THE ALASKA EARTHQUAKE, MARCH 27, 1964:
EFFECTS ON COMMUNITIES

Effects of the Earthquake of March 27, 1964 on Various Communities

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A description of the damage, principally from waves, vertical tectonic movements, and seismic vibration, to inhabited places throughout the earthquake-affected part of Alaska

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THE
ALASKA EARTHQUAKE
SERIES

The U.S. Geological Survey is publishing the results of investigations of the Alaska earthquake of March 27, 1964, in a series of six Professional Papers. Professional Paper 542 describes the effects of the earthquake on communities. Reports on Anchorage, Whittier, Valdez, Homer, Seward, and Kodiak have already been published. This report is the final chapter of Professional Paper 542.

Other Professional Papers describe the history of the field investigation and reconstruction efforts; the regional effects of the earthquake; the effects on the hydrologic regimen; and the effects on transportation, communications, and utilities. The final volume on lessons learned and conclusions drawn is in preparation; it will include an index for the entire series. A selected bibliography and an index for the entire series will be published in the concluding volume, Profesional Paper 546.

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EFFECTS OF THE EARTHQUAKE OF MARCH 27, 1964 ON VARIOUS COMMUNITIES

By George Plafker, Reuben Kachadoorian, Edwin B. Eckel, and Lawrence R. Mayo

ABSTRACT

The 1964 earthquake caused widespread damage to inhabited places throughout more than 50,000 square miles of south-central Alaska. This report describes damage to all communities in the area except Anchorage, Whittier, Homer, Valdez, Seward, the communities of the Kodiak group of islands, and communities in the Copper River Basin; these were discussed in previous chapters of the Geological Survey's series of reports on the earthquake. At the communities discussed herein, damage resulted primarily from sea waves of diverse origins, displacements of the land relative to sea level, and seismic shaking. Waves took all of the 31 lives lost at those communities; physical damage was primarily from the waves and vertical displacements of the land relative to sea level.

Destructive waves of local origin struck during or immediately after the earthquake throughout much of Prince William Sound, the southern Kenai Peninsula, and the shores of Kenai Lake. In Prince William Sound, waves demolished all but one home at the native village of Chenega, destroyed homesites at Point Nowell and Anderson Bay, and caused varying amounts of damage to waterfront facilities at Sawmill Bay, Latouche, Port Oceanic, Port Nellie Juan, Perry Island, and western Port Valdez. The local waves, which ran up as high as 70 feet above tide level at Chenega and more than 170 feet in several uninhabited parts of the Sound, took nearly all of the lives lost by drowning at these communities. Destructive local waves that devastated shores of Anderson Bay and adjacent parts of western Port Valdez probably were generated primarily by massive submarine slides of glacial and fluvioglacial deposits; the origin of the waves that caused damage at most of the other communities and at extensive uninhabited segments of shoreline is not known. At these places the most probable generative mechanisms are: unidentified submarine slides of unconsolidated deposits, and (or) the horizontal tectonic displacements, of 20 to more than 60 feet, that occurred in the Prince William Sound region during the earthquake.

A train of long-period seismic sea waves that began about 20 minutes after the start of the earthquake inundated shores along the Gulf of Alaska coast to a maximum height of 35 feet above tide level. At the communities described, they virtually destroyed two logging camps at Whidbey Bay and Puget Bay on the south coast of the Kenai Peninsula, caused moderate damage to boat harbors and docks at Seldovia and Cordova, floated away some beach cabins in the Cordova area, and drowned two people, one at Point Whitshed near Cordova and one at the Cape Saint Elias Light Station. The seismic sea waves were generated by regional tectonic uplift of the sea floor on the Continental Shelf.

Vertical tectonic displacements of the land relative to sea level that accompanied the earthquake affected virtually all the coastal communities. Tectonic subsidence of 5 to 6 feet, augmented locally by surficial subsidence of unconsolidated deposits, required either the relocation or raising of structures at Portage, Girdwood, and Hope on Turnagain Arm. Shoreline submergence resulting from about 3½ feet of tectonic subsidence at Seldovia necessitated raising all waterfront facilities and the airstrip above the level of high tides. On the other hand, tectonic uplift of the land in the Prince William Sound region required deepening of the small-boat harbors at Cordova and Tatitlek, dredging of the waterways in the Cordova area, and lengthening of some docks or piers at Cordova, the Cape Hinchinbrook Light Station, and in Sawmill Bay.

Significant structural damage from direct seismic shaking was largely confined to fluid containers and a pier facility near Kenai. Indirect damage from fissuring and differential settling of foundation materials in the vicinity of the Cordova airfield caused damage to a building, underground utilities, an airfield fill, and the highway. Minor amounts of direct and indirect damage from seismic vibrations were sustained by most of the communities situated on unconsolidated deposits as far east as Yakutat, north to Fairbanks, and west to King Salmon. Except for a few cracked or toppled chimneys, all the damage from shaking was confined to areas of thick, unconsolidated deposits. Foundation damage was almost entirely restricted to water-saturated unconsolidated deposits which, when liquefied by seismic shaking, could spread laterally toward free faces and (or) settle differentially through compaction.

INTRODUCTION

The great earthquake of March 27, 1964, took 114 lives and did more than $300 million damage to private and public property. Although a significant part of the damage was to interurban transportation and communications systems (Grantz, Plafker, and Kachadoorian, 1964; Eckel, 1967), by far the greater part of life and property losses occurred in cities, towns, and villages. Nearly all the inhabited places that were affected are in south-central Alaska, in a relatively small part of the State but some (not discussed here) are as far away as northern California. All the larger cities that were extensively damaged, and some of the smaller communities, are covered in other reports in this series (table 1).

This report completes the U.S. Geological Survey series of descriptions of earthquake effects on communities. Damage at all previously undescribed Alaskan communities where there was loss of life or physical damage beyond such minor effects as cracked plaster, disloged building contents, or muddied wells is described herein. The communities and the nature of their damage are listed in table 2; their locations are shown on plates 1 and 2. The scores of additional inhabited places in Alaska and Canada where the earthquake was reportedly felt but where it did no damage are shown in plate 1, but they are not described here.

This report is based primarily on personal observations of Kachadoorian, Plafker, and Mayo, one or all of whom visited each of the communities as a part of their general studies of geologic effects of the earthquake throughout south-central Alaska during the field seasons of 1964 and 1965. Their information, supplemented by that from other sources, was largely assembled by Eckel while the first two authors were busy on other assignments. All four authors share responsibility for the facts presented and for their interpretation.

TABLE 1.—*Alaskan communities damaged by the earthquake of March 27, 1964, treated in other U.S. Geological Survey reports*

[Place names and locations are as given by Orth (1967); some spellings differ from that in referenced descriptions. Except as noted, populations are as of 1960 census. Deaths from Alaska Dept. Health and Welfare (1964). Numbers in descriptions column refer to U.S. Geological Survey series of Professional Papers on the Alaska Earthquake of March 27, 1964 (see "References cited"): 541, Hansen and others (1966); 542-A, Hansen (1965); 542-B, Kachadoorian (1965); 542-C, Coulter and Migliaccio (1966); 542-D, Waller (1966a); 542-E, Lemke (1967); 542-F, Kachadoorian and Plafker (1967); 543-A, McCulloch (1966); 543-D, Plafker and Kachadoorian (1966); 543-E, Ferrians (1966); 544-A, Waller (1966b); 544-B, Waller (1966c); 545-A, Logan (1967); 545-B, Eckel (1967); 545-D, McCulloch and Bonilla (1968)]

Place	Location [1]		Population 1960	Deaths	Principal causes of damage (1, primary; 2, secondary; 3, much damage also from waterfront fires)						Descriptions
	Latitude, N.	Longitude, W.			Subsidence	Fire	Landslides		Vibration	Waves	
							Land	Submarine			
Afognak	58°00′30″	152°46′00″	190	0	2					1	541, s. 96, 542-F, p. 28-32; 543-D, p. 30-39.
Anchorage	61°13′05″	149°53′30″	[1] 44,237	9			1		1		541, p. 73, 83-85, 100-103; 542-A, p. 1-68; 544-B, p. 1-18; 545-B, p. 3-4, 8-9, 19-24.
Chugiak	61°23′50″	149°28′40″	51	0					1		544-A, p. 19.
Eagle River	61°19′20″	149°34′00″	130	0					1		541, p. 19.
Eklutna powerplant	61°28′	149°22′	50	0					1		545-1, p. 1-24.
Glannallen	62°07′	149°33′	169	0					1		543-E, p. 25.
Gulkana	62°16′	145°23′	59	0					1		543-E, p. 25.
Homer	59°38′40′	151°33′00″	1,247	0	1			2	2		541, p. 80, 88, 91; 542-D, p. 1-28; 544-A, p. 21; 545-B, p. 12.
Kadiak Fisheries Cannery			2	0	2				1	1	543-D, p. 13, 15-19, 43.
Kaguyak	56°51′40″	153°46′00″	36	3						1	542-F, p. 37-38; 543-D, p. 30-39.
Kodiak	57°47′20″	152°47′10″	[2] 2,628	[3] 9	2					1	541, p. 92-94; 542-F, p. 1-28; 543-D, p. 30-39; 545-B, p. 5, 14, 24.
Larsen Bay	57°32′20″	153°58′45″	72	0	1						542-F, p. 40; 543-D, p. 30-39.
Lawing	60°24′15″	149°21′50″	[4] 8	0						1	543-A, p. 12-18.
Lee's Guide Service			[4] 4	0					1		543-E, p. 25.
McCord	57°08′30″	153°11′45″	8	0	2				2	1	541, p. 19.
Old Harbor	57°12′15″	153°18′00″	193	0	2					1	542-F, p. 34-37; 543-D, p. 30-39.
Ouzinkie	57°55′30″	152°29′50″	214	6	2					1	542-F, p. 33-34; 543-D, p. 30-39.
Moose Pass	60°29′20″	149°22′00″	136	0					1		545-D, (in press).
Seward	60°06′30″	149°26′30″	1,891	13		3		1	2	1	541, p. 73-79, 85, 90; 542-E, p. 1-43; 544-A, p. 24-26; 545-B, p. 6, 12, 25.
Sheep Mountain Inn	61°50′	147°31′	[4] 5	0					1		543-E, p. 25.
Tazlina Glacier Lodge	62°04′	146°27′	[4] 4	0					1		543-E, p. 25.
Tonsina Lodge	61°39′20″	145°10′30″	[4] 4	0				1			543-E, p. 25.
Tsina Lodge	61°11′45″	145°33′30″	[4] 4	0				1			543-E, p. 25.
Valdez	61°07′	146°16′	1,000	31	2	3		1		1	541, p. 79, 85-87, 98-99; 542-C, p. 1-36; 544-A, p. 26; 545-B, p. 15-17, 25.
Whittier	60°46′30″	148°41′00″	[4] 70	13	1	3		2	2	1	541, p. 80, 99; 542-B, p. 1-21; 545-B, p. 6, 26.

[1] 82,833 including military personnel.
[2] 4,788 including personnel at Kodiak Naval Station.
[3] Includes 7 persons who were on highways, on boats, or in isolated places in the Kodiak Islands.
[4] Estimated by authors as of March 27, 1964.

TABLE 2.—*Alaskan communities damaged by the earthquake of March 27, 1964, treated in this report*

[Place names and locations are as given by Orth (1967); some spellings differ from that used in other U.S. Geological Survey reports on the earthquake. Locations of places marked with asterisk are shown on plate 1; all others are on plate 2. Except as noted, populations are as of 1960 census. Deaths from Alaska Dept. Health and Welfare (1964). Physical damage relative to size and importance of community]

Place	Location		Population	Damages			Principal causes of damage (1, primary; 2, secondary)					
	Latitude N.	Longitude W.		Deaths	Physical damage		Subsidense	Uplift	Landslides		Vibration	Waves
					Major	Minor			Land	Submarine		
Anderson Bay and vicinity, Port Valdez	61°05′	146°33′	1	1	×							1
Cape Hinchinbrook Light Station	60°14′15″	146°38′40″	(1) 6	0		×		2	2		2	
*Cape Saint Elias	59°47′30″	144°36′15″	4	1		×			2		2	1
Chenega	60°16′45″	148°04′30″	75	23	×			2		2		1
*Chisik Island (see Tyonek)	60°08′	152°35′	[1] 20									
Cooper Landing	60°29′25″	149°50′00″	100	0		×					1	
Cordova and vicinity	60°33′	145°45′	1,128	1	×			1			2	2
Crab Bay (see Sawmill Bay)	60°03′45″	148°00′00″										
Ellamar	60°53′45″	146°42′30″	1	0		×		1				
*English Bay	59°21′30″	151°55′20″	78	0		×	1				2	
*Fairbanks	64°50′45″	147°43′15″	13,311	0		×					1	
Girdwood	60°56′30″	149°10′00″	63	0	×		1					
Hope	60°55′15″	149°38′30″	54	0		×	1				2	
*Kenai and vicinity	60°33′	151°16′	778	0		×					1	
*King Salmon and vicinity	58°41′30″	156°39′30″	618	0		×					1	
Latouche	60°03′05″	147°54′	0	0	×			2				1
*Middleton Island	59°26′	146°20′	[1] 12	0		×		1				
*Naknek (see King Salmon)	58°43′40″	157°00′45″	249									
*Nikiski (see Kenai)	60°41′	151°24′										
*Palmer and vicinity	61°36′00″	149°06′30″	1,181	0		×					1	
Perry Island	60°43′	147°55′	2	0		×					2	2
Point Nowell	60°26′27″	147°56′23″	1	1	×							1
Point Whitshed (see Cordova)			[1] 10									
Portage	60°50′15″	148°58′45″	71	0	×		1				2	
Port Ashton (see Sawmill Bay)	60°03′30″	148°03′00″										
*Port Graham	59°21′10″	150°49′30″	139	0		×	1					
Port Nellie Juan	60°33′00″	148°09′45″	3	3	×							1
Port Oceanic	60°12′45″	147°49′00″	2	0		×		2				1
Puget Bay	59°56′	148°31′	[1] 2	0	×			2	2		2	1
Rocky Bay	59°14′15″	151°25′00″	[1] 4	0		×	2					1
San Juan Cannery (see Sawmill Bay)	60°03′	148°04′										
Sawmill Bay and vicinity	60°03′30″	148°00′30″	[1] 15	1	×					2	2	1
*Seldovia	59°26′15″	151°42′30″	460	0	×		1					
*South Naknek (see King Salmon)	58°41′	157°00′	142									
Sutton	61°42′40″	148°53′30″	162	0		×					1	
Tatitlek	60°52′45″	146°41′00″	96	0		×		1			2	
*Tyonek and southwest shore Cook Inlet	61°04′00″	151°08′20″	187	0		×					1	
Whidbey Bay	59°56′	158°56′	[1] 4	0	×						2	1
*Yakataga	60°04′05″	142°25′45″	48	0								
*Yakutat	59°33′	139°44′	230	0		×					1	

[1] Estimated by authors, as of March 27, 1964.

