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Reconnaissance Engineering Geology of the Wrangell area, Alaska, with Emphasis on Evaluation of Earthquake and Other Geologic Hazards

By

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By Richard W. Lemke

SUMMARY

Purpose of study

The Alaska earthquake of March 27, 1964, pointed up the need for engineering geologic studies of urban areas in seismically active regions. A reconnaissance study of the Wrangell area constitutes part of an overall program to evaluate earthquake and other geologic hazards in most of the larger Alaska coastal communities. The resulting tentative evaluations should be useful in city and regional land-use planning so that new facilities can be built, as nearly as possible, in the best geologic environment.

Geography

The mapped area described in the report, which comprises about 2 square miles (5 km^2) of land in and immediately adjacent to the city of Wrangell, is about 140 miles (225 km) southeast of Juneau and 90 miles (145 km) northwest of Ketchikan. Wrangell, in 1970, had a population of about 2,000 people. Except for two hills, which rise to heights of approximately 400 and 300 feet (122 and 91 m), all of the mapped area lies below 150 feet (46 m) and is characterized by gentle slopes. Drainage generally is poor owing to a pervasive cover of muskeg, and small muskeg ponds abound on flatter surfaces. Zimovia Strait, Eastern Passage, Dry Strait, and other straits and inlets surrounding the mapped area are part of the glacially scoured fiord system that characterizes southeastern Alaska. The Stikine River is continuing to expand the margin of its large delta in the northern part of the mapped area and is supplying a large sediment load to the surrounding offshore areas.

Glaciation and associated land-level changes

Glacier ice has advanced over the area at least once and probably several times during the Pleistocene Epoch. There presently are no glaciers on Wrangell Island but glaciers are present nearby on the mainland. On the basis of the presence of emergent marine deposits, the land in the mapped area has been uplifted at least 200 feet (61 m) since major deglaciation about 13,000 years ago. The rate of relative uplift during the past 50 years has been 0.01 foot (0.3 cm) per year. Most or all of this uplift appears to be due to rebound as a result of deglaciation.

Bedrock

The bedrock consists of a sequence of metamorphic rocks intruded by igneous rocks. The metamorphic rocks are part of the Wrangell-Revillagigedo belt of rocks that extends for many miles to the southeast and to the northwest. The igneous rocks are part of the Coast Range batholith that forms the Coast Range Mountains of the adjacent mainland to the northeast. The metamorphic rocks were formerly sedimentary rocks that probably were deposited at least in part during Paleozoic time and are believed to have been metamorphosed in Mesozoic time. The igneous rocks are quartz diorites and are believed to be of Mesozoic age.

Surficial deposits

The surficial deposits have been divided on the map into the following units on the basis of their time of deposition, mode of origin, and grain size: (1) elevated fine-grained marine deposits (Qem), (2) elevated beach deposits (Qeb), (3) muskeg deposits (Qm), (4) late shore deposits (Qs), and (5) delta deposits of the intertidal zone (Qd). Man-made fill (mf) also is mapped as a separate unit. Till, colluvial deposits, and offshore deposits are not included as map units but are discussed in the report.

Structure

Southeastern Alaska lies within the tectonically active belt that rims the northern Pacific Basin and has been active since at least early Paleozoic time. The outcrop pattern is the result of late Mesozoic and Tertiary deformational, metamorphic, and intrusive events. Large-scale faulting has been common. The two most prominent fault systems in southeastern Alaska and surrounding regions are: (1) the Denali fault system, and (2) the Fairweather-Queen Charlotte Islands fault system. Of the two fault systems, the Fairweather-Queen Charlotte Islands fault system is the more active and of most significance in relation to the Wrangell area. The Wrangell area lies within the northwest trend of the Gravina-Nutzotin belt of fault thrusting. The trends of linear fiords in and near the area may be controlled by faults that at least in places are indicated to have been active in late Pleistocene time. The strike of the schistosity or cleavage of the metamorphic rocks in the area is to the northwest; dips commonly are 30°-45° northeast.

Seismicity of southeastern Alaska

Southeastern Alaska lies in one of the two most seismically active zones in Alaska, a State where 6 percent of the world's shallow earthquakes have been recorded. Between 1899 and 1970, five earthquakes having magnitudes of 8 or greater have occurred in or near southeastern Alaska or in adjacent offshore areas, three have occurred having magnitudes of between 7 and 8, at least eight with magnitudes of between 6 and 7, 15 with magnitudes of between 5 and 6, and about 140 have been recorded with magnitudes of less than 5 or of unassigned magnitudes. All of the earthquakes with magnitudes greater than 8, and a large proportion of the others, appear to be related to the Fairweather-Queen Charlotte Islands fault system or to the connecting Chugach-St. Elias fault to the northwest.

Seismicity of the Wrangell area

There are no recorded epicenters of earthquakes in the Wrangell area and only two epicenters, with magnitudes of 5 or less, within 100 miles (161 km). However, about 25 earthquakes having epicenters elsewhere have been felt or were possibly felt at Wrangell. Swarms of microearthquakes have been recorded in recent years 175, 130, and 50 miles (281, 209, and 80 km), respectively, northwest and north of Wrangell, but only a few were recorded in the immediate vicinity. It is not clear whether the microearthquakes are related to faulting or to glacier movement.

Earthquake probability in the Wrangell area

The placing of the Wrangell area in seismic zone 3, as shown on a seismic probability map prepared by the U.S. Army Corps of Engineers in 1968, seems reasonable to the writer on the basis of present knowledge. This is a zone where the largest expectable earthquakes could have magnitudes greater than 6 and where major damage to manmade structures could be expected. As judged solely from the seismic record, few if any future earthquakes with epicenters in or near the Wrangell area are indicated. However, the seismic record probably is far too short to be fully meaningful. The high earthquake activity of southeastern Alaska as a whole, particularly on the Fairweather-Queen Charlotte Islands fault system, as well as the fact that the local structure is poorly known, makes it prudent to assign a higher risk factor than is indicated solely from the seismic record. As more detailed investigations are made of the faults of the area and a longer seismic record accrues, the evaluation of the earthquake probability of the Wrangell area should be reassessed to determine whether the present evaluation is valid.

Inferred effects from future earthquakes

Inferred effects from earthquakes in the Wrangell area include: (1) surface displacement along faults and other tectonic land changes, (2) ground shaking, (3) compaction, (4) liquefaction in cohesionless materials, (5) earthquake-induced slides and slumps, (6) water-sediment ejection and associated subsidence and ground fracturing, (7) reaction of sensitive and quick clays, (8) effects of tsunamis, seiches, and other abnormal waves, (9) effects of ground water and streamflow, and (10) effects on glaciers and related features. These effects are discussed in the report under their respective topical headings.

If the Wrangell area is strongly shaken by an earthquake, it seems likely that the harbor facilities and other manmade structures in low-lying parts of the city will be the most heavily damaged. This supposition is based on the nature of the geologic units (fig. 3) upon which the facilities are built and upon the proximity of the facilities to the sea. Any nonengineered loose fills that consist of surficial deposits and have been emplaced along the shore to elevate low-lying areas above high tide are expected to be subject to comparatively strong shaking; they also may be subject to settlement, possible liquefaction, water-sediment ejection, and associated ground fracturing. The beach deposits along the shoreline also are expected to be subject to comparatively strong shaking and, where fairly thick, to differential settlement, ground fracturing, landsliding, and possibly to liquefaction. Large-scale submarine sliding appears unlikely on the steeper offshore slopes, such as in the vicinity of Point Shekesti, because of the indicated thinness of sediments. However, where the underwater slopes are gentler and there are greater accumulations of fine-grained sediments, such as is indicated offshore from the lumber mill, moderate to large-scale sliding may occur. The potential for sliding, with resultant damage to docks and other facilities, could be particularly high if the deposits were subject to liquefaction. Local waves generated by earthquake-induced submarine sliding or by subaerial landsliding into water probably have the greatest destructive potential in the harbor area of any type of abnormal wave because of possible high local runup and because they can hit the shore almost without warning during or immediately after an earthquake. They would be particularly destructive if they arrived during a time of normal high tide. Although tsunami waves also can be highly destructive, it is unlikely that the generation source for such waves would be near Wrangell. Tsunami waves arriving from a distant source probably would be greatly attenuated in traveling up the inlets to Wrangell from the open ocean. It should be noted, however, that in a few instances such waves have been known to travel considerable distances up long narrow inlets and still attain runups on land of 5 to 10 feet (1.5-3 m). Although it is highly unlikely that any future local earthquakes will produce significant land-level changes due to faulting in the Wrangell area, large-scale regional deformation, possibly associated with major faulting along the Fairweather-Queen Charlotte Islands fault system, could possibly result in substantial uplift or subsidence. Uplift or subsidence of land of even 1 foot (0.3 m) could produce adverse effects in the harbor area, where there is a critical relation between height of land and water. Greater amounts of uplift could result in the water's becoming too shallow to allow normal boat-loading operations or of entering the inner harbor area at low tide. Substantial land subsidence could render docks inoperative and cause local flooding at high tide of some facilities along the waterfront.

Earthquake effects probably would be considerably fewer and generally less severe for the part of Wrangell and vicinity upslope from the harbor area. Most of the effects would result directly from shaking. The muskeg deposits (fig. 3), because of their very low rigidity, can be expected to shake strongly during a large earthquake, except possibly where too thin to amplify the ground motions in the underlying materials. Likewise, large lateral deformation of the deposits can be expected, which might be particularly damaging to buildings or other structures built on muskeg slopes. Comparatively strong shaking of elevated beach deposits and elevated fine-grained marine deposits also can be expected, except where they are too thin to amplify ground motions of underlying materials. Little or no landsliding is expected other than possibly along the steep southwest side of Dewey Hill, where fractured bedrock stands in near-vertical slopes. Here rockslides of considerable size are a possibility. It is highly unlikely that tsunami or other abnormal waves would attain sufficient runup heights to reach this part of the city.

Few earthquake effects would be expected at the Wrangell Airport. The fill, although locally fairly thick, is an engineered fill, and effects of shaking expectably would be less than for nonengineered fills. Also, the runway and airport aprons probably are too high above sea level to be affected by tsunami or other types of abnormal waves, other than possibly some wave-produced erosion along the base of the ends of the runway.

The Stikine River delta area directly north of Wrangell Island undoubtedly would be the most severely affected of all areas under discussion in this report. Although the delta is presently of little or no concern because of the absence of manmade facilities there, extremely careful consideration should be given regarding potential effects if a bridge or causeway connecting Wrangell with the mainland were planned across this area. The delta deposits forming this part of the delta are believed to be particularly subject to strong shaking in comparison to other deposits. They also probably would be subject to compaction, with resultant differential settlement, as well as to liquefaction and water-sediment ejection. The front of the delta would be particularly subject to landsliding and submarine sliding, especially if shaking were sufficiently strong to cause liquefaction of the deposits. Damage from tsunami waves and other abnormal waves, such as slide-induced waves, could be high, even from those waves with low runups, because of the intertidal position of the area.

A strong earthquake might have some effect on the water supply of Wrangell. The biggest danger would be the possibility of failure of the reservoir dams caused by debris flows or rockslides. Reservoir capacity also could be severely diminished by filling of the reservoir with slide material. A temporary increase in turbidity and change in taste of the water could also be expected.

Inferred future effects from geologic hazards other than those caused by earthquakes

Geologic hazards in the area that are not caused by earthquakes are believed to be relatively minor. They include: (1) effects of nonearthquake-induced landsliding and subaqueous sliding, (2) effects of flooding, and (3) effects of sediment accumulation. Of these, subaqueous sliding probably has the greatest destructive potential.

Recommendations for additional studies

Because of the reconnaissance nature of the study, the evaluations of geologic hazards described in this report must be regarded as tentative and subject to revision. In order that more rigorous interpretations may be made in the future, several recommendations are made for additional studies.

INTRODUCTION

Purpose and scope of study

The devastating Alaska earthquake of March 27, 1964, demonstrated the need for additional engineering geologic studies in seismically active regions. As a result, Wrangell was one of nine communities in southeastern Alaska that were selected for reconnaissance investigations as part of a program of earthquake studies recommended by the Federal Reconstruction and Development Commission for Alaska. Initiation of the studies was based on the premise that some Alaskan communities, which were too far from the area of strong ground motion to be affected by the 1964 earthquake, may nevertheless lie in areas of high seismic activity and have geologic settings similar to those of towns that were heavily damaged by that earthquake.

The study of the Wrangell area is an attempt to evaluate future effects of earthquake hazards and other hazards. The resulting tentative evaluations should be useful in city and regional land-use planning, so that new facilities can be built, as nearly as possible, in the best geologic environment and can be designed so as to minimize future damage, injuries, and death.

Methods of study and acknowledgments

Approximately 2 man-weeks of project fieldwork were spent in the Wrangell area during 1965, 1968, and 1972. This includes about 4 days of fieldwork by Lynn A. Yehle of the U.S. Geological Survey in 1965 and 1968.

Mapping was done on aerial photographs, topographic maps, and base maps of the city of Wrangell. The base map for the geologic map was compiled from a number of sources: (1) Petersburg B-2 quadrangle map, 1953, by the U.S. Geological Survey; (2) city plat and topographic map of Wrangell by the Alaska State Housing Authority (1968); (3) U.S. National Ocean Survey Chart 8165, 1972; and (4) unpublished maps. The base maps used in the compilation were of various scales and degrees of reliability. Therefore, parts of the base map for this report may not be completely accurate, and distances between specific points may be somewhat in error.

Fieldwork was directed mainly toward delineating the different surficial deposits in and near Wrangell and collecting data on their physical properties. Laboratory analyses of samples of surficial materials were made in the Denver laboratories of the U.S. Geological Survey. Bedrock samples, collected by the writer and Lynn A. Yehle, were studied by R. A. Sheppard of the U.S. Geological Survey.

Grateful acknowledgment also is made to Harold W. Olsen of the U.S. Geological Survey for assistance in helping prepare parts of the report pertaining to soils engineering and seismology. Subsurface data were obtained chiefly from boring logs provided by the Alaska Department of Highways, the Alaska Division of Aviation, the U.S. Army Corps of

Engineers, and the engineering firm of Hubbell and Waller, Seattle, Washington. Because of the nearly ubiquitous surface cover of muskeg over the mapped area, these subsurface data provided the key control in determining the location of most of the geologic contacts. Thus, the map units are most accurately delineated along the main streets and roads, in the harbor area, in the immediate vicinity of the airport, and in some other localities within the city limits of Wrangell where major manmade structures have been constructed. Map units are considerably less accurately located in most undeveloped parts of the mapped area. In addition to the above acknowledged assistance, the writer gratefully acknowledges many sources of information and the complete cooperation of Federal, State, and city organizations and individuals.

It should be emphasized that because of the short period of study in the area and the reconnaissance nature of the mapping, this report must be regarded as preliminary. Therefore, assessments of the geologic hazards of the area, as they affect man and his facilities, should not be rigorously interpreted. Data on the physical properties of the geologic units are so few that only broad generalizations can be made, and even some of these must be regarded as tentative. Evaluation of specific land use or of a specific locality will require more detailed geologic and engineering studies. Also, it should be emphasized that responsibility for final site selection and design of a specific structure rests with the engineer. In spite of these limitations, it is hoped that the information and evaluations contained herein will provide broad guidelines useful to engineers, planners, and architects; to Federal, State, and city officials; and to the public.

In order to try to make the information as understandable as possible to a wide range of users, a number of the more frequently used technical terms have been defined in a glossary at the end of the report. For definition of other terms or for more complete definitions, the reader is referred to standard textbooks on geology, soil mechanics, and seismology, and to references cited in this report.

The reader is referred to the report by Lemke and Yehle (1972a), entitled "Regional and other general factors bearing on evaluation of earthquake and other geologic hazards to coastal communities of southeastern Alaska." This report provides regional background information for evaluating earthquake probability in southeastern Alaska. In addition, it cites numerous examples of effects of past large earthquakes in different parts of the world in relation to how coastal communities in southeastern Alaska might be similarly affected by future earthquakes.

The reader also is referred to a report on the Haines area (Lemke and Yehle, 1972b) and a report on the Skagway area (Yehle and Lemke, 1972). These reports furnish additional information on the evaluation of earthquakes and other geologic hazards in somewhat different geologic environments from those of the Wrangell area.

GEOGRAPHY

Location and extent of area

The Wrangell area is in southeastern Alaska, about 140 miles (225 km) southeast of Juneau and about 90 miles (145 km) northwest of Ketchikan. Petersburg, the nearest town to Wrangell, is approximately 32 miles (51 km) to the northwest (fig. 1). The city of Wrangell is built near the northwest end of Wrangell Island along the eastern shore of Zimovia Strait (fig. 2). Across the strait to the southwest is Woronkofski Island. To the northwest and across Eastern Passage are Mitkof Island and several smaller islands. The mouth of the Stikine River lies about 10 miles (16 km) to the north, and its large delta extends to within approximately 1 mile (1.6 km) of the north end of Wrangell Island. The city of Wrangell has developed in a semicircular pattern around Wrangell Harbor, a good deep water port (fig. 3, in pocket). Scattered development extends northward, from the corporate limits to near Point Highfield, and southward to about 2 miles (3.2 km) past Wrangell Institute (fig. 2). The geologically mapped part of the area described in this report comprises about 2 square miles (5 km^2) of land. The remaining described areas are covered by water or are intertidal areas.

Topographic setting

Wrangell Island, upon which the city of Wrangell is built, is one of a large number of islands of southeastern Alaska. It is about 42 miles (68 km) long, as much as 14 miles (23 km) wide, and is characterized in most places by fairly rugged mountainous terrain. Higher peaks are at altitudes of between 2,500 and 2,800 feet (762 and 853 m). In contrast, the topography within the area of geologic mapping (fig. 3) is much more subdued. Except for two areas within or north of the city, nearly all the area is below 150 feet (46 m) (mean lower low water[1/]), with gentle slopes. The two higher areas are Dewey Mountain, within the corporate limits of Wrangell, which attains an altitude of slightly more than 400 feet (122 m), and a hill near Point Highfield, which rises to an elevation of slightly more than 300 feet (91 m). Southeast of the area of geologic mapping, the land rises fairly steeply to an elevation of approximately 1,500 feet (457 m), as shown in the southeast corner of figure 3.

Drainage in most parts of the mapped area is poor, owing to the pervasive cover of muskeg, and small muskeg ponds abound on the flatter surfaces. Three very small (probably intermittent) streams discharge into Wrangell Harbor, and a couple of others empty into Eastern Passage, in the vicinity of the Wrangell Airport. The largest stream in the area of figure 3, but outside the mapped area, is one that provides the

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[1/] Following general usage for construction and other purposes in the Wrangell area, contour lines and other elevation points are given in feet above mean lower low water (MLLW). This datum plane will be used generally throughout the report unless otherwise specified.

Figure 1.--Map of Southeastern Alaska and adjacent Canada showing pertinent geographic features.

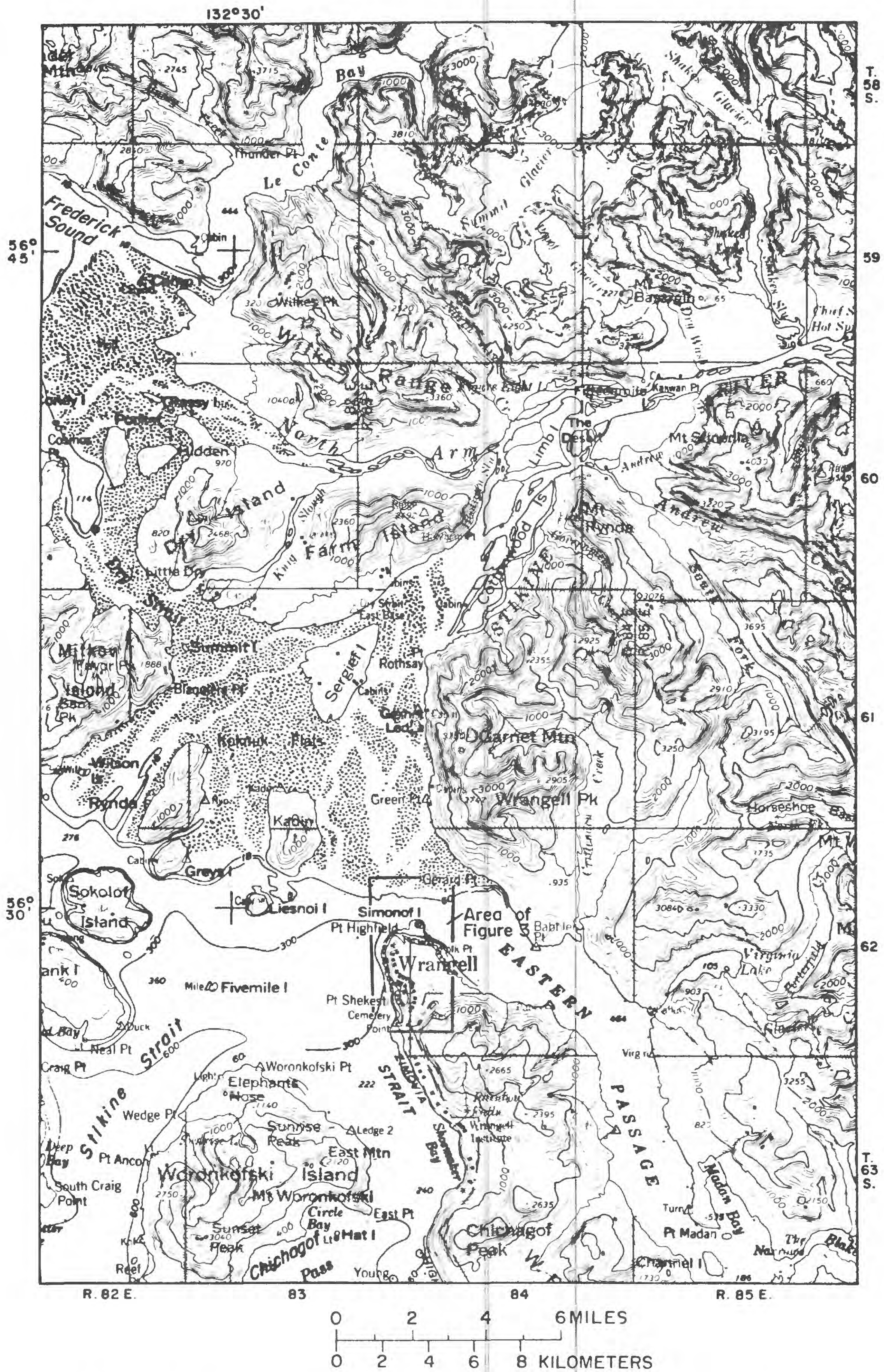

Figure 2.--Location map of Wrangell and surrounding region, Alaska.

water supply for the city of Wrangell. It flows directly north for a distance of approximately 1 mile (1.6 km) and down a fairly steep slope to a well-defined southwest-trending valley, where Reservoir No. 2 has been constructed. Thence, it follows the valley southwestward, to empty into Zimovia Strait. Reservoir No. 1 is downstream from Reservoir No. 2.

Bathymetry and tides

Zimovia Strait, Eastern Passage, Dry Strait, and other straits and inlets in the vicinity surrounding Wrangell (fig. 2) are part of the glacially scoured fiord system that characterizes southeastern Alaska. Most of these waterways have fairly smooth floors, commonly with water depths of 300 to 500 feet (91-152 m). In contrast, Dry Strait has been completely filled near the mouth of the Stikine River by delta deposits and is covered by marine waters only during periods of high tide.

An underwater platform a few hundred feet wide and approximately outlined by the 3-fathom (18-ft, 5.5-m) bathymetric contour (fig. 3) rims the northern part of Wrangell Island. In Wrangell Harbor the platform, if it exists, is narrow, and only short wharves have had to be constructed in order that larger boats can be docked. Within the Public Boat Harbor and the City Inner Boat Harbor, the connecting channel and mooring basins have been dredged to a depth of 10 feet (3 m) below MLLW.

The following tidal data for Wrangell were taken from the records of the U.S. Coast and Geodetic Survey, based upon tidal observations for the period April 9 to May 12, 1954:

	Feet	Meters
Highest tide (estimated)--	21.5	6.5
Mean higher high water----	16.10	4.90
Mean high water-----------	15.20	4.63
Half tide level-----------	8.35	2.54
Mean low water------------	1.50	0.46
Mean lower low water------	0.00	0.00
Lowest tide (estimated)---	-4.5	-1.37

Climate and vegetation

The climate is predominantly marine, and is characterized by mild winters, cool summers, and year-round rainfall. The maximum temperature recorded was 92° F; the minimum was -10° F (Alaska State Housing Authority, 1968). Average temperature is 43.8° F, ranging from an average of 57.6° F in July to an average of 29.7° F in January. Average annual precipitation is 82.70 inches (210 cm), the highest precipitation being in October and the lowest in June. Average annual snowfall is 72.4 inches (183 cm). Snow is often mixed with rain, and rarely accumulates to depths greater than 2 feet (0.6 m).

All of Wrangell Island, except for the city of Wrangell and vicinity, lies within the Tongass National Forest, where there are dense rain forests of hemlock, Sitka spruce, and other types of trees. Muskeg covers poorly drained areas. Within the mapped area of figure 3, muskeg, scrub trees, and smaller plants characterize the flatter areas. Large trees cover Dewey Mountain and, before clearing in connection with the airport, also covered the hill near Point Highfield.

Economy and population

The economy of Wrangell largely depends upon wood-processing activities, fish processing, institutional services, tourism, and transportation (Alaska State Housing Authority, 1968). The manufacturing industries, which include logging, two lumber mills (one in town and one about 1 mile (1.6 km) south of Wrangell Institute), and fish-processing plants, accounted for 40 percent of the area's total employment in 1965.

The city of Wrangell, the second oldest non-native settlement in southeastern Alaska and dating back to 1834, had a population of 1,315 in 1960 and a population of 2,029 in 1970 (U.S. Bur. Census, 1971). In 1967, of the 2,240 persons currently estimated to be living in the Wrangell area, approximately 65 percent lived within the corporate city limits, about 5 percent lived to the north, and almost 30 percent, including students at the Wrangell Institute, lived south of the city (Alaska State Housing Authority, 1968). Later figures for the number of people living both within and outside the corporate city limits are not available.

Transportation and other facilities

Wrangell is served regionally by water and air forms of transportation. The Alaska Marine Highway System, started in 1963, connects Wrangell with Petersburg, Sitka, Juneau, Haines, and Skagway to the northwest, and with Ketchikan and Prince Rupert (in British Columbia) to the southwest. Cruise ships and boats stop frequently during the summer months, and fishing and lumber boats dock throughout the year.

The Alaska Airlines makes regularly scheduled flights to the city, with connecting stops between Seattle, Washington, and Anchorage, Alaska. Planes land at the Wrangell Airport, which was opened in October 1968 and is 5,050 feet (1,539 m) long. Additional construction (removal of a bedrock "hump" about midway of the field) is planned before the landing strip is paved.

At present there are no nearby connecting roads on the mainland, and there are only a relatively few roads on Wrangell Island. The longest road segment extends southward from Wrangell about 11 miles (18 km) along the shoreline of Zimovia Strait to about 6 miles (10 km) south of Wrangell Institute (fig. 2). It is paved as far as the Pacific Northern Lumber Company wharf, approximately 1 mile (1.6 km) south of the Wrangell Institute. About the only other roads are the ones extending northward from Wrangell toward Point Highfield, new roads extending northeast from Bennett Street to the airport (Airport Spur Road), and the Wrangell East Road, which has been built southeastward to near Eastern Passage--a total length of about 1-1/2 miles (2.4 km). Future plans call for Wrangell to be connected to the continental highway system via a route up the Stikine River valley (Alaska State Housing Authority, 1968). The plan most favored is for a road to be built down the west coast of the Eastern Passage (a continuation of the Wrangell East Road), across the Blake Channel narrows and up the mainland side of the Eastern Passage to the Stikine Highway (see fig. 2). However, there also is a proposal to conduct an engineering study to determine the feasibility of a causeway bridge from the northern end of Wrangell Island via Simonof Island to the mainland.

