680-960 km) an hour. As they enter shallow coastal waters they can greatly increase in height.

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APPENDIX I

Preliminary examination of volcanic ash and lapilli samples from near Sitka, Alaska. Slightly modified from R. E. Wilcox (U.S. Geological Survey, written commun., 1971).

Ten samples of volcanic ash and lapilli from deposits near Sitka, Alaska (loc. B and C, fig. 2), were examined using a petrographic microscope. Samples were prepared by the following methods: (1) sample crushed to pass U.S. Standard sieve No. 100, 0.0059-inch (0.149-mm), and separated in heavy liquid (specific gravity 2.85) for microscopic examination in immersion mounts, or (2) sample mounted directly in balsam and thin sectioned for petrographic examination.

Upper unit (two samples examined: Nos. 65 AYe-20g, 68 AYe-Si-1j):

Composed mainly of light-brown pumiceous glass granules as much as 0.008 inch (0.2 mm) in diameter with subordinate amounts of lithic basaltic and andesitic grains. The pumice granules are angular to subrounded, vesicular, colorless to pale-yellow glass of refractive index ranging from 1.51 to 1.52. Outer margins of the granules are altered to pale brown. Microphenocrysts of plagioclase and pyroxene are sparsely distributed, and a few phenocrysts of plagioclase and orthopyroxene, rarely clinopyroxene, as much as 0.004 inch (0.1 mm) in length, are seen in thin section. Composition of plagioclase averages about 45-50 percent anorthite, with marked zoning.

Middle unit (three samples examined: Nos. 65 AL-20c, 68 AYe-Si-1h, 68 AYe-Si-1i):

Composed mainly of light- to dark-brown andesitic fragments as much as 0.3 inch (8 mm) in diameter, mostly dense, a few containing vesicles. The fragments in cross section are seen to consist of crowded microlites of plagioclase, pyroxene, and magnetite in a very subordinate matrix of yellow to brown glass of refractive index ranging between 1.535 and 1.545. A few fragments have less crowded microlites and a refractive index of about 1.53. There are scattered phenocrysts of zoned plagioclase (anorthite, 55-60 percent), orthopyroxene, and magnetite. Sparse clinopyroxene phenocrysts are present, and many orthopyroxene phenocrysts carry thin overgrowths of clinopyroxene. A few phenocrysts of apatite were noted in the heavy-mineral concentrate of one sample from locality B, figure 2. A minor number of the fragments are more coarsely crystalline volcanic and metamorphic rocks, and some metamorphic minerals are seen in the heavy-mineral fraction in the same sample noted above.

Lower unit (four samples examined: Nos. 65 AL-20e, 68 AYe-Si-1d, 58 AYe-Si-$1e_1$, 68 AYe-Si-1g):

Composed mainly of dark-brown and dark-gray basaltic to andesitic rock fragments, of both vesicular dark glass and fine crystalline material. Many of the smaller fragments appear to be a brown cryptocrystalline alteration of basaltic glass. Other fragments are so dark that the refractive index of the glass which is probably present could not be determined. Phenocrysts include calcic plagioclase (anorthite, 60-70 percent), olivine, clinopyroxene, and magnetite.

From comparison of refractive indices and the suite of phenocrysts in the three units of the volcanic ash and lapilli deposits it is apparent that the upper unit has appreciably more silica and less iron than do the two underlying units.