ACKNOWLEDGMENTS

We are greatly indebted to numerous individuals who provided us with eyewitness accounts of their experiences during and immediately after the earthquake. Some of these people are mentioned by name in the descriptions of the effect of the earthquake at specific communities; there were literally hundreds of others who gave useful information but whose contributions could not be specifically acknowledged here.

EARTHQUAKE QUESTIONNAIRE

As part of the Geological Survey's effort to gather as much information as possible on the geological effects of the earthquake, Earl Brabb prepared and distributed a questionnaire designed to elicit such information from as many eyewitnesses as could be reached. Copies were mailed to every postmaster in Alaska, and many other copies were delivered personally by field geologists in the course of their investigations; these men also found the questionnaires useful for jotting notes during their interviews with local people.

Response to the questionnaire was gratifying. About 75 percent of the more than 350 copies distributed were returned. Of these, virtually all contained useful information, and many provided leads to further information that was gathered by correspondence or by followup interviews. These responses increased the amount of information available far beyond what could have been collected by individual field investigators.

In order to show the kind of information that was sought and to aid future earthquake investigators, the questionnaire is reproduced here. It may seem formidable at first glance, but the response to it shows that most people found it easy to answer; indeed, many were sufficiently interested to append long notes or letters that provided a wealth of additional details. The text of the questionnaire follows.

312-357 O—69——2

U.S. GEOLOGICAL SURVEY
Alaskan Geology Branch
345 Middlefield Road
Menlo Park, California

EARTHQUAKE QUESTIONNAIRE FOR SUPPLEMENTARY GEOLOGIC DATA

Section A—Did you or anyone in your area feel the earthquake? __

1. Nature of ground motion:
   a. Fast __ or slow? __ Don't know __
   b. Rolling __ or jarring? __ Don't know __
   c. For how long? ______
   d. If there were different types of motion during the earthquake, estimate the duration and order of each type ________________
   ____
   e. Did you see waves in the ground? __ If so, how many and how far apart? __
   f. What was the main direction of ground movement? (circle) N–S, NE–SW, E–W, SE–NW Don't know __
   g. Motion felt by several in community __, most __, all __, observer __.
2. Location of observer during earthquake:
   a. Indoors __ outdoors __
   b. If indoors, were you lying down __, sitting __ or active? __
   c. If indoors, does the house or building rest on bedrock __, filled in ground __, muskeg __, soil __, don't know __
3. Effect of earthquake on objects:
   a. Rattled windows __, doors __, dishes __
   b. Creaked walls __
   c. Swayed doors __, lamp __
   d. Shook trees and bushes slightly __, moderately __, violently __
   e. Shifted small objects __
   f. Overturned small objects __, lamps __
   g. Shifted large, heavy objects __
   h. Overturned large, heavy objects
   i. Cracked plaster __, windows __, walls __, chimneys __
   j. Caused to fall: knicknacks __, books __, pictures __, plaster __, walls __, chimney __
   k. Broke dishes __, furniture __
   l. Caused damage to house or building: slight __, considerable __, great __, total __; house or building is log construction __, brick __, wood frame __, masonry __, concrete __
   m. Offset road __, fence __, house __ as much as __ feet.
4. Effect of earthquake on natural features:
   a. Did any cracks form in ground? __ If yes, how many? __ How long after the initial shock of the main earthquake did they form? __ seconds, __ minutes, __ hours, other __, don't know __

      Average length __, average width __, average depth __; dimensions of largest crack __ long, __ wide, __ deep; approximate orientation of most cracks ____. How far apart were most of the cracks? __ Were the cracks in ice __, snow __, mud __, sand __, rock __, other __?
   b. Did any low mounds ("mole tracks") or pressure ridges form? __ If yes, how many? __ How long after the initial shock of the main earthquake did they form? __ seconds, __ minutes, __ hours, other __, don't know __. Average length __, average width __; dimensions of largest ridge __ long, __ wide; approximate orientation of most ridges __. How far apart? __ Were the ridges in ice __, snow __, mud __, sand __, rock __, other __? Were the pressure ridges along the banks of a lake __, bay __, river __, stream __, pond __, other __?
   c. Did any landslides develop? __ If so, how long after the initial shock did they develop? __ seconds, __ minutes, __ hours, other __, don't know __. How long did the movement last __? Did the ground move as a unit __ or did it break up in large blocks __ or small blocks __? Was the material in the landslide mostly rock __, mostly soil __, don't know __? Was the material mainly wet __, dry __, frozen __, don't know __. How large an area was affected by the largest landslide __ feet by __ feet? Location of this landslide:
      ____
      Were any houses __, roads __, or other structures __ damaged by the landslide? Did the slide material fall into a lake __, bay __, river __, other __? If so, was a wave created? __ If so, how high? __ Any damage from the wave? __ Did the landslide dam any rivers? __
   d. Did any ground subside (sink) __? If yes, how large an area was affected __? How much did it sink? __ Is the material in the area of subsidence mostly rock __, mostly soil __, don't know __?
   e. Did you see any water spouts __? If yes, how long after the initial shock did they occur __? Was the spout mostly water __, a mixture of mud and water __, or mostly mud __? How high was the highest one __? How long did it last __? Did it form a crater __? If so, how large was the crater __? If you did not see any water spouts, did you see any craters that could have been caused by water spouts? __ Where are the craters located?
      ____
      How large is the largest? __ Are they isolated mounds or do they occur in a line? ______
   f. Were any healthy trees broken by the force of the earthquake? __ If so, about how many? __ How large __ inches in diameter? Did they fall mainly in one directions __ If yes, which way do most of the crowns point? __

Section B—Water effects

1. Was your area affected by a tidal wave or by unusually high tides ____? If yes, what time did the first wave or tide arrive ____? How long was this after the initial shock ____? How high was the first wave or tide ____ feet? Were there more than one wave or tide ____? If so, how many ____? At what times ____? How high ____? Did the highest water level rise come during high tide ____, low tide ____, half way in between ____? From which direction did the highest water come ____? How far inland did the water come ____? How high above ocean level did the water come ____? How much damage was done?
   ____
   ____
   What is the main orientation of the shoreline affected by the wave or tide
   ________________?
2. Were any of the wells in your area affected ____? Did the water get muddy ____? Change in taste ____? Did the water level rise ____, fall ____, stay

the same ____, don't know ____? Any other changes ______________________?

How long after the earthquake was the well affected? ______?

3. Did any springs change flow ____? Increase flow ____? Decrease flow ____? Any new springs ____?
4. Did any streams increase flow ____? Decrease flow ____? How long after the earthquake ____? How long before the flow returned to normal ______?
5. Did the water level in any lakes drop ____? Rise ____? How many feet ____? How long after the initial shock of the earthquake ____? Did the water level return to normal ____? When ______?
6. Did tide level change in your area ____? If yes, is tide lower ____ or higher ____? by how many feet ____? When was the change first noticed ______? Has the time of high and low tide changed ____? Are they later ____ or earlier ____? By how much ____? Was this effect temporary ____ or is it still in effect ____? Are measurements on bedrock ____?

Section C—Miscellaneous Effects

1. Are there any volcanoes in your area ____? If yes, has there been any increase ____, or decrease ____ in their activity ____? If so, when did this occur ______________________?
2. Are there any glaciers in your area ____? If yes, has there been any increase ____ or decrease ____ in their movement? If so, when did this occur

Remarks (anything not covered above or any comments you wish to make)

Name of person filling out form ______

Address______

Can you be reached by telephone? __

If so, please give number ______

CATEGORIES OF EARTHQUAKE-RELATED DAMAGE

Property damage to communities described in this report resulted from a variety of causes which, for convenience, are grouped into the following three broad categories: (1) seismic vibrations, (2) vertical tectonic displacements, and (3) water waves. Seismic vibrations include both the direct effects of shaking on structures and their indirect effects from foundation failures caused by ground fissuring, sliding, or differential settlement of the materials on which the structures are built. Vertical tectonic displacements include regional uplift and subsidence of the land relative to sea level which, in some localities, was augmented by subsidence of surficial unconsolidated deposits. Destructive waves include (1) local waves that were generated during or immediately after the earthquake by subaqueous slides, horizontal tectonic displacements, or other, unknown causes, and (2) the train of long-period sea waves generated by tectonic uplift of the sea floor in the Gulf of Alaska.

Lateral or vertical displacements of the surface along earthquake-related faults can cause enormous damage to buildings, dams, pipelines, or other structures whose foundations they cross. This kind of damage, indeed, is one of the most feared effects of future earthquakes in heavily populated places on or near active faults such as the famous San Andreas fault in California. Fortunately, the only surface fault breaks that developed as a result of the Alaska earthquake of March 27, 1964, were on uninhabited Montague Island and on the sea floor southwest of the island (Plafker, 1967). Had Montague Island been inhabited, or had fault displacements occurred within any of the larger towns, the toll of death and destruction would almost certainly have been even greater than it was.

Of the 31 lives lost at communities discussed herein, all were by drowning—29 in locally generated waves and 2 in seismic sea waves. Most of the physical damage was caused by the waves and by vertical displacements of the shore relative to sea level. Except at Kenai, structural damage from direct seismic vibrations was minor. The distribution of casualties by community, as well as the nature and extent of damage are summarized on table 2. In this section, the general categories and distribution of earthquake damage are discussed briefly to provide background for the descriptions of damage to individual communities that follow.

SEISMIC VIBRATIONS

Vibrations set up by the earthquake, which had a Richter magnitude variously estimated as 8.3 (revised U.S. Coast and Geodetic Survey) or 8.4 (Pasadena Seismograph Station) were recorded instrumentally throughout the world, but the places and areas where they were felt and reported by humans are limited to Alaska and nearby parts of Canada (pl. 1). We have no data from the Chukotsk Peninsula, on the Russian side of Bering Strait, but seismic shaking quite possibly may have been detectable there also.

As shown on plate 1, shaking was felt over a land area of more than a million square miles. Among the more distant points where movement was noted are (1) Gambell, on Gambell Island, 800 miles northwest of the epicenter; (2) Wainwright, on the arctic coast, 750 miles north; (3) Watson Lake, Yukon Territory, 650 miles east; (4) in the general vicinity of Prince Rupert, British Columbia, more than 800 miles southeast; and (5) the U.S. Weather Station on Adak Island, about 1,300 miles southwest of the epicenter.

Throughout Alaska and Canada the predominant reported direction of seismic shaking was between north-south and northwest-southeast. Some stations reported changes in direction during the earthquake, and a few reported predominant motions in east-west and northeast-southwest directions.

The duration of shaking as measured or estimated by hundreds of individuals, ranged from 15 seconds to about 8 minutes. Where it was timed at localities close to the epicentral region, it most commonly was between 3½ and 4½ minutes. Anomalously short durations of between 15 seconds and 1½ minutes were reported from Perl Island, Rocky Bay, and Seldovia at the southwestern tip of the Kenai Peninsula. In general, observers on or near bedrock reported notably shorter durations and less violent motion than those on thick deposits of unconsolidated sediments.

Reports of sensory perception of vibration varied from descriptions of rolling motions to sharp jolts; most observers on unconsolidated sedimentary materials reported rolling motions. In some outlying stations, as the one at Nome, observers reported that they felt nauseated before they realized that they were feeling an earthquake. Motion sickness was characteristic of nearly all Alaskan station reports that were more than 300 to 350 miles from the epicenter.

DIRECT VIBRATORY DAMAGE

Even though the earthquake's vibrations were felt by people over nearly all of Alaska and adjacent parts of Canada, seismic motion strong enough to damage structures was confined to a relatively small area. Such damage occurred at many places within an area of about 50,000 square miles (pl. 1), in an elongate belt that extends from Glennallen on the northeast to the southwestern part of Kodiak Island. Outside this belt, there was slight vibratory damage at Yakutat, 300 miles east of the epicenter, and in the King Salmon-Naknek area 375 miles west of the epicenter.

The most severe shaking and nearly all of the related damage to communities and major transportation routes occurred in areas of thick, saturated unconsolidated deposits; some of the larger areas of such deposits are delineated on plate 1. In these areas, structural damage resulted primarily from failure of the ground beneath buildings—failure such as ground cracking, landslides, and differential settlement of the natural unconsolidated deposits or of artificial fills. To a far lesser extent, the strong ground motion alone caused direct damage to structures in such areas. In contrast, no vibratory damage, other than a few broken chimneys and slightly cracked walls, was sustained by structures built on indurated rock anywhere in the region.

FISSURED GROUND

Fissured or cracked ground caused directly by seismic shaking or indirectly by vibration-induced movement of unconsolidated materials was widespread. Ground fissures were observed over an area of about 100,000 square miles; they were seen as far north as Fort Yukon, 400 miles north of the epicenter, at Juneau, some 500 miles to the southeast, and at Quinhagak, more than 500 miles to the west.