Wrangell obtains its water from two reservoirs in the mountainous area directly south of the city (fig. 3). At the time of our investigation in August 1965, there was the possibility of a severe water shortage from these sources. Since then, however, the dam at Reservoir No. 1 has been replaced, the dam at Reservoir No. 2 has been upgraded, a new 10-inch (25.4-cm) water main leading from the reservoirs has been installed, and a 180,000-gallon (681,300-ℓ) storage tank has been added. Alaska State Housing Authority (1968) calculated that with these improvements the capacity of the reservoirs was sufficient to carry the city through 53 days of dry or freezing weather, or almost three times the preimprovement level. Further upgrading of facilities, particularly of the water distribution system within the city, is planned, because of the heavy dependence of the city's major industries upon an adequate water supply. Additional sources of water will be needed in the future, and investigations should be directed toward nearby lakes and streams, or possibly toward wells. Two test holes were drilled in 1959, one near the south edge of town to a depth of 240 feet (73 m) and the other in the southeastern part of town to a depth of 100 feet (30.5 m).[1/] Neither test provided water in sufficient quantity for a municipal supply. Logs of the holes and other pertinent data (Waller and Tolen, 1962) are given on the following page.

[1/] On the basis of a small-scale map that accompanies the report by Waller and Tolen (1962) and on altitudes given, test well No. 1 probably was drilled just outside the corporate limits and upslope from the junction of Zimovia Highway and Berger Street. Test well No. 2 probably was drilled near the junction of Wrangell Avenue and Zimovia Avenue.

City of Wrangell (test well No. 1). Altitude 75 feet (22.8 m).
Drilled by G. H. Ramsey. Cased to 25.44 feet (7.75 m).
Yield: 20 gal/min (76 ℓ/min); drawdown 180 feet
(54.8 m) after 16 hours' bailing

Material	Thickness		Depth	
	(feet)	(meters)	(feet)	(meters
Gravel and clay, hard---	26	7.9	26	7.9
Black slate-------------	26	7.9	52	15.8
Black rock, very hard---	100	30.5	152	46.3
Black rock, hard--------	41	12.5	193	58.8
Black rock, very hard---	19	5.8	212	64.6
Black rock, hard--------	28	8.5	240	73.1

City of Wrangell (test well No. 2). Altitude 90 feet (27.4 m).
Drilled by G. H. Ramsey. Cased to 60.97 feet (18.58 m).
Yield: 10 gal/min (38 ℓ/min); drawdown 85 feet
(25.9 m) after 2 hours' bailing

Material	Thickness		Depth	
	(feet)	(meters)	(feet)	(meters
Muskeg------------------	3	0.9	3	0.9
Hard clay and boulders--	25	7.6	28	8.5
Black slate-------------	6	1.8	34	10.4
Black rock, very hard---	16	4.9	50	15.2
Black rock, hard--------	50	15.2	100	30.4

GLACIATION AND ASSOCIATED LAND- AND SEA-LEVEL CHANGES

Although the glacial geology of the Wrangell area is poorly known, regional studies of southeastern Alaska indicate that glacier ice has advanced over the area at least once and probably several times during the Pleistocene Epoch. Inasmuch as glacier ice attained altitudes of between 4,000 and 5,000 feet (1,220 and 1,525 m) in the region (Coulter and others, 1965), even the higher peaks on Wrangell Island were covered by ice at least once. The inlets, straits, and other waterways in and near the Wrangell area are believed to have been formed for the most part by large trunk glaciers moving seaward from the high mountainous areas of the adjacent mainland. Several large "through valleys" on Wrangell Island (south of mapped area) are believed to have been formed or modified by advancing ice that flowed across divides or by valley glaciers that flowed in opposite directions from the same head and cut down the intervening divide (Buddington and Chapin, 1929). Within the mapped area (fig. 3), the topographic expression exhibited by Dewey Mountain and the hill near Highfield Point strongly suggests smoothing and rounding by glacier action. Also, the northeast-trending valley, where reservoirs Nos. 1 and 2 have been built, also may have been carved or modified by glacier ice, inasmuch as the valley seems to be too large for its stream and the stream enters the valley from an acute angle.

Deglaciation probably was well advanced or even completed in the Wrangell area by about 13,000 years ago. Radiocarbon dating (sample W-1734) of marine shells in marine deposits, collected by the writer 212 feet (64.6 m) above present sea level in the Petersburg area (approximately 32 miles (51 km) northwest of Wrangell), indicates deglaciation of that area prior to 12,400 years ago. Similar conditions probably prevailed in the Wrangell area. Glaciers are not now present on any of the islands near the Wrangell area but are abundant in the mountainous terrain of the adjacent mainland.

During deglaciation in late Pleistocene time, the land was still depressed from the effect of former glacier loading. Marine waters extended into low areas formerly occupied by glacier ice, and marine sediments were laid down. As load effect of the ice slowly diminished, the land began to emerge above sea level, and shore processes began to modify preexisting deposits.

On the basis of the known presence of elevated marine deposits, the land in the mapped area has been uplifted at least 200 feet (60 m) relative to sea level since major deglaciation. Evidence of greater uplift may well be present in the unmapped part to the southeast but has not been observed by the writer. On the basis of tidal records during the period 1910-1960, the land in the Petersburg area is presently emerging from the marine waters at the rate of 0.37 cm (0.012 ft) per year (Hicks and Shofnos, 1965). The rate of uplift in the Wrangell area is probably about 0.3 cm (0.01 ft) per year. Whether some of the present emergence, as well as past emergence, may be due to tectonic activity is not known. In my opinion, however, most of it can be attributed to rebound of the land as a result of deglaciation.

Although there is not yet complete agreement, worldwide (eustatic) sea level is believed by a number of investigators to have risen approximately 100 feet (30 m) during the past 10,000 years (Shepard, 1963; Shepard and Curray, 1967; Redfield, 1967). With sea level used as a datum, the amount of eustatic sea-level rise must be added to the apparent uplift of land to obtain the absolute amount of land uplift. Therefore, on the basis of 100 feet (30 m) of sea-level rise, the total amount of land uplift in the mapped area since deglaciation probably exceeds 300 feet (90 m).

DESCRIPTIVE GEOLOGY

Bedrock

The bedrock in the mapped area (fig. 3) consists of a sequence of metamorphic rocks intruded by igneous rocks. The metamorphic rocks are part of the Wrangell-Revillagigedo belt of rocks that extends for many miles to the southeast and to the northwest (Buddington and Chapin, 1929). The igneous rocks are part of the Coast Range batholith that forms the Coast Range Mountains of the adjacent mainland to the northeast. The metamorphic rocks were formerly sedimentary rocks that probably were deposited at least in part during Paleozoic time and are believed to have been metamorphosed in Mesozoic time. The igneous rocks are believed to be of Mesozoic age (Buddington and Chapin, 1929; Dutro and Payne, 1957; Brew and others, 1966).

Because of the paucity of outcrops, the metamorphic and igneous rocks have not been differentiated on the map (fig. 3) but are described separately below. Exposed or nearly continuously exposed areas of bedrock (bex) are shown separately from areas of bedrock that are generally covered (bc) but that are believed to be within 3 to 5 feet (0.9-1.5 m) of the surface.

The metamorphic rocks are the predominant rock type and probably underlie most of the flatter and low-lying terrain as well as some of the more mountainous areas. Outcrops are limited mostly to shore areas, where wave action has produced intertidal marine platforms and bedrock cliffs, commonly 10 to 15 feet (3-4.6 m) high. The rocks also are well exposed in the four quarries shown on the map as well as in other construction cuts at the Wrangell airport.

The metamorphic rocks in the mapped area have been variously described as schists, phyllites, and slate (Buddington and Chapin, 1929; State of Alaska Dept. Highways, 1963, 1966, 1969), and a foliated graywacke (R. A. Sheppard, U.S. Geol. Survey, written commun., 1965). Although all four classes of rock may be present in the area, the same rock has been classified differently by different workers. Thus, the principal rock type in the quarry 1.1 miles (1.8 km) north of Wrangell, as well as four other samples of metamorphic rock from other parts of the mapped area, were all classified by R. A. Sheppard of the U.S. Geological Survey (written commun., 1965) as schists, whereas the State of Alaska Department of Highways (1963) classified the main rock type in the quarry north of Wrangell as a phyllite. Probably the differences upon which the classifications were based are so slight that they are unimportant for this report.

Although local variations exist throughout the mapped area, the metamorphic rocks exposed in the quarry 1.1 miles (1.8 km) north of Wrangell probably are fairly typical. A sample from this locality was classified as a biotite-chloritoid-quartz schist by R. A. Sheppard (written commun., 1965). He stated that the rock probably originally was a silty shale. Minerals constituting the rock include quartz, chloritoid, biotite, pyrite, garnet, muscovite, and calcite.

The State of Alaska Department of Highways (1963) classified the metamorphic rock in the same quarry as a phyllite, and described it as dark gray, fine grained, thinly bedded, highly fractured, and moderately to well foliated. Other properties of the rock were described as follows:

> "Resistance to chemical and physical weathering is fair to moderately good. Because of its highly fractured nature, drilling properties are considered fair and blasting properties are considered good. The rock breaks into slabs and irregular-shaped wedges. Laboratory test results indicate the phyllite is of adequate quality for use as asphaltic concrete aggregate but construction personnel in Wrangell and our previous experience with this kind of rock indicate that, in general, phyllites tend to degrade readily under wearing action, such as from traffic loads."

The metamorphosed rock in the quarry along the south side of the Wrangell East Road (fig. 3) was described by the State of Alaska Department of Highways (1966) as ranging from a somewhat friable phyllitic slate to a more indurate and massively foliated graywacke. It was further described as "fine grained, thinly bedded, moderately hard and durable, and highly fractured." Drilling and blasting properties were considered moderately good, the rock breaking into slabs and plates. Also, it was stated that the rock tends to degrade, when subject to wearing action and that experience has shown that, in general, rock of this type is not suitable for use as topping materials on gravel-surfaced roads.

In the quarry at the southwest edge of the airport apron, the State of Alaska Department of Highways (1969) classified the metamorphic rock present as a phyllite that breaks into angular fragments, is fractured, and is only locally foliated. It was used as base course and as riprap in construction of the airport.

The types of metamorphic rocks that crop out along the shoreline are similar to those exposed in the quarries. Thus, schists or phyllites are the predominant metamorphic rocks in the northern part of the mapped area. In the southern part of the mapped area, in the vicinity of Shakes Island and Point Shekesti, partly metamorphosed graywackes are intercalated with the schists or phyllites. The strike of the schistosity or cleavage of the metamorphic rocks along the shorelines ranges in most places from S. 10° E. to S. 45° E. Dips range in most places from 30° to 45° NE.

Two specimens of pelecypod shells were found in a black slatelike rock just north of Wrangell but were too poorly preserved to be definitely identified (Wright and Wright, 1908).

The intruded igneous rocks are quartz diorites, except for possibly some later-intruded small dikes and sills that may be more basic in composition (Buddington and Chapin, 1929; State of Alaska Dept. Highways, 1963, 1966, 1969). Most igneous bodies exposed along the shore are 1 to 20 feet (0.3-6 m) wide, and have been intruded conformable to the schistosity or cleavage of the adjacent metamorphic rocks. Those that form part of the marine platform of the intertidal zone generally stand as ridges a few feet above the metamorphic rocks because of their greater resistance to wave erosion.

The largest exposed intruded body of igneous rocks in the mapped area crops out on Dewey Hill, which rises to a height of approximately 440 feet (134 m) within the corporate limits of the city of Wrangell. Although outcrops are not plentiful, it is believed that most, if not all, of the hill consists of igneous rock. The long axis of the hill trends in a southeasterly direction, roughly accordant to the prevailing strike of the schistosity or cleavage of the enclosing metamorphic rocks. The rocks forming the top of the relatively flat hill are highly fractured or jointed. Although no petrographic studies were made, the rocks appear to be identical to those identified as quartz diorite in nearby quarries.

Igneous rocks apparently also constitute the main mountain mass in the vicinity of the quarry along the south side of Wrangell East Road, whereas metamorphic rocks form the adjoining ridge. The igneous rock generally is a medium-grained quartz diorite consisting of plagioclase, mica, and quartz, with minor ferromagnesium minerals (State of Alaska Dept. Highways, 1966). It is further described as light gray, massive, hard, durable, and only slightly fractured. Drilling was indicated to be slow and blasting to yield rather large blocks.

A relatively small body of quartz diorite also cropped out (in 1965) in a face of the quarry 1.1 miles (1.8 km) north of Wrangell. It has been described (State of Alaska Dept. Highways, 1963) as hard and durable and of adequate quality for use as concrete aggregate. However, the quantity present was indicated to be small.

The bedrock of the area has been used chiefly for road and street construction, for construction of the Wrangell Airport, for pads around buildings and other facilities in muskeg areas, and as riprap. Specific uses will be described in greater detail under the heading "Manmade fill (mf)."

Surficial deposits (shown on map)

The surficial deposits have been divided on the map into the following units on the basis of their time of deposition, mode of origin, and grain size: (1) elevated fine-grained marine deposits (Qem), (2) elevated beach deposits (Qeb), (3) muskeg deposits (Qm), (4) late shore deposits (Qs), and (5) delta deposits of the intertidal zone (Qd). Manmade fill (mf) also is mapped as a separate unit. Till, colluvial deposits, and offshore deposits are not included as map units but are discussed in the report under the heading "Surficial deposits (not shown on map)."

The almost continuous muskeg cover in the mapped area makes it difficult to determine the nature and extent of the underlying surficial units. In general, the muskeg is designated a map unit if it is 3 or more feet (1 m) thick. Although the paucity of data on muskeg thickness makes this method subject to considerable error, subsurface data obtained from test holes drilled in connection with construction of sewerlines and those related to street and highway construction have provided enough data for a reasonable extrapolation into areas beyond control points.

Elevated fine-grained marine deposits (Qem)

The deposits are marine sediments that were laid down in fiords and inlets by settling of fine-grained material derived from glaciers, rivers, and streams. Subsequently, the sediments have been elevated above sea level by rebound of land owing to deglaciation of the area and possibly as a result of tectonism. They probably underlie fairly large parts of the lower, flatter lying terrain of the mapped area, but in most places they are overlain by elevated beach deposits (Qeb) or muskeg (Qm) of mappable thickness. They commonly rest directly on bedrock but in places may overlie till. The deposits extend from sea level to a height of at least 150 feet (46 m) above MLLW.

The State of Alaska Department of Highways (1966, 1969) has conducted numerous tests on the physical properties of the deposits in connection with construction of new roads in the mapped area. Data from test holes drilled relative to building the Airport Spur Road and the Wrangell East Road have been especially helpful to the writer. These data, combined with those obtained from exposures in the vicinity of the Wrangell Airport, constitute the main sources of information. Because of the nearly continuous muskeg cover, little is known about the deposits elsewhere. Therefore, the areal extent of the deposits probably will be subject to considerable revision when more subsurface information becomes available.

The deposits generally are dark bluish gray, and are composed chiefly of varying amounts of clay and silt and sand-size particles. Thicknesses of 10 to 15 feet (3-4.5 m) are common, and in a few places may be as much as 30 feet (9 m). In most places the deposits are indistinctly bedded, moderately dense, and relatively impervious. Plasticity ranges from nonplastic to moderately plastic. Natural water content may be near or slightly more than the liquid limit. In classifying highway subgrade materials, the State of Alaska Department of Highways (1966,

1969) has classified the deposits in most of the places tested as A-4[1] and as having a frost susceptibility of F-4[2]. They also recommended that, in order to maintain bank stability, cut slopes under normal conditions should not exceed 2:1.

The deposits were well exposed in 1972 in construction cuts at the Wrangell Airport. A roadcut at the southeastern edge of the airport apron (fossil loc. M 5757 on fig. 3) exposed the following section, from top to bottom:

[Elevation of top of section is approximately 60 feet (18 m) above MLLW, or approximately 52 feet (15.8 m) above MSL]

	Thickness		Depth to bottom of stratum	
	(feet)	(meters)	(feet)	(meters)
Muskeg (Qm):				
Fibrous peat with some sticks, mostly brown----------------------	2.8	0.85	2.8	0.85
Elevated beach deposits (Qeb):				
Gravel, fine, and sand, coarse; stained brown from downward percolation of water through the overlying muskeg-------------	3.1	.94	5.9	1.80
Elevated fine-grained marine deposits (Qem):				
Dark bluish gray; indistinctly bedded clay, silt, and sand-size particles with a few pebbles; highly fossiliferous (see table 2)------------------------	15+[3]	4.6+	20.9+	6.4+

A sample, taken 3 feet (0.9 m) from the top of the unit, which appears to be fairly representative of the exposure, was analyzed in 1972 by Philip S. Powers of the U.S. Geological Survey for physical properties. The results are shown in table 1.

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[1] This classification is described in the American Society for Testing and Materials (1958, p. 212-216). Materials classified as A-4 are mostly of silt and clay size, with more than 35 percent passing the No. 200 sieve.

[2] Materials in the F-4 group have especially high frost susceptibility, as defined by the U.S. Army Corps of Engineers (1962, p. 7-8).

[3] A test hole drilled by the State of Alaska Department of Highways (1969), at approximately this location, penetrated 29 feet (8.8 m) of these deposits without reaching bedrock. The presence of bedrock a short distance downslope indicates that this is nearly the maximum thickness of the deposits at this locality.

Table 1.--Physical properties of a sample of elevated fine-grained marine deposits (Qem) from the Wrangell area, Alaska

Laboratory No.	Field No.	Hydrometer analysis (percent)		Mechanical analysis (percent)		Shrinkage		Atterberg limits			Unified soil classification[6]	Dilatancy[5]
		Clay[1]	Silt[2]	Sand[3]	Gravel[4]	Limit[5]	Ratio[5]	Liquid limit[5]	Plastic limit[5]	Plasticity index[5]		
D801-887	L-64 (N-32)	32	38	23	7	19	1.81	25	17	8	CL	Slow

[1]Clay, <0.00015 in (<0.0039 mm).

[2]Silt, 0.00015-0.0025 in (0.0039-0.0625 mm).

[3]Sand, 0.0025-0.079 in (0.0625-2.0 mm).

[4]Gravel, 0.079-2.52 in (2.0-64 mm).

[5]See glossary for definitions.

[6]This classification system takes into account the engineering properties of soils. Soils classified as CL are generally predominantly silts and clays with a liquid limit of less than 50 (U.S. Bur. Reclamation, 1968, p. 2, and chart facing p. 14).

Elevated fine-grained marine deposits also are well exposed along the southwestern embankment of the airport runway about midway the length of the strip (fossil loc. M5756 on fig. 3). The section is of particular interest because of the presence of a nearly solid shell layer overlying the elevated fine-grained marine deposits. The section, whose surface elevation is approximately 80 feet (24 m) above MLLW (approximately 72 feet (22 m) above mean sea level), is as follows:

	Thickness		Depth to bottom of stratum	
	(feet)	(meters)	(feet)	(meters)
Muskeg (Qm):				
Peat, fibrous, with some sticks, brown--------------------------	5.5	1.7	5.5	1.7
Elevated beach deposits (Qeb):				
Sand and fine gravel; stained brown from downward percolation of water through the overlying muskeg. Basal 1.2 feet (0.4 m) consists of a nearly solid layer of shells with abundant large clam shells (see table 2). Most of the shells are crushed, but some have both valves attached, indicating little or no transportation---------------------------	6.4	2.0	11.9	3.7
Elevated fine-grained marine deposits (Qem):				
Clay, silt, and sand, dark-gray, fossiliferous------------------	15.5+	4.7+	27.4+	8.4+

Fine-grained deposits, exposed at low tide in the City Inner Boat Harbor and in the small harbor area directly northwest of the lumber mill, also have been mapped as part of the (Qem) deposits. Those in the boat harbor were excavated to a depth of 10 feet (3 m) below MLLW. Some preexcavation borings penetrated as much as 18 feet (5.5 m) of "soft" material before reaching bedrock, whereas bedrock was indicated to be nearly at the surface in other parts of the excavated area (U.S. Army Corps Engineers, 1956, unpub. map and logs). The "soft" material is interpreted to be deposits consisting chiefly of clay, silt, and sand similar to those exposed in the side of the excavated area at low tide, although the upper few feet may be relatively recent marine sediments. However, material having a larger grain size than the deposits in the area of the airport was penetrated in some of the borings. Also, some of the material was classified as "hard material," or "tough clay," or as containing "boulders." Some of this material may be glaciomarine diamicton deposits rather than (Qem) deposits.

In places, particularly at elevations between 60 and 80 feet (18.3 and 24.4 m) above MLLW, the deposits are highly fossiliferous. One of the earliest accounts of fossils in these deposits was given by Buddington and Chapin (1929), who reported that marine shells had been found in clay during digging of the foundations for the old cable office at Wrangell. The fossils shown in table 2 were collected by the writer from the two previously described exposures in the vicinity of the airport.

The oldest elevated fine-grained marine deposits in the area probably are at least 13,000 years old. This view is supported by a radiocarbon date of 12,400±800 years (sample W-1734) for elevated marine deposits in the Petersburg area at an altitude of 212 feet (64.6 m). In the Wrangell area, a radiocarbon date of 9,700±350 years (sample W-2326) was obtained for pelecypod shells from elevated fine-grained marine deposits from shell locality M5757 (fig. 3) at the southwest side of the airport runway, at an elevation of approximately 70 feet (21 m) above MLLW. Inasmuch as topographically higher deposits are present in the Wrangell area, a minimum age date of 13,000 years for the oldest deposits seems reasonable. Most of the land emergence probably took place within the first few thousand years after deglaciation (see discussion by Lemke and Yehle (1972a) on rates of land uplift in southeastern Alaska), and therefore the age of most of the elevated marine deposits corresponds to that age bracket. However, slow uplift of the land is continuing to take place, and thus the deposits date to the present.

Elevated beach deposits (Qeb)

The deposits are believed to represent the near-shore facies of the elevated marine deposits, and thus are time equivalents of the elevated fine-grained marine deposits (Qem) deposited in deeper offshore waters. In areas of flatter lying terrain, they generally overlie the elevated fine-grained marine deposits, but on somewhat steeper slopes they commonly directly overlie bedrock. They are overlain nearly everywhere by muskeg. The deposits have been found in the mapped area up to an elevation of approximately 180 feet (55 m) above MLLW. Higher deposits may be present, however, in the unmapped areas to the south.

Because of the nearly continuous muskeg cover, knowledge of the areal extent, character, and thickness of the deposits is based almost entirely upon test holes drilled in connection with construction activities and upon a few manmade cuts. Much useful information was obtained from numerous test holes drilled by the State of Alaska Department of Highways (1963, 1966, 1969) relative to construction of streets and roads in the mapped area and from test holes drilled for construction of sewerlines (Hubbell and Waller Eng. Corp., unpub. profiles, 1955). Manmade exposures in the vicinity of the Wrangell airport and at a quarry site about 1 mile (1.6 km) north of town were additional sources of information.

Table 2.--Cenozoic marine megafossils in elevated fine-grained marine deposits (Qem) from the Wrangell area, Alaska

[Identification by W. O. Addicott, U.S. Geological Survey (written commun., 1965)]

Fossil form	U.S. Geological Survey Cenozoic locality	
	M5756[1]	M5757[2]
Gastropoda		
Mitrella cf. M. gouldi (Carpenter)	X	
Neptunea lirata (Gmelin)		X
Vermetid		X
Undet. fragments	X	X
Pelecypods		
Protothaca sp. - fragment	X	
Saxidomus giganteaus (Deshayes)	X	
Chlamys rubida hindsii (Carpenter)		X
Chlamys rubida (Hinds)		X
Clinocardium cf. C. ciliatum (Fabricius)		X
Hiatella arctica (Linne)		X
Macoma calcarea (Gmelin)		X
Macoma obliqua (Sowerby) [= M. incongrua of some earlier workers]		X
Mya truncata Linne? - fragments		X
Serripes sp		X
Echinoid spines	X	
Barnacle plates	X[3]	X
Ostracodes - a few valves	X	

[1] Collected from a 1.2-foot- (0.37-m-) thick shell layer at top of elevated fine-grained marine deposits, about 1 mile (1.6 km) north-northeast of Wrangell in a cut along southwest side of airport runway about a quarter of a mile (0.4 km) from northeast end of runway and at an elevation of about 70 feet (21 m) above MLLW (about 62 feet (19 m) above mean sea level).

[2] Collected from elevated fine-grained marine deposits, about 1 mile (1.6 km) northeast of Wrangell in highway cut at southeast end of airport apron at elevations between approximately 60 and 75 feet (18-23 m) above MLLW (approximately 52 to 67 feet (16-20 m) above mean sea level).

[3] Very abundant along certain horizons of the exposure.

The deposits consist chiefly of poorly to moderately well stratified coarse sand and fine gravel, with minor amounts of intermixed silt; a few cobbles are locally present. The State of Alaska Department of Highways (1963, 1966, 1969) has classified the deposits in most places tested as A-1-b[1/] and as having a frost susceptibility of F-2[2/]. In most places the deposits are stained brown, owing to downward percolation of water through the overlying muskeg. Thicknesses rarely exceed 8 feet (2.4 m) in the mapped area, and in most places are less than 5 feet (1.5 m). Most of the deposits are fairly loose and have a high permeability, but the lower parts of some thicker deposits are moderately dense, and permeability may be somewhat lower. Where the deposits underlie flat muskeg areas, they are completely saturated. On steeper slopes where muskeg is thin to absent, drainage generally is better and they probably are not everywhere saturated.

The deposits are well exposed in three manmade cuts. In a roadcut at the southeastern edge of the airport apron, 3.1 feet (0.9 m) of coarse sand and fine gravel overlies at least 15 feet (4.6 m) of elevated fine-grained marine deposits, described previously. Along the southwestern embankment of the airport runway, 5.2 feet (1.6 m) of elevated beach deposits is exposed. Approximately 8 feet (2.4 m) of sand and fine gravel, with a few intermixed cobbles and boulders, is exposed at an elevation of about 180 feet (55 m) above MLLW in the quarry approximately 1 mile (1.6 km) north of Wrangell. The deposits at this site, which rest directly on bedrock, underlie approximately 4 feet (1.3 m) of soil containing a few boulders.

The thickest exposed deposits within the corporate limits of Wrangell are in a highway cut of Zimovia Highway and along the bank of a small stream about 200 feet (60 m) south of Spruce Street. The section exposed in the highway cut, whose top is at an elevation of about 80 feet (25 m) above MLLW, is described on the following page.

As indicated from fairly numerous exposures of sand and gravel along Zimovia Highway south of Cemetery Point and outside the mapped area, elevated beach deposits flank the mountain front for at least several miles along Zimovia Strait. A rather conspicuous bench at an elevation of about 100 feet (30 m) above MLLW may mark the crest of these deposits. On the other hand, the bench may be underlain mainly by till or a till-like glaciomarine diamicton similar to material exposed in roadcuts south of the mapped area.