Except for minor fissuring in rock at the heads of some large landslides and in the immediate vicinity of the earthquake faults on Montague Island, virtually all of the fissures that were observed developed in unconsolidated sediments and soils, particularly where the materials were saturated or where the water table was close to the surface. Some fissures on deltas, outwash trains, and beach-ridge complexes were extensive; on the Copper River Delta and the coastal plain east of the delta, for example, many fissures as much as 6 feet wide and a quarter of a mile long were formed.

Ejections of fine sand and water characterized many fissures, particularly in the Copper River and Portage areas, on the Kenai Lowland, and elsewhere. Such ejections occurred mainly on the lower parts of deltas, on alluvial flood plains, along the shore of shallow bays, on sand dunes, and on elevated beach ridges.

Ground fissures and associated sand-water spouts resulted in widespread, but relatively minor, damage to roads and underground utilities in several communities discussed herein and in some of the larger communities, most notably Anchorage, Seward, and Valdez. In a few places the fissures also extended beneath buildings and cracked and dislocated foundations or walls. On the whole, however, ground fissures did far more damage to the highway and railroad systems throughout south-central Alaska than they did to the communities (Grantz, Plafker, and Kachadoorian, 1964; Kachadoorian, 1968; McCulloch and Bonilla, 1968).

CRACKED ICE

All, or nearly all, of the lakes and rivers in Alaska were ice-covered at the time of the earthquake; parts of the sea's surface, particularly in the north and along the shores of relatively calm inlets and bays, were also frozen. Within an area of 500,000 square miles, inland ice and also much sea ice was extensively cracked by the seismic vibrations (pl. 1). From the epicentral region, cracked ice was observed as far north as Wainwright on the Arctic coast, at Point Hope (775 miles distant), 400 miles east to Crillon Lake near Lituya Bay, and 430 miles west to the vicinity of Ugashik on the Alaska Peninsula. Ice on larger lakes and rivers tended to be more readily broken than that on smaller ponds and streams. Locally, pressure ridges were formed and blocks of ice piled one on another as a result of seiche waves in waters beneath the ice. Neither ice cracking nor ice shove caused any noteworthy damage to the communities of south-central Alaska.

LANDSLIDES AND AVALANCHES

Seismic vibrations triggered innumerable subaerial landslides and avalanches and subaqueous slides throughout an area of some 100,000 square miles of south-central Alaska (pl. 1). The landslides included a wide variety of falls, slides, and flows involving bedrock, unconsolidated deposits, and snow or ice in varying proportions. (The classification and nomenclature for landslides used herein correspond to those of Varnes, 1958.) The greatest concentration of landslides was in the rugged mountains that encircle the earthquake's epicenter—particularly in the Kenai Mountains, the Chugach Mountains north of Turnagain Arm and near Katalla, and the Talkeetna Mountains. Most of the slides involved hard sedimentary and metamorphic rocks of early Tertiary or pre-Tertiary age and, in a few instances, granitic intrusive rocks. Near Katalla the landslides were chiefly in younger Tertiary rocks, which are less indurated than the older ones but nevertheless are complexly folded and intensely faulted. Large subaqueous slides along the fiorded coast of Prince William Sound and the Kenai Peninsula and at Kenai Lake caused direct damage to Seward, Valdez, Whittier, Homer, and a segment of The Alaska Railroad along the shore of Kenai Lake. Such slides, however, caused no direct damage to the communities described herein, although local waves generated by them were indirect causes of damage.

Subaerial landslides and, to a lesser extent, avalanches did much damage to transportation and communication lines throughout south-central Alaska. Avalanches were particularly widespread along the Seward-Anchorage Highway, on the Richardson Highway near Thompson Pass, and in the more rugged parts of the Talkeetna and Chugach Mountains (Post 1967; Kachadoorian, 1968). However, because most of them took place in remote and uninhabited areas, their effects were of far greater geologic and geomorphic than economic interest. Only at Anchorage did subaerial landslides do more than minor damage to a community. There, great translatory slides in the residential area of Turnagain Heights and in the business heart of the city wrought even more havoc than did the seismic vibrations (Hansen, 1965). It should be emphasized that the slides at Anchorage were unique, requiring a special set of geologic conditions that are not, so far as we know, duplicated at any other community in the earthquake-affected part of Alaska.

VERTICAL TECTONIC DISPLACEMENTS

Vertical tectonic movements, both upward and downward, occurred over an area of more than 110,000 square miles in south-central Alaska (Plafker, 1969). The deformed region, which is about 600 miles long and as much as 250 miles wide, lies along the continental margin between long 142° and long 155°. It consists of a major seaward zone of uplift bordered on the northwest and north by a major zone of subsidence. These two zones are separated by a line of zero land-level change that trends northeastward to intersect the mainland between Seward and Prince William Sound. The line then curves eastward through Port Nellie Juan to the vicinity of Valdez and crosses the Copper River valley about 50 miles above the mouth of the river.

The zone of subsidence includes most of the Kodiak group of islands, Cook Inlet, the Kenai Mountains, and the Chugach Mountains. The axis of maximum subsidence within this zone trends roughly northeastward along the crest of the Kodiak and Kenai Mountains and then bends eastward in the Chugach Mountains. Maximum recorded downwarping is about 7½ feet on the south coast of the Kenai Peninsula.

In the southeastern part of the deformed area, uplift averages about 6 feet over a wide zone including most of the Prince William Sound region, the mainland east of the sound, and offshore islands as far southwest as Middleton Island at the edge of the Continental Shelf. Maximum recorded uplift on land, through combined warping and surface faulting, was 38 feet at the southwestern end of Montague Island.

Regional vertical tectonic movements seriously affected many navigable waterways and harbors, as well as land transportation routes and installations at virtually all coastal communities. Throughout the zone of uplift, docks and piers were raised above water level at most stages of tide and required lengthening in order to reach deep water. Boat harbors and channels had to be dredged in some localities to restore their pre-earthquake water depths. Many homes along the shore in uplifted areas were rendered inaccessible by boat except at the highest tides. Even more seriously affected were some shoreline installations in areas of tectonic subsidence. Many roads, railroads, canneries, and homes in such areas had to be raised to protect them from inundation during high tides. Extensive stretches of beach that had been used for cattle grazing, storage of sawn logs, or other purposes, were also partially or entirely obliterated by drowning of the shore lines.

WAVES AND RELATED SUBAQUEOUS SLIDES

Sudden violent local waves, that struck during or immediately after the earthquake, were the major cause of property damage and casualties. (As used in this report, "local wave" refers to water waves, generated either along the coast or in lakes during the earthquake, that affected areas of limited extent. The waves were originated at or close to the shoreline in part by subaqueous slides, but probably also by other mechanisms such as tectonic movements, seiches, or subaerial landslides. The term "local wave" is used to distinguish these waves from the train of long-period seismic sea waves that first struck the coast of the Gulf of Alaska 19 to 20 minutes after the earthquake began.) These local waves were later followed by seismic sea waves that damaged property and took additional lives all along the Gulf of Alaska and as far south as northern California. Extensive damage to uninhabited coasts, in the form of scoured shorelines, smashed trees, and displaced driftwood and shoreline deposits, clearly indicates that damage would have been far more severe had the coast been more heavily populated or had the earthquake occurred at a high, rather than low, stage of tide.

Seismic sea waves were also noted at remote localities east of Prince William Sound on Middleton Island, at the Cape Saint Elias Light Station on Kayak Island, and by the fishing boat *Roald* that was anchored on the east side of Wingham Island. The *Roald* was buffeted by swift and erratic currents and rapid fluctuations in water level that began approximately half an hour after the earthquake. The current at Wingham Island was described by the captain, Joe Clark, as strong enough to move boulders along the shore.

LOCAL WAVES AND SUBAQUEOUS SLIDES

The intense and prolonged ground shaking during the earthquake triggered many subaqueous slides along the seacoast (submarine "landslides") and lake shores (sublacustrine "landslides") of south-central Alaska. A substantial part of the property damage resulting from the earthquake is attributable directly to subaqueous slides which carried away the port facilities of Seward (Lemke, 1967) and Valdez (Coulter, and Migliaccio, 1966), the small-boat harbor at Homer (Waller, 1966a), shoreline facilities along Kenai Lake (McCulloch, 1966), and segments of the railroad and fuel docks at Whittier (Kachadoorian, 1965). Numerous other slides are known to have occurred in the sparsely inhabited epicentral area of Prince William Sound and the adjacent Kenai Peninsula; undoubtedly, many others that occurred entirely underwater have gone unrecognized. The distribution of the larger known and inferred subaqueous slides is shown on plate 2.

Violent local waves generated by subaqueous slides caused major damage to adjacent shorelines and loss of life in the cities of Seaward, Valdez, and Whittier. However, localized waves of unknown origin, though not specifically identifiable with submarine slides, were responsible for most of the shoreline damage in these same general areas, including many of the Prince William Sound communities described herein. The local waves, and combinations of local waves and subaqueous slides, caused most of the earthquake-related fatalities in Alaska (tables 1 and 2).

PHYSIOGRAPHIC SETTING OF THE AFFECTED REGION

Prince William Sound and the Kenai Peninsula to the west are regions of high rugged mountains which are indented by long, narrow glacier-scoured fiords that make good natural harbors. The rocky shores of many of these fiords drop off precipitously to depths of 600 to 2,000 feet. Subaerial and subaqueous bedrock slopes commonly exceed 35° and locally may be nearly vertical. Similar glacier-scoured valleys and basins on the mainland are occupied by deep lakes, among the largest of which is Kenai Lake.

At places, especially at the heads of the fiords, streams have built prisms of poorly consolidated alluvial and glacial deposits, which provide almost the only large level sites for buildings, dock facilities, and railroad yards. Elsewhere, glacial deposits of intercalated till and outwash form low crescentic bars or shoals across the fiords that mark the end positions of former glaciers. Lateral moraines and kame terraces that were deposited along the sides of the valley glaciers occur along the fiords of eastern Prince William Sound. Although apparently absent at the surface along the coast in much of northern and western Prince William Sound and eastern Kenai Peninsula, such deposits are quite possibly present under water in some places, because depressed cirque levels and submerged ancient forests in these areas indicate that the shorelines of the northern part of Prince William Sound and much of the Kenai Peninsula have been drowned since the last major glaciation (Grant and Higgins, 1910, p. 17–18; 1913, p. 57; Plafker, 1968, figs. 38–39).

DISTRIBUTION AND NATURE OF LOCAL WAVE DAMAGE

Most of the known localized waves and subaqueous slides were concentrated along the shores of fiords and bays in northern and western Prince William Sound, at Resurrection and Aialik Bays on the south coast of the Kenai Peninsula, and along the shore of Kenai Lake (pl. 2). Coastal damage generally occurred along the shores of steep-walled fiords and islands, but at least some of it was in shallow embayments that are virtually closed off from the sea. Shorelines damaged by the waves show no preferred orientation, although much of the most extensive damage tends to occur at the heads of embayments on east-west or northeast-southwest shores. One of the most striking characteristics of the damage is its highly localized and seemingly erratic distribution along the shorelines. An excellent example of this localization was along the north shore of sheltered Jack Bay near the entrance to Port Valdez in northeastern Prince William Sound (pl. 2). At that locality a 600-foot-long section of shoreline was stripped bare of timber to a maximum elevation of 39 feet by a violent surge of water; yet this small area and a nearby cove are the only segments along the north shore of Jack Bay that show evidence of wave damage.

The extent of wave damage to shorelines ranged from the splashing of mud and seashells above high-water line to the stripping of vegetation and soil. The affected region is one of moderate climate and high rainfall, so a dense forest of conifers crowds the shoreline except in recently deglaciated areas or places where cliffs are too precipitous for the trees to gain a foothold. As a consequence, wave damage to shorelines was best recorded by scarred, broken, or uprooted trees and brush. Locally, muskeg and soil were stripped from the bedrock, and seashells, driftwood, and beach deposits as large as boulders were thrown up above the level of the highest tides. At a few places all trees, including some 2 feet in diameter, were uprooted or broken to heights 110 feet above tide level, barnacle-covered boulders 6 feet across were carried more than 100 feet above the shoreline, and material from marine deposits was splashed more than 170 feet above tide level. Relative intensities of the damage, rated on a scale of increasing damage from 1 to 5, and described and shown on plate 2 and are shown in more detail on figures 1, 7, 12, 17, and 19.

In the absence of eyewitnesses, the direction of motion for the larger waves as shown on plate 2 could generally be inferred from the orientation of the damaged shorelines and from the directions in which limbs and trunks of trees and brush were scarred, bent, or broken. On shores bare of vegetation, only the orientation of the affected shoreline and the distribution of displaced driftwood and beach deposits could be used as directional indicators.

The earthquake occurred almost at a zero tide (mean lower low water). Consequently, effects of the localized waves along the coast were visible only where they were high enough to reach above the extreme high-tide line, which is approximately 15 to 20 feet above lower low water along the coasts of Prince William Sound and the Kenai Peninsula.

TIME AND SEQUENCE OF THE WAVES

An important characteristic of the damaging local waves, where observed by eyewitnesses at 10 widely scattered localities in Prince William Sound, Resurrection Bay, and Kenai Lake, is that single large waves struck during the earthquake or within minutes after it ended. Much smaller waves immediately preceded or followed the large wave, but runup from these waves rarely rose above extreme high-tide level. Nondestructive sudden water disturbances were noted by numerous other observers elsewhere in these same areas as well as in the Kodiak group of islands, on the southern Kenai Peninsula, and on the mainland coast and offshore islands east of Prince William Sound. By the time the initial crest of the train of seismic sea waves reached the outer coast of the Kenai Peninsula, 19 to 20 minutes after the earthquake began, the strong water disturbances generated by the local waves had largely subsided.

SEISMIC SEA WAVES

Most major earthquakes that involve vertical tectonic displacements beneath the sea are followed by seismic sea waves (tsunamis or "tidal" waves); the earthquake of March 27, 1964, generated one of the larger seismic sea-wave trains of modern times. These waves took 20 lives and caused destruction all along the Alaskan coast between the southern tip of Kodiak Island and Kayak Island. They were especially destructive in areas such as the Kodiak group of islands and the Kenai Peninsula, which during the earthquake were lowered relative to sea level by tectonic subsidence or by tectonic subsidence and compaction of unconsolidated deposits. Two casualties were caused by these waves at communities described in this report. In addition, the sea waves, which were recorded on tide gages throughout the Pacific Ocean, caused 15 deaths and major damage in British Columbia, Oregon, and California. The inferred source area of the seismic sea waves, reported arrival times of the initial wave at shore stations in the near-source area, and maximum runup heights are given by Van Dorn (1964) and Plafker (1969, fig. 15, table 2).

The first of a train of at least seven large-amplitude seismic sea waves with periods of 55 to 90 minutes was reported at Cape Chiniak on Kodiak Island at 6:10 p.m.—34 minutes after the earthquake. It was not preceded by a warning withdrawal of water as so commonly occurs before seismic sea waves. The wave was described as a cresting breaker at Narrow Cape on the exposed southeastern coast of Kodiak Island and as a fast-rising tide in the Kodiak area. At Narrow Cape the first wave reached farthest inland, whereas at the city of Kodiak the fourth wave (between 11:16 p.m. and 11:20 p.m.), which almost coincided with high tide, was highest, cresting at about 23 feet above high-tide level (Plafker and Kachadoorian, 1966; Kachadoorian and Plafker, 1967). In the Kodiak group of islands, the city of Kodiak, the Kodiak Naval Base, and several small communities in low-lying areas were severely damaged by the waves. The entire waterfront area of the city of Kodiak was destroyed and many fishing boats—the mainstay of the local economy—were lost or damaged.

Along the shores of Shelikof Strait and Cook Inlet the seismic sea waves, which were less than 5 feet high, caused rapid tide changes that were accompanied by swift erratic currents. However, the waves barely reached above the level of highest tides, which in this area of large tidal range exceeds 18 feet as a rule, and they caused no property damage.

Seismic sea waves that struck the south shore of the Kenai Peninsula caused heavy property losses to Seward at the head of Resurrection Bay and to three isolated logging camps along this otherwise uninhabited stretch of coast. Except for the head of Resurrection Bay, all these areas experienced a train of waves which came in as large swells but did not break. The first waves reached the logging camps at Whidbey Bay and Puget Bay on the southeast coast of the Kenai Peninsula (pl. 2) between 19 and 20 minutes after the earthquake began. The highest wave at Whidbey Bay was the second one, which followed 10 to 12 minutes after the first wave and ran up to an estimated elevation of 35 to 40 feet above the normal predicted tide stage. Within approximately 30 minutes after the start of the tremors, the first waves arrived at the logging camp at Rocky Bay near the southwest tip of the Kenai Peninsula (pl. 1) and were breaking near Seward. In contrast to the initial water motion at most nearby localities, the first wave at Rocky Bay reportedly was preceded by a withdrawal of about 18 feet. The highest wave, which came in on the high tide after midnight, left swash marks 11 feet above extreme high-tide level.

In Resurrection Bay the seismic sea waves inundated low-lying areas of Seward, the flats at the head of the Bay, and nearby Lowell Point to an estimated height of 25 to 35 feet above lower low water. The initial wave destroyed such docks as had not already been wrecked by the subaqueous slide and swept many houses and boats from the vicinity of the small-boat harbor into the lagoon north of Seward and onto the flats at the head of Resurrection Bay. Estimates of the height of the highest wave, which crested at about 11:00 p.m. near high tide, and the amount of withdrawal that preceded it, indicated that it may have had an amplitude of as much as 70 feet near Seward (Grantz, Plafker, and Kathadoorian, 1964; Lemke, 1967).

The seismic sea waves within Prince William Sound were described by all observers as fast-rising tides with associated strong currents. The first wave, which reached Boswell Bay on Hinchinbrook Island at about 6:00 p.m., was about 12 feet high. Throughout the sound the highest waves were recorded close to high tide between midnight and 1:00 a.m. They inundated shorelines in the eastern and northern parts of Prince William Sound to a maximum of about 17 feet above the existing tide level and caused some damage and one casualty at Cordova. Elsewhere in Prince William Sound, the seismic sea waves did not result in loss of life, although waves 6 to 10 feet above normal tide levels repeatedly inundated low-lying areas of Valdez that had settled differentially during the earthquake and also shorelines in those parts of northwestern Prince William Sound that had been significantly lowered by tectonic subsidence.

Seismic sea waves were experienced at remote localities east of Prince William Sound on Middleton Island, at the Cape Saint Elias Light Station on Kayak Island, and at Yakataga and Yakutat. One coastguardsman at Cape Saint Elias was drowned in the initial waves, but no wave damage was sustained at the light station or at any of the other remote localities where waves were reported.

EFFECTS ON COMMUNITIES

The following section outlines the earthquake effects on communities at which loss of life or noteworthy physical damage occurred and which are not described in other chapters of this Professional Paper. These communities are listed and the effects of the earthquake at each place are summarized in table 2. The communities are grouped into five broad geographical areas as follows: (1) communities of Prince William Sound; (2) communities of the coastal belt east of Prince William Sound and offshore islands of the Continental Shelf; (3) Kenai Peninsula communities (other than those along the shore of Prince William Sound); (4) communities of western Cook Inlet and the Alaska Peninsula; and (5) inland communities, generally along the highway and railroad net north of the coastal mountains belt.

PRINCE WILLIAM SOUND COMMUNITIES

Compared to their size, a disproportionately large amount of damage from a variety of causes was sustained by the few small fishing communities along the coast of Prince William Sound in the earthquake's epicentral region. Despite proximity to the epicenter, structural damage from shaking was relatively minor partly because of the prevailing wood-frame construction and partly because virtually all communities along the rugged fiorded coast are founded on bedrock or bedrock overlain by a relatively thin veneer of unconsolidated deposits.

Much of the property damage and all loss of life at Valdez and Whittier were related to massive vibration-induced submarine landslides and the violent waves they generated. At other localities, notably at Chenega, local waves of unknown origin that appeared suddenly during or immediately after the earthquake caused heavy damage and casualties. In contrast to the destructive effects of the sudden waves of local origin, the effect of the long-period seismic sea waves that entered the sound was to cause large quiet fluctuations in tide level. Superimposition of the waves on high tide, roughly 6 hours after the earthquake, resulted in flooding of some shorelines and moderate damage in the Cordova area.

Vertical tectonic displacements that accompanied the earthquake in Prince William Sound caused a regional northward tilting about a zero line that extends roughly from Port Nellie Juan in the western part of the sound northeastward almost through the earthquake epicenter in Unakwik Inlet and then eastward through Port Valdez. Shores north of the line were submerged as much as 7 feet, whereas those south of the line emerged as much as 38 feet (Plafker, 1969). Regional warping caused extensive long-term damage through its adverse effects on coastal installations, navigable waterways, and harbors. Docks and piers throughout the area of uplift were raised above water level at most stages of tide, and reduced water depths limited the usefulness of certain waterways and harbors. On the other hand, few communities in the area of subsidence were seriously affected by widespread inundation of waterfront areas.

In addition to the vertical movements, horizontal displacements in a relative southeasterly direction occurred. They range from about 20 to 64 feet and increase in general from north to south. These displacements resulted in no known direct damage. However,

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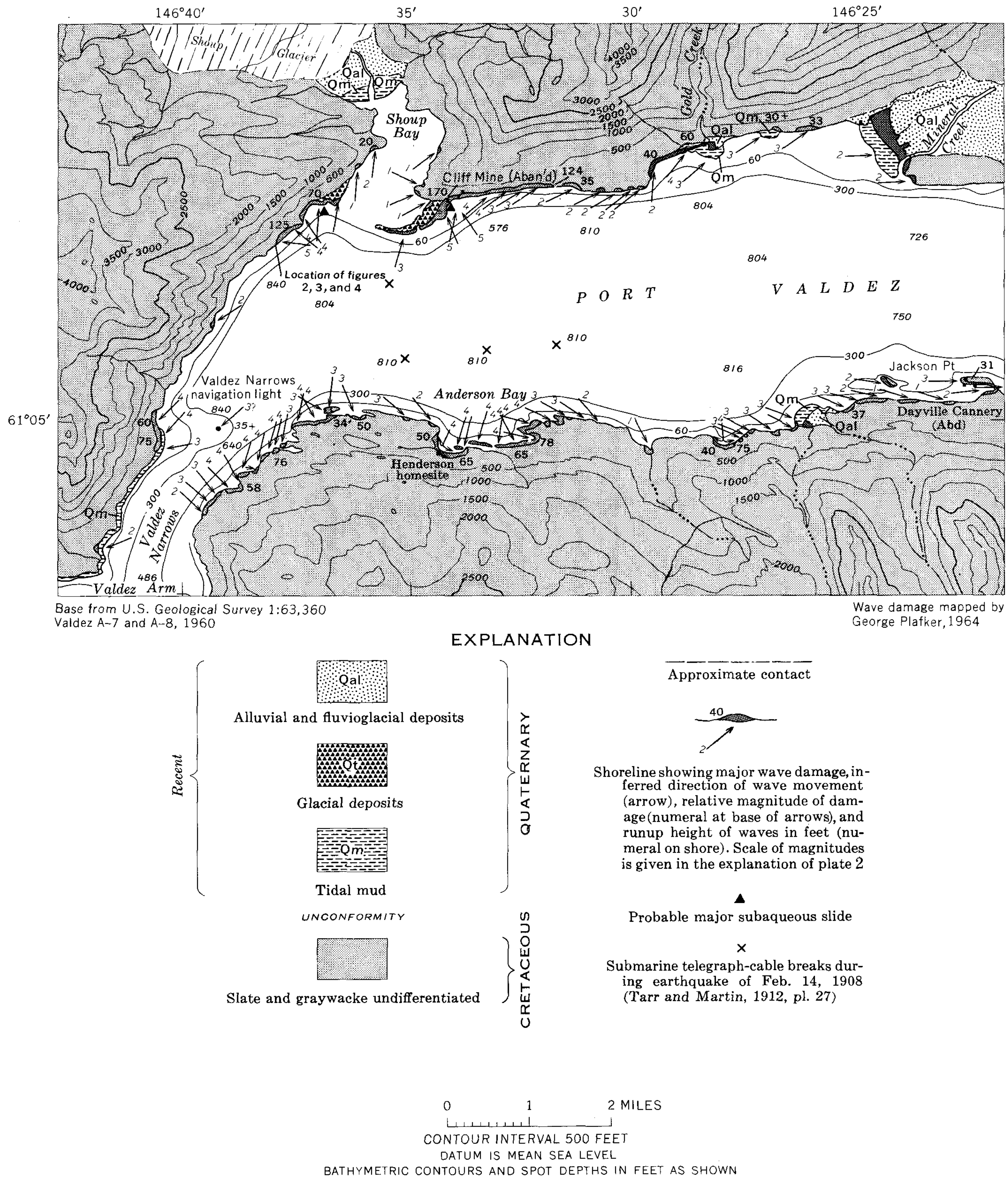


1.—Map showing distribution and intensity of wave damage in the western part of Port Valdez.

horizontal movement of steep-sided basins and fiords relative to their contained water bodies, if it occurred fast enough, may have caused many of the unexplained water disturbances that accompanied the earthquake in Prince William Sound and elsewhere (Plafker, 1969).

The following section summarizes earthquake-related damage in all the communities along the shore of Prince William Sound with the exception of Whittier and Valdez, which have been described separately by Kachadoorian (1965) and by Coulter and Migliaccio (1966). The locations of all communities referred to, as well as shorelines damaged by wave inundation, are shown on plate 2.

ANDERSON BAY AND VICINITY

Anderson Bay, along the south shore of Port Valdez, was the site of a small fishing camp (fig. 1). Its sole inhabitant, Harry Henderson, is missing and presumably was drowned in violent local waves that struck the shore during or shortly after the earthquake. The waves, which ran up to as much as 78 feet above lower water in the bay, swept away Henderson's cabin and appurtenant structures at the camp, leaving only the driven piling foundations to mark its former location.

All structures at a large abandoned mine, the Cliff mine, located directly across Port Valdez from Anderson Bay, were also obliterated by waves that deposited driftwood 170 feet above lower low water and splashed silt and sand up to an elevation of 220 feet. The abandoned Dayville cannery at Jackson Point, 5 miles east of Anderson Bay, was extensively damaged by waves as much as 31 feet high. Elsewhere along the shore violent waves broke 24-inch-diameter spruce trees at elevations as high as 101 feet and deposited barnacle-covered boulders estimated to weigh 1,700 pounds 88 feet above the shoreline (figs. 2, 3, and 4). The waves that moved westward out of Port Valdez overtopped and destroyed the Valdez Narrows navigation light situated on top of a reinforced concrete pedestal 35 feet above lower low water (fig. 1).

2.—Spur west of Shoup Bay in Port Valdez that was overtopped by a local wave traveling from right to left. Trees and branches are broken to an elevation of more than 100 feet above lower low water. Location shown in figure 1.