Fossil shells have been reported from several test holes drilled by the State of Alaska Department of Highways (1963, 1966, 1969). An examination of exposures in 1972, however, indicated that most or all of the

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[1/] Materials classified as A-1-b are granular, with 35 percent or less passing the No. 200 sieve (Am. Soc. Testing and Materials, 1958, p. 212-216).

[2/] Materials in the F-2 group have a moderate frost susceptibility, as defined by the U.S. Army Corps of Engineers (1962, p. 7-8).

shells are found in a highly fossiliferous layer forming the base of the elevated beach deposits. As noted previously, an almost solid layer of shells, 1.2 feet (0.37 m) thick, constitutes the basal part of the elevated beach deposits in an exposure along the southwestern embankment of the airport runway. Shells also have been reported from test holes within the city, particularly along Second Avenue and Church Street between McCormack and McKinnon Streets.

	Thickness		Depth to bottom of stratum	
	(feet)	(meters)	(feet)	(meters)
Muskeg (Qm)----------------------	0.8	0.2	0.8	0.2
Alluvium(?):				
Gravel, fine, and sand, coarse; orange yellow, loose, and poorly sorted. Probably is stream deposited--------------	.9	.3	1.7	.5
Elevated beach deposits (Qeb):				
Sand, medium to coarse; includes some silt and possibly clay-size material. A few granitic pebbles as much as 3 in (7.6 cm) long. Oxidized grayish tan. No stratification noted. More compact than unit above-------------------------	6.3	1.9	8.0	2.4
Sand, medium-grained; some flat phyllite pebbles 3-4 in (7.6-10 cm) long. Gray (unoxidized). Probably represents basal unoxidized part of above unit--------------------------	1.0+	.3+	9.0+	2.7+

Inasmuch as the elevated beach deposits are believed to represent the shore facies of the elevated fine-grained marine deposits (Qem), the ages of the two deposits should be approximately the same. Thus, the highest and oldest elevated beach deposits probably were laid down at least 13,000 years ago. The rather extensive deposits within the corporate limits of Wrangell, between elevations of about 60 and 120 feet (18 and 36 m) above mean sea level, probably also were laid down within the first few thousand years after deglaciation. This assumption is supported by the radiocarbon date of 9,700±350 years (sample W-2326) obtained from shells in elevated fine-grained marine deposits that underlie the elevated beach deposits, at an elevation of about 70 feet (21 m) above MLLW.

If elevated beach deposits do form the 100-foot- (30-m-) high bench (previously described), along Zimovia Strait south of the mapped area, then a prominent preexisting shoreline may be represented by the bench. Such a shoreline would be formed when there was a stillstand of the land (neither uplift nor subsidence in relation to sea level) over a substantial period of time. In line with the one radiocarbon date for the area and on postulated rates of uplift, it is reasonable to assume that the inferred shoreline was formed between approximately 10,000 and 13,000 years ago. Inasmuch as uplift of the land is currently taking place, present beach deposits (Qs) are slowly being uplifted beyond the high-tide line to become elevated beach deposits (Qeb), although most of the near-shore deposits are too small to map. Thus, the age of the deposits ranges from about 13,000 years ago to the present.

Muskeg (Qm)

For purposes of this report, the term "muskeg" is defined as "Organic-rich deposits consisting of peat and other decaying vegetation that are commonly found in swamps and bogs." The term "peat" will be used more or less interchangeably with the word "muskeg."

As indicated by the literature on muskeg from Canada and other regions, many of the physical and chemical properties of muskeg are unique compared to those of other geologic materials. Unless muskeg deposits are drained by man or there are drought conditions, they generally are saturated to the surface and have an exceptionally high moisture content. Moisture contents commonly range from 600 percent to 1,400 percent, but extremes as high as 3,235 percent have been noted (Pihlainen, 1963). As the peat constituting the muskeg dries, it shrinks and becomes firmer. Colley (1950) reported shrinkage of samples from 10 percent to 50 percent of the original volume. Permeability varies widely, depending upon such things as the fibrous nature of the material, the degree of decomposition of the peat, and the amount of mineral matter in the deposits. Fibrous muskegs have very high void ratios, whereas amorphous muskegs have low void ratios. Void ratios in the range between 3 and 25 have been noted, although a range between 5 and 15 is more common (Pihlainen, 1963). Specific gravity of the solids is greater than 1. The range generally is from 1.1 to 2.5, with the average being about 1.5 (MacFarlane, 1969). The "spongy" nature and consequently low bearing capacity of muskeg is one of the obvious characteristics. Under load, most muskegs exhibit exceptionally high compressibility. A large portion of the resulting settlement generally takes place soon after loading. Shear strength can range from very low to moderate, varying inversely with its water content and directly with its ash content and degree of deformation in compression (Wyld, 1956). Generally there is an increase in strength of muskeg with depth, and an extraordinarily high increase in strength as the muskeg consolidates (Pihlainen, 1963). Muskeg generally has an acidic reaction, owing to the presence of carbon dioxide and humic acid arising from its decay. Peaty waters generally show pH values of 4-7, although values as low as 2 and as high as 8 have been reported (Lea, 1956). As the peat undergoes decomposition, marsh gas (methane with lesser amounts of nitrogen and carbon dioxide) is produced. The effects of gas in the deposits show up particularly in consolidation results. In a laboratory consolidation test, a large initial consolidation and an indistinct completion of primary consolidation in time-compression curves reflect the presence of gas (Moran and others, 1958). Also, there may be a potential fire hazard when buildings or fills are built upon muskeg containing large amounts of gas, although this danger appears to be very low (Moran and others, 1958).

In the Wrangell area, muskeg forms the surface cover of nearly all the flatter terrain as well as of some moderate slopes. The surface is characterized by small ponds, marshy areas, and spongy ground. Vegetational growth on thicker deposits commonly is limited to stunted trees, small brush, or open areas supporting growths of sedges, mosses, and grasses. Thinner deposits on steeper, better drained slopes generally support larger tree growth.

Knowledge of the thicknesses and physical characteristics of the muskeg is based largely upon data obtained from numerous test holes drilled in connection with road and street construction and the building of the Wrangell Airport. A few manmade cuts, particularly those in the vicinity of the airport, have supplied most of the remaining information. The muskeg is mapped as a separate unit where it is interpreted to be 3 or more feet (1 or more m) thick; where it is interpreted to be less than 3 feet (1 m) thick, the underlying unit is mapped. Because of the paucity of thickness measurements, the extent and configuration of the map units may have to be revised considerably when more data become available as a result of future construction.

Most of the muskeg in the Wrangell area appears to consist of sphagnum moss peat and fibrous sedge peat. Spruce and conifer roots and branches form, at least locally, two or more fairly distinct horizons in the deposits. Profile examinations of the muskeg were made by Dachnowski-Stokes (1941) in a number of places on Wrangell Island as part of his studies of peat resources in Alaska. Those made along the eastern limits of Wrangell were considered by him to reveal fairly typical examples of the successive stages of peat deposition that form shoreward types of muskeg. A typical section, as described by him, follows:

> "0-10 inches: upper 2 to 3 inches straw-colored spongy sphagnum moss peat which grades sharply into grayish-brown partly decomposed moss peat. pH 4 in reaction, and about 7 inches in thickness; below it are spruce stumps with flat based roots, and the woody shoots of heaths.
>
> "10-65 inches: brown fibrous sedge peat somewhat compressed and more or less cohesive from the presence of finely divided organic residue, having a reaction of pH 4.8-5.0; between the 38- and 42-inch level are stumps of conifers buried within the sedge peat; the woody roots are flat and rest on fine, partly decomposed, dark-brown sedge peat; at the 50-inch level the sedge peat is reddish brown, matted, more or less felty fibered; near the 60-inch level the sedge peat contains sand and merges into a sandy, gravelly mineral substratum."

Thicknesses of muskeg in the mapped area range widely, but commonly are 5 to 10 feet (1.5-3 m). Test holes (State of Alaska Department of Highways, 1969) drilled along the Airport Spur Road and the Wrangell East Road showed that the average thickness of muskeg in that area is 6 feet (1.8 m). The maximum thickness penetrated was 12 feet (3.6 m). On the basis of borings made by the State of Alaska Division of Aviation (unpub. maps, 1967), the muskeg in the area along the southwest side of the Wrangell Airport runway commonly is 6 to 10 feet (1.8-3 m) thick. The thickest deposits within the corporate limits of Wrangell are inferred to be in the largely undeveloped northeast and southeast sectors. In the northeast sector, thicknesses similar to those already described for areas to the east and northeast are likely. In the southeast sector, test borings by the State of Alaska Department of Highways (1966), along the route of a proposed road extending eastward from Zimovia Highway and paralleling Hemlock Street, showed a maximum thickness of 9 feet (2.7 m) but considerably less in most places. Test holes drilled in a housing project upslope from Zimovia Highway between Cedar and Hemlock Streets showed that the muskeg thickness ranged from about 3.5 to more than 12 feet (1.1 to more than 3.6 m) in this area and averaged about 8 feet (2.4 m) (Alaska State Housing Authority, 1968).

Inasmuch as data on the physical and chemical properties of muskeg in the Wrangell area are few, knowledge of these properties must depend in large part upon extrapolation of published data from other areas described previously. The few data that are available are based almost entirely upon information obtained by the State of Alaska Department of Highways (1963, 1966, 1969). In their classifying of highway subgrade materials, the Department of Highways placed the peat in an A-8[1/] group, with a frost susceptibility of F-4[2/]. Moisture content of samples from the southeastern part of the city and along the Airport Spur Road and the Wrangell East Road ranged from 752 to 1,393 percent. In order to maintain slope stability, cuts in muskeg were recommended not to exceed 1/2:1. The pH of several small streams ranged from 5.5 to 6.8.

In road and street construction in the Wrangell area, muskeg has been treated in two different ways: (1) removal of all or most of the muskeg from the road alinement, and (2) placement of roadbed material directly on the undisturbed muskeg in those places where the road grade is a minimum of 2.5 feet (0.76 m) above the existing ground elevation. Complete removal of the muskeg results in an immediately strong stable roadway with uniform conditions and minimum maintenance. This method generally is used for reconstruction of streets and for roads with an expectably high traffic volume. A roadbed placed over muskeg possesses the undesirable aspects of nonuniform subsidence, poor stability, and high maintenance (State of Alaska Department of Highways, 1966, 1969).

[1/]Material in this group has high compressibility (Casagrande, 1948, table 3, p. 10).

[2/]Material in this group has especially high frost susceptibility (U.S. Army Corps Engineers, 1962, p. 7-8).

However, the initial construction cost may be considerably less using the second method. The second method was recommended by the State of Alaska Department of Highways for roads having a low traffic volume, such as Wrangell East Road. It was further recommended by them that, when the fill is placed directly on the muskeg, it consist largely of granular materials. Where paving is planned within 3 years of construction, rapid consolidation and reasonable stability can be achieved by overloading the muskeg sufficiently to compact it immediately to the point of ultimate settlement for the proposed final design load. This could be done by use of a "rolling surcharge" (State of Alaska Department of Highways, 1969). Using this method, it is estimated that settlement of the underlying muskeg will be 40 to 60 percent of its original thickness.

In the construction of residential buildings in muskeg areas, piling is generally driven through the muskeg into the underlying surficial deposits or to bedrock. Although the presence of muskeg adds to the construction cost, it does not render the land unusable for building purposes.

Most or all of the muskeg in the mapped area postdates the elevated fine-grained marine deposits (Qem) and the elevated beach deposits (Qeb). Muskeg probably began to form shortly after emergence of these deposits and has continued to form to the present. Thus, the basal part of the highest and oldest deposits may be nearly 13,000 years old; the upper part of the deposits is modern.

The commercial possibilities of the peat should be studied further. A general study was conducted by Dachnowski-Stokes (1941) in his appraisal of the peat resources of Alaska, but no definitive statements of the commercial possibilities for the Wrangell area were given. However, as noted previously, he gave a description of a typical cross section of the peat east of town. If this section has commercial possibilities, reserves apparently are readily accessible in the area between town and the airport and in areas to the east and to the north.

Late shore deposits (Qs)

Most of the deposits mapped as late shore deposits (Qs) occur between higher high water and lower low water. Along the west shore of the mapped area, they consist chiefly of sand, gravel, cobbles, and boulders. Along the north and northeast shores, they consist mostly of clay and silt-size material. Point Highfield approximately marks the dividing line between the coarse-grained beach deposits and the fine-grained water-suspended deposits, although there is some overlap of the two size fractions.

The coarse-grained deposits along the west shore of the mapped area represent rather typical beach deposits that have been deposited in small, relatively protected areas between outcrops of bedrock. In these areas the deposits commonly range in thickness from a thin veneer over bedrock to several feet. In the Wrangell Harbor area, deposits a few feet thick overlie elevated fine-grained marine deposits (Qem). Where the deposits are interpreted to be less than 3 feet (1 m) thick, the underlying deposit is shown as the map unit. The beach material is currently being deposited as a result of normal wave erosion processes combined with sorting and transportation by tide and current action. Thus, even the oldest deposits are considerably younger than most of the elevated beach and fine-grained marine deposits.

The fine-grained deposits along the north and northeast shores of the mapped area represent very recent deposition of water-suspended sediments as a result of rapid expansion of the front of the Stikine River delta, approximately 1 mile (1.6 km) away. The heavy load of suspended sediment in the waters of Eastern Passage between these points is clearly visible from the air. In most places along the shore, the sediments are only a few feet thick and rest directly on bedrock or on typical coarser grained beach deposits that were laid down when the delta front was still some distance away. In more exposed places, the fine-grained sediments and coarser grained beach deposits have been intermixed by wave and current action. Some suspended sediment is carried all the way to the Wrangell Harbor area.

Delta deposits of the intertidal zone (Qd)

The delta deposits shown on figure 3 constitute part of the southern margin of the large delta of the Stikine River (fig. 2). They are about 10 miles (16 km) from the head of the delta. The main distributary channel of the river presently is supplying the sediment load to the area.1/ The other major distributary channel crossing the delta is North Arm, which deposits its load into Frederick Sound to the north (Berwick and others, 1964).

The deposits form the interchannel areas of the delta that are completely exposed during intervals of mean lower low water and that are completely covered by water during periods of mean higher high water. Outlines of the intertidal areas are based upon National Ocean Survey Chart No. 8165 (1972).

There are two main reasons for including the delta deposits within the area of figure 3: (1) to more clearly show the geographic relation of these deposits to the other near-shore and offshore deposits, and (2) to furnish geologic information in connection with the possibility that a segment of a proposed highway joining Wrangell with the mainland and British Columbia via the Stikine River crosses these deposits (Alaska State Housing Authority, 1968).

1/Although distributary channels crossing the delta have constantly shifted positions during the entire growth of the delta, hydrographic surveys by the U.S. Coast and Geodetic Survey indicate that, at least since 1886, the course of the main distributary channel of the Stikine River has been southward across approximately the area of figure 3.

The nature of the deposits is inferred from aerial observations and from test-hole data obtained from Stikine River delta deposits outside the mapped area. As observed from the air, the deposits probably consist chiefly of fine sand, silt, and clay-size materials; some coarser sand and fine gravel may be present locally. The test-hole data were obtained from six holes drilled by the State of Alaska Department of Highways (1967) in Dry Strait (fig. 2), about 10 miles (16 km) northwest of the mapped deposits, in connection with proposed construction of a bridge between Mitkof Island and Dry Island. Depths of the holes ranged between approximately 60 feet (18 m) and 150 feet (46 m). None of the holes reached bedrock. Logs of the holes indicate that the entire area in the vicinity of the holes is underlain by a nearly uniform deposit of fine-grained, silty sand with a few traces of fine gravel, thin silt lenses, and scattered organic layers. In five of the holes, the upper 20-30 feet (6-9 m) of material was loose to very loose but with gradual increase in density with depth. In one hole the material was dense to very dense between depths of 105 feet (32 m) and 147 feet (44.8 m) (bottom of hole). In the sixth hole (the one nearest Dry Island), the materials were slightly coarser than in the other holes and were loose to very loose; the total depth of the hole was 57 feet (17.4 m). Whether the delta deposits in the area of figure 3 have characteristics similar to those penetrated by the test holes outside the area is, of course, speculative. In general, one would expect that the deposits in the area of figure 3 would be considerably finer grained, inasmuch as they have been deposited a considerably greater distance from the head of the delta. On the other hand, at least the near-surface delta deposits have been laid down by streamflow in or near the main distributary channel of the Stikine River and, thus, they may be coarser grained than otherwise would be expected.

Thicknesses of the deposits in the mapped area are not known. The test holes drilled in Dry Strait show that the deposits in that area exceed 150 feet (45 m) in thickness. A similar minimal thickness in the mapped area seems reasonable, except possibly where there might be buried bedrock islands or buried moraines. Also, the deposits, in most places in the mapped area, can be assumed to be at least as thick as the height of the delta front, which extends from a depth of about 180 feet (55 m) to the surface. Inasmuch as fairly thick prodelta deposits (those out beyond the toe of the delta) are indicated to cover the bedrock floor of Eastern Passage in the vicinity of the delta front, a thickness considerably greater than 180 feet (55 m) can be assumed for the delta deposits. Buddington and Chapin (1929), on the basis of a water depth of 500 feet (152 m) in inlets within 3 miles (4.8 km) of the delta front and on the presumption that a fiord of similar depth extended toward the Stikine River, suggested an average thickness of 500 feet (152 m) for the delta deposits.

Test data concerning the physical properties of the deposits within the mapped area also are lacking. Some extrapolation of data from the holes drilled in Dry Strait may be possible. These extrapolations will be discussed later under the headings "Inferred effects from future earthquakes" and "Inferred future effects from geologic hazards other than those caused by earthquakes."

Historical records show that the Stikine delta southeast of Mitkof Island (fig. 2) has been advancing at a relatively rapid rate. Kerr (1936) compared the mapped extent of the delta in 1793 with that in 1886-87. He indicated that the delta along more than 7 miles (11.2 km) of its margin[1/] (presumably that part between Mitkof Island and Kadin Island, shown on fig. 2) had advanced at least 1-1/3 miles (1.7 km) during the 94-year interval and may have advanced as much as 2 miles (3.2 km), or at an estimated annual rate of 75 to 105 feet (22.9-32 m). He also noted that comparison of the 1936 position of the delta front with the 1886-87 position showed a continued but less rapid rate of advance except for that part north of Wrangell Island (area of fig. 3), where growth appeared to be retarded by sea currents. The 1793 records are not accessible to the writer, but comparison of the 1886-87 data[2/] with those shown on the latest hydrographic charts (Chart 8160 of 1963 and Chart 8165 of August 1972) was made. These data indicate that the greatest advance during the past 86 years (1887-1972) has been north of Wrangell, largely in the area of figure 3. In that area, the margin of the delta appears to have advanced in most places 4,000 to 5,000 feet[3/] (1,220-1,525 m), or roughly at a rate of 50 to 60 feet (15-18 m) a year. Directly north of Simonof Island, where one of the major distributaries of the Stikine River has been more or less localized during the period of comparison, the rate of advance is indicated to be even greater. The rate of advance of the delta margin between Mitkof and Kadin Islands (fig. 2) during this same period, although substantial, appears to be considerably less than in the area of figure 3. Such changes in rate of growth of different portions of the delta from time to time are not unexpected and can be attributed to changes in size and the shifting of positions of the stream channels that are carrying the main sediment load across the delta.

Assuming that the margin of the delta has been advancing at a rate of 100 feet (30 m) per year (based upon the rate of advance during the period 1793-1887), Kerr (1936) estimated that it took approximately 4,300 years for the formation of the entire delta. It is doubtful that Kerr's assumption of a uniform rate of advance is valid because of

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[1/] As presumably used by Kerr and as will be used in this report, the margin of the delta is regarded as the outer edge of the delta that is exposed at approximately mean lower low water.

[2/] Hydrographic Survey field sheet No. H-1806, dated 1887, of the U.S. Coast and Geodetic Survey was used mainly in the comparison for this period. Hydrographic Survey field sheet No. H-1742, dated 1886, also covers the area, but it lacks sufficient soundings and definitiveness of the MLLW line to be used effectively.

[3/] Because of the difficulty of accurately registering the maps being compared and of determining the MLLW line on the old maps, these figures must be regarded as approximate.

different climatic conditions and glacier positions that prevailed in the past from those that were in existence during the period of study. Nevertheless, it seems evident that a considerable thickness of sediments has been deposited very recently. This is indicated from three radiocarbon dates of wood fragments obtained from boring No. 4 made in Dry Strait about midway between Mitkof Island and Dry Island by the State of Alaska Department of Highways (1967). One sample (W-2163), from a depth of 90 feet (27.4 m), was dated as 1690±250 years B.P.; a second sample (W-2164), from a depth of 80 feet (24.3 m), was dated as 960±250 years B.P.; a third sample (W-2165), from a depth of 60 feet (18.3 m), was dated as 1580±250 years B.P. The second date appears to be anomalous in respect to the other two dates but does not seem to invalidate the assumption concerning the recency of the deposits.

The slope and other characteristics of the underwater part of the delta front as well as of the prodelta deposits are described in the section "Offshore deposits (not shown on map)." The possible effect of the advancing delta margin and of shoaling of marine waters upon navigation in the Wrangell area will be discussed in the section "Inferred future effects from geologic hazards other than those caused by earthquakes."

Manmade fill (mf)

There are essentially two types of man-emplaced fill obtained locally in the Wrangell area: (1) fairly thick fills consisting chiefly of surficial deposits emplaced along the shore to elevate low-lying areas above high tide, and (2) fills consisting mostly of crushed bedrock laid down as thin to thick blankets to obtain firm bases for roads and streets, for the airport runway and apron, and for parking area pads surrounding buildings.

Probably the thickest section of fill that consists chiefly of surficial deposits has been emplaced in the former intertidal area between Front Street and Drive Street, where the City Hall building, a supermarket, and other buildings are located. The surface of this fill, in most places, is 8 to 10 feet (2.4-3 m) above mean higher high water, and the fill may be as much as 15 feet (4.6 m) thick near its outer margin. Inasmuch as the fill was obtained mostly from the dredged area of the City Inner Boat Harbor, it probably consists chiefly of intermixed clay, silt, sand, and some gravel-size material. Crushed bedrock, laid down as a topping, forms approximately the upper 1 foot (0.3 m) of the fill, and angular pieces of bedrock-derived riprap, 1 to 2 feet (0.3-0.6 m) long, have been emplaced along the outer edge to prevent wave erosion. As judged from bedrock outcrops near the outer margin of the fill, and from old photographs, and hydrographic charts, the fill has been placed directly on bedrock in most places.

A second large fill was emplaced to elevate a low-lying area along the shore west of Shakes Street where the lumber mill is located. Less is known to the writer about the composition of this fill. In most places the fill probably is not as thick as the one previously described. Old hydrographic field sheets (1882) show two areas that were above high tide before emplacement of the fill. It seems likely that fill was emplaced in the intertidal areas between these two areas to form a fairly level surface. As indicated from surface material, at least some and perhaps a large part of this fill consists of sawdust and larger wood fragments from the lumber mill. This fill probably also was emplaced directly on bedrock in most places.

The largest areal extent of manmade fill and locally the thickest underlies the Wrangell Airport runway and parking apron.[1/] As much as 25 feet (7.6 m) of fill was emplaced near the northwest end of the runway and a maximum of about 20 feet (6.1 m) was emplaced at the southeast end. Between 3,000 and 4,400 feet (915 and 1,340 m) from the northwest end of the runway, excavation was in original ground and essentially no fill was emplaced. A considerable amount of this excavation was in bedrock. A maximum of approximately 10 feet (3 m) of fill underlies part of the parking apron. Both selected surficial materials excavated from the runway and bedrock from the two adjacent quarries were used as fill. However, most or all of the muskeg along the alinement apparently was stripped and wasted. Riprap, emplaced on a 1-1/2:1 slope along the shoreward side of the northwest end of the runway, apparently was obtained from the two adjacent quarries. Where riprap was not used, the fill slope is 3:1.

Considerable fill (not shown on geologic map) has been used in constructing roads and streets in the Wrangell area. For newer roads such as the Airport Spur Road and the Wrangell East Road, where the fill commonly is placed on the original ground surface, the amount of fill is determined largely by the frost susceptibility of the original surface material. Thus, minimum overlays of fill generally range from 13 inches (33 cm), where surface material has a moderate frost susceptibility, to minimum overlays of 51 inches (130 cm) of fill on some city streets where fill has been emplaced on muskeg (State of Alaska Department of Highways, 1963). Crushed bedrock from nearby quarries constitutes most of the fill for recently constructed roads, especially where the fill directly overlies muskeg. Where the roads are excavated through bedrock, the bedrock in the cut also generally is suitable for common embankment fill. Silty deposits, such as elevated fine-grained marine deposits (Qeb), generally are not used for fill because of their fine texture, high frost susceptibility, and high natural moisture content. Sand and gravel, used as selected material and for aggregate on some streets and roads, have been barged in from a source near the mouth of the Stikine River or have been obtained from pits along the Zimovia Highway about 6 miles (9.6 km) south of Wrangell.

As Wrangell continues to expand into areas underlain by relatively thick muskeg deposits, more and more fill is being used to construct firm pads for parking and other purposes. Pads of considerable areal extent have been emplaced around the newly constructed elementary

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[1/] Information on thickness and classification of fill underlying the runway and apron is based on unpublished cross sections prepared by the State of Alaska Division of Aviation.

school and general hospital along Bennett Street, as well as at new housing developments, mobile home sites, and other types of development. The fill constituting the pads generally consists of crushed bedrock placed directly on the muskeg, and commonly is 2 or 3 feet (0.6 or 1.0 m) thick. Rock pieces, commonly as much as 1 foot (0.3 m) in size, are used as a base and are compacted by rolling; finer crushed rock is added as a topping.

Surficial deposits (not shown on map)

Diamicton, colluvium, and offshore deposits are described under this heading. These deposits, although probably all present in the mapped area, are not exposed, are poorly exposed, or are too thin or too small in areal extent to be mapped separately.

Diamicton

Diamicton, which resembles till in appearance but which may be of glaciomarine origin, is exposed in the mapped area only in the lower 2 feet (0.6 m) of an 11-foot- (3.3-m-) high roadcut on the west flank of Dewey Hill. The diamicton at that locality is grayish blue, compact, and has numerous pebbles in a silty to sandy matrix. Similar-appearing deposits are exposed in several places along Zimovia Highway to the south of the mapped area and are inferred from drilling logs to underlie other surficial deposits in a number of places in the mapped area.

A 10-foot- (3-m-) thick section of diamicton, exposed in a roadcut about a third of a mile (0.5 km) north of the Wrangell Institute (fig. 2), probably is typical of similar material that is believed to underlie parts of the mapped area. The material at that location is gray, compact, and has a silty matrix. Flat chips of phyllite are fairly numerous, as well as granitic cobbles and boulders. Muskeg, about 1 foot (0.3 m) thick, overlies the deposit, which appears to form a broad flat bench about 45 feet (14 m) above MLLW. A nearby exposure of the diamicton to the north, at an elevation of about 30 feet (9 m) above MLLW, is overlain by approximately 2-1/2 feet (0.8 m) of dirty gravel, which is interpreted to represent elevated beach deposits (Qeb).

Diamicton may have been penetrated in a few places by borings made by the State of Alaska Department of Highways (1966), where the material was generally described as moderately dense and consisting of gravelly, silty sand with some clay. On the other hand, the material may represent a more stony facies of the elevated fine-grained marine deposits (Qem). The approximately 25 feet (7.6 m) of "hard clay and boulders" penetrated in test wells No. 1 and No. 2 (see section entitled "Transportation and other facilities") may be diamicton. However, the material directly underlies muskeg and also may represent a more stony facies of the elevated fine-grained marine deposits. Likewise, there is some question as to whether the "hard material" or "tough clay" penetrated by test holes in the City Inner Boat Harbor (see description under the heading "Elevated fine-grained marine deposits (Qem)") is really diamicton.