Brief examinations of the wave effects at two localities in Port Valdez, shortly after the earthquake, led Plafker to infer that the shoreline damage was caused by a wave that entered the port from the west (Grantz, Plafker, and Kachadoorian, 1964, p. 12). Detailed examination of the damage distribution during the followup studies (Plafker and Mayo, 1965, fig. 16) clearly indicates that the highest waves in western Port Valdez probably originated mainly at the sites of large submarine slides of segments of the Shoup Glacier end moraine that blocks the mouth of the bay (fig. 1). The moraine is a crescentic deposit of coarse unconsolidated glacial debris perched at the lip of a hanging valley whose floor is more than 500 feet above the bottom of Port Valdez. The damage distribution, submarine soundings, and changes in shoreline configuration indicate that the largest slides probably originated near the Cliff mine and at the west side of Shoup Bay near the points indicated by triangles on figure 1. Downslope movement of such masses triggered by the

high wave generated by submarine sliding at the head of the fiord 10 miles east of Shoup Bay is difficult to reconcile with the directions and relative heights of waves in western Port Valdez as indicated by the pattern of wave damage along the shoreline (fig. 1).

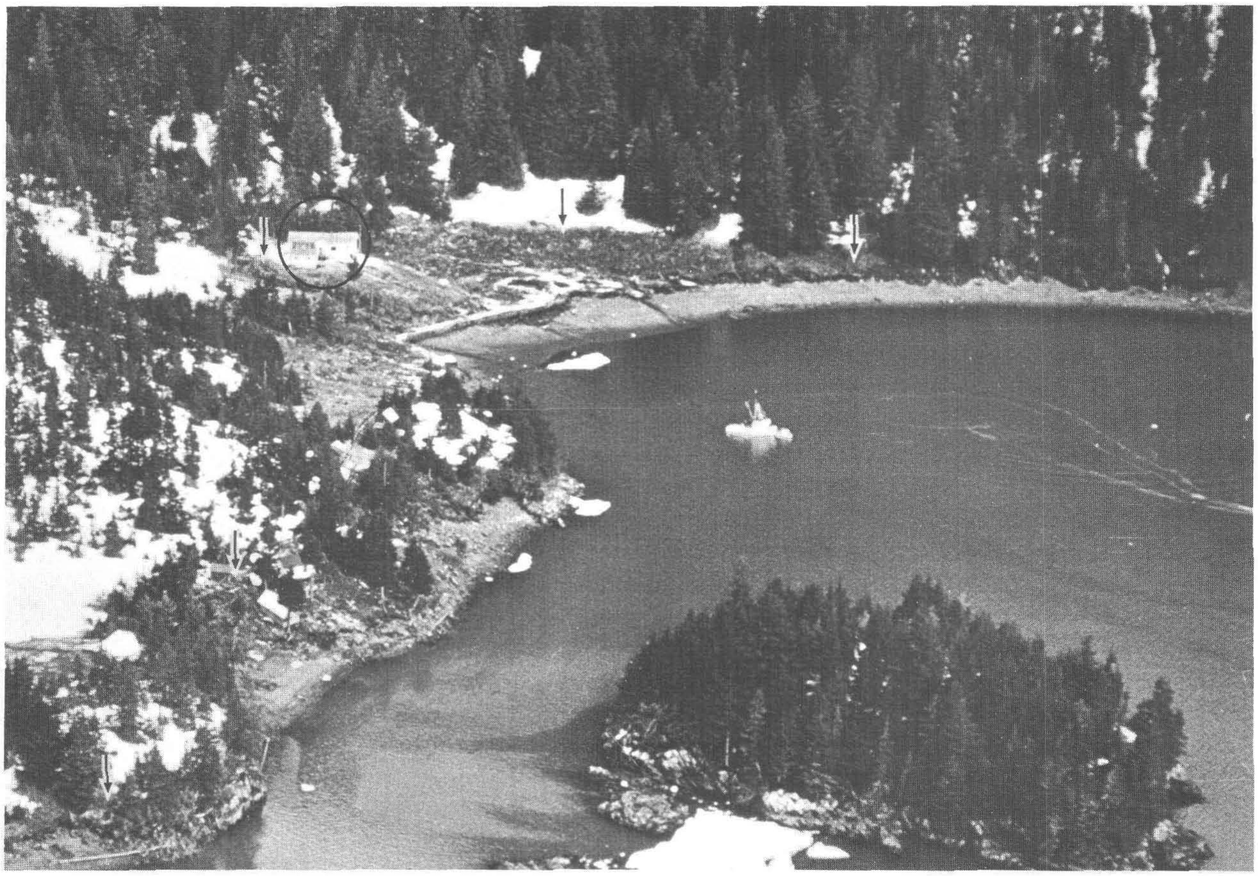
Two eyewitnesses to the event (Delbert and "Red" Ferrier) were in a small boat outside Valdez Narrows. They saw waves coming from the direction of Shoup Bay approximately 5 minutes after the earthquake began and watched the first wave overtop and destroy the Valdez Narrows navigation light. Although the wave dissipated rapidly outside Valdez Narrows, the boat barely rode it out without swamping. On their way to Valdez, at 8 p.m., 2½ hours after the

3 (left).—Living spruce trees 2 feet in diameter that were snapped off by a local wave at elevations between 88 and 101 feet above lower low water at the locality near Shoup Bay shown in figure 1.

earthquake must have forced a sudden withdrawal of water from the area which they had occupied. Water moving into the surface depressions created high-velocity surge waves that first struck the shores immediately adjacent and then spread radially outward with gradually diminishing runup heights (fig. 1). Smaller earthquake-triggered slides elsewhere along the fiord may have contributed to the observed wave damage.

An alternative suggestion made by Coulter and Migliaccio (1966, p. C14) that wave damage in the western part of Valdez Arm was somehow caused primarily by a "component" of the 20- to 30-foot-

4 (right).—Boulder estimated to weigh 1,700 pounds thrown up 88 feet above the shoreline by a local wave at the place near Shoup Bay shown in figure 1.



5.—Aerial view of the Chenega village site at the head of Chenega Cove. Lower limits of snow, as shown by arrows, indicate the approximate limits of wave runup; the schoolhouse is circled. Photograph taken March 29, 1964.

earthquake, these men saw large numbers of dead red snappers of exceptional size floating in the water near Valdez Narrows. The red snappers, which normally inhabit deep water and are extremely sensitive to rapid pressure changes, probably were killed when they were forced up off the bottom by turbulence related to the inferred submarine slides.

A past history of repeated submarine slides in Port Valdez is suggested by breaks of submarine telegraph cables and fish kills during at least five earthquakes in 70 years (Coulter and Migliaccio, 1966, p. C9). Breakage of two submarine cables during one of these earthquakes (in 1908) between Shoup Bay and Anderson Bay, at localities shown on figure 1, is strongly suggestive of previous submarine sliding in the same general area.

CHENEGA

Chenega was a native fishing village on the southern end of Chenega Island, on Knight Island Passage in western Prince William Sound. All its buildings except one house and the school were destroyed by sea waves, and 23 of its 75 inhabitants were lost. The village site was abandoned immediately after the earthquake and the survivors were resettled at Tatitlek after several months of care in Cordova.

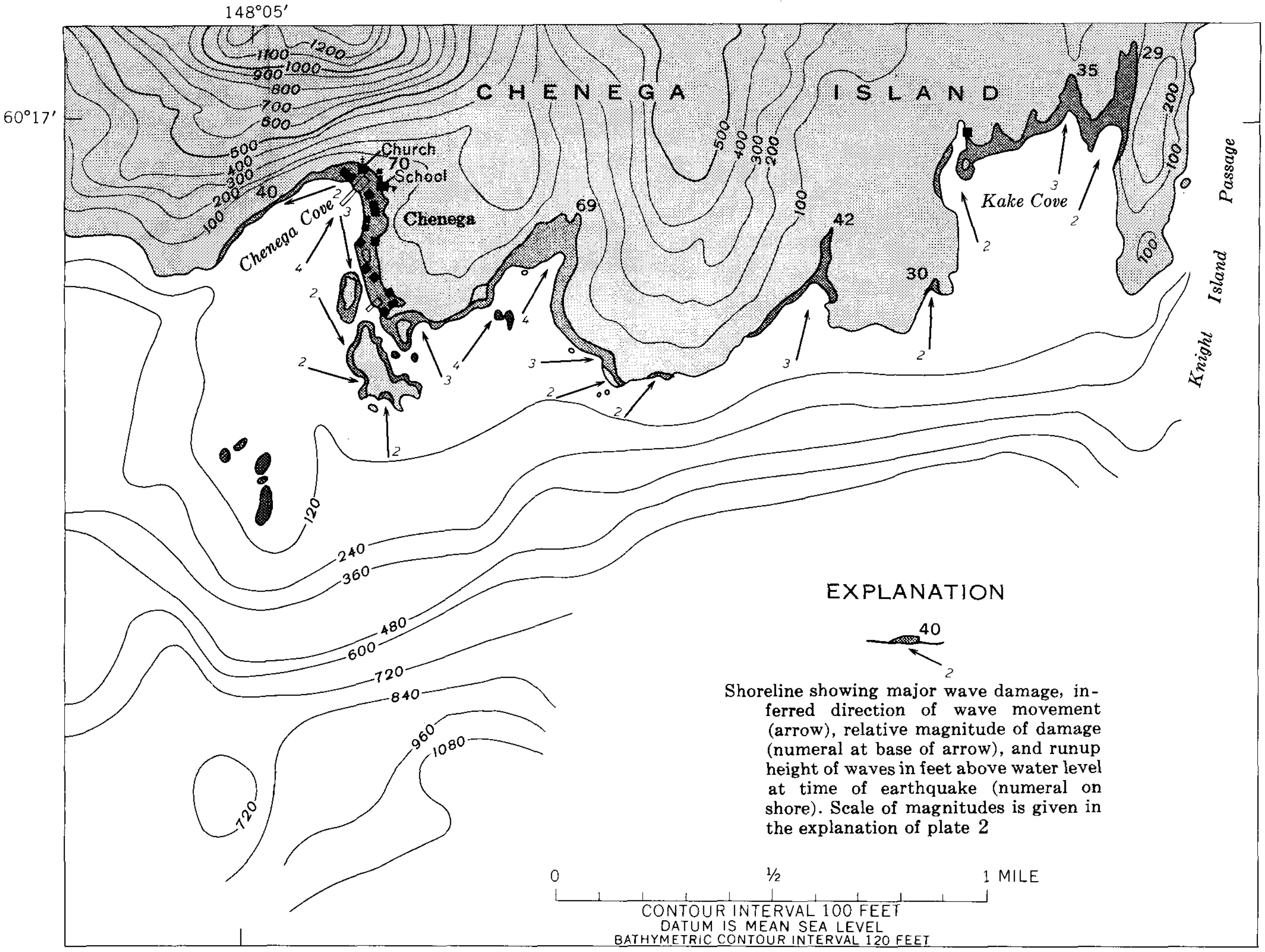
Chenega was built on bedrock or thin alluvium over bedrock around the head of Chenega Cove. There are no large subaerial masses of unconsolidated deposits along the shore anywhere at or near Chenega. Most of the 8 or 10 frame houses, the store, and the church were built on dug piling foundations on the slopes around the cove. A wood seawall protected part of the shore from erosion by normal tides. The reinforced concrete school was on slightly higher ground at an elevation of about 70 feet above post-earthquake mean lower low water (figs. 5, 6). A narrow rocky beach was below the seawall and served as a playground for the children.

The earthquake shaking, which began gently but became much stronger within 1 minute, lasted an estimated $4\frac{1}{2}$ to 5 minutes. Understandably, there are no reports of vibration damage. Mike Ele-

6.—Main part of the Chenega village site. Piling in ground marks the former locations of homes that were swept away by waves. Schoolhouse on high ground was undamaged.

shansky and Joe Komkoff estimated that between 60 and 90 seconds after shaking began the first wave rose quietly but rapidly about half way up the beach. It receded rapidly almost at once, exposing the floor of the entire cove to an estimated depth of 20 or more fathoms and for a distance of about 300 yards offshore. A second and much higher wave arrived within 4 minutes of the earthquake's onset and before shaking had ceased. This wave, which was about 35 feet high, ran up to the schoolhouse foundation, a height of 70 feet. All the buildings except one house and the school were either smashed into the trees or swept out to sea with the backwash. The inundated shoreline, maximum wave runup heights, and general direction of wave movement as inferred from damage distribution are shown on figure 7. People who were on the beach or had not had time to join the exodus to higher ground were carried away. In addition to all its other belongings, the village lost all but three of its boats. Only one of the surviving craft was in port at the time; the other two were out with hunting parties. They were welcome additions to the rescue effort the next day. The surviving villagers spent the night huddled in the snowy woods high above the school, for fear of later and even higher waves. These did not materialize and the school, with its nearby powerplant, was unharmed except for some water in the basement. As shown on figure 7, waves comparable in size to those at Chenega struck elsewhere along the coast of the island, particularly in the cove just east of Chenega. There, most of the muskeg and all of the trees were stripped from the surface; blocks of bedrock were even torn from a 20-foot seacliff.

The cause of the waves at and near Chenega is uncertain although their sudden appearance during the earthquake clearly indicates a local origin. The timing and sequence of waves suggest the possibility that they were caused by a sizable submarine slide in Knight Island Passage. Moreover, as at Anderson Bay, great numbers of large red snappers appeared at the surface of Knight Island Passage within a few hours



Base from U.S. Geological Survey 1:63,360, Seward B-3, 1950
Bathymetry by L. R. Mayo and D. S. McCulloch, 1964

Wave damage mapped by L. R. Mayo and George Plafker

7.—Distribution and intensity of wave damage at Chenega and vicinity, Chenega Island.

of the earthquake. These fish may have been killed by rapid vertical movements related to landslide-generated turbidity currents. Detailed fathometer profiles of the area offshore from Chenega made by Mayo and McCulloch in 1964 (L. R. Mayo, written comm., 1965) show no significant bottom changes when compared to pre-earthquake soundings to indicate that a major submarine slide had occurred at a depth of less than 100 fathoms. On the contrary, their soundings indicate that at least the upper part of the steep submarine slope into Knight Island Passage is probably mainly bedrock without any large potential slide masses in the form of unconsolidated deposits. A possible alternative explanation is that these waves were generated by the horizontal tectonic displacement of Chenega Island southward relative to the water body in Knight Island Passage. This displacement, which amounted to roughly 55 feet (Plafker, 1969, fig. 16), could have generated the observed waves if it occurred fast enough. The fish kill in the Knight Island Passage area, however, probably resulted from submarine slides whose relationship to the destructive Chenega waves is unknown.

CORDOVA AND VICINITY

Cordova is now a fishing, canning, and distribution center for much of the Prince William Sound region; earlier in its history it was the rail-ocean transshipment point for copper ore from the rich Kennecott mining district farther inland. Of all the communities affected by the earthquake, it stands out as the one where tectonic uplift did far more damage than seismic vibration and waves combined. The city is accessible only by air or water, but completion of the Copper River Highway, which was itself severely damaged by the earthquake (Kachadoorian, 1968), will eventually tie it to the road net of interior Alaska.

Cordova is on the mainland along the south side of Orca Inlet, opposite Hawkins Island (pl. 1). Most of the city is built on argillite and graywacke bedrock. A number of dwellings in "old town" on the south side of the city are founded on unconsolidated fluvioglacial deposits that fill a low divide between the waters of Orca Inlet and Eyak Lake, a large body of fresh water east of Cordova (fig. 8). The small-plane airport for the city is along the shore of Eyak Lake; a larger airport and Federal Aviation Agency facilities, employing about 40 people, are about 13 miles east of the city, on the edge of a great prism of unconsolidated sediments that make up the Copper River Delta (pl. 1). A few fishermen's cabins are along the shores of Orca Inlet. An FAA (Federal Aviation Agency) navigation facility, a satellite tracking station, and several homes are at the east end of Hinchinbrook Island at and near Boswell Bay.

Everyone in Cordova and at the airport felt the violent shaking of the earthquake. Estimates of its duration range from 3 to 5 minutes. Most observers agree that the initial movement was in an east-west direction, but a few individuals stated that it was more nearly north-south. It was described as a rolling motion with occasional sharp jars. The intensity of the motion apparently was considerably higher at the FAA facility on the Copper River Delta than in the city proper. Observers in town report relatively little difficulty in standing or moving about during the earthquake and negligible shifting or toppling of items in homes and stores. In contrast, violent ground motion at the FAA facility made it difficult or impossible to stand or walk about in some homes, and large and small objects were shifted or thrown down in all homes and other buildings. Several people at the airport and along the highway saw surface ground waves, with crests, estimated at 20 to 30 feet apart, "exactly like waves on water." Ice was cracked on Eyak Lake and one pressure ridge developed there. Innumerable ground fissures occurred throughout the Copper River Delta, but none in the city itself. One observer at the FAA station reported that fissures outside the control building opened and slapped closed intermittently during the earthquake.

Despite the heavy shaking, there was no structural damage in the city. Damage at the airport was caused entirely by fissures that intersected the foundation of the FAA control building (fig. 9), taxiways, and underground utilities (Eckel, 1967). All bridges on the segment of the Copper River Highway between the city and the airport that cross unconsolidated deposits of the delta were destroyed or badly damaged, and the roadway itself settled differentially and was cut by fissures (Kachadoorian, 1968). The bridge spanning Eyak River which has foundations on bedrock was not damaged.

Reports differ as to the number and timing of the sea waves that struck Cordova. The first wave observed near Boswell Bay was a strong surge at about 6 p.m. (S. I. Starbuck, oral commun., July 1964). Many rapid but gentle rises and withdrawals, presumably due to passage of seismic sea waves, at Cordova and vicinity in the hours immediately after the cessa-

8.—Cordova, as it appeared in September 1966, with port facilities rebuilt to compensate for the 6-foot tectonic uplift of the shoreline. Looking south, with end of Eyak Lake and Copper River Highway in left center, and Cordova sawmill, destroyed by seismic sea waves, toward upper right. The white angular patch, lower right, is new land made from material dredged from the deepened and enlarged small-boat basin. Photograph by U.S. Army.

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tion of shaking caused no damage. The highest wave, which almost coincided with the predicted high tide of 13 feet, struck the waterfront area at about 12:30 a.m. on the 28th. This wave, about 20 feet high, flooded the shore to a height of about 34 feet above postearthquake mean lower low water, or about 5 feet above the extreme high-water level. All waves were calm, without breakers, but high water and swift currents during these and possibly even later waves did considerable damage to the port facilities and to moored boats. The deck of the city dock was lifted off its pilings and displaced; one cannery was damaged when a boat smashed against its piling. The waves also struck the low area

9.—One of numerous ground fissures in fluvioglacial outwash deposits at the Cordova FAA airport station. Fissures such as this one displaced the concrete foundation of the station building in the background and broke underground utility lines throughout the facility area.

toward Eyak Lake, where several small structures were washed away and a sawmill was destroyed (fig. 10). The city's radio tower, on the tidal flats, swayed violently with the shock waves, but remained intact until much later when it was struck and toppled by a floating structure. The waves also damaged the roadway and washed out a bridge at Hartney Bay on the road between Cordova and Point Whitshed (pl. 1).

At Point Whitshed, a small fishing camp located 8½ miles southwest of Cordova at the mouth of Orca Inlet, 10 cabins were washed away by waves and one man was drowned. As reported by Alec Colner, the first wave to arrive was calm and like a very high tide. This wave was followed within several minutes by much higher and stronger waves that struck from opposite sides of the point on which the camp is situated, joined, and rushed up the slope behind the camp. Withdrawal of the combined wave floated the cabins away (Cordova Times, April 2, 1964).

10.—Seismic sea wave damage at the Cordova sawmill along Orca Inlet.

Tectonic uplift raised the land surface in the vicinity of Cordova about 6 feet (Plafker, 1969, pl. 2). This uplift was far more disastrous to all port facilities than were the earthquake vibrations or the seismic sea waves. One cannery at Crystal Falls, on the edge of the Copper River Delta about 5 miles south of Cordova, was abandoned because boats could no longer reach it. At Cordova, all dock facilities were raised so high that they could be reached by boats only at highest tides. Several nearby canneries had to extend their docks more than 100 feet to permit access. The area in the vicinity of the city dock and the small-boat basin was above water at most tides; an extensive and difficult dredging project, together with new breakwaters and dock repairs, was necessary to make the facilities usable. In the course of this work, which was done by the Corps of Engineers, the boat basin was much enlarged, and about 20 acres of new land, eventually usable for industrial purposes, was made from material dredged from the boat basin (fig. 8).

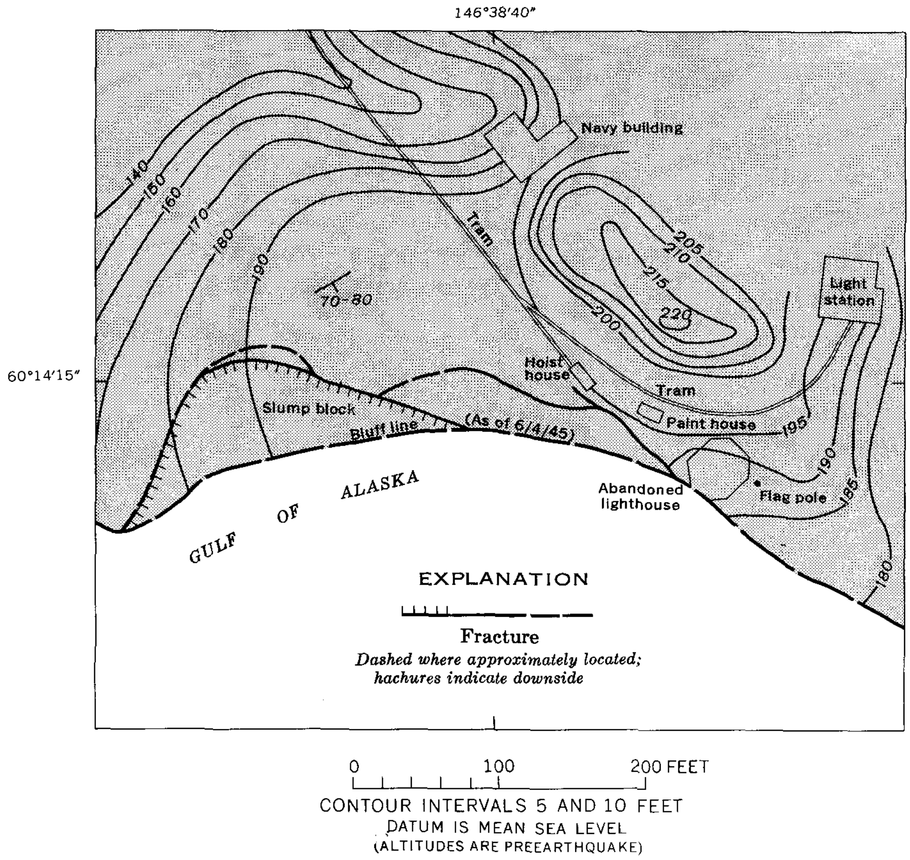
Damage to the port facilities was not the only adverse result of tectonic uplift. The Cordova fishing fleet normally uses Orca Inlet in its travel between town and the shallow fishing grounds off the Copper River Delta. Because uplift made the inlet waters too shallow for even small boats, laden vessels had to wait for extremely high tides or take the much longer and more hazardous route through Hinchinbrook Entrance and through Orca Bay. Because neither solution was economically practicable, it was necessary for the Corps of Engineers to dredge a new channel through almost the entire length of Orca Inlet. The total cost of dredging, port facilities, and repairs to the town's uplifted sewer outfall was about $3 million, but part of this cost was offset by enlargement of the small-boat basin over its preearthquake capacity and by development of new industrial land.

HINCHINBROOK LIGHT STATION

The Hinchinbrook Light Station, with a crew of six men, is on the southwest tip of Hinchinbrook Island in Prince William Sound. It was undamaged by the earthquake, but there were fears, later shown to be groundless, that reactivated old landslides would endanger the station.

The earthquake, which lasted about 5 minutes, was severe enough to snap some live trees, to cause the main station building to oscillate, and to displace small objects from shelves. Large movable objects were not shifted, however, and there was no structural damage to any buildings. At least 10 strong aftershocks, which occurred within the first week after the earthquake, contributed substantially to apprehensions of the crew members.

The topography and geology in the immediate vicinity of the station are shown in figure 11. The main building is on a gently undulating bench about 150 feet north of a near-vertical seacliff that is 180 to 190 feet high near the station but somewhat lower toward the west. Structures are built on well-indurated medium-grained blocky graywacke sand-



11.—Map of Cape Hinchinbrook Light Station. Present bluff is substantially north of that shown, because of erosion since 1945 when the base map was made. Bedrock is graywacke.

stone. The beds range from a few inches to at least 100 feet in thickness; some thin beds of black argillite are interlayered with the sandstone. Bedding strikes about N. 60° E. and dips 70°–80° SE.

Two fracture-bounded incipient landslide blocks are along the seacliff. The larger one, 40 feet wide, extends 200 feet westward along the cliff from the foundation of the old abandoned lighthouse. A concentric tension fracture, locally 2 feet wide and at least 15 feet deep, marks the inner edge of the block. A second incipient landslide, 75 feet long and less than 15 feet wide, is farther west of the old lighthouse site. It overlooks an old slump block, and it too is bounded by an open tension fracture. Aside from one small tension crack near the southwest side of the hoist house, no other fractures were found in the station area.

There is abundant evidence that erosion and slumping had been causing rapid recession of the seacliff since at least 1907. Available maps show that at the abandoned lighthouse the cliff receded 20 feet from 1907 to 1931 and an additional 20 feet from 1931 to 1964. About 120 feet east of the old lighthouse the cliff receded about 40 feet from 1907 to 1931 and an unknown amount after that date. Cliff erosion also occurred west of the abandoned lighthouse—certainly 5 feet from 1945 to 1964—and an unknown amount in earlier years.

New tension cracks and incipient slides that developed during the 1964 earthquake are but the latest episodes in a long history of cliff recession. The 8 feet of tectonic uplift that accompanied the earthquake has brought the base of the seacliff above the reach of all but extremely high storm waves; hence the former rapid erosion of the cliff has been arrested, at least for many years to come. An adverse effect of the uplift, however, was the raising of the station dock above the level of most tides; this raising required extension of the dock at a cost of nearly $100,000.