In summary, it is likely that diamicton is sparingly present as a subsurface deposit in the mapped area. However, it probably almost everywhere is thin, and occurs chiefly in bedrock declivities or in the lee of bedrock promontories, such as at Dewey Hill.

Colluvial deposits

Colluvium is the general term given to surficial material, including rubble, that has moved downslope, principally under the influence of gravity. Colluvial deposits are sparingly present in the mapped area and probably are confined mostly to the lower flanks of Dewey Hill and the hill near Point Highfield. Nine feet (2.7 m) of colluvium overlying 2 feet (0.6 m) of diamicton is exposed in a roadcut on the west side of Dewey Mountain. The upper 7 feet (2.1 m) of the colluvium ranges in grain size from a clay-silt-sand matrix to angular cobbles and boulders. There is some incorporated organic material, and parts of the deposit are stained orange brown to mottled gray. The lower 2 feet (0.6 m) of the colluvium is tannish gray and is finer grained than the overlying material; also, there are some coarse sand and gravel lenses about 8 inches (20.3 cm) thick. This lower part may have been derived largely from elevated beach deposits (Qeb), whereas the upper 7 feet (2.1 m) appears to have been derived largely from bedrock from the steep slope of Dewey Hill immediately to the east.

Offshore deposits

Knowledge of offshore deposits within the area of figure 3 is limited to data from hydrographic maps prepared by the U.S. Coast and Geodetic Survey, to seismic traverses and bottom sampling by the U.S. Geological Survey, and to data related to construction along the shore in the immediate vicinity of Wrangell.

Intertidal delta deposits (Qd), shown in the northern part of figure 3, were discussed previously, and it was noted that the southern margin of the Stikine delta is advancing at a relatively fast rate. In this section, the front of the delta below mean lower low water and the prodelta deposits will be discussed.

Profile studies, based upon soundings from recent hydrographic maps, furnish moderately good information on the slope of the Stikine River delta front[1/] in the area of figure 3. Using the soundings obtained by the U.S. Coast and Geodetic Survey in 1961 (Hydrographic Survey H-1861),[2/] the writer constructed five profiles of the delta front north of Wrangell to determine average slope as well as extremes of

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[1/]As used here, the front of the delta is the sloping outer submarine surface of the delta, extending from approximately mean lower low water to the relatively flat sea floor.

[2/]Data were used from this source rather than using the bathymetric contours shown on figure 3 because of more accurate control on H-1861.

slope. These profiles show that, in most places, the upper part of the delta front is fairly steep down to a depth of about 10 fathoms (60 ft, 18.3 m). At about 10 fathoms there commonly is a rather abrupt flattening of slope and a gradual diminution of slope to the toe of the delta front at more or less 30 fathoms (180 ft, 54.9 m). The average slope between 1 and 10 fathoms (6 ft, 1.8 m, and 60 ft, 18.3 m) is about 12°, ranging from a low of 7° to a high of 16°. The steepest slope is commonly between 3 and 5 fathoms (18 ft, 5.5 m, and 30 ft, 9.1 m), where it may be as much as 30°. Slopes between depths of 10 and 20 fathoms (60 ft, 18.3 m, and 120 ft, 36.6 m) average about 5°, ranging from a low of 3° to a high of 7°. Slopes between 20 and 30 fathoms (120 ft, 36.6 m, and 180 ft, 54.9 m) average about 3°, ranging from a low of 2° to a high of 4°.

Some information on the nature of offshore deposits in Eastern Passage, Zimovia Strait, and Stikine Strait is available as a result of seismic traverse data and bottom sampling done by the U.S. Geological Survey in 1967. Only limited preliminary interpretations of the records have been made to date by S. C. Wolfe and H. C. Wagner (written commun., 1973). These tentative interpretations indicate that at least three units that differ in acoustic character overlie the bedrock floors of these inlets. They are described by H. C. Wagner (written commun., 1973) as follows:

> "The uppermost unit is a well-bedded group of sediments locally more than 300 ft thick (based on assumption that sediments are water-filled with acoustic velocity of 5,000 ft per sec). I would assume that these sediments are probably post-Wisconsinan and deltaic in origin. They lap onto the underlying unit, apparently without a period of erosion.
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> "The next youngest unit is fairly well bedded and also may have been deltaic in origin. The lack of continuity to the acoustic signal may be the result of less power reaching that unit. On profile 11, the contact between these two units is seen very clearly, suggesting that there is a sharp acoustic contrast between the two units. I assume an acoustic velocity of about 5,500 ft per sec for this unit. On that basis, its thickness ranges from near zero to about 175 ft and averages about 130 ft. The structure within the thickness variations in the unit suggest that the offshore area was lowered somewhat irregularly and that compaction over underlying highs occurred locally.
>
> "The third unit from the top has a very irregular upper surface, as suggested by the overlapping hyperbolic signals. The short bedding signals and lack of bedding in the unit suggest the possibility that the unit is composed of disconnected bedded and gravelly sediments. These combined observations suggest that the unit may be morainal in origin. Thickness, based on an acoustic velocity between 5,500 and 6,000 ft per sec, averages about 210 ft and ranges from near zero to 350 ft. The distribution of thickness suggests irregular downwarping of the underlying surface since deposition."

The seismic profiles indicate that the thickest composite deposits occur along a moderately steep walled bedrock trough that trends northeasterly from Stikine Strait (northwest of Woronkofski Island) to Eastern Passage about midway between the northern part of Wrangell Island and Liesnoi Island (fig. 2). Along this trough the combined thickness of the three units commonly is 600 to 700 feet (183-214 m), reaching a maximum of about 750 feet (229 m).

Bathymetric contours indicate considerable shoaling in Eastern Passage between Simonof Island and the southern margin of the delta in the area of figure 3. The shoaling probably represents substantial thickening of the prodelta sediments (uppermost unit of seismic profiles), owing to deposition of large amounts of material from the main distributary channel of the Stikine River directly to the north. Unfortunately, sufficient interpretations of the seismic profiles have not been made to permit estimating total thickness of sedimentation in that area.

The seismic traverses indicate some evidence of faulting in the lower of the three units in Zimovia Strait west of Wrangell; the middle unit in the same area appears to be only folded (H. C. Wagner, written commun., 1973). The indicated faulted unit probably is late Pleistocene in age; the middle and upper units probably are Holocene in age. Only a few faults were noted in the lower unit. However, other faults possibly are present in that unit but were not identified because of the limited interpretations that have been made thus far of the records.

Bottom sampling (S. C. Wolf, unpub. data, 1967) shows a progressive decrease in grain size of the sediments from the southern margin of the Stikine River delta southward to at least as far as Zimovia Strait between Woronkofski Island and Wrangell Island in the vicinity of Wrangell Institute (fig. 2). This is as one would expect, inasmuch as the Stikine River is about the only source of supply of sediments in this area. In the immediate vicinity of the front of the delta, the bottom sediments typically consist of 40 to 45 percent silt, 30 to 55 percent very fine to fine sand, and 2 to 5 percent medium to very coarse sand. Samples taken between the northwest end of Wrangell Island and Liesnoi Island typically consist of approximately 70 percent silt size or smaller, and 30 percent very fine to medium-size sand. Between Woronkofski Island and Wrangell Institute, nearly all samples consist of 99 percent silt-size material or smaller.

Limited information on the nature and thicknesses of offshore deposits is available in the Wrangell Harbor area as a result of construction of docks and other harbor facilities. As already noted (see section entitled "Elevated fine-grained marine deposits"), as much as 18 feet (5.5 m) of "soft" material was penetrated in borings in the City Inner Boat Harbor in connection with the deepening of the harbor. This material, which probably represents in large part deposition of water-suspended material, is underlain in places by "hard material" which may be diamicton and which in turn rests on bedrock. Such a sequence of near-shore deposits probably is typical in the Wrangell area. In the construction of the main wharf for the lumber mill in Wrangell (fig. 3), piling was driven on a sloping underwater surface (average slope of 7°) to points of refusal. Profiles drawn in connection with the pile driving (Hubbell and Waller Eng. Corp., 1964, unpub. maps) show that the piles along the northwest corner of the wharf (where the water is 35 to 40 feet (10.7-12.2 m) deep) commonly penetrated 30 to 40 feet (9.1-12.2 m) of bottom material before reaching refusal on hard rock. The maximum thickness of the "surface mud" was about 5 feet (1.5 m). The kind of material constituting the remaining thicknesses down to the point of refusal is not described on the profiles. However, it probably is similar to the "hard material" in the City Inner Boat Harbor, although penetration of decomposed bedrock might account for a very small part of the thickness. Along the shoreward side of the wharf, penetrations of 5 to 10 feet (1.5-3 m) were common, with the "soft material" thinning to extinction shoreward. Probably a more atypical profile of near-shore deposits is indicated in the area of the ferry terminal, where the underwater slope down to a depth of 70 feet (21.3 m) is approximately 19°. Five holes were jetted to depths of between 9 and 17 feet (2.7 and 5.2 m) in 20 to 34 feet (6.1-10.4 m) of water in connection with construction of the docking part of the structure. The material encountered throughout the length of all the holes consisted of gravel with large boulders (Toner and Nordling, Engineers, 1962, unpub. map). It is not clear whether the holes were bottomed on bedrock, but is suggested by the presence of numerous outcrops of bedrock along the adjacent shore.

Sediment-laden tidal waters, originating from the Stikine River delta area, are carried at least as far as the Wrangell Harbor area during each tidal cycle. The murky-appearing water in Wrangell Harbor is believed to be due to the presence of silt and clay in suspension. In 1961 the U.S. Army Corps of Engineers (Sawyer, 1963) conducted an extensive "condition survey" of the deep draft portion of Wrangell Harbor, particularly in the dock area of the lumber mill (see fig. 3), to determine how much sediment was being deposited in the harbor area. Maps prepared by the U.S. Army Corps of Engineers, showing soundings in 1939, 1948, and 1961, were compared. The Corps of Engineers concluded that no appreciable differences in bottom elevations had occurred during the period of study. They also noted that a "condition survey" in 1962 of the two inner small-boat mooring basins indicated no appreciable shoaling and that maintenance dredging need not be anticipated for several years. They attributed the absence of appreciable sediment accumulation to tidal currents that keep the sediment in suspension by agitation and that flush it out of the harbor area during ebbtide.

The writer, in attempting to obtain an assessment of the rates and locations of accumulation of sediment within the immediate vicinity of the mooring basins of Wrangell Harbor as well as in the deeper offshore area, compared soundings over as long a time span as data permitted. Bathymetric maps of Wrangell Harbor, prepared in 1948 and 1965 by the Corps of Engineers, first were compared. These maps indicate that during this period 4 to 6 feet (1.2-1.8 m) of sediment was deposited locally in the deeper part of the harbor about midway between the breakwater that extends from Point Shekesti and Shakes Island. This is at an average accumulation rate of 3 to 4 inches (7.6-10 cm) a year for this particular area. Soundings made in 1916, 1937, and 1961 by the U.S. Coast and Geodetic Survey (Hydrog. Surveys H-3938, H-6282, and H-8620, respectively) next were compared by the writer to determine sediment accumulation in the deeper water along the western edge of the Wrangell Harbor area. Three profiles, constructed from approximately mean lower low water to a depth of 30 fathoms (180 ft, 54.8 m), indicate that an average of about 4 feet (1.3 m) of sediment has accumulated in the deeper water during the 45 years being compared, or at an average accumulation rate of about 1 inch (2.54 cm) a year. Very little sediment appears to have accumulated on the steeper upper slopes, probably as a result of tidal action. It should be pointed out that, because of the problem of accurately registering the maps being compared, and also because of possible inaccuracies in the depths and positions shown for the soundings on the older maps,[1/] the above given rates of accumulation must be regarded as rough approximations. Therefore, they should not be rigorously interpreted for navigation or construction purposes. They do point up, however, the desirability of conducting additional detailed studies of the rate of sedimentation in the area.

STRUCTURE

Summary of regional structure

Southeastern Alaska lies within the active tectonic belt that rims the northern Pacific Basin. It has been tectonically active since at least late Paleozoic time, and the bedrock outcrop pattern is the result of late Mesozoic and Tertiary deformational, metamorphic, and intrusive events (Brew and others, 1966). Large-scale faulting, mostly with strong right-lateral strike-slip movement, has been common.

The trends of many linear fiords of southeastern Alaska are believed to be controlled by major faults or fault zones (Twenhofel and Sainsbury, 1958); other fiords, such as the northeast-trending ones transecting Baranof Island (fig. 1), are believed to be controlled by joints (Brew and others, 1963). The fiords are formed along faults or joints chiefly as a result of outlet glaciers scouring and deepening preglacial river valleys whose courses followed, at least in part, the more easily erodible fault or joint planes. Many other linear features such as straight valleys, coastlines, and troughlike depressions reflect faults, shear planes, and joints. The more conspicuous of these lineaments, most of which are believed to be fault traces, are shown on figure 5.

Two of the most prominent fault systems in southeastern Alaska and surrounding regions are: (1) the Denali fault system, and (2) the Fairweather-Queen Charlotte Islands fault system. Also, of major tectonic

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[1/] An attempt also was made to compare soundings made in 1882 (U.S. Coast and Geod. Survey Hydrog. Survey H-1623a). However, the results were largely inconclusive because of map registration problems and possibly because of inaccuracies of the depth measurements.

importance are the Totschunda fault system, which appears to connect with the Denali fault system, and the Chugach-St. Elias fault, which joins the northwestern end of the Fairweather fault. These fault systems, as well as inferred connections between individual fault segments, are shown on figures 4 and 5 and were described in more detail in a regional report by Lemke and Yehle (1972a). Two other prominent lineaments in southeastern Alaska, which are nearer the Wrangell area and which may be faults, are the Clarence Strait lineament and the Coast Range lineament. Recency of faulting in relation to earthquake risk is discussed under the heading "EARTHQUAKE PROBABILITY."

Denali fault system and associated faults

As first reported by St. Amand (1954) and by Sainsbury and Twenhofel (1954) and later described in more detail by St. Amand (1957) and Twenhofel and Sainsbury (1958), the "Denali fault" is a great arcuate series of related faults and branches about 1,300 miles (2,090 km) long. The "fault" was described as extending from the Bering Sea across the northern flank of Mount McKinley, through northernmost British Columbia, and thence down the Chilkat River valley and Chilkat Inlet to Lynn Canal and Chatham Strait (fig. 4). Thus, in Canada and southeastern Alaska it included the Shakwak valley, Chilkat River, Chatham Strait, and Lynn Canal fault segments (fig. 5). Grantz (1966) called this series of related faults and branches the Denali fault system but restricted the Denali fault itself to that part of the Denali fault system that extends from the Kuskokwim River drainage east of Bethel to northernmost British Columbia (a length of about 870 miles (1,400 km)).

Some doubt was expressed by Hamilton and Myers (1966) as to the continuity of the Denali fault into British Columbia and southeastern Alaska, as described by St. Amand (1957) and others. Instead, they suggested that the Denali fault system extends southeastward along a lineament that Richter and Matson (1971) named the Totschunda fault system. Furthermore, they noted that this fault was alined with the Fairweather fault to the southeast and assumed that the two faults connect. Richter and Matson (1971) left open the question of whether or not there is a connection between the Denali fault and the Totschunda fault system and only suggested that the Totschunda fault might connect with the Fairweather fault. However, Plafker (1971; written commun., 1971) does not believe that the Totschunda fault is a continuation of the Fairweather fault. Also, more recently, Berg and Plafker (1973) have cast doubt on the previous suggestion that there is a direct connection between the Chatham Strait-Chilkat River fault and the Shakwak valley fault. On the basis of several lines of evidence, they believe that the two faults are separated by a 100-km (62-mi) gap and that their trends are divergent.

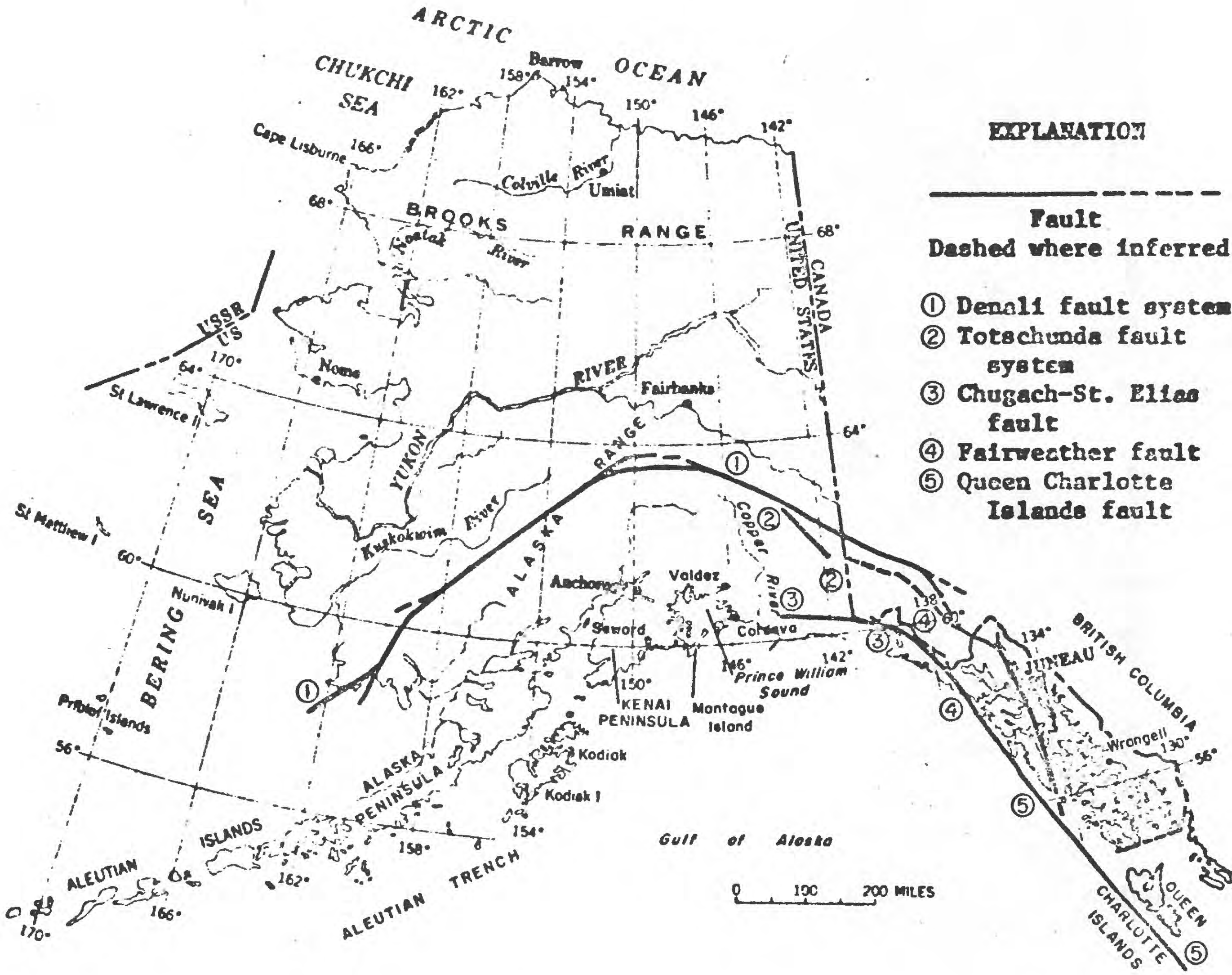

Figure 4.--Map of Alaska showing major elements of the Denali and Fairweather-Queen Charlotte Islands fault systems. Modified from Grantz (1966), Tobin and Sykes (1968), Plafker (1969, 1971), Richter and Matson (1971), Berg, Jones, and Richter (1972), Berg and Plafker (1973), and Page and Gawthrop (1973).

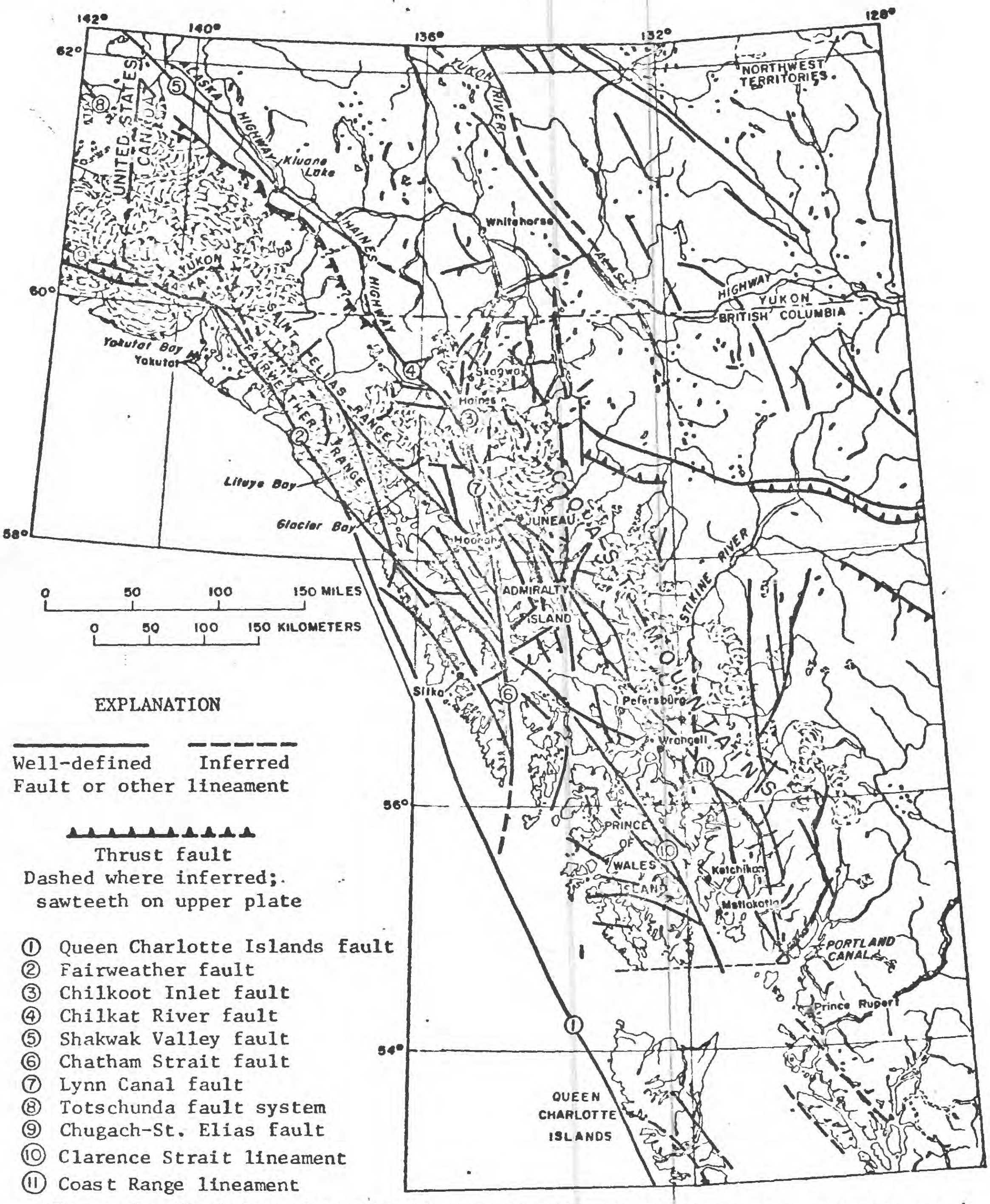

Figure 5.--Map of southeastern Alaska and adjacent Canada showing major faults and selected other lineaments interpreted to be probable or possible faults, shear zones, or joints. Taken from St. Amand (1957), Twenhofel and Sainsbury (1958), Gabrielse and Wheeler (1961), Brew, Loney, and Muffler (1966), Tobin and Sykes (1968), Geological Survey of Canada (1969a, b), King (1969), Plafker (1969, 1971), Souther (1970), Richter and Matson (1971), Berg, Jones, and Richter (1972), Berg and Plafker (1973), and Page and Gawthrop (1973), with additions and modifications by the writer.

Instead, they suggested that the Chatham Strait-Chilkat River fault may be linked, via the Duke River thrust fault,[1/] to the Totschunda fault.

These differences in interpretation as to the true trend of the Denali fault system cannot be resolved in this report. However, for purposes of discussion here, the Chilkat River fault, Lynn Canal fault, and the Chatham Strait fault (fig. 5) will be considered as probably an older part of the Denali fault system, and the Totschunda fault system as possibly a younger part of that system.

Fairweather-Queen Charlotte Islands fault system

The Fairweather fault and the Queen Charlotte Islands fault probably are a part of the same tectonic element but are generally described separately (St. Amand, 1957; Grantz, 1966; Tobin and Sykes, 1968; Page, 1969; George Plafker, written commun., 1971; Richter and Matson, 1971; Page and Gawthrop, 1973). The onland part of the Fairweather fault is a segment about 125 miles (200 km) long that extends southeastward from Yakutat Bay to Icy Point (figs. 4, 5), where the fault lies largely in a linear valley partly filled by glaciers and separates crystalline rocks of the Fairweather Range from partly younger and less altered rocks of the coastal region (Miller, 1960). As mapped by Plafker (1969, 1971), the northwestern end of the Fairweather fault joins the eastern end of the Chugach-St. Elias thrust fault (figs. 4, 5) and, as noted previously, does not link up with the Totschunda fault system. The offshore southeastern extension of the fault follows the continental slope off southeastern Alaska and, for purposes of discussion here, joins the Queen Charlotte Islands fault at about latitude 55°30'. The Queen Charlotte Islands fault is inferred to continue southeastward along the southwest side of the Queen Charlotte Islands on the basis of the configuration of offshore topography and the presence of a belt of high seismicity (Menard and Dietz, 1951; St. Amand, 1957; Wilson, 1965; Brown, 1968; Chase and Tiffin, 1972).

Clarence Strait lineament

This prominent lineament, which probably reflects faulting along part or all of its length, is at least 218 miles (350 km) long (Grantz, 1966) and may be more than 250 miles (400 km) long (Twenhofel and Sainsbury, 1958). It extends northwesterly from the mouth of Clarence Strait in Dixon Entrance to at least Kupreanof Island (figs. 1, 5). A possible northwestward extension across Kupreanof Island and Admiralty Island to the Chatham Strait fault is not evident. However, Twenhofel and Sainsbury (1958) speculated that the inferred fault probably underlies Tertiary rocks of those islands and crosses Chatham Strait and

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[1/] This thrust fault, southwest of Kluane Lake in the Yukon, forms part of the southwest boundary of the Gravina-Nutzotin belt described by Berg, Jones, and Richter (1972). The relation of the Gravina-Nutzotin belt to the Wrangell area will be further described under the heading "Local structure."

Chichagof Island to join the large fault along the southwest side of the Fairweather Range. If the Clarence Strait lineament is a fault, the northeast side is indicated to have been uplifted (probably during late Early and Late Cretaceous time) at its southeast end, with displacement decreasing to the northwest (Grantz, 1966). Evidence for lateral slip, according to Grantz, is lacking.

Coast Range lineament

This lineament, according to Twenhofel and Sainsbury (1958), is 370 miles (595 km) long and extends from the southern border of southeastern Alaska to Lynn Canal (figs. 1, 5). At least part of the lineament represents faulting, but precise data on amount and type of movement on the structure is lacking. Buddington and Chapin (1929, p. 291), in describing a part of the lineament southeast of Juneau, noted that "a highly mashed overthrust fault zone is indicated by the cataclastic texture of the rocks in a belt on the mainland adjacent to Stephens Passage." The relationship of the Coast Range lineament with the Lynn Canal-Chatham Strait lineament is not clear because the inferred intersection is concealed beneath the fiord waters. Twenhofel and Sainsbury (1958) speculated that possibly both lineaments are splits from the Denali fault.

Local structure

The local structure in and adjacent to the Wrangell area is not well known. Knowledge is limited largely to broad regional studies by Buddington and Chapin (1929), Twenhofel and Sainsbury (1958), Brew, Loney, and Muffler (1966), and Berg, Jones, and Richter (1972). Because bedrock outcrops in the mapped area (fig. 3) are limited chiefly to the shorelines, little is known of the inland structure. Also, the major inferred faults of the area, as indicated from the trends of the lineaments, are concealed for the most part beneath the waters of the fiords.

As noted previously, Buddington and Chapin (1929) assigned the Wrangell area to the Wrangell-Revillagigedo belt of metamorphic rocks that extends for many miles to the southeast and to the northwest. The Wrangell area lies near the axis of a northwestward-trending structural low which Brew, Loney, and Muffler (1966, fig. 8-3) called the Mitkof Low. The strike of the schistosity or cleavage of the metamorphic rocks in the area is roughly parallel to this trend, and dips commonly are 30°-45° NE.

More recently, Berg, Jones, and Richter (1972) have shown the Wrangell area as lying within the Gravina-Nutzotin belt. According to them, the Gravina-Nutzotin belt is a narrow belt of Middle(?) Jurassic to middle Cretaceous sedimentary and volcanic rocks that extends almost continuously in a northwesterly direction from southeastern Alaska through the Yukon and to the Alaska Range in eastern Alaska. In southeastern Alaska, they believe that rocks of late Paleozoic and early Mesozoic age structurally overlie the younger Gravina-Nutzotin rocks. They presume that major imbricate thrust faulting has produced the inverted sequence and that the belt is a part of a deformed upper Mesozoic arc. The thrust fault shown on figure 6 is a segment of a thrust zone that they believe bounds the northeast side of the Gravina-Nutzotin belt in the Wrangell area. On Annette and Gravina Islands near Ketchikan, thrust faults of this zone displace bedded rocks as young as late Mesozoic and are offset by high-angle faults, probably mainly of middle Tertiary age (Berg, 1972). It should be noted that the fault segment in the vicinity of Wrangell is shown (fig. 6) as concealed and its position to be largely assumed. Therefore, its significance in respect to the Wrangell area cannot now be evaluated with any degree of certainty.

Three long lineaments, which may reflect major faulting or other significant tectonic structure, are shown on figure 6. One of these, the Coast Range lineament, is conspicuously reflected by the alined valleys of South Fork, North Arm, and part of Bussy Creek. In the northwest sector of figure 6, it apparently is coincident with the inferred thrust fault of the Gravina-Nutzotin belt. It seems likely that the segment of the Coast Range lineament to the southeast also reflects faulting. The trends of the other two large lineaments shown on figure 6 are largely coincident with the trends of the larger fiords of the area. One lineament trends northward up Zimovia Strait just offshore from Wrangell and a second trends up Eastern Passage, the two joining at Farm Island and continuing northwestward as a single lineament up Frederick Sound (fig. 6). Thus, if these lineaments represent faulting, the faults are largely concealed beneath the waters of the fiords. Other smaller lineaments shown on figure 6 also may reflect faulting. In addition, there may be many faults in the Wrangell area, especially small ones, that are not reflected by conspicuous lineaments. Speculation regarding recency of local faulting is discussed under the heading "EARTHQUAKE PROBABILITY."

EARTHQUAKE PROBABILITY

As yet it is not possible to predict when or where the next destructive earthquake will strike in the world or what its size and other characteristics will be. We do know, however, that some regions are much more likely to have destructive earthquakes in the future than other regions. The determination of likelihood is based upon two factors: (1) the seismicity or historical record of earthquakes in a certain region or area, and (2) the degree of tectonic activity of the region or area, as indicated chiefly by the recency of fault movement. Assessment of these two factors affords a means of determining the earthquake probability of an area.

Seismicity

A large part of Alaska lies in the circum-Pacific earthquake belt--one of the world's greatest zones of seismic activity. Six percent of the world's shallow earthquakes are recorded in the State, chiefly in two seismic zones (St. Amand, 1957; Wood, 1966). One of these zones includes the Aleutian Islands, Aleutian trench, Alaska Peninsula, Alaska Range, and eastward as far as the Copper River (fig. 4). The second zone, which encompasses the Wrangell area, includes southeastern Alaska, southwestern Yukon, and the coastal areas of British Columbia.

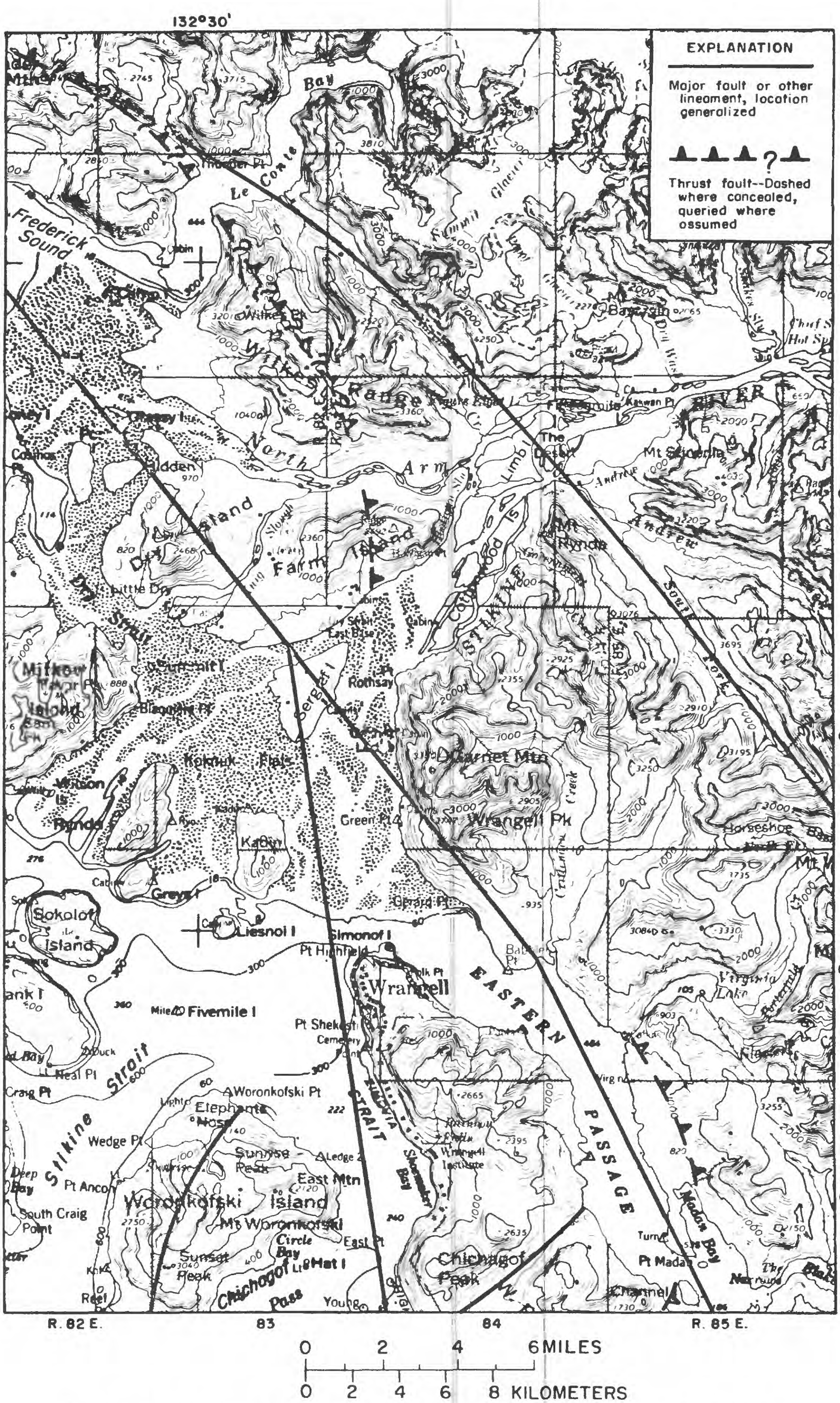


Figure 6.--Map of the Wrangell area and vicinity showing faults or other lineaments. Modified from Twenhofel and Sainsbury (1958), and Berg, Jones, and Richter (1972).

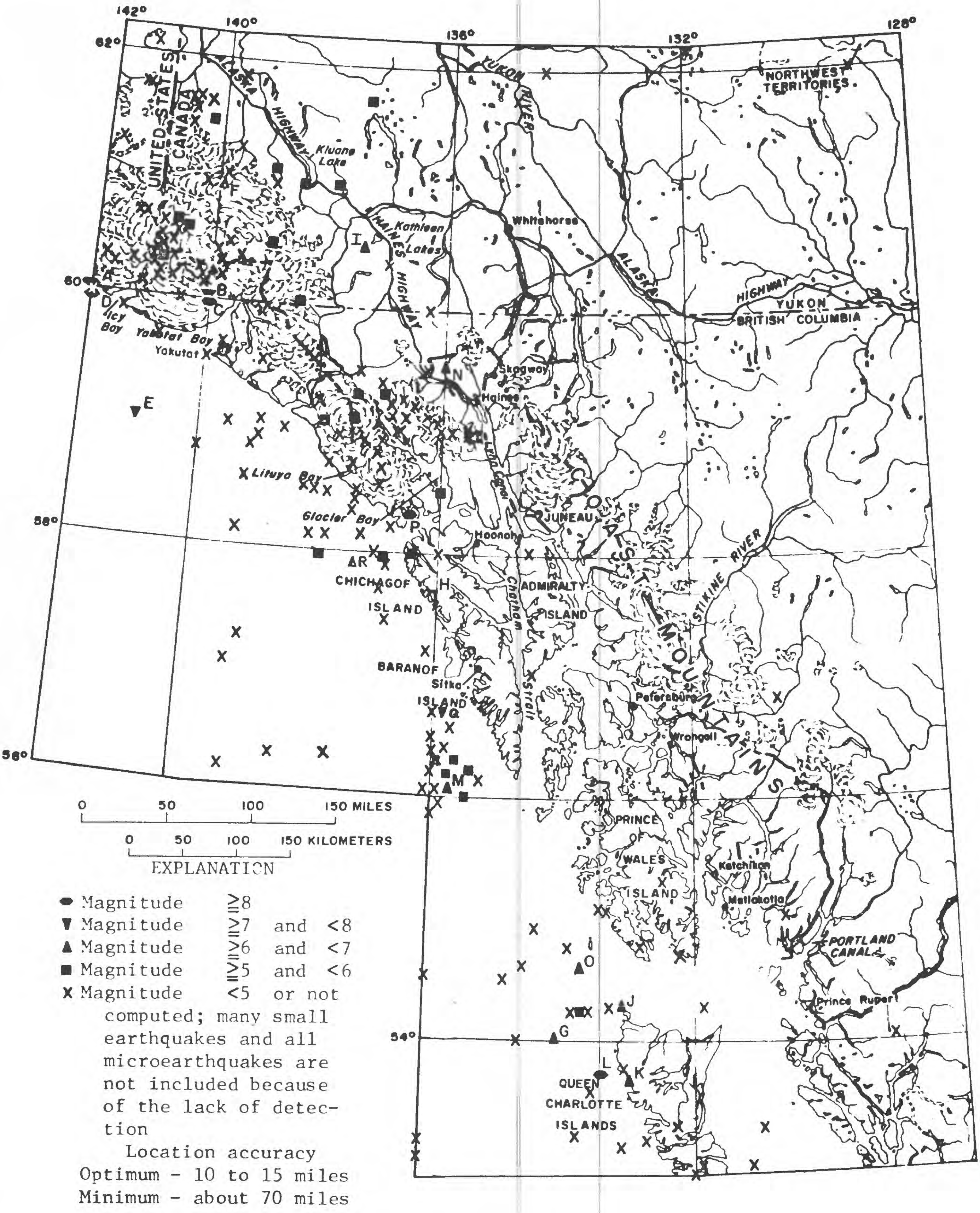
The historical record of earthquakes in southeastern Alaska and adjacent areas is so short that most of the data are limited to that obtained in the present century. These data show that five earthquakes of magnitude 8 or greater have occurred offshore or on land in southeastern Alaska and adjacent Canada (fig. 7). During this time there also have been four earthquakes with magnitudes between 7 and 8, at least eight with magnitudes between 6 and 7, more than 17 with magnitudes between 5 and 6, and about 140 have been recorded with magnitudes of less than 5 or of unassigned magnitudes in this region. In addition, there undoubtedly have been many additional unrecorded earthquakes of low magnitude since 1899. All five of the earthquakes with magnitudes greater than 8 were offshore or near the coast, and appear to be related to movement along the Fairweather-Queen Charlotte Islands fault system and the connecting Chugach-St. Elias fault or to their splays and extensions (figs. 4, 5). Most of the other larger earthquakes (magnitudes greater than 6) and a large proportion of the smaller ones also appear to be related to these tectonic features.

There are no recorded epicenters of earthquakes within the Wrangell mapped area, and only two epicenters with magnitudes of 5 or less within 100 miles (160 km).[1/] The closest epicenter for any earthquake of magnitude 6 or greater is about 135 miles (217 km) northwest of Wrangell. This earthquake (designation Q on fig. 7) occurred July 30, 1972, in the vicinity of Sitka, and had a magnitude of 7.1-7.6. The closest earthquake with a magnitude of 8 (designation L on fig. 7) or greater occurred August 22, 1949, approximately 200 miles (320 km) south of Wrangell in the vicinity of the Queen Charlotte Islands, and had a magnitude of 8.1.

Although no instrumentally recorded earthquakes had epicenters in the mapped area, at least 20 earthquakes that had epicenters elsewhere were felt or possibly felt at Wrangell (table 3). There probably have been many more felt earthquakes in the Wrangell area, but they have not been reported or the published source is obscure.

Of the definitely felt earthquakes at Wrangell, the one of July 30, 1972, in the vicinity of Sitka (designation Q on fig. 7, magnitude 7.1-7.6) was the most recent and presumably the most strongly felt, probably because of the closeness of its epicenter. It was assigned an intensity of IV (Modified Mercalli scale) at Wrangell (Lander, 1973).

[1/] Because of the difficulty of accurately determining the location of epicenters (particularly of early historic earthquakes), assigned locations probably are at least 10-15 miles (16-24 km) in error and in some instances may be mislocated by as much as 70 miles (112 km).



(See following page for figure number and 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 7.--Map showing locations of epicenters and approximate magnitudes 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 3.--Partial list of earthquakes felt and possibly felt at Wrangell, Alaska, 1847-1972, and July 1, 1973

[Compiled by Lynn A. Yehle, U.S. Geological Survey]

Date 1/	Description 2/	Epicentral location from Wrangell (see fig. 7)	Magnitude	Radius of perceptibility 3/	Location nearest Wrangell at which known to have been felt	Reference 4/
Apr. 6, 1847	Felt? Generally felt along coast------	--------------------	?	-------------------	Sitka, 120 mi. (190 km) NW----	1
Oct. 26, 1880	Felt? Appears to have been felt along British-American coast and accompanied by a "tidal" wave.	--------------------	?	-------------------	SE. end Admiralty Island, 100 mi. (160 km) NW.	2
Fall 1900 or spring 1901.	Felt? Prince of Wales Island, frequent light tremblings.	--------------------	?	-------------------	Prince of Wales Island, center 60 mi. (95 km) SSW.	3
Aug. 7, 1906	Felt?---------------------------------	--------------------	?	-------------------	Loring, 70 mi. (110 km) SE----	3
Apr. 10, 1921	----do--------------------------------	185 mi. (295 km) SSW.	6 1/2	180 mi. (290 km)----	----do----------------------	4
Oct. 24, 1927	Felt; little damage, but submarine cables to Petersburg broken.	170 mi. (270 km) NW.	7.1	260 mi. (415 km)----	----------------------------	1
May 30, 1936	Felt? Bell Island, slight shocks------	--------------------	?	-------------------	Bell Island, 50 mi. (80 km) SE.	1
Aug. 3, 1945	Felt?---------------------------------	160 mi. (255 km) SSW.	6 1/4	150 mi. (240 km)----	Queen Charlotte Islands, 170 mi. (270 km) S.	5
Apr. 26, 1947	Felt? Bell Island, mild earthquake----	--------------------	?	-------------------	Bell Island, 50 mi. (80 km) SE.	4
Aug. 21, 1947	Felt? Submarine cable-break near Wrangell attributed to an earthquake.	?	?	?	?	10
Feb. 28, 1948	Felt?---------------------------------	200 mi. (320 km) SSW.	6 1/2	180 mi. (290 km)----	Annette Island, 100 mi. (160 km) SSE.	1
Nov. 30, 1948	----do--------------------------------	--------------------	?	-------------------	Craig, 75 mi. (120 km) SW., Little Port Walter, 90 mi. (145 km) W.	4
Aug. 22, 1949	Felt? Craig, brick chimneys tumbled; felt over a large area of southern SE. Alaska. (Not felt at Wrangell, but submarine telephone cables put out of commission.)	200 mi. (320 km) SSW.	8.1	>360 mi. (>575 km)--	Craig, 75 mi. (120 km) SW-----	4
Oct. 31, 1949	Felt?---------------------------------	135 mi. (215 km) WSW.	6 1/4+	150 mi. (240 km)----	Sitka, 120 mi. (190 km) NW---	5
Nov. 17, 1956	Felt? Ketchikan, IV; Petersburg, IV---	140 mi. (225 km) SSW.	6 1/2	180 mi. (290 km)----	Ketchikan, 85 mi. (135 km), Petersburg, 30 mi. (48 km) NW.	1

May 5, 1958	Felt?	185 mi. (295 km) NW.	-------	--------------------	Petersburg, 30 mi. (48 km) NW.	1
July 10, 1958	V, felt by all; submarine cable-break near Wrangell attributed to the earthquake.	205 mi. (330 km) NW.	8	360 mi. (575 km)	------------------------------	1, 10
Mar. 28, 1964	Felt, Petersburg, II or III	645 mi. (1,030 km) NW.	8.4	>360 mi. (>575 km)	Petersburg, 30 mi. (48 km) NW.	6, 8
July 30, 1972	IV	140 mi. (225 km) WNW.	7.1-7.6	~280 mi. (~450 km)	------------------------------	7
Aug. 4, 1972	Felt?	135 mi. (215 km) WSW.	5.0	90 mi. (145 km)	Sitka, 120 mi. (190 km) NW	11
Aug. 4, 1972	do	120 mi. (190 km) W.	5.8	125 mi. (200 km)	Petersburg, 30 mi. (48 km) NW.	11
Aug. 15, 1972	do	130 mi. (210 km) W.	5.0	90 mi. (145 km)	Sitka, 120 mi. (190 km) NW	11
Nov. 17, 1972	do	125 mi. (200 km) WSW.	5.0	90 mi. (145 km)	do	11
July 1, 1973	Felt?	215 mi. (345 km) NW.	6.7	200 mi. (320 km)	Sitka, 120 mi. (190 km) NW	12

1/ Dates are u.t. (universal time) except first and third entries.

2/ Felt — Published report of single or multiple earthquake shock of unknown intensity at Wrangell.
Felt? — Earthquake possibly felt at Wrangell but not known to have been reported there. The "felt?" evaluation is based upon the known occurrence of an earthquake elsewhere combined with its possible radius of perceptibility and general evaluation of regional geologic structure.

V, Published report of earthquake intensity, Modified Mercalli scale (see table 4).

3/ Gutenberg and Richter (1956, p. 141).

4/
1. U.S. Coast and Geodetic Survey (1930-1969), Heck (1958), Eppley (1965), or Wood (1966).
2. Rockwood (1881).
3. Tarr and Martin (1912).
4. U.S. Weather Bureau (1918-1958).
5. Davis and Echols (1962).
6. Leipold and Wood (1969).
7. Lander (1973).
8. Grace Williams, Wrangell, Alaska (written commun., 1964).
9. U.S. National Oceanic and Atmospheric Administration (1972).
10. Heezen and Johnson (1969).
11. U.S. National Oceanic and Atmospheric Administration (1973a).
12. U.S. National Oceanic and Atmospheric Administration (1973b).

In contrast, the severe earthquake of March 28, 1964 (magnitude 8.4), was barely perceptible at Wrangell because of the great distance from its epicenter. There is only one report (Grace Williams, Wrangell, Alaska, written commun., 1964) of its being felt at Wrangell, and then only for "an instant." This report also stated that water in a domestic well became muddy and stayed muddy for 2 days. Other individuals in Wrangell (oral commun., 1965), who did not feel the earthquake, reported changes of water level in the Wrangell Harbor area which apparently still existed at the time of interview in 1965. The opinion of dock workers and boat operators was that either the tides were coming in after the earthquake approximately 1 foot (0.3 m) lower or the land had risen by that amount. Tugs reportedly were able to cross a "reef" in the harbor area only at high tide after the earthquake, whereas before the earthquake there had been no problem at any tidal stage. Likewise, there reportedly was 6-8 inches (15-20 cm) less water after the earthquake in the log pond of the lumber company northwest of Shakes Island, which created problems in floating the logs at low tide. Also, after the earthquake a nearby rock frequently projected 6 inches (20 cm) above the surface of the water at low tide that formerly was seen only about once a year. All these accounts, as well as reports from nearby Petersburg, are in close agreement that there was a land-level or sea-level change of approximately 1 foot (0.3 m) in the area. However, the U.S. Coast and Geodetic Survey, in their tidal observations from five control tide stations after the earthquake, did not find any land-level changes in southeastern Alaska attributable to the earthquake (J. M. Symons, written commun., 1966). Although none of the five control tide stations upon which the observations were made were located at Wrangell or Petersburg, additional postearthquake tide observations were made at Petersburg which agreed within a tenth of a foot with those obtained before the earthquake. Thus, the discrepancy between the eyewitness reports of at least four individuals who were in key positions to be fully aware of any land- or sea-level changes and the apparent negating observations of the U.S. Coast and Geodetic Survey is unexplained.

The July 10, 1958, earthquake (designation P on fig. 7; magnitude 8) was felt strongly by all at Wrangell, although its epicenter was approximately 205 miles (330 km) to the northwest. An intensity of V was assigned for Wrangell (U.S. Coast and Geod. Survey, 1930-1969).

At least three other earthquakes are known to have affected the Wrangell area. The great earthquake of August 22, 1949 (designation L on fig. 7; magnitude 8.1), in the vicinity of the Queen Charlotte Islands, was not felt at Wrangell but submarine telephone cables were broken. A Mr. Engdahl of Wrangell (oral commun., 1965) reports "a good shake in 1945(?)," at which time the tide came in and went out several times during the day of the earthquake. This probably was the earthquake of August 3, 1945 (designation J on fig. 7; magnitude 6-1/4), whose epicenter was near the northern coast of the Queen Charlotte Islands. The earthquake of October 24, 1927 (designation H on fig. 7; magnitude 7.1), whose epicenter was northwest of Sitka, did little damage at Wrangell, but submarine cables to Petersburg were broken.

A number of microearthquake seismicity studies have been made in recent years in southeastern Alaska and adjacent parts of Canada (Boucher and Fitch, 1969; Rogers, 1969, 1972a, b, 1973; Johnson, 1972; Johnson and others, 1972). The studies by Boucher and Fitch in the vicinity of Haines and along the Denali fault system to the northwest have been described previously (Lemke and Yehle, 1972b).

Most of the microearthquake studies have been done in northwest British Columbia in the vicinity of Edziza volcano (about 150 miles (240 km) northeast of Wrangell), in selected areas to the north and northwest of Edziza volcano, and in southeastern Alaska along the Coastal Range northwest of Wrangell. Studies in these areas in 1968 and 1969 indicated a swarm of microearthquakes (magnitudes ranging from 2.7 to 0) occurring at a rate as great as several hundred per day (Rogers, 1972b). The main group of epicenters was located in southeastern Alaska near the head of Endicott Arm, about 130 miles (210 km) northwest of Wrangell. Another concentrated area of epicenters was at Mount Ogden, approximately 20 miles (32 km) east of Taku Inlet along the Alaska-British Columbia border, about 175 miles (280 km) northwest of Wrangell. A third and considerably smaller concentration was along the Alaska-British Columbia border in the vicinity of Shakes Glacier, about 50 miles (80 km) northeast of Wrangell. Although a seismograph station was located during part of 1969 at Wrangell, only a few microearthquakes were recorded with epicenters in the general area, none during that period being closer than about 50 miles (80 km). Rogers (1972b), in earlier studies, believed that the most likely interpretation for the epicentral locations was that they were associated with lineaments that may be faults. In this respect, David Brew, U.S. Geological Survey (oral commun., 1971), noted that the concentration of epicenters at Endicott Arm is along the Coast Range lineament, where he has mapped a thick mylonite zone. Later, however, Rogers (1973) was of the opinion that the microearthquakes may be related to glacier movement.

In 1970, Johnson, Couch, Gemperle, and Banks (1972) established nine stations along the Inside Passage to record microearthquakes associated with the Queen Charlotte Islands fault system. Microearthquakes were recorded with epicenters in the southern St. Elias Mountains and in the northern part of the Lynn Canal, but none from Chatham Strait. Johnson (1972) is of the opinion, from these studies, that the northern part of the Lynn Canal may be the site of moderate seismic activity along the Lynn Canal inferred fault and may be related to the microearthquake seismic activity on the Denali fault noted by Boucher and Fitch (1969). He also suggested that the lack of microearthquake epicenters south of the Lynn Canal area may be due to the fact that the Chatham Strait fault is inactive.

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

The variable accuracy of locating earthquake epicenters, particularly during the 19th century and early 20th century, plus incomplete knowledge of fault locations, makes it difficult to directly relate seismicity in southeastern Alaska to known and inferred faults. In spite of these difficulties, most of the larger and many of the smaller earthquakes probably can be related to the faults shown on figures 4, 5, and 6.

All of the large and many of the moderate and smaller size historical earthquakes in southeastern Alaska and adjacent areas appear to be related to the Fairweather-Queen Charlotte Islands fault system and the connecting Chugach-St. Elias fault or to their branches (figs. 4, 5). Thus, most have epicenters close to the outer coast.

The onland segment of the Fairweather fault, as well as probably its western extension, the Chugach-St. Elias fault (fig. 7), has been very active tectonically during Quaternary time (Grantz, 1966; Page, 1969; George Plafker, written commun., 1971). The epicenter of the great Yakutat earthquake of September 10, 1899 (magnitude 8.6), was not accurately located but is believed to have been near the head of Yakutat Bay, where there was movement on portions of the Fairweather fault or on one of its western extensions (Tarr and Martin, 1912). Likewise, during the Lituya Bay earthquake of 1958 (magnitude 8.0) there was movement along the entire onland length of the Fairweather fault, with 21-1/2 feet (6.5 m) of right-lateral slip and 3-1/2 feet (1.1 m) of associated dip slip (up on the south) measured in one place (Tocher and Miller, 1959; George Plafker, written commun., 1971). From late Pliocene or early Pleistocene to Holocene time, the land northeast of the fault is thought to have been uplifted more than 3 miles (5 km), and the fault has undergone associated right-lateral slip of unknown magnitude (Grantz, 1966).