LATOUCHE AND VICINITY

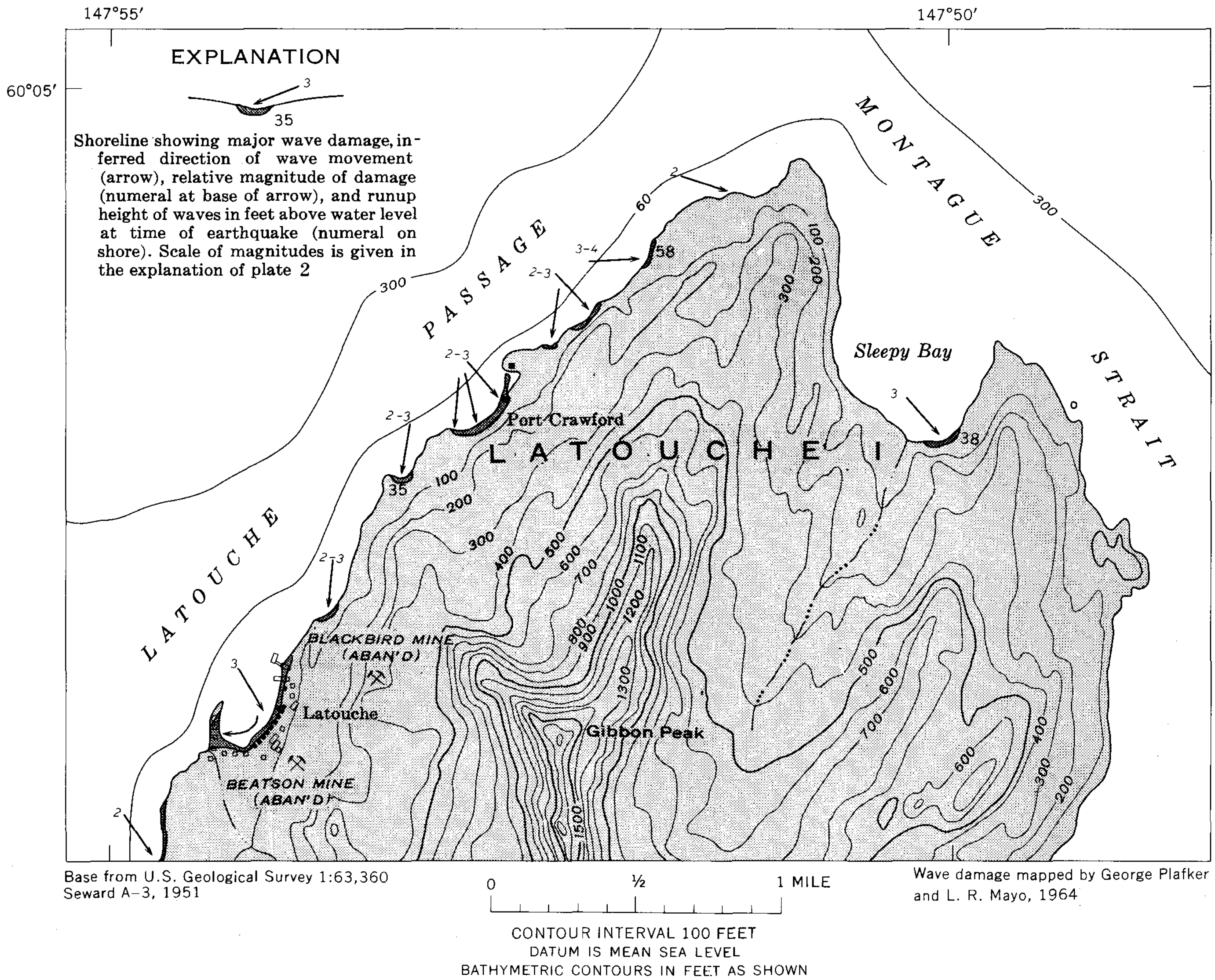
Latouche is a large abandoned mining camp situated along a cove on the rocky northwest shore of Latouche Island (fig. 12). Bedrock consists of firm argillite and sandstone of early Tertiary age. There are no large masses of unconsolidated deposits along the shore at Latouche or anywhere on land in the immediate vicinity.

Because the island was uninhabited at the time of the earthquake, the effects of shaking on existing structures, most of which were in a poor state of repair, are not known. Northern Latouche Island was raised between 10 and 11 feet, by tectonic uplift, presumably during the earthquake.

Local waves of unknown origin destroyed all the docks and piers along the shore at Latouche and either demolished or extensively damaged many of the waterfront buildings (fig. 13). Extensive wave damage with runup as high as 58 feet was also apparent elsewhere along the shore of Latouche Passage and in Sleepy Bay at the northern tip of Latouche Island. At Port Crawford, 1.3 miles northwest of Latouche, an abandoned sawmill building was displaced and damaged by the waves, and several smaller structures nearby were destroyed.

PERRY ISLAND

Perry Island is in the northwest part of Prince William Sound, between Perry Passage and Lone Passage and about 24 miles southeast of Whittier (pl. 1). A small camp consisting of a two-story house, a large storage house, and a boathouse, is at the head of South Bay near the southern tip of the island. The camp, occupied by "Chick" and "Red" Comstock, is built on a bay-head gravel bar overlying bedrock. There are no large masses of unconsolidated deposits anywhere along the shore.



12.—Distribution and intensity of wave damage at Latouche and adjacent parts of northern Latouche Island.

13.—Remains of buildings partially damaged by waves along part of Latouche waterfront. Docks, piers, and some buildings in this area were swept away. Approximately 11 feet of tectonic uplift has raised this former port above the reach of most tides.

Shaking, in a northeast-southwest direction and gradually decreasing in intensity, lasted about 4 minutes. One chimney fell, the bay water was ruffled, and trees swayed, but there were no other effects from the shaking.

Immediately after the earthquake, and with no prior withdrawal, an 8- to 10-foot wave of unknown origin moved in with great force. The wave receded within 2 minutes and exposed the bay floor for an estimated 200 yards offshore. No sooner had the bay gone dry than another wave was seen approaching from near the lighthouse at the mouth of South Bay. This second wave moved in quietly, but flooded over the beach bar to a height of about 21 feet above lower low water. The Comstocks, who were standing outside the house, were washed into the slough behind the beach bar and narrowly escaped drowning. The boathouse was floated away, but the two other buildings, which were protected by snow embankments, were undamaged. No other waves reached above the normal high-water line at Perry Island.

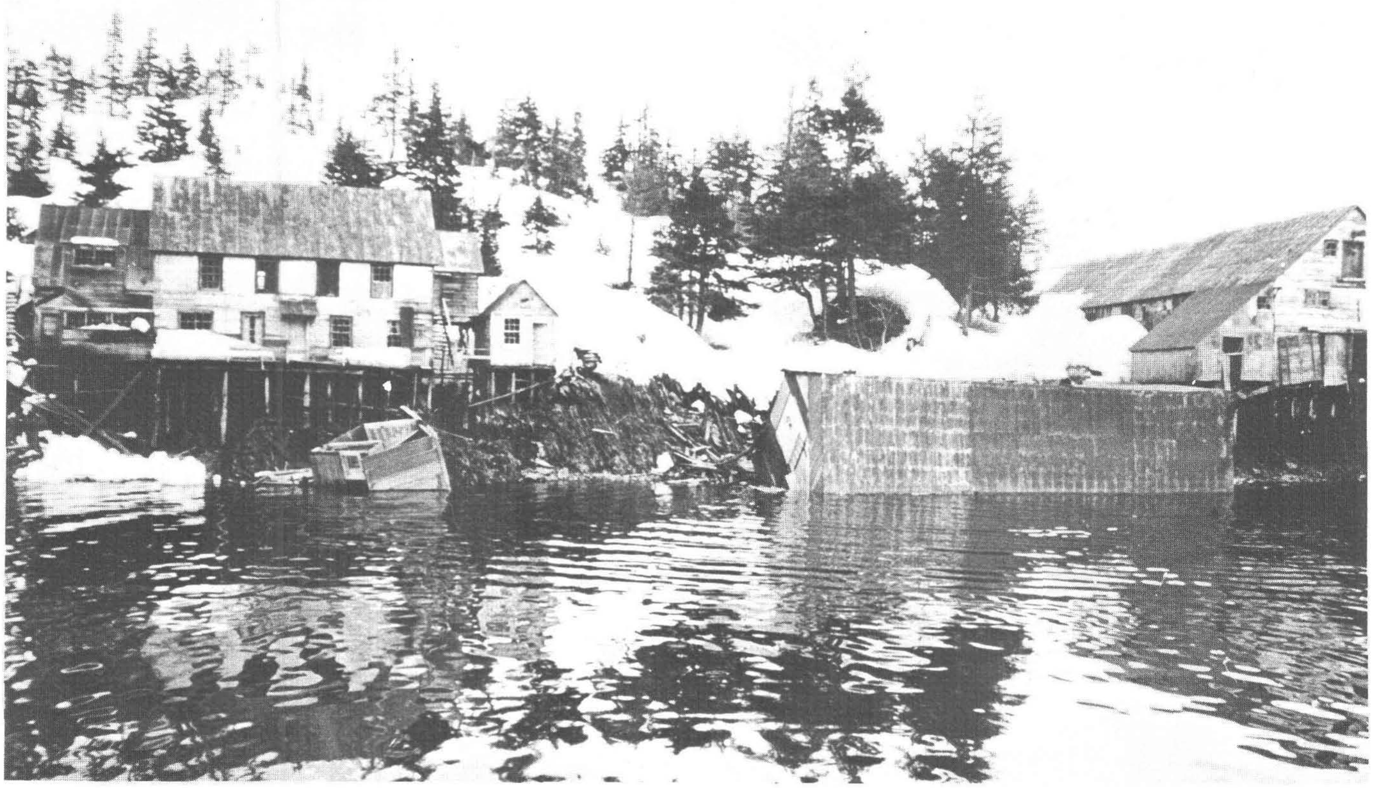
POINT NOWELL

Point Nowell is the site of a fishing camp on a small low peninsula that juts southward from the mainland near the northern entrance to Knight Island Passage. The peninsula is underlain by bedrock; there are no large masses of unconsolidated deposits along the shore anywhere near the point.

A destructive wave entered the inlet behind the peninsula and flooded the area to a depth of at least 37 feet above mean lower low water. Several frame buildings were displaced and some smashed into trees. Many trees 12 to 18 inches in diameter were broken by wave-propelled debris. The damage distribution indicates that the wave entered the inlet from the south. Disappearance of the one inhabitant, presumably by drowning, strongly suggests a wave that struck without warning at the time of the earthquake—a wave, similar to those observed at nearby Chenega and Perry Island.

PORT NELLIE JUAN

Port Nellie Juan was the site of an inoperative cannery on the northeast shore of McClure Bay, a small arm of the much larger body of water also called Port Nellie Juan. The cannery was



14.—Wave-damaged structures at Port Nellie Juan cannery. A wave, which ran up to the snow trimline along the shore, damaged these structures, washed away the dock, and presumably drowned the three resident caretakers of the cannery. Photograph taken April 4, 1964.

built on tightly folded argillite and graywacke of probable early Tertiary age.

All three of the resident cannery caretakers are missing and presumed to have drowned when the cannery dock was washed away in a wave that must have struck suddenly and probably at the time of the earthquake (fig. 14). Local waves with runup heights of as much as 110 feet also caused extensive damage to vegetation at numerous other localities along the uninhabited shores of Port Nellie Juan and its westward extension, Kings Bay (fig. 15). One large barge that was tied up at the mouth of a small creek on the north side of Port Nellie Juan was lifted by violent waves, overturned, and deposited 200 feet inland among the trees (fig. 16).

The cause of the destructive waves in Port Nellie Juan is unknown. Comparison of pre- and postearthquake soundings by Mayo and McCulloch (L. R. Mayo, written commun., 1965) indicates that the highest waves in Kings Bay were at least in part generated by massive submarine landslides of deltaic deposits at the head of the bay and at two localities along its north shore. There are no comparable large unconsolidated deposits exposed at the surface in Port Nellie Juan, although it is conceivable that such deposits are present but are entirely submerged.

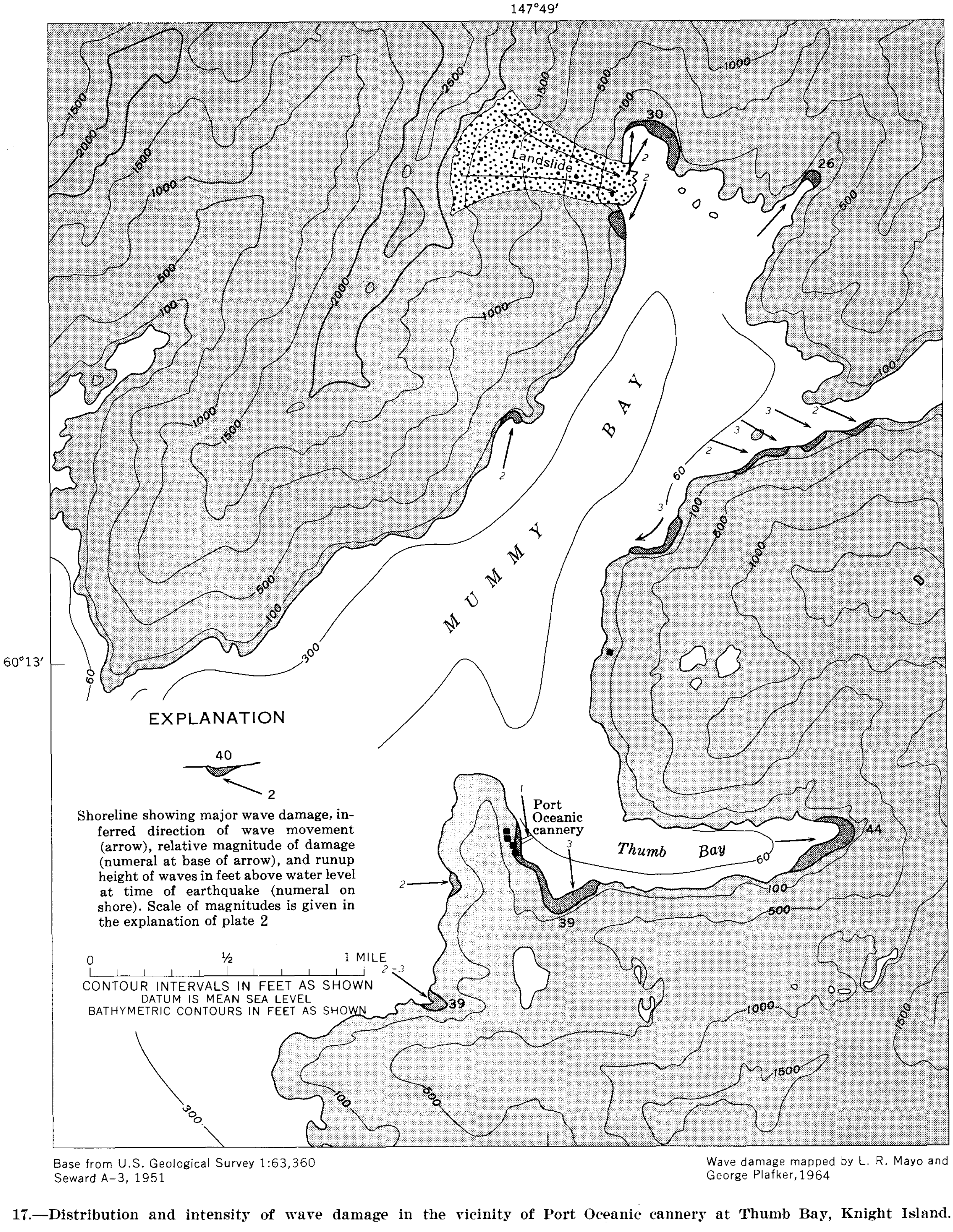
PORT OCEANIC

Port Oceanic, the site of an inoperative cannery, is on Thumb Bay, an arm of Mummy Bay, near the southern tip of Knight Island, in western Prince William Sound (fig. 17). The cannery is built mainly on graywacke and slate bedrock, but the bunkhouse is in part on filled land. Thumb Bay is a sheltered, shallow body of water surrounded by fairly steep forested slopes.

According to George Flemming, one of the two cannery caretakers, the quake tremors lasted 3 to 4 minutes. Motion came from the southeast or south-southeast; the ground rolled and twisted with 1- to 2-foot amplitudes and 1- to 2-second periods. Rumbling noises preceded short, sharp aftershocks at intervals during the night and for the next several days. Vibration displaced small objects and moved a stove a few inches but caused no other damage except for

15.—Shore near the head of Kings Bay swept bare of timber to an altitude of 110 feet by slide-generated local waves. Bare areas of rock on the spur in the right middle distance were scoured clean of the soil and muskeg cover.

16.—Barge, which is 60 feet long and 25 feet wide, that was broken loose from its mooring by a violent local wave in Port Nellie Juan, turned upside down, and deposited among the trees 200 feet from the shoreline at about 30 feet above mean lower low water.



17.—Distribution and intensity of wave damage in the vicinity of Port Oceanic cannery at Thumb Bay, Knight Island.

18.—Buildings at the Port Oceanic cannery damaged by a wave that struck within 2 to 3 minutes of the initial shock and had a crest height about even with the cannery floor level. Photograph taken April 4, 1964.

slight settling of one end of a bunkhouse which was built on filled land.

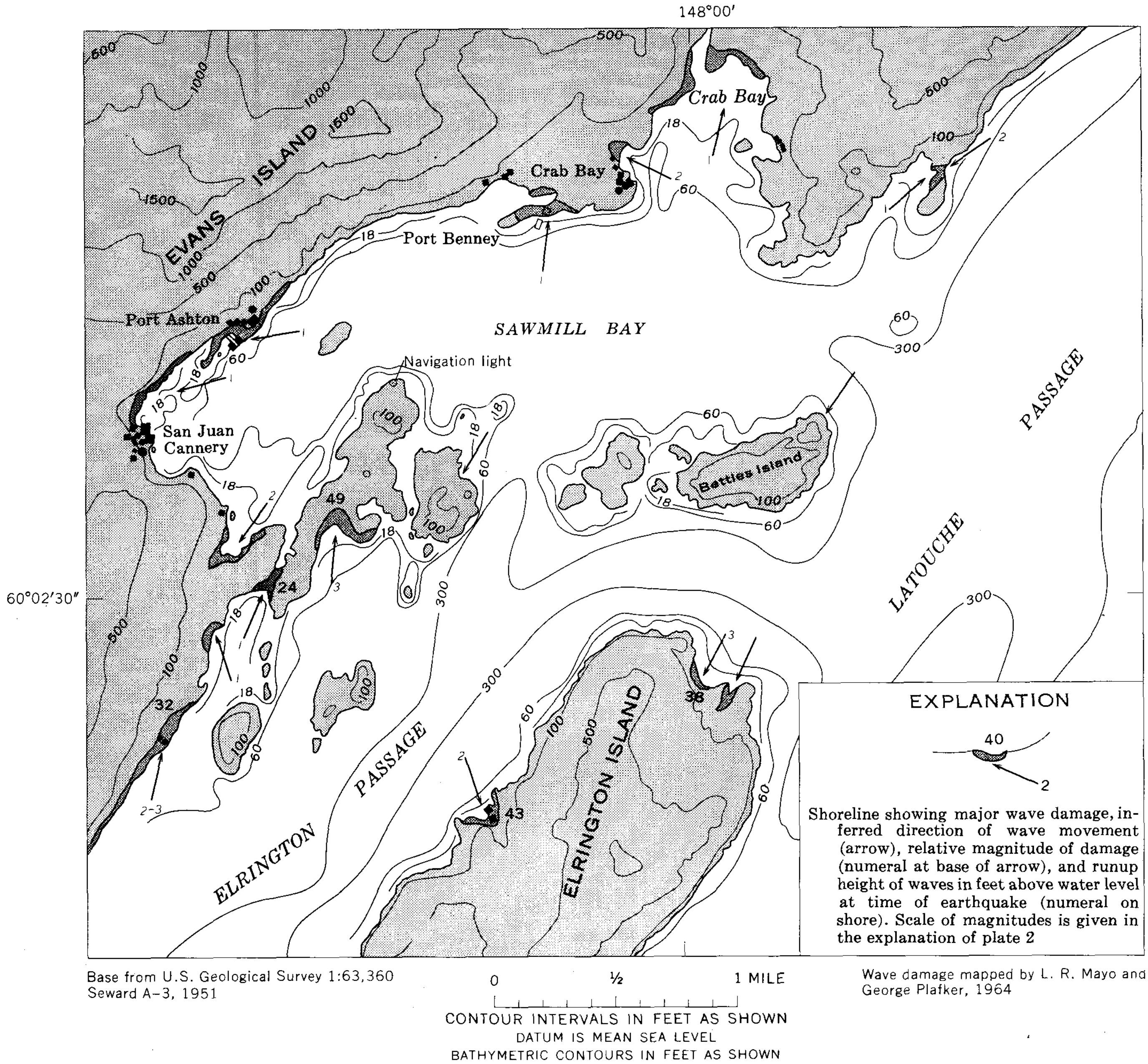
The area was uplifted about 6 feet during the earthquake. One wave, doubtless of local origin, arrived within 2 to 3 minutes of the initial shock. It rose about 3 feet above the tectonically elevated highest tide line at the cannery site, with a runup of at least 22 feet above that level (44 feet above mean lower low water) at the head of the bay. This wave destroyed the dock, several boats, and washed some piling supports out from under the cannery (fig. 18). No later waves were observed in Thumb Cove.

The cause of the local waves in Thumb Cove is uncertain. The cove, is less than 125 feet deep, hence probably too shallow to have had large submarine slides, but the remote possibility that slide-generated waves moved into it from Mummy Bay cannot be discounted from the available evidence. A landslide that fell into shallow water near the head of Mummy Bay (fig. 17) could not have displaced a large enough volume of water to cause damaging waves except, perhaps, in its immediate vicinity.

SAWMILL BAY AND VICINITY

Sawmill Bay, in the southwestern part of Prince William Sound, is an indentation on Evans Island off the junction of Latouche and Elrington Passages (fig. 19). Along its shores are several homes, a fuel depot, and three canneries, one of them inoperative. All these structures are on bedrock or bedrock with a thin veneer of sediments; there are no large masses of unconsolidated deposits along the shores. As at nearby Chenega, local waves did far more damage than any other earthquake-related cause.

According to estimates of several eyewitnesses, the earthquake lasted 4 to 5 minutes in the Sawmill Bay area; it was preceded and accompanied by sounds like booming thunder. Shaking began with a northwest-southeast swaying motion that soon became fast and jarring, but much of the later movement seemed to be almost vertical. Pilings of the Crab Bay cannery dock were lifted upward clear of the water, but the caps and dock deck were not displaced. Three poorly constructed chimneys were cracked or toppled and



19.—Distribution and intensity of wave damage in Sawmill Bay and vicinity, Evans Island.

some movable objects in homes and canneries fell or moved about. The ice was cracked on a small artificial water-supply lake back of Port Ashton. Moreover, small leaks, not large enough to require repairs, developed beneath the lake's concrete dam. These leaks, which suggest that vibration caused some cracking of the concrete, are one of the very few examples of earthquake damage to dams throughout the stricken area. The San Juan cannery dock at the head of Sawmill Bay was not affected nor was there any other damage from the shaking.

Sawmill Bay is a short distance west of Montague Island, where the greatest recorded tectonic uplift took place. Uplift in the vicinity of the bay was about 10 feet; it required modification of the dock facilities and lengthening of grid skidways in order to float stored fishing boats before the canneries could resume operations.

Local waves of unknown origin that caused most of the damage in the vicinity of Sawmill Bay began 2 minutes after onset of the earthquake, according to Carl Blindheim. The water first rose smoothly and slowly for an estimated 1 minute, then rushed out to at least the minus 20-foot level in a few seconds; all the bottom of Crab Bay and large expanses of Sawmill Bay were exposed. Within a few moments the sea rushed back with tremendous roar and turbulence to as high as 10 feet above the extreme high-tide level along segments of the uplifted shore (fig. 19). All this happened before cessation of seismic shaking. There were no other large waves, but smaller surges continued to come in at intervals for about 5 hours on a rising tide. The highest of these, at about 1:00 a.m., reached close to the tectonically elevated extreme high-tide level but caused no damage.

The waves damaged piling beneath some structures and demolished one dock. Vessels and skiffs near San Juan Cannery and Port Ashton were beached or carried away; two 20- by 70-foot scows were swept up into the trees and deposited one on the other. Two residents at Port Ashton who were swept into the water barely escaped drowning, but one man at Crab Bay was drowned in the first high wave while trying to secure a skiff.

Numerous local waves caused shoreline damage at various uninhabited localities along Elrington and Latouche Passages (pl. 2). Many were higher and more violent than those in Sawmill Bay. One unoccupied house on Elrington Passage, just southwest of Sawmill Bay (fig. 19), was destroyed.

The origin of the destructive waves in various parts of Sawmill Bay and vicinity is unknown. Surges observed at Sawmill Bay later during the night of March 27 and morning of March 28 undoubtedly were due to passage of the long-period seismic sea waves that entered the sound from the Gulf of Alaska.

TATITLEK AND VICINITY

Tatitlek is a fishing village on Tatitlek Narrows, between Valdez Arm and Port Fidalgo, near the northeast corner of Prince William Sound. Its population was increased to about 150 when the survivors of the Chenega tragedy (about 50) were resettled at the village. The inactive mining camp of Ellamar is nearby. Both localities are underlain by argillite-graywacke-greenstone bedrock or bedrock with a thin veneer of glacial drift. All buildings are wood, most with dug piling foundations. Damage was slight and was caused by tectonic uplift rather than by vibration or waves.

According to Karol Kompkoff and Ivan D. Anten of Tatitlek, rumbling sounds were heard about 10 seconds before the onset of the earthquake vibrations, which lasted from 3½ to 5 minutes. The church bell rang, small objects fell from shelves, and standing was difficult to impossible, but there was no structural damage. The small village reservoir became completely empty but filled again after 2 weeks. Effects were much the same at Ellamar, though one chimney fell and some windows were broken, according to the caretaker, Carl Aranson.

The sea at Tatitlek withdrew "immediately" during the earthquake and came back up to 17 or 18 feet above normal mean lower low water, but did not reach above the extreme high-tide line, which had been tectonically elevated about 4 to 5 feet. High and erratic tides were noted for several hours after the earthquake, but none caused any damage.

Tatitlek's port facilities were actually improved somewhat as a result of the earthquake. The port, which is close to the village, depends on a natural anchorage in Tatitlek Narrows that is partly protected by rocky reefs. The normal water depth of 6 feet below mean lower low water was partially lost when the land was raised 4 to 5 feet, but the Corps of Engineers compensated for the uplift by dredging the anchorage 6 feet deeper. Because the reefs were also upraised, the basin now has more protection from storms than it did originally.

There is no obvious cause for the single wave observed at Tatitlek during the earthquake. The timing and characteristics of the high tides that followed suggest passage of seismic sea waves.

20.—Typical extensively fissured sand dune on the Copper River Delta.

COMMUNITIES OF THE COASTAL BELT EAST OF PRINCE WILLIAM SOUND

The coastal belt east of Prince William Sound and the offshore islands are sparsely inhabited, and were relatively undamaged by the earthquake. The only permanently inhabited localities include a small Coast Guard light station at Cape Saint Elias on Kayak Island, an FAA facility on Middleton Island, a small settlement at Yakataga, and a fishing village with several Government installations at Yakutat (pl. 1). There are no other communities between Yakutat and the panhandle of southeastern Alaska, a distance of about 150 miles.

The earthquake was strongly felt throughout most of the coastal belt. Seismic shaking caused widespread ground fissuring in unconsolidated fluvioglacial, alluvial, eolian, and marine deposits along the coastal belt as far east as Russell Fiord in the Yakutat area, some 300 miles east of the epicenter. Ground fissures developed in large areas of the Copper River Delta (Reimnitz and Marshall, 1965), along the margins of Controller Bay, and throughout much of the coastal lowlands extending from Cape Suckling eastward to Yakutat Bay (figs. 20–22). Many of these fissures were accompanied by extrusion of sand, gravel, and silt on sand dunes, elevated beach ridges, alluvial flood plains, and tidal flats.

Numerous landslides and avalanches, many of enormous size, were triggered in the foothills and mountains north of the coastal lowland at least as far eastward as the Yakataga area, 200 miles from the epicenter, and ice was cracked on lakes as far as Crillon Lake, about 400 miles east of the epicenter.

Tectonic uplift affected the entire coastal belt and adjacent offshore islands to the east of Prince William Sound. It was between 6 and 10 feet at the Copper River Delta and possibly as much as 14 feet at Cape Suckling; it decreased progressively eastward and died out near Yakataga (Plafker, 1969, pl. 1.)

Unlike most of the other coastal regions in the earthquake-affected area, there are no known places in the coastal belt east of Prince William Sound where local waves or seismic sea waves reached above the elevated extreme high-water levels.


0
100 FEET


0
50 FEET

CAPE SAINT ELIAS