That the southeastern offshore extension of the Fairweather fault is also active is indicated by the fairly large number of earthquake epicenters in that area (fig. 7). Although the assigned epicentral locations are not well alined, probably most of the earthquakes are related to movement along the Fairweather fault. Lack of alinement can be explained by inaccurately located epicenters or by the epicenters being along more than one branch of the fault system. That there is branching and splaying along at least part of the fault system is verified by the fault pattern on land in the Yakutat-Lituya Bay area (Grantz, 1966; Plafker, 1969, 1971).

High seismicity along the entire length of the concealed Queen Charlotte Islands fault (as far south as Vancouver Island) is well documented by the large number of earthquakes that appear to be related to the fault. These earthquakes have ranged in size from the large earthquake (magnitude 8.1) of August 22, 1949 (L on fig. 11), through several earthquakes of magnitude 6 to 7, to numerous earthquakes of smaller magnitude. Here, also, the epicenters are not well alined but they do fall, nevertheless, along a fairly definite offshore northwest-southeast belt that strongly suggests a relation to an active fault zone (Gutenberg and Richter, 1954; St. Amand, 1957; Wilson, 1965; Tobin and Sykes, 1968).

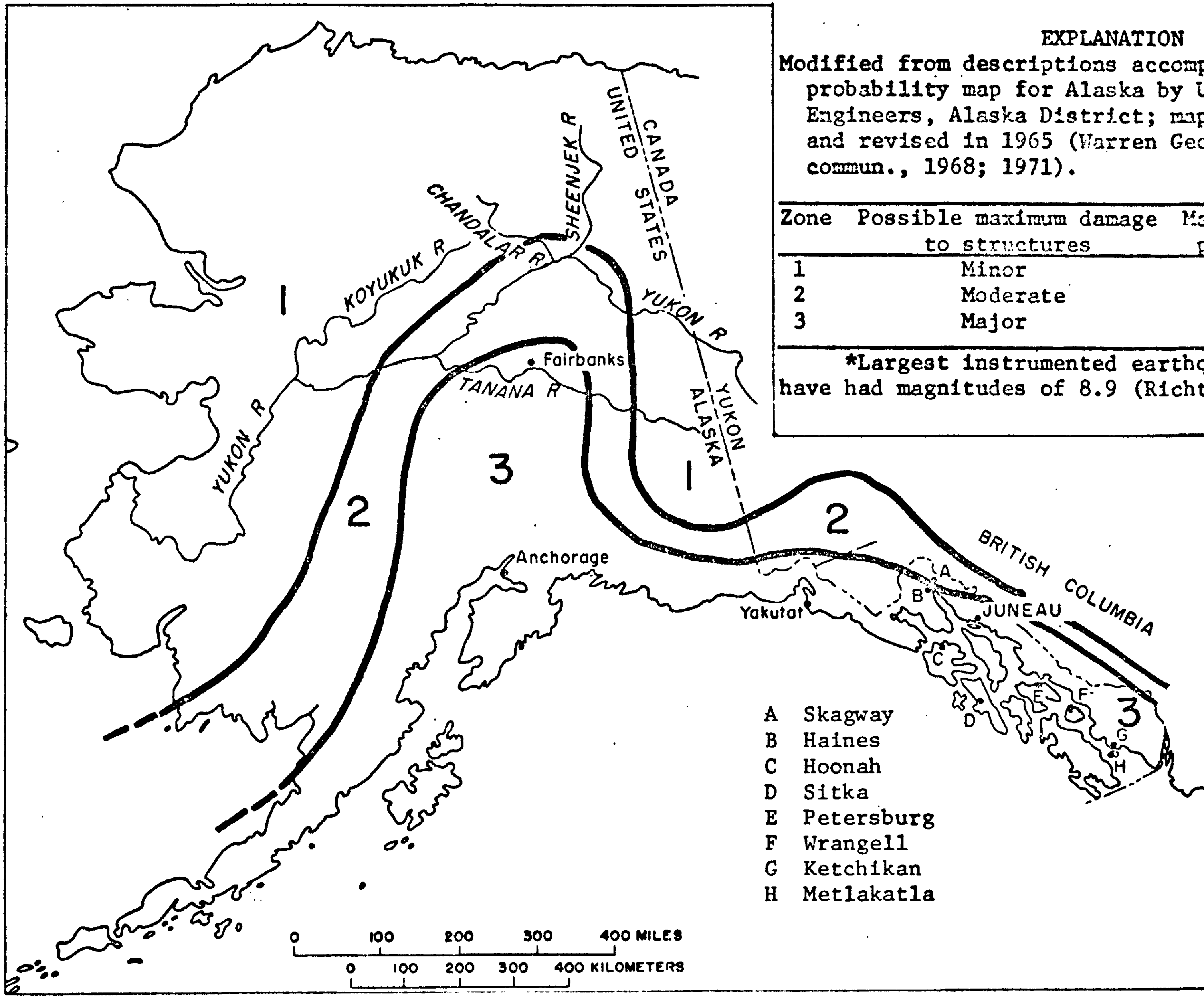
As shown on figure 7, the number of earthquakes related to segments of the Denali fault system in southeastern Alaska is small as compared to the number along the Fairweather-Queen Charlotte fault system. The relatively low seismicity on these fault segments may be due to the fact that this part of the Denali fault system may have been rendered relatively inactive tectonically in favor of movement along the newer Totschunda fault system, although few earthquake centers appear to be related to this supposedly newer fault. As suggested by Richter and Matson (1971), the Totschunda fault system may represent part of a new transform fault segment of the Denali fault system (figs. 4, 5), which bypasses the Denali fault system in Canada and southeastern Alaska, leaving it a more passive tectonic element. However, all parts of the southeastern end of the Denali fault system are not passive, as evidenced by the number of earthquake epicenters that appear to be related to some segments. The Shakwak valley fault segment, northwest of Kluane Lake (fig. 5), is believed to have moved in recent centuries (Bostock, 1952). Its prominent topographic trace along the Shakwak valley is marked locally by fault scarps of Holocene age and by right-laterally offset topographic features. Right-lateral offsetting of 1 mile (1.6 km), and perhaps as much as 3 miles (4.8 km), of the glaciated Shakwak valley is suggested to have occurred since early Pleistocene time. Several earthquakes that occurred in historical time may be related to the more recent movement (fig. 7). Also, Boucher and Fitch (1969) concluded, on the basis of their microearthquake studies, that "The Denali fault is active in some sense along its entire length east of Mount McKinley * * * and it probably should not be dismissed as a relic fault of no current tectonic importance."

Known and inferred faults in the general vicinity of Wrangell are not known to have moved during Holocene time. If there has been any fault displacement on the Clarence Strait lineament, it probably took place during late Early or Late Cretaceous time (Grantz, 1966), although Johnson (1972) suggested that the lineament may be "a major structural feature separating the Coast Crystalline belt from the insular Tectonic belt and the Alexander Archipelago." Data on the amount and time of possible movement on the Coast Range lineament are largely lacking. As noted previously, a cluster of microearthquakes has been recorded along the Coast Range lineament at Endicott Arm, but they may have been due to glacier movement (Rogers, 1972b, 1973). On Annette and Gravina Islands near Ketchikan, thrust faults associated with the Gravina-Nutzotin belt have displaced bedded rocks as young as late Mesozoic and are offset by high-angle faults, probably mainly of middle Tertiary age (Berg, 1972). The two lineaments near Wrangell, shown on figure 6, are largely concealed beneath fiord waters, and evidence is largely lacking on recency of movement. However, as described previously (see "Offshore deposits"), faulting is indicated to have occurred in probable late Pleistocene time along the Zimovia Strait lineament west of Wrangell.

Assessment of earthquake probability in the Wrangell area

As indicated in a regional report by Lemke and Yehle (1972a), data still are too few to permit more than a general assessment of earthquake probability in southeastern Alaska. Therefore, a rigorous evaluation of earthquake probability in the much smaller Wrangell area must await a longer record of seismic events and a better knowledge of the tectonic framework of the area. However, some generalizations, based upon the present state of knowledge, appear warranted.

Seismic probability maps, as well as strain-release and earthquake acceleration probability maps, compiled for southeastern Alaska and adjacent Canada, permit a general assessment of earthquake probability in the Wrangell area. A seismic probability map (fig. 8), prepared by the U.S. Army Corps of Engineers in 1957 and revised in 1965 (Warren George, U.S. Army Corps Engineers, written commun., 1968, 1971), places Wrangell in zone 3--a zone where the largest expectable earthquakes would have magnitudes greater than 6.0 and where major damage to manmade structures could be expected. A seismic zone map (fig. 9) in the 1970 edition of the Uniform Building Code (Internat. Conf. Building Officials, 1970) places Wrangell in zone 2--a zone where moderate damage to manmade structures is possible. On the other hand, a recent detailed study of earthquakes in Canada has led to the development of a new seismic zone map (fig. 10), which shows all of the coastal region of western Canada, all of southeastern Alaska, the northwestern part of British Columbia, and most of the Yukon Territory as being in zone 3 (Natl. Research Council Canada, 1970). Zones are similar to those prepared for the United States, ranging from 0, where no damage is expected, to 3, where major destructive earthquakes may occur (Hasegawa, 1971). In zone 3 of this map the estimated maximum intensity, as measured on the Modified Mercalli scale, falls between VIII and IX and the corresponding horizontal ground acceleration may be taken as 50 percent of gravity (Ferahian, 1970). According to a strain-release map (fig. 11) of Milne (1967), Wrangell falls between contours 0 and 1 of his map, which indicates that a single earthquake between magnitudes 3.7 and 5 would be necessary to release all the energy that accumulates in 100 years. A 100-year probability map (fig. 12) of Milne and Davenport (1969) shows that Wrangell is in an area in which a peak earthquake acceleration of about 10 percent of gravity is probable. Thus, on the basis of table 4, which shows approximate relations between acceleration, magnitude, and intensity, an earthquake of magnitude 4 and with an intensity on firm ground of IV is expectable in a 100-year period in the Wrangell area. However, the relationship shown in table 4 between acceleration and magnitude, although widely used, may not be valid. Ambraseys (1973) pointed out that there appeared to be a fairly good relationship between acceleration and magnitude when there were just a few records. However, as more data became available he found that "for all practical purposes, there is no significant correlation between magnitude, distance, and acceleration in the near field. At large distances or for small accelerations, these three variables become more interdependent."



EXPLANATION

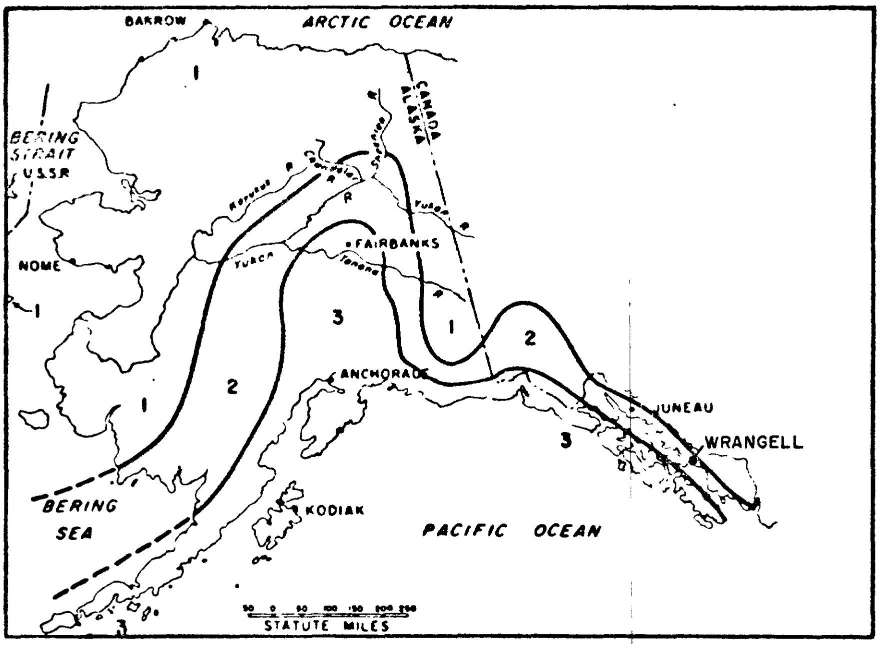
Modified from descriptions accompanying the seismic probability map for Alaska by U.S. Army, Corps of Engineers, Alaska District; map prepared in 1957 and revised in 1965 (Warren George, written commun., 1968; 1971).

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).

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

Figure 8.--Seismic probability map for most of Alaska as modified from U.S. Army



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

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

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

*Modified Mercalli Intensity Scale of 1931

Figure 9. Seismic zone map of Alaska. Modified from the 1970 edition of the Uniform Building Code (International Conference of Building Officials, 1970).

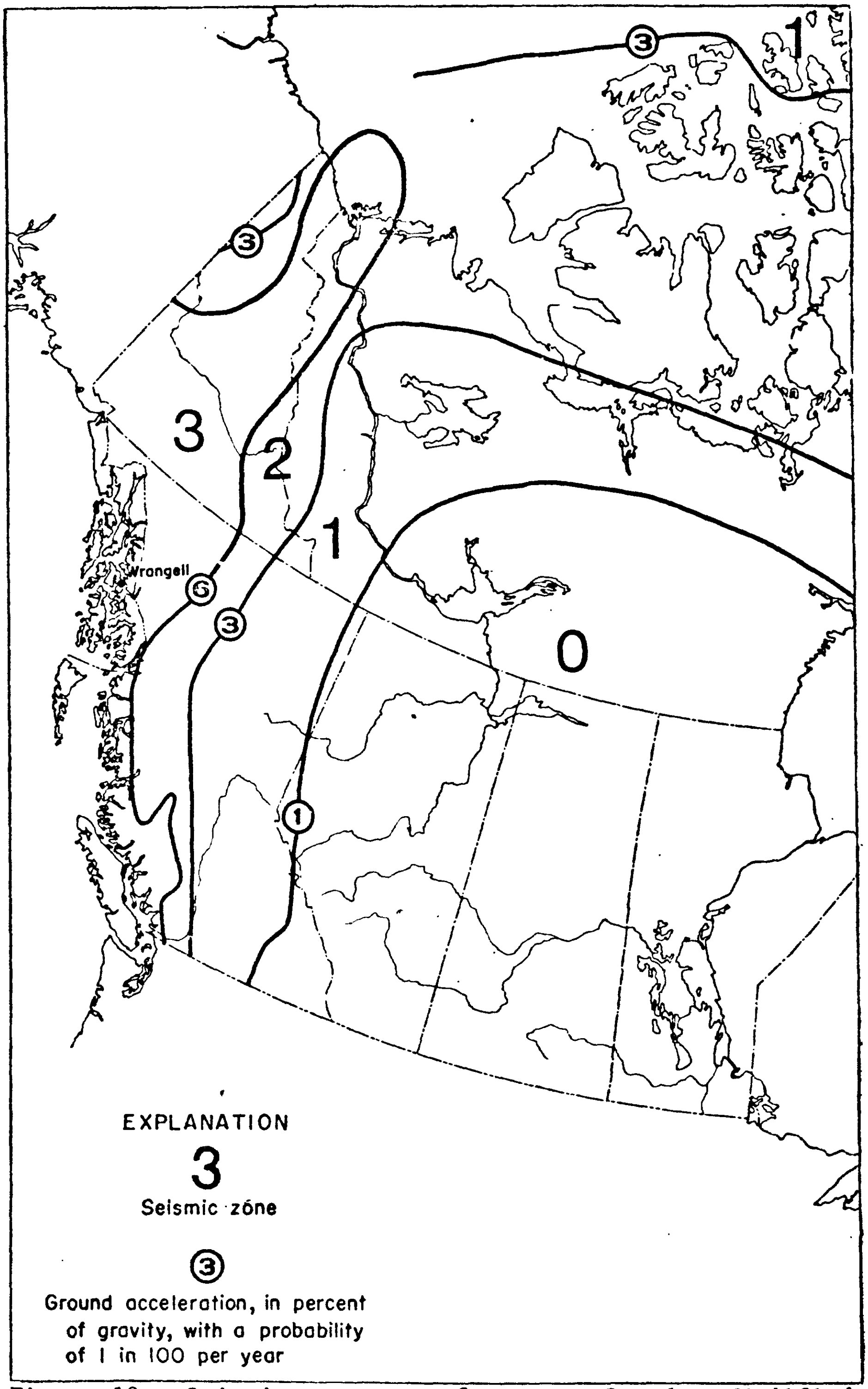


Figure 10.--Seismic zone map of western Canada. Modified from National Research Council of Canada (1970).

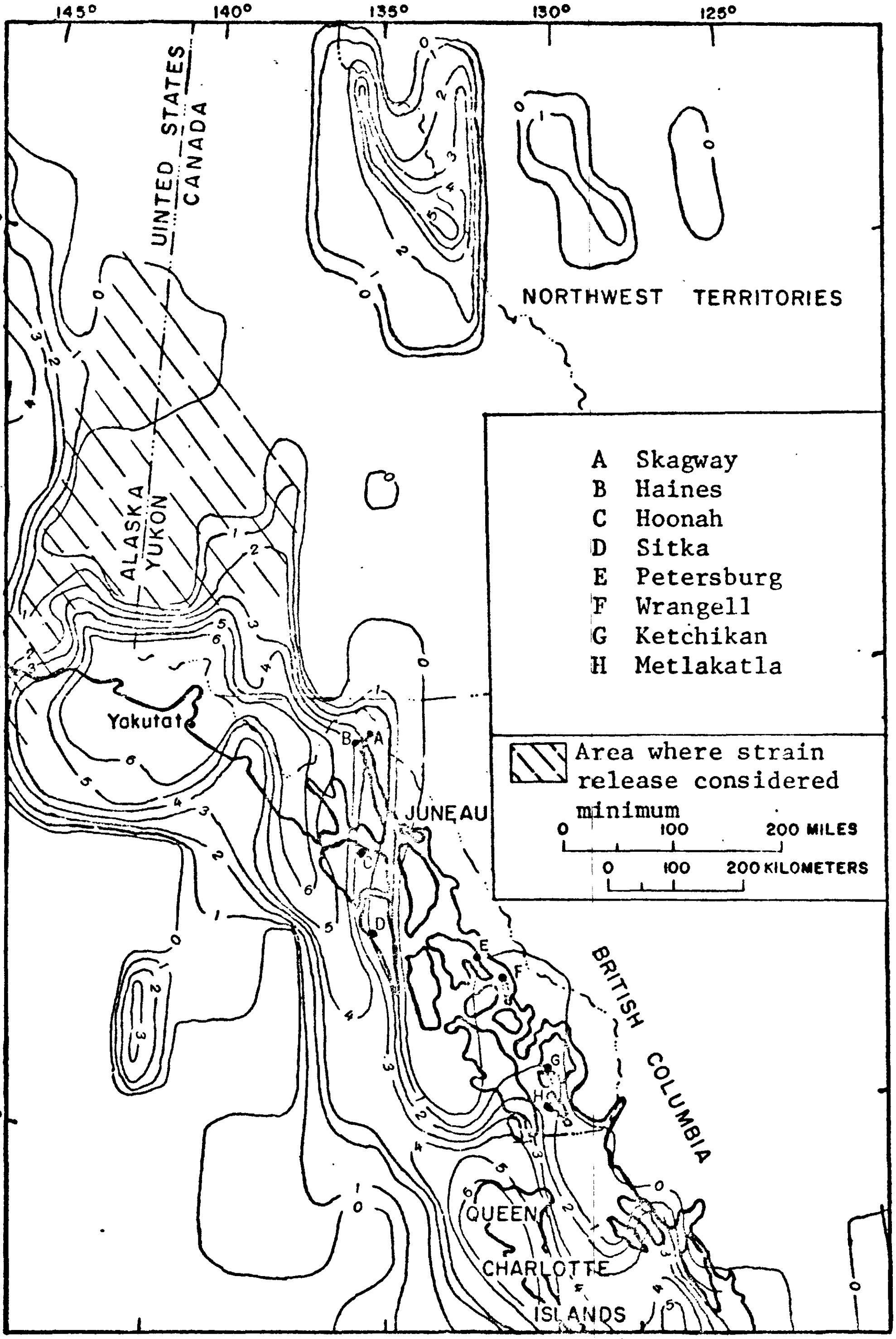


Figure 11.--Strain-release map of seismic energy 1898-1960, inclusive, in southeastern Alaska and part of adjacent Canada with explanation showing interpreted frequency of energy release. Modified from Milne (1967).

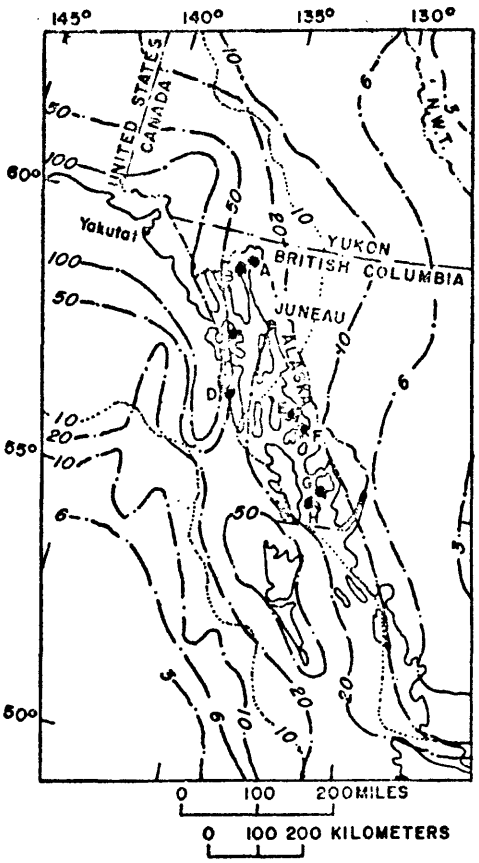
EXPLANATION FOR FIGURE 11

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

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

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

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



EXPLANATION

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

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

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

*See table 4 showing relations between acceleration units, energy, magnitude, and intensity.

Figure 12.--One-hundred-year probability map showing peak earthquake accelerations for southeastern Alaska and part of adjacent Canada. Modified from Milne and Davenport (1969). Based upon earthquake strain release from 1898-1960 (extended to a 100-year interval) as interpreted by an extreme-value method and using data from all instrumented earthquakes. For comparison of method, another interpretation is offered through an average-value method (dotted contour on map) which uses only earthquakes having an acceleration of 10 percent gravity.

Table 4.--Approximate relations between earthquake magnitude, energy, ground acceleration, acceleration in relation to gravity, and intensity (modified from U.S. Atomic Energy Commission, 1963)

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

These relations until 1971 are believed to have applied fairly well in southern California, where the average focal depth of earthquakes has been about 10 miles (16 km). (See Gutenberg and Richter, 1956; Hodgson, 1966.) However, revisions of these relations may be necessary because of the exceptionally high accelerations resulting from the San Fernando, Calif., earthquake of February 9, 1971, as well as other recent earthquakes. Also see discussion by Ambraseys (1973) in the text.

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

It is obvious that agreement is not close between the above-described maps as to earthquake probability in the Wrangell area. At least part of this divergence is due to the fact that some of the maps, such as the strain-release map of Milne (1967) and the earthquake acceleration map of Milne and Davenport (1969), are based solely upon the seismicity of the area since 1898. As discussed previously, the seismic record of southeastern Alaska is far too short to permit an assessment of earthquake probability on this basis alone. Also, the seeming differences in assessment of seismic risk between the U.S. Army Corps of Engineers map (fig. 8), the Uniform Building Code map (fig. 9), and the seismic zone map of western Canada (fig. 10) may be more apparent than real, because the three maps do not assess all of the same factors. The Uniform Building Code seismic zone map sets up only minimum building standards to be met by industry. The earthquake probability map of the Corps of Engineers, on the other hand, attempts to assess the overall earthquake probability of the area, and thus, expectedly, would show a higher risk value. The Uniform Building Code seismic zone map and the seismic zone map of Canada, although similar in some respects, apparently differ in some of their derivative factors.

In addition to assessing the earthquake probability of the Wrangell area on the basis of the above-described maps, a number of specific geologic factors, whose pertinency has been demonstrated in studies of earthquakes in numerous other places, also have to be considered. These factors are: (1) faults that long have been inactive may suddenly become reactivated, (2) faults active during Quaternary time may be inactive during most of historical time but suddenly become reactivated, (3) certain presently inactive segments of otherwise active fault systems can be expected to become active in the future, (4) the occurrence of small earthquakes is not necessarily an indication of where large earthquakes may occur, or vice versa, and (5) large earthquakes may occur in areas where there has been a record of only minor or moderate seismicity previously and no obvious major tectonic structure that would result in a large earthquake. This was catastrophically demonstrated by the great Alaska earthquake of March 27, 1964 (U.S. Coast and Geod. Survey, 1964; Eppley, 1965; Tobin and Sykes, 1966), as well as by a number of other large earthquakes in different parts of the world. These five factors, most of which cannot now be properly evaluated locally, were discussed in a regional report of southeastern Alaska by Lemke and Yehle (1972a); also, a number of worldwide earthquake examples were given in that report to illustrate how the factors apply.

In summary, it is not now possible to assess with any great degree of accuracy the earthquake probability of the Wrangell area. However, the placing of the area in seismic zone 3, as shown on the U.S. Army Corps of Engineers map, seems reasonable to the writer on the basis of present knowledge. This is a zone where the largest expectable earthquakes could have magnitudes greater than 6 and where major damage to manmade structures can be expected. As judged solely from the seismic record, few if any earthquakes with epicenters in or near the Wrangell area are indicated. However, the high earthquake activity of southeastern

Alaska as a whole, where earthquakes of magnitude 8 and greater have occurred, makes it prudent to assign a higher risk factor than is indicated solely from the local seismic records. It has been dramatically demonstrated in the past that damaging earthquakes can occur in areas where locally only minor seismic activity was previously exhibited, particularly where the local structure is imperfectly known. It also should be emphasized that large earthquakes of magnitude 8 or greater can be expected to occur from time to time along the Fairweather-Queen Charlotte Islands fault system. These earthquakes will be attenuated with distance from the epicenter, but their effects still may be sufficiently strong at Wrangell to cause damage either directly or indirectly from shaking.

INFERRED EFFECTS FROM FUTURE EARTHQUAKES

Because of a lack of knowledge of a number of geologic factors that are critical in considering the earthquake potential of the Wrangell area a conservative approach is deemed desirable in evaluating the potential effects. Therefore, the effects described below generally should be considered to be maximum or near maximum. It further should be emphasized that for every major destructive earthquake[1/] that may occur in the area there is a likelihood that there will be a fairly large number of smaller earthquakes having little or no effect upon man.

Because of the reconnaissance nature of the study and sparsity of laboratory data on physical properties of geologic units, the discussion of inferred geologic effects from future earthquakes in the mapped area and immediately adjacent areas must of necessity be largely empirical and generalized. The inferences, by and large, are based upon the effects of major earthquakes on similar-appearing geologic units in other places, particularly the effects of the Alaskan earthquake of 1964 (Lemke and Yehle, 1972a). It must be emphasized, however, that the properties of the geologic units in the mapped area (fig. 3) may not be the same as those being compared from other areas even though they superficially may resemble them. Moreover, the physical setting and other factors, which could markedly influence the effects, also may differ. For these reasons, the assumptions that follow should not be rigorously interpreted or applied. Rather, they are intended as broad guidelines useful in assessing the kind and degree of hazard that may be present in the Wrangell area and leading toward minimizing these hazards as they affect man and his structures. As such, they are directed to structural and civil engineers, city and regional planners, public and private utility companies, and all other public and private groups or individuals who are responsible for the safety and welfare of

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[1/] Major damage generally is associated with earthquakes having a magnitude of about 7 or greater. Exceptions of lower magnitude generally are earthquakes having a very shallow depth of focus, in which cases there may be catastrophic damage from earthquakes with magnitudes not much greater than 5. Earthquakes with magnitudes between 7 and 8 commonly are referred to as major earthquakes; those with magnitudes of 8 or larger commonly are referred to as great earthquakes.

Wrangell and its environs, now and in the future. However, the interpretations that follow are in no way intended to preclude the making of additional detailed geologic and engineering studies, particularly those studies that pertain to small tracts or individual sites. In fact, it is recommended that such additional studies be made whenever possible.

Surface displacement on faults and other tectonic land-level changes

Introduction

Profound land-level changes due to faulting and land tilting have accompanied many large earthquakes. The Alaska earthquake of 1964 (magnitude 8.5) dramatically illustrated the wide areal extent and amount of uplift and subsidence that can occur, as well as the corresponding severity of adverse effects. The land was warped along a belt nearly 600 miles (965 km) long and at least 200 miles (320 km) wide (Plafker, 1969). The maximum measured uplift was approximately 38 feet (11.6 m), and the maximum subsidence (more than 200 miles from the epicenter) was approximately 7-1/2 feet (2.3 m). The land-level changes caused heavy damage to works of man and to the flora and fauna of the region. Docks, piers, and other shipping facilities were placed beyond the reach of boats in areas of uplift, and harbors and channels became too shallow to be navigable. In areas of subsidence, low coastal areas were inundated and many port facilities were rendered useless. Coastal forests, bird-nesting areas, fish-spawning grounds, and shellfish habitats also were adversely affected.

Inferred effects in the Wrangell area

Uplift or subsidence of land in the Wrangell area might be produced either by local faulting or by large-scale regional deformation associated with fairly distant major faulting, such as along the Fairweather-Queen Charlotte Islands fault system.

Future land-level changes due to local faulting are expected to be small or nonexistent, inasmuch as no large active faults are known to be present in or near the Wrangell area. Probably only the two large lineaments that trend up Zimovia Strait and Eastern Passage (fig. 6) need to be considered in relation to possible earthquake effects upon manmade structures. As discussed previously, movement along at least part of the Zimovia Strait lineament in late Pleistocene time is indicated, but no movement along either lineament is known to have occurred in Holocene time. Although the trace of either inferred fault could be in a belt 2 or 3 miles (3.2-4.8 km) wide, it is unlikely that any present manmade structures lie directly athwart the inferred faults other than possibly submarine communication cables that might be broken if there were sufficient horizontal or vertical movement. However, even a small amount of movement along the Zimovia Strait lineament could affect those waterfront facilities at Wrangell where there is a critical relation between land and water levels. Vertical or horizontal movement along the Eastern Passage lineament could adversely affect any bridge or causeway built in connection with a proposed highway connecting Wrangell Island with the mainland.

Large-scale regional deformation along the Fairweather-Queen Charlotte Islands fault system perhaps could cause as much as 10 feet (3 m) of uplift or subsidence in the Wrangell area, as judged by some past large earthquakes elsewhere. Although this amount of land change is unlikely, it is discussed because of the highly adverse effects that would result. Effects from lesser amounts of uplift or subsidence, of course, would be correspondingly less severe.

A land uplift of 10 feet (3 m) in the Wrangell area would produce particularly adverse effects in the harbor area. The City Inner Boat Harbor and the Public Boat Harbor would be too shallow to allow most boats to enter at low tide. Water also would be too shallow along most of the docks to permit normal boat-loading operations. The log pond and some of the other facilities of the lumber mill would be rendered inoperative. Higher projecting offshore rocks would create additional navigation problems, and considerable additional beach would be exposed locally. Outside the harbor area, probably the effects would be most evident in the delta area of the Stikine River. All of the delta deposits shown in the northern part of figure 3 would be raised several feet above high tide, and additional land would be exposed. The uplifted Stikine River would soon erode to grade and cut a few deep channels in the delta deposits. Whether this would help or impede navigation up the Stikine River is difficult to determine.

A land subsidence of 10 feet (3 m) probably would cause somewhat fewer adverse effects than an equal amount of uplift. However, most docks would be rendered inoperative and there would be local flooding at high tide of some facilities along the waterfront. Most of the streets and buildings of Wrangell, however, would remain above normal high tide. Likewise, the airport is sufficiently above sea level not to be adversely affected. All of the delta deposits of the Stikine River in the mapped area (fig. 3), however, would be inundated with water several feet deep even at low tide, and the Stikine River would deposit its load some distance upstream from present points of discharge. As in the case of uplift, it is difficult to speculate on whether this would help or impede navigation up the Stikine River.

Ground shaking

Introduction

As seismic waves propagate from a fault to the ground surface they cause shaking of the ground. Shaking induces vibrations in structures and deformations in the subsurface. Structures incur damage from vibrations and also from the interaction of foundations with ground deformations. Ground deformations also induce various kinds of ground failure, including landslides, subsidence, ground fracturing, and water-sediment ejection.

In a given region, the extent of earthquake damage varies with local differences in both the intensity of ground shaking and the resistance of ground to deformation and failure. This section is concerned only with local variations in the intensity of ground shaking.

The intensity of ground shaking at any one location is governed by: the amount of energy being carried by the approaching seismic waves, and also the distribution of energy among the wave types, and wave frequencies; the topography, degree of fracturing, and depth of weathering at the bedrock surface; and the type and thickness of the surficial materials overlying bedrock.

The characteristics of seismic waves that approach a location, such as the Wrangell area, are governed by the earthquake mechanism and magnitude, its epicentral distance and focal depth, and the type and structure of rock through which the waves propagate. Because of the small size of the Wrangell area, these factors are believed to be constant for purposes of this discussion.

At bedrock surfaces important local variations in ground shaking occur where the reflection and refraction of seismic waves are influenced by variations in the topography, degree of fracturing, and depth of weathering. In the Wrangell area these factors are believed to vary significantly only in the exposed bedrock areas. In most of the area that is overlain by unconsolidated materials, variations in the topography and the extent of fracturing and weathering are believed to be negligible.

Local variations in ground motions are substantial in unconsolidated materials and also between unconsolidated materials and exposed bedrock. To a limited extent, these variations can arise from changes in the amplitude and length of seismic waves that occur as the waves propagate through a subsurface bedrock interface. Of greater importance, however, is the potential for waves to be amplified by multiple reflections between the bedrock interface and the surface of an unconsolidated surficial unit. The consequent increase in the intensity of ground shaking is known as ground amplification.

Maximum amplification occurs when the length of a shear wave entering a surficial unit from bedrock is four times the thickness of the surficial unit. This condition exists when the fundamental frequency of the surficial unit coincides with the predominant frequency of underlying bedrock shaking. Amplifications of lesser amount also occur if the second or higher natural frequencies of the surficial unit coincide with the predominant frequency of bedrock motions. On the other hand, no amplification occurs when all the natural frequencies of a surficial unit are substantially higher than the predominant frequency of bedrock shaking. This condition exists when the thickness of the unit is less than one-fourth the length of the shear waves entering the unit from bedrock. Therefore, some geologic units in the Wrangell area may be too thin to amplify earthquake-induced shear waves, and the ground shaking will be determined largely by that of the underlying unit.

The variables that govern the natural frequencies of a surficial unit, and hence its potential for ground amplification, are (1) the thickness of the unit, and (2) the stiffness of the unit. Stiffness, in turn, varies with the physical properties and degree of saturation of the materials. Generally, the finer the grain and the looser the deposit, the lower the stiffness. Water saturation has a more pronounced effect upon fine-grained cohesive deposits such as clays than upon noncohesive deposits such as clean sands because of the much greater range in stiffness between wet and dry clay.

Published field observations strongly indicate that ground amplification, and hence the intensity of ground shaking, increases with thickness but decreases with stiffness of surficial materials. Pertinent literature describing observed relations is so large that it is not feasible to cite it all here. It comes principally from seismically active regions (United States, Japan, U.S.S.R., and New Zealand). A good reference source for literature up to 1957 is Duke (1958). A more recent comprehensive source is Barosh (1969). Some examples of different types of ground effects that may have pertinence for the Wrangell area were described by Lemke and Yehle (1972a) in a regional report on southeastern Alaska.

The above generalizations, based upon observed field effects, are supported in large measure by recent experimental records. Neumann and Cloud (1955) stated that instrumental records show that an area of unconsolidated deposits may have as much as a 10- to 15-fold greater acceleration than an adjoining rock outcrop such as granite, and, with certain assumptions, possibly as much as a 22-fold difference (Neumann, 1954). Gutenberg (1957), in comparing records of relative amplitudes of earthquake motion for different types of ground, found that the ratio of amplitudes at sites on fairly dry alluvium more than 500 feet (152 m) thick to those on crystalline rock was 5:1 or more for earthquake waves having periods of 1 to 1-1/2 seconds. Moreover, amplitudes of earthquake waves on water-saturated soft ground may be 10 times or more greater than those in bedrock. Also, strong shaking may last several times as long on alluvium as on hard rock but decreases as the thickness of the alluvium decreases. Gutenberg assigned the following amplitude factors, using solid rock as 1: sandstone, as much as 3; dry sand, about 3-1/2; and marshy land, 12. Richter (1959) pointed out that alluvial deposits are particularly subject to strong shaking when seismic waves emerge directly from rock into alluvium. A very comprehensive evaluation (Barosh, 1969) of the ground response of different kinds of materials (using granite as a comparative standard), slope and boundary conditions, and degree of seismic risk was made by Popov (1959), based upon earthquake investigations in the U.S.S.R. More recently, Borcherdt (1970), in studies of measurements of ground motion generated by nuclear explosions in Nevada and of strong motion recordings of the San Francisco earthquake of March 22, 1957, noted that there are "marked amplitude variations which are related consistently to the geologic setting of the recording site. For sites underlain by a layer of younger bay mud or artificial fill, maximum horizontal ground velocities generally increased with thickness of the layer and were as much as ten times greater than those recorded on nearby bedrock. The maximum vertical velocities for these sites were between 1 and 3.5 times greater. * * * Maximum ground velocities for the older bay sediment sites were about twice those recorded on bedrock." The instrumental results also correlated well with observed relations between intensities and ground types reported by Wood (1908) for the great San Francisco earthquake of 1906, which lends support to the validity of using observed relations in the absence of instrumental data. Dezfulian and Seed (1969) confirmed that records of ground motion of recent earthquakes provide convincing evidence of the important effects of local soil conditions on the amplitude and frequency characteristics of ground-surface motions.

However, as indicated from studies by Seed and Idriss (1970) of peat deposits in Union Bay in Seattle, Washington, ground motion in some instances may be amplified by seismic waves originating from a distant source but attenuated from a nearby earthquake. At the study site of Seed and Idriss, 58 feet (17.7 m) of peat (muskeg) is underlain by 42 feet (12.8 m) of clay, which in turn is underlain by till. Accelerometers placed in each layer showed that during both a local earthquake (magnitude 4.5) and a distant nuclear shock the motions at the surface of the glacial till were amplified in the clay. The amplification factor was approximately 3.4 for the local earthquake and 1.5 for the distant shock. However, whereas the maximum acceleration recorded in the peat deposits for the distant shock was about 6 times larger than that recorded in the till, it considerably attenuated the stronger motions induced by the local earthquake. This points up that, although broad generalizations can be made on expectable ground motion of different geologic materials without instrumental data, caution must be exercised in making too rigorous interpretations.

Although damage to manmade structures generally is greatest where ground motion of the underlying soil type is greatest, it should be emphasized that structures have their own characteristics and that there generally is not a direct relation between ground shaking and building damage. Whether a structure is built of wood, cinder blocks, bricks, or concrete (reinforced or nonreinforced) can markedly affect the amount of damage. Likewise, the design of the building in relation to the foundation conditions and whether it is built to be earthquake resistive or not are significant factors. Also, the height and rigidity of the building, particularly in respect to the natural frequency of the building in comparison to the period of the seismic waves, are factors that may significantly affect the damage potential. Thus, a more or less direct comparison between amount of ground shaking from a particular earthquake and ensuing damage to structures can be made only between similar structures in the same locality. It is the responsibility of the engineer, therefore, to be as aware as possible of the comparative intensities of the different geologic units, to collect additional data on soil properties whenever necessary, and to design accordingly.

Inferred effects in the Wrangell area

Sufficient geological and seismological data are not available for the Wrangell area to assess the expectable amount of shaking of the different geologic units during a particular earthquake. However, it is felt that reasonable inferences can be made on relative variations in intensity between the geologic units. In attempting to make such comparisons, the geologic units have been tentatively divided into three general categories: (1) those units where the strongest shaking is expected, (2) those units where shaking is expected to be intermediate between the other two categories, and (3) those units where the least shaking is expected. In some cases, one unit may fall into more than one category.

On this basis, the geologic units in the Wrangell area are tentatively assigned to the following categories:

Category 1. Strongest expectable shaking:

A. Manmade fill, mf (part of unit)
B. Delta deposits of the intertidal zone, Qd
C. Late shore deposits, Qs
D. Muskeg deposits, Qm

Category 2. Intermediate expectable shaking:

A. Manmade fill, mf (part of unit)
B. Elevated beach deposits, Qeb
C. Elevated fine-grained marine deposits, Qem

Category 3. Least expectable shaking:

A. Bedrock, bex and bc

Geologic units in category 1 (strongest expectable shaking)

Manmade fill, mf (part of unit).--As noted previously, there are essentially two types of man-emplaced fill in the Wrangell area: (1) fairly thick fill consisting chiefly of surficial deposits emplaced along the shore to elevate low-lying areas above high tide, and (2) fill consisting mostly of thin blankets of crushed bedrock to obtain firm bases for roads, the airport runway and apron, and the parking-area pads surrounding buildings. Parts or all of the first type of fill is placed in category 1.

The first type of fill generally consists of surficial deposits that probably are susceptible to strong ground motion during a large earthquake unless the fill is an engineered fill (properly compacted by standard engineering methods) or is not thick enough to amplify underlying bedrock motions. Although the fill between Front Street and Drive Street probably is thick enough to amplify bedrock motions, it is not known to the writer whether or not it is an engineered fill. If the fill in the area of the lumber mill (fig. 3) consists largely of sawdust and other wood waste as indicated, and if it is sufficiently thick to amplify bedrock motions, then comparatively strong shaking probably can be expected.

Except for the fill in parts of the airport runway, the second type of fill generally consists of only a thin blanket of crushed rock generally overlying surficial deposits. Therefore, the degree of expectable shaking of the fill probably would be determined largely by the nature of the underlying material, which in most places is muskeg. The fill in the airport, which consists of crushed rock and surficial deposits, is an engineered fill. Because it probably is more compact than the other fills and less likely to exhibit strong ground motion, it has been placed in category 2.

Delta deposits of the intertidal zone, Qd.--The delta deposits of the intertidal zone in the Wrangell area probably are subject to particularly strong shaking in comparison to other deposits, because they are mostly if not entirely fine grained, loosely consolidated, have considerable thickness, and are completely saturated to the surface or to within a few feet of the surface. No manmade structures are built upon these deposits. None are likely to be built, other than possibly causeways or bridges in connection with a proposal to build a highway from Wrangell Island to the mainland; one of several proposed alternate routes is across these deposits. Extremely careful consideration should be given to the susceptibility of these deposits to shaking and to secondary effects (discussed later) in connection with any planned construction.

Late shore deposits, Qs.--There probably is a considerable range of susceptibility of the deposits in the mapped area to shaking. Because the deposits along the north and northeast shore consist mostly of fine-grained material, they probably are subject to as much shaking as the delta deposits where thick enough to amplify the underlying bedrock motion. On the other hand, the deposits along the west shore generally are coarser grained and therefore tend to be less subject to shaking. Both types of shore deposits are saturated to or nearly to the surface, which increases their susceptibility to shaking. The main facilities built on the deposits are along the beach in the immediate vicinity of Wrangell.

Muskeg deposits, Qm.--The deposits, because of their very low rigidity, can be expected to shake severely during a major earthquake except possibly where too thin to amplify the ground motions in the underlying materials. Likewise, large lateral deformation of the deposits can be expected, which could be particularly damaging to buildings or other structures built on muskeg-covered slopes. Whether the muskeg in the Wrangell area would behave similarly to that of the peat in the Seattle area in respect to induced motions from distant and local earthquakes, as previously described, is not clear. The materials from the two areas probably differ considerably. The muskeg at Wrangell undoubtedly has a higher water content, is less cohesive, and probably is less rigid--all factors that normally result in amplification of ground motion.

Geologic units in category 2 (intermediate expectable shaking)

Manmade fill, mf (part of unit).--As noted in the discussion of manmade fill in category 1, the fill in the airport runway is as much as 25 feet (7.6 m) thick, and consists of crushed rock and surficial deposits. Inasmuch as it is an engineered fill, it probably is considerably more compact than most of the other fills and therefore has been placed in category 2. Where the fill is only a few feet thick it is underlain by bedrock, and seismic waves are transmitted directly into the fill. Where the fill is thicker, it generally rests on surficial deposits that themselves may amplify the ground motion from the underlying unit. The surficial deposits in most places are elevated fine-grained marine deposits (Qem) and muskeg (Qm).

Elevated beach deposits, Qeb.--These deposits, although similar in grain size to the late shore deposits (Qs) in the immediate vicinity of Wrangell, seem to be somewhat more compact, and where they underlie steeper slopes probably are not always saturated. Primarily for these reasons, they have been placed in category 2. However, because they rarely exceed 8 feet (2.4 m) in thickness, they may be too thin in places to amplify the ground motion of the underlying unit.

Elevated fine-grained marine deposits, Qem.--These deposits, although fine grained and probably generally saturated, are moderately dense and relatively thin (commonly 10 to 15 feet (3-4.5 m) thick). Hence, they are expected to be subject to an intermediate degree of shaking, although in places they may be less dense and subject to greater shaking.

Geologic units in category 3 (least expectable shaking)

Bedrock, bex and bc.--Damaging intensities on bedrock in the Wrangell area probably would be reached only during a large earthquake. However, the topography of the outcrop, degree of fracturing, and depth of weathering are factors that can affect seismic motion in bedrock. Davis and West (1973) concluded that the effects of topography on ground motion probably are not important when the seismic wavelengths are much larger than the dimensions of the topographic feature. However, when there are short wavelengths and steep slopes, instrumental records strongly suggest that seismic motions can be much larger on the tops of topographic highs (mountains, hills, etc.) than where the topography is relatively flat. In fact, Davis and West (1973) stated that the difference can be so great that in "selecting a hardrock site on a mountain rather than an alluvium site in a valley might not improve, and might even worsen, the seismic risk to the facility." Thus, the largest seismic motions on bedrock in the Wrangell area (fig. 3) probably would be on Dewey Hill and the hill near Point Highfield. Also, inasmuch as highly fractured bedrock is expected to increase the expectable intensity, the fractured bedrock forming Dewey Hill and the hill near Point Highfield probably is the most subject to increased ground motion. Weathered bedrock generally is subject to stronger ground motion than unweathered bedrock. However, the bedrock in the Wrangell area, so far as is known, is essentially unweathered, and therefore the expectable effects of this factor probably are negligible.

Compaction

Introduction

When loose cohesionless soils (those containing no significant clay content) are shaken by strong ground motion during an earthquake, there is a tendency for them to compact with associated settlement of the ground surface. The resulting densification of the materials, also under some conditions, produces liquefaction and water-sediment ejection. Only the associated effect of settlement will be discussed here.

Settlement of the ground surface, where underlain by loose cohesionless materials, probably has accompanied every severe earthquake. Ensuing damage can be severe, especially where differential settlement occurs. The amount of settlement generally is dependent upon (1) the looseness of the material, (2) the intensity of shaking, (3) the duration of strong ground motion, and (4) the relation between the natural vibrational frequencies of the material and the predominant frequencies of the ground motions in the underlying unit. Thus, the higher the void ratio of the material, the greater the intensity of shaking, the longer the duration of strong ground motion, and the closer the frequency of the underlying ground motion is to the natural frequency of the material, the greater the expectable compaction and resulting ground settlement. Although the vibrational effects on clays are considerably less than for cohesionless materials like sand, even soft clay compacts to some extent when subjected to intense vibrations having a frequency close to the natural frequency of the clay (Terzaghi and Peck, 1948).

Compaction in the Wrangell area

The delta deposits of the intertidal zone (Qd) probably would be subject to the greatest amount of compaction because of the presumably loose nature of the deposits and because of their considerable inferred thickness. Inasmuch as most of the ground surface of the deposits is only 1 to 5 feet (0.3-1.5 m) above water at low tide, settlement of only a few feet would result in complete inundation of the area. This possibility should be considered in any planning connected with building a causeway or other type of highway structure across these deposits.

In nonengineered fills (Qf), where loose, relatively cohesionless materials have been emplaced, compaction may be as great or nearly as great as in the delta deposits. The fill in the vicinity of the lumber mill in Wrangell might be such an example, although total settlement would be smaller because the fill presumably is much thinner. If the fill between Drive and Front Streets were properly compacted when emplaced, little settlement would be expected. However, if it were not an engineered fill, some differential settlement and resultant damage might occur during a severe earthquake.

Although the muskeg deposits (Qm) are subject to great compressibility under load, it is not clear how much they may compact when strongly shaken but not loaded. Because of their fairly high content of tree branches, twigs, roots, and the like, the deposits might have a springiness or rebound characteristic that would tend to negate compaction. Where loaded, such as where fills for roads and parking areas have been emplaced directly on muskeg, differential settlement and resultant damage can be expected during a severe earthquake.

The late shore deposits (Qs), especially the sandy deposits between Wrangell and Point Highfield, and the elevated beach deposits (Qeb) probably also are subject to considerable compaction when strongly shaken. However, in most places both kinds of deposits are believed to be thin, and settlement can be expected to be negligible unless the underlying deposits also are subject to compaction. Piers, docks, and other harbor works would be the main facilities affected by settlement.

Liquefaction in cohesionless materials

Introduction

Loose to medium-dense materials that are saturated and virtually cohesionless tend to compact when subjected to strong ground shaking. As a result of the closer packing of the solid particles, there is an excess of water and the load is transferred from the solids to the fluid. In consequence, the material can be transformed from a solid to a liquefied state. This process is known as liquefaction.

Other factors being equal, fine sand and coarse silts are most subject to liquefaction (Terzaghi and Peck, 1948). Also, the higher the void ratio, the greater is the tendency for the material to liquefy.

There are three basic types of ground failure associated with liquefaction (Seed, 1968): (1) flow landslides, (2) landslides with limited displacement, and (3) quick condition failures. In addition, ejection of water and sediment may be a source of damage associated with liquefaction during an earthquake (Ambraseys and Sarma, 1969). This last type of ground failure will be discussed under the heading "Water-sediment ejection and associated subsidence and ground fracturing."

In the first type of ground failure associated with liquefaction, unrestrained masses of earth materials may travel considerable distances as liquefied flows or as intact materials riding on liquefied flows. Flow ceases only when the driving shear forces are reduced (such as by slope reduction) to values less than the viscous shear resistance of the flowing material (Youd, 1973). The flows, which commonly are triggered by seismic shaking, can move down slopes of low gradient and can cause heavy loss of life and property destruction. There were several examples of large near-shore landslides and close offshore submarine slides of this type of ground failure generated during the Alaska earthquake of 1964.

In the second type of ground failure, limited flow may develop when conditions are favorable for liquefaction but the sediments are too dense to allow unlimited flow (Youd, 1973). Examples of this type are common in the literature but generally are described as "earth lurches," "land spreading," or "lateral spreading." There were numerous reports of this type of ground failure resulting from the Alaska earthquake of 1964 as well as during the San Francisco earthquake of 1906.

In the third type of ground failure, seepage forces, caused by upward-percolating pore water, tend to reduce the strength of granular soils to a point of stability, commonly called a "quick" condition (Youd, 1973). This condition can be caused by seismic compaction at depth and generally is limited to sand layers extending from below the water table to the surface. Loss of bearing capacity is a common result. Buoyant rise of buried tanks and other containers is another common effect. These effects were well illustrated during the Niigata, Japan, earthquake of June 16, 1964. The most dramatic case was the settlement and tilting of some apartment buildings; one building tilted through 80°, and the occupants were able to evacuate the structure by walking down the side of the building (Seed and Idriss, 1970).

Inferred effects in the Wrangell area

The delta deposits of the intertidal zone (Qd) probably are the most susceptible of any units in the Wrangell area to liquefaction during strong ground motion. Although the composition of the deposits is largely inferred, loosely packed fine sand and silt likely predominate. This grain-size characteristic, combined with saturation virtually to the surface most of the time, would tend to make these deposits highly subject to liquefaction. In support of this conclusion, the State of Alaska Department of Highways (1967) stated that the delta deposits in Dry Strait, when vibrated, become "quick" and lose their bearing capacity. The inferred effects of liquefaction of these deposits, as well as the other described units that follow, are discussed under the headings "Earthquake-induced slides and slumps" and "Water-sediment ejection and associated subsidence and ground fracturing."

Some manmade fill (mf) in the city of Wrangell may be sufficiently loose and of favorable grain size to liquefy. However, too little is known about the internal composition and degree of compaction of most of the fills to make any judgment regarding which particular fill or part of a fill may liquefy. It is doubtful, though, that any part of the fill for the airport runway would liquefy because it presumably is moderately dense (an engineered fill) and probably is fairly well drained.

Portions of the late shore deposits (Qs) likely are susceptible to liquefaction, but in most places the deposits are too thin and of too small an areal extent to be significantly affected. Similar deposits below mean lower low water (seaward limit of mapping) may be considerably thicker, but because of insufficient data their liquefaction potential cannot be evaluated.

The grain size of the elevated beach deposits (Qeb) probably favors liquefaction, but other factors such as incomplete saturation, somewhat greater consolidation than the late shore deposits, and thinness make it less likely than for the late shore deposits. The underlying elevated fine-grained marine deposits (Qem) probably are too fine grained and consolidated in most places to be subject to liquefaction.

The muskeg deposits probably are not subject to liquefaction because of their composition and internal structure.

Earthquake-induced slides and slumps

Introduction

Under this heading will be discussed slides and slumps, both on land and under water. Earthquake-induced slides on land are confined most commonly to steep slopes, but sliding also may take place on moderate to nearly flat slopes. On steeper slopes, either bedrock or surficial deposits may be involved. On moderate slopes to nearly flat surfaces, sliding generally is confined to fine-grained surficial deposits that are subject to liquefaction. Submarine slides are confined generally to steep underwater slopes such as the foreslopes of deltas. However, underwater sliding may occur on fairly gentle slopes if the involved deposits are subject to liquefaction.

Spectacular sliding, due at least in part to liquefaction of the involved deposits, took place along the fronts of several fan deltas during the great Alaska earthquake of 1964 and resulted in catastrophic damage, particularly to the towns of Seward and Valdez. As noted by Lemke (1967), of the several types of landsliding in the Seward area during the 1964 earthquake the most spectacular was large-scale subaerial and subaqueous landsliding of alluvial fan-delta deposits along the waterfront. Harbor facilities were almost completely destroyed, and the entire economic base of the town was wiped out. A strip of land approximately 4,000 feet (1,220 m) long and 50-500 feet (15-152 m) wide slid into Resurrection Bay. Ground behind the slide scarp was intricately fractured for a landward distance of as much as 800 feet (244 m), owing to almost horizontal movement of the landmass toward a free face. The submarine sliding resulted in marked deepening of water in the immediate vicinity of the former shoreline but in shoaling farther offshore where the slide debris came to rest. Similar failure of fan-delta deposits and extremely heavy damage ensued at Valdez.

Inferred effects in the Wrangell area

The delta deposits of the intertidal zone (Qd) and the associated underwater foreslopes of the delta probably are the most susceptible deposits to earthquake-generated sliding in the Wrangell area. Loose, largely cohesionless delta deposits are being laid down along the front of the delta on slopes that probably are barely in equilibrium even without shaking from an earthquake. If, as seems likely, the deposits also are subject to liquefaction, they could move rapidly down the face of the delta as high-density submarine flows and spread out for a considerable distance along the bottom of Eastern Passage. Concomitant with submarine flow, progressive landward migration of sliding in the form of flows and "land spreading" could be expected for probably as long as strong ground motion continued. In addition, a "quick" condition might develop in parts of the deposits. These inferred effects should be seriously considered if future plans call for building a causeway and road across these deposits to connect Wrangell Island with the mainland.

Little sliding from earthquake shaking is expected on land in the mapped area, except possibly along a few steep slopes. One such steep slope is the southwest flank of Dewey Hill, where fractured bedrock stands in near-vertical slopes and rockslides of considerable size are a possibility. Less high but equally steep slopes along the shore between Wrangell and Point Highfield might be subject to minor rock falls or slumping. Also, in order to assess potential effects to the inhabitants of Wrangell from earthquake-induced slides, an area southeast of the mapped area, where Wrangell obtains its entire water supply, should be evaluated. Very steep bedrock slopes along the southeast valley wall above reservoirs Nos. 1 and 2 may be subject to rocksliding, whereas more gentle slopes on the opposite valley wall might be subject to debris sliding during strong ground motion. Rock or debris slides could: (1) temporarily dam portions of the stream course, with later sudden release of abnormal quantities of water and possible damage to or rupture of the earth dams downstream; (2) fill one or both reservoirs with slide material; or (3) directly destroy the earth dams by inundation from slide material. An evaluation should be made as to whether the dams might also be breached during strong ground motion by direct failure of their earthen embankments. In the area of the Wrangell waterfront, minimal sliding on land is likely because of the gentleness of the slopes and general thinness of the deposits. Some slumping, ground fracturing, and lurching, however, may take place in parts of the manmade fill and locally elsewhere if ground motion is sufficiently strong.

The possibility of submarine sliding in Wrangell Harbor is difficult to evaluate because of lack of data. The steepest underwater slopes in the Wrangell Harbor area are those immediately west of Point Shekesti and directly offshore from the ferry terminal. The average slope off Point Shekesti, down to a depth of 50 fathoms (300 ft, 91 m) is approximately 15°. As judged from shore exposures and limited other data, essentially bare bedrock forms the upper slope down to a depth of at least 10 fathoms (60 ft, 18 m). Below that depth, a gradual increase in accumulation of fine-grained marine sediments with depth is indicated, but there probably are no thick accumulations until gentler slopes farther offshore are reached. Thus, large-scale submarine sliding in this area seems unlikely unless the fine-grained marine sediments are subject to liquefaction. The average underwater slope in the area of the ferry terminal is approximately 19° down to a depth of 10 fathoms, with gravel and boulders probably 10 to 20 feet (3-6 m) thick overlying bedrock. During severe shaking, the gravel and boulders might slide down the underlying sloping bedrock surface, with attendant damage to structures built on these deposits. There probably are other near-shore areas between the ferry terminal and Point Highfield that have similar bathymetric and geologic relations.

Sediments in the outer harbor area in the vicinity of the lumber mill, where underwater slopes are much gentler but the sediments are considerably thicker than offshore from Point Shekesti, may be subject to submarine sliding. Although the cause of collapse in August 1964 of the outer corner of the main dock of the lumber mill is not clear, it may have been due to failure of underlying sediments. As noted previously, piles used in the construction of the wharf penetrated 30 to 40 feet (9-12 m) of bottom material before reaching refusal on bedrock. The underwater slope under the dock is approximately 7°, whereas the bedrock slope appears to range from about 10° to 25°. Possibly sliding occurred along the bedrock-sediment interface, being triggered at that time perhaps by the heavy load of lumber and other equipment that reportedly had been stacked on the part of the dock that collapsed. This failure cannot be correlated with any known earthquake in the region. Under dynamic conditions of an earthquake, the slide potential would be considerably higher than under normal static conditions, especially if the deposits were subject to liquefaction.

Water-sediment ejection and associated subsidence and ground fracturing

Introduction

In at least half of approximately 50 major earthquakes, water and sediment have been ejected from surficial deposits (Waller, 1968). The ejection phenomena, which are a consequence of liquefaction of the deposits (Ambraseys and Sarma, 1969), have been called fountaining, sand spouts or sand boils, mud or sand craters, blowouts, and other names. The ejecta may range from clear water, through mud, to water containing material as large as coarse gravel. Sand, however, is a common size fraction. Ejecta heights of several feet are common, but fountaining to a height of as much as 100 feet (30 m) has been reported. The ejections are associated with surface or near-surface unconsolidated deposits where there is a high water table or a confined-water condition (where the top of the water zone is in contact with an overlying, relatively impervious zone). Associated fractures can form an intricate mosaic pattern of ground breakage, and generally range in width from hairline cracks to 1 or 2 feet (0.3 or 0.6 m), but some have been reported to be as wide as 30 feet (9.1 m) and open to a depth of 25 feet (7.6 m) (Foster and Karlstrom, 1967). The water-sediment ejection and associated subsidence and ground fracturing can cause extensive damage by filling basements with ejecta material, covering agricultural land with a blanket of infertile soil, and filling or partly filling small ponds. Also, where a "quicksand" condition is produced, structures can sink into the liquefied materials. Moreover, where material has been removed from beneath the surface by ejection, the surface collapses and structures built on it may be heavily damaged.

Inferred effects in the Wrangell area

The delta deposits of the intertidal zone (Qd) are most likely to be subject to water-sediment ejection and to associated subsidence and ground fracturing. As discussed previously, these sediments probably are the most prone of any of the deposits to liquefy, and the water table is virtually at the surface. However, because there is not a restrictive layer overlying the deposits to effect a confined-water condition, sufficient pressure may not be built up to produce fountaining or jetting of water and sediment. Instead, the water and sediment may merely well up and overflow the surface to produce a quicksand condition. Local subsidence can be expected whether or not there is jetting, and ground fracturing is likely.

Portions of the manmade fill (mf) that may be subject to liquefaction also may be subject to water-sediment ejection and associated subsidence and ground fracturing. Likewise, portions of the late shore deposits (Qs) may be subject to these effects, but probably on a small scale because of the thinness of the deposits.

Reaction of sensitive and quick clays

Introduction

Sensitive clays lose a considerable part of their strength when shaken. During an earthquake, such clays may fail and become rapid earth flows that can cause heavy damage and loss of life. Sensitivity of a clay is defined as the ratio of undisturbed shear strength of a clay to remolded shear strength of the same specimen (Terzaghi and Peck, 1948). The term "quick" clay denotes a clay of such high sensitivity that it behaves as a viscous fluid in the remolded state (Mitchell and Houston, 1969).

Inferred effects in the Wrangell area

It is highly unlikely that there are any clays in the mapped area that are sufficiently sensitive to be classed as "quick" clays. Some parts of the elevated fine-grained marine deposits (Qem) may contain slightly sensitive clays. This is suggested by the fact that the water content of some samples from these deposits is close to the liquid limit (State of Alaska Dept. Highways, 1969). However, more sampling and analyses are needed to confirm this possibility.

Effects of tsunamis, seiches, and other abnormal water waves

Introduction

Abnormal water waves associated with large earthquakes commonly cause vast property damage and heavy loss of life. Tsunami effects can be devastating to coastal areas many thousands of miles from the generation source. Seiche effects generally are confined to inland bodies of water or to relatively enclosed coastal bodies of water such as bays. Other abnormal waves, generated by submarine sliding or by subaerial landsliding into water, generally produce only local effects but, nevertheless, may be highly devastating.

Tsunamis, otherwise known as seismic sea waves and erroneously referred to as tidal waves, are generated by sudden tectonic displacement of the ocean bottom. In the oceanic depths, tsunami waves travel at speeds of about 425-600 miles (684-965 km) an hour, but in shallower water, such as in bays and inlets, their speeds are considerably less. As tsunami waves approach a coast, they greatly increase in height and (or) runup onto land. The waves generally are higher where the offshore zone is gently shelving. Also, tsunami waves running into the heads of funnel- or triangular-shaped bays may be considerably higher than at the mouths of those bays. Wave runup onto shore can range from a barely perceptible abnormal rise in tide level to heights of more than 100 feet (30 m) (Wiegel, 1964). Damage can be exceptionally great. In addition to heavy loss of life and damage to near-shore buildings, docks, and other harbor and coastal installations, moored boats can be extensively damaged by pounding against each other or by being carried ashore and beached.

Seiches are periodic oscillations (standing waves) in lakes, bays, inlets, reservoirs, and rivers produced by changes in wind stress, atmospheric pressure, or by earthquakes. Seiches produced by earthquakes (seismic seiches) are believed to be caused by horizontal acceleration of short-period seismic surface waves (McGarr and Vorhis, 1968). Seiching also may be produced during an earthquake by tectonic tilting of the water basin, which causes periodic wave oscillations (McCulloch, 1966). Because the surface waves that cause seiches travel so much faster than tsunami waves, seiche waves are operative in an area before the tsunami waves arrive.

Local waves generated by earthquake-induced submarine sliding or subaerial landsliding into water can be highly destructive. Because they generally hit the shore suddenly, during or immediately after an earthquake, and because their runup height at any particular locality is largely unpredictable, a warning system is not possible. Wave heights have ranged from barely perceptible rises in water levels to a record runup height of 1,720 feet (524 m) during the Lituya Bay earthquake of 1958 (Miller, 1960). Slide-induced waves violently struck a number of coastal communities during or immediately after the Alaska earthquake of 1964 and were a major cause of loss of lives and property.

Inferred effects in the Wrangell area

It is beyond the scope of this paper to try to predict the maximum height of tsunami waves and of runup on land that might be reached in the Wrangell area. The fact that the magnitude of an earthquake generally has to be 7 or greater to produce a noticeable tsunami and generally 8 or greater to produce a disastrous tsunami (Wiegel, 1964) makes it unlikely that the generation source for a large tsunami would be near Wrangell. Moreover, to generate a tsunami requires a considerable vertical displacement of the ocean bottom such as can occur along a dip-slip fault. Most earthquakes in southeastern Alaska large enough to generate a tsunami have been along the Fairweather-Queen Charlotte Islands fault system, where movement has been chiefly horizontal. Although tsunami waves could arrive in the Wrangell area from a far-distant source, it seems likely that they would be greatly attenuated during travel up a fiord system of considerable length and of varying depth and configuration before reaching the area. It should be noted, however, that under certain conditions tsunami waves can travel up long narrow inlets and attain runups of 5 to 10 feet (1.5-3 m) (see discussion in Lemke and Yehle, 1972a).

Height of tsunami wave runup and resultant damage at Wrangell would depend in part upon the arrival time of the waves in relation to the phase of the tide. Inasmuch as there is a normal tidal range of approximately 16 feet (4.8 m) at Wrangell, a tsunami wave of this height could crest at lower low tide and still not have a runup above normal higher high water. On the other hand, a 10-foot- (3-m-) high wave arriving at Wrangell during high tide could cause devastating damage to the harbor area and other low-lying areas of town, particularly if it came crashing into shore as a breaker.

Potential effects of seiching in the Wrangell area are considered to be negligible. The only completely enclosed bodies of water in the immediate vicinity of Wrangell are the two city water reservoirs southeast of town. These probably are too small for significant seiche waves to be generated. Also, it seems doubtful that seiching could develop in any of the surrounding inlets because of their openness at each end.

The Wrangell area probably has a fairly high potential for damage from slide-induced waves in the event of a moderately strong earthquake. As noted previously, the greatest indicated potential for submarine sliding is the forefront of the Stikine delta. The northern tip of Wrangell Island probably would be in the most direct path of any slide-generated waves from that source. Other than the airport, there presently are few facilities to be affected from that source. Although all of the airport runway is more than 30 feet (9 m) above mean lower low water, waves 10-20 feet (3-6 m) high arriving at high tide could cause considerable erosion and other damage to both ends of the runway. The Wrangell harbor area probably would be largely protected from waves originating from the part of the delta lying to the north and northeast of Point Highfield. However, it would be much more exposed to waves originating along the front of the delta to the northwest. Although the distance of travel would be greater and some wave attenuation would occur, it seems likely that large waves generated in that area could hit the harbor area with devastating force.

In summary, of the three types of waves, the slide-generated waves probably would have the greatest destructive potential in the Wrangell area because of probable higher runup and because they can hit the shore almost without warning during or almost immediately after an earthquake.

Ground water and streamflow

Introduction

Large earthquakes can significantly affect ground water and streamflow. Waller (1966a, b) noted that short-term effects of the Alaska earthquake of March 27, 1964, on ground water included (1) surging of water in wells, (2) water-sediment ejection, (3) failure of well systems, and (4) turbidity of water in wells and springs. Long-term effects included temperature changes, chemical-quality changes, and the lowering or raising of water levels or artesian pressures. Surface-water changes included diminished or increased streamflow. Changes in streamflow commonly were controlled by ground fracturing in or near streambeds and by snow and rock avalanching. Most landslides blocked streams for only short periods, but effects from some persisted for months (Waller, 1966a; Lemke, 1967).

Inferred effects in the Wrangell area

Inasmuch as Wrangell obtains its entire water supply from surface sources, any changes in ground-water flow or quality are not presently pertinent. However, if wells are drilled and used for municipal supply in the future, they may be affected in one or more of the ways described above. It seems unlikely that the quantity of the surface supply would be greatly affected, unless landsliding occurred, because the source is from a stream that flows much of its length on bedrock. Where the stream does flow on surficial deposits, temporarily increased turbidity and changes in taste and chemical composition might result.

In flatter undrained areas underlain by muskeg, considerably more surface water than now exists as small ponds could be expected to accumulate if the muskeg were subject to appreciable compaction. On better drained slopes, compaction would result in water draining out of the muskeg, perhaps in copious amounts for a short period of time, down the presently intermittent small stream channels. Drainage of this kind into the reservoirs from which Wrangell gets its water supply could result in temporary discoloration and changes in taste and chemical composition of the water.

Glaciers and related features

Introduction

Strong ground motion and land-level changes resulting from earthquakes can affect glaciers and related features in several ways: (1) cause thickening of glacier ice; (2) cause thinning of glacier ice; (3) disrupt glacier-fed streams; (4) change flow characteristics of glacier ice, resulting in glacial advance; (5) cause accelerated calving of the termini of tidewater glaciers, resulting in possible retreat of glaciers; (6) cause glaciers to advance or retreat owing to land-level changes; and (7) produce long-term changes in mass or flow characteristics of glaciers because of tectonic displacement (Post, 1967).

Inferred effects in the Wrangell area

Inasmuch as there are no glaciers on Wrangell Island, the only part of the Wrangell area that might possibly be affected would be the Stikine River delta area. In the somewhat unlikely event that streamflow down one or more tributaries of the Stikine were significantly disrupted owing to glacier ice or snow damming, there first would be diminished streamflow, possibly affecting navigation down the river in the mapped area. Upon breaching of the dam, there could be a sudden release of a large quantity of water down the river, resulting in the scouring of new channels across the delta deposits and possible damage to any manmade structure (such as a highway) built on these deposits.

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

Geologic hazards other than those caused by earthquakes are believed to be relatively minor in the Wrangell area. However, some may occur so much more frequently than those from major earthquakes that their aggregate effects could be significant. Three kinds of geologic hazards are discussed here: (1) effects of nonearthquake-induced landsliding and subaqueous sliding, (2) effects of flooding, and (3) effects of sediment accumulation.

Landsliding and subaqueous sliding

The greatest potential for nonearthquake-triggered sliding in the mapped area is in the intertidal delta deposits of the Stikine River and associated subaqueous deposits. As noted previously, a number of breaks in cables offshore from the delta have been attributed to submarine sliding that has not been correlated with times of earthquakes. There is every reason to believe that sliding will continue in this area at such times as the forefront slopes of the delta become oversteepened by normal depositional processes. Whether the scale of submarine sliding under nonearthquake conditions would be large enough to cause a damaging wave at Wrangell cannot be ascertained. No damage is known to have occurred in the past in the Wrangell area from a wave of this kind.

Sliding also can be expected locally on steep underwater slopes where there may be perched bodies of sediment. Such materials can fail suddenly when heavily loaded manmade structures, such as docks, are built upon them. Therefore, careful studies should be made, before construction, of the fairly steep near-shore slopes between the ferry terminal and Point Shekesti as well as of other areas to the north and south.

The potential for nonearthquake-triggered subaerial sliding in the mapped area of Wrangell Island appears to be low. Rocksliding off the steep southwest flank of Dewey Hill and small-scale sliding of the steep but relatively low cliffs along parts of the shoreline probably are about the only present possibilities.

Accelerated erosion and debris flows may follow large-scale clearing and cutting of timber on steeper slopes. Swanston (1969), who has made an extensive study of this cause-and-effect relation in southeastern Alaska, stated that the erosion occurs mainly as mass soil movements associated with steep slopes and high water levels in the soil. He noted more than 3,800 large-scale debris avalanches and debris flows in southeastern Alaska. Although most of these landslides are the direct manifestation of natural mass wastage and slope reduction, some are the direct result of logging and logging-road construction. Fairly numerous rock and debris slides have been noted by Swanston (1969) and others on the steep mountain slopes in the southeastern part of Wrangell Island. Although there is no major timber cutting at present in the mapped area, these potential effects should be considered if future large-scale logging is contemplated.

Flooding

There are no major streams in the mapped area, and therefore the potential for damage from flooding is minimal. Perhaps the only threat to the city of Wrangell would be in the event that sufficient precipitation fell to cause the overtopping or collapse of the dams that hold back the reservoirs from which the city gets its water supply.

Sediment accumulation

The relatively rapid seaward expansion of the Stikine River delta and of offshore accumulation of sediments may pose a problem sometime in the future in the use of some facilities in the Wrangell area. As noted previously, the margin of the delta directly north of Wrangell has been advancing about 50 to 60 feet (15-18 m) a year during the past 86 years, and parts of the delta in the previous 94 years may have advanced at a rate of 75 to 105 feet (22.8-32 m) a year. Assuming the minimum rate of 50 feet (15 m) a year for future advance, it would take approximately 60 years for Eastern Passage between the front of the delta and Simonof Island to be filled with sediment. Between Simonof Island and the northern part of Wrangell Island, the water is so shallow that the area probably would be filled with water-suspended sediments during the same period. Actually, purely on the basis of past rate of sediment accumulation, 60 years is too long a time for the complete filling of Eastern Passage between the margin of the delta and Wrangell Island, because the water offshore will become progressively shallower as filling proceeds, and less sediment will be needed. On the other hand, erosion of the front of the delta by the action of tides and currents may greatly retard blocking of the channel as the channel becomes narrower.

As the margin of the delta continues to expand southward, increasingly greater quantities of water-suspended sediments will be carried into Wrangell Harbor. As discussed previously, 3 to 4 inches (8-10 cm) of sediment now appears to be accumulating annually in the deeper part of the harbor area between Point Shekesti and Shakes Island. A greater annual increase in sediment accumulation would require progressively more maintenance dredging. On the other hand, if tidal currents play an important role in keeping the sediments in suspension by agitation and the sediments are largely flushed out of the harbor area during ebbtide (Sawyer, 1963), then the potential problem is much smaller. Obviously, detailed studies are needed of the rate of delta growth and of sediment accumulation along the shores of Wrangell Island.

RECOMMENDATIONS FOR ADDITIONAL STUDIES

The reconnaissance nature of the writer's studies in the Wrangell area did not permit making all the geologic studies necessary to fully evaluate geologic hazards and other aspects of the area. Also, additional geophysical, soils mechanics, and seismological studies are necessary to assess more adequately some aspects of the problems. Listed below in approximate order of importance are some of the additional studies that the writer believes should be made by geologists or specialists in other disciplines to help fulfill the objective of evaluating the potential geologic hazards and other characteristics of the area that are pertinent to proper land-use planning:

1. In order to permit a more adequate assessment of the earthquake probability of the area, studies should be made to locate more accurately all the major local and regional faults and to determine the kind and amount of past movement and present degree of activity. Sophisticated instrumentation studies, particularly, should be made of the active Fairweather-Queen Charlotte Islands fault system. Fairly long term microearthquake studies should be done in the Wrangell area to determine possible local fault movement.

2. A fairly large number of additional analyses are needed to more adequately determine the physical properties of the surficial deposits in the mapped area as they relate to earthquake and other geologic hazards. Particular emphasis should be directed toward those analyses that will give additional information on (1) comparative amounts of shaking of the different kinds of deposits during a major earthquake, (2) expectable degree of slope stability, (3) liquefaction potential, (4) sensitivity of fine-grained deposits, and (5) compaction and resultant settlement characteristics. The information gained from the studies described above should be supplemented, where needed, by drilling and geophysical work to determine thicknesses of individual units and the characteristics of deposits at depth, as well as the topographic relations of the deposits to bedrock.

3. For navigational and possible construction purposes, additional bathymetric data and long-range studies are needed to determine rate of growth of the Stikine River delta and of offshore sediment accumulation, particularly in Wrangell Harbor. Also, for assessing subaqueous slide potential, additional data are needed to determine the nature and thicknesses of sediments on underwater slopes.

4. Research studies are needed that will lead toward estimating maximum expectable wave heights and runup of tsunamis in long linear inlets, in order to assess the tsunami hazard in the Wrangell area from waves that originate from a distant source.

5. Studies should be made to determine the commercial possibilities of the large deposits of peat in the vicinity of Wrangell.

6. In the event of a major earthquake in or near the Wrangell area, a multidisciplinary team, including geologists, geophysicists, seismologists, and engineers, should study the affected area to determine the actual ground effects and the effects upon the structures built thereon. Such a study not only will add to the overall knowledge of earthquake effects but, in this particular instance, where some previous engineering geology studies have

been made, it will afford an opportunity to compare the actual effects with the writer's present assessments. Only in this way will it be possible to assess the accuracy of the evaluations made in this report and at the same time furnish guidelines for increasing the worth of future studies of this nature.

GLOSSARY

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

Acceleration: The time rate of change of velocity in either speed or direction. The force imposed on structures by ground shaking varies with the acceleration of ground shaking. The acceleration reaches a maximum during each shaking cycle when the direction of ground movement reverses. The maximum acceleration varies with the change in velocity that occurs and the elapsed time during which the change in velocity takes place. Maximum accelerations are commonly expressed as a percentage of the acceleration of gravity. For example, an acceleration of 16.1 feet (4.9 m) per second per second may be expressed as 50 percent g where g is the acceleration of gravity, 32.2 feet (9.8 m) per second per second.

Amplitude: In relation to ground motion caused by earthquakes, refers to the maximum value of the displacement in an oscillatory motion.

Diamicton: A nonsorted or poorly sorted sediment that consists of particles larger than sand in a matrix of sand, silt, and clay-size particles. The term is noncommittal as to how the deposit was formed.

Dilatancy: An increase in bulk volume during deformation. The rapidity of appearance of water during shaking of a fine-grained sample and of its disappearance during squeezing assists in identifying the character of the fines in a soil (U.S. Bur. Reclamation, 1968, p. 14).

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.

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

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

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

Ground amplification: The amount by which the amplitude of ground motions at the surface of a surficial unconsolidated deposit exceeds the amplitude of ground motions at the surface of the underlying bedrock. Amplification arises from the multiple (successive) reflection of seismic waves between the ground surface and the bedrock surface underlying the unconsolidated deposit. Maximum amplification occurs when the internal deformations induced by the reflected waves augment the deformations induced by the incoming waves from underlying bedrock; in other words, when the reflected waves are in phase with the incoming waves.

Ground shaking: The severity of ground shaking at a specific location during an earthquake is defined qualitatively in terms of Intensity scales (see Intensity) and quantitatively in terms of instrumental observations of ground motions. The latter permits ground shaking to be characterized by three factors: (1) the amplitude of the strongest ground motions which may be expressed in terms of accelerations, velocities, or displacements; (2) the predominant frequency or period of the strongest motions; and (3) the duration of strong shaking.

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

Intensity: Refers to the severity of ground motion (shaking) at a specific location during an earthquake and is based on the sensations of people and visible effects on natural and manmade objects. The most widely used intensity scale in the United States is the Modified Mercalli intensity scale. (See table 4.)

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

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

Liquefaction: The transformation of a granular material from a solid state into a liquefied state as a consequence of increased pore-water pressure (Youd, 1973).

Liquid limit: The water content in percent of dry weight at which soil passes from the liquid state into the plastic state (Terzaghi and Peck, 1948, p. 32-36).

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.

Moisture content: The loss in weight when a material is dried to a constant weight and expressed as a percentage of the dry material.

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

Muskeg: "Muskeg" is derived from a Chippewa Indian word meaning grassy bog. It was soon recognized that this interpretation was not broad enough and that both the surface features and the subsurface characteristics should be included in the definition. To provide the widest general agreement, the following definition, which emphasizes "organic terrain" as a substitute expression, was provided: "Muskeg has become the term designating organic terrain, the physical condition of which is governed by the structure of the peat it contains, and its related mineral sublayer, considered in relation to topographic features and the surface vegetation with which the peat co-exists" (Radforth, 1969). This definition is inclusive enough to be useful in a variety of studies, and several kinds of classifications have been adopted to facilitate these studies. However, for purposes of this report the term "muskeg" will be used in more or less of an engineering sense and with the material itself being emphasized more than the landform. Thus, muskeg is defined here as "Organic-rich deposits consisting of peat and other decaying vegetation that are commonly found in swamps and bogs." The term "peat" is used more or less interchangeably with the word "muskeg" in this report.

Peat: A component of organic terrain consisting of more or less fragmented remains of vegetable matter sequentially deposited and fossilized (MacFarlane, 1969). See "Muskeg (Qm)."

Plasticity index: The numerical difference between the liquid limit and the plastic limit. Represents the range of moisture content within which a soil is plastic (U.S. Bur. Reclamation, 1968, p. 8, 28).

Plastic limit: The water content of a soil in percent of dry weight at the boundary between the plastic state and the solid state (Terzaghi and Peck, 1948, p. 32-36).

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

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

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

Seismic waves: Waves that carry earthquake energy from a causative fault to the ground surface and which are the cause of ground shaking.

Shrinkage limit: The water content below which further loss of water by evaporation does not result in a reduction of volume of a soil (Terzaghi and Peck, 1948, p. 33).

Shrinkage ratio of a soil: The ratio between volume change, in percentage of the dry volume, and corresponding change in water content above the shrinkage limit expressed as a percentage of the weight of the oven-dried soil (U.S. Bur. Reclamation, 1968, p. 433).

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

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

Tsunami: A sea wave, otherwise known as a seismic sea wave, generated by sudden large-scale vertical displacement of the ocean bottom as a result of submarine earthquakes or of volcanic action. Tsunamis in the open ocean are long and low, and have speeds of 425-600 miles (680-960 km) an hour. As they enter shallow coastal waters they can greatly increase in height and also in height and distance of runup onto land.

Void ratio: The ratio of the volume of the voids to the volume of the solids.

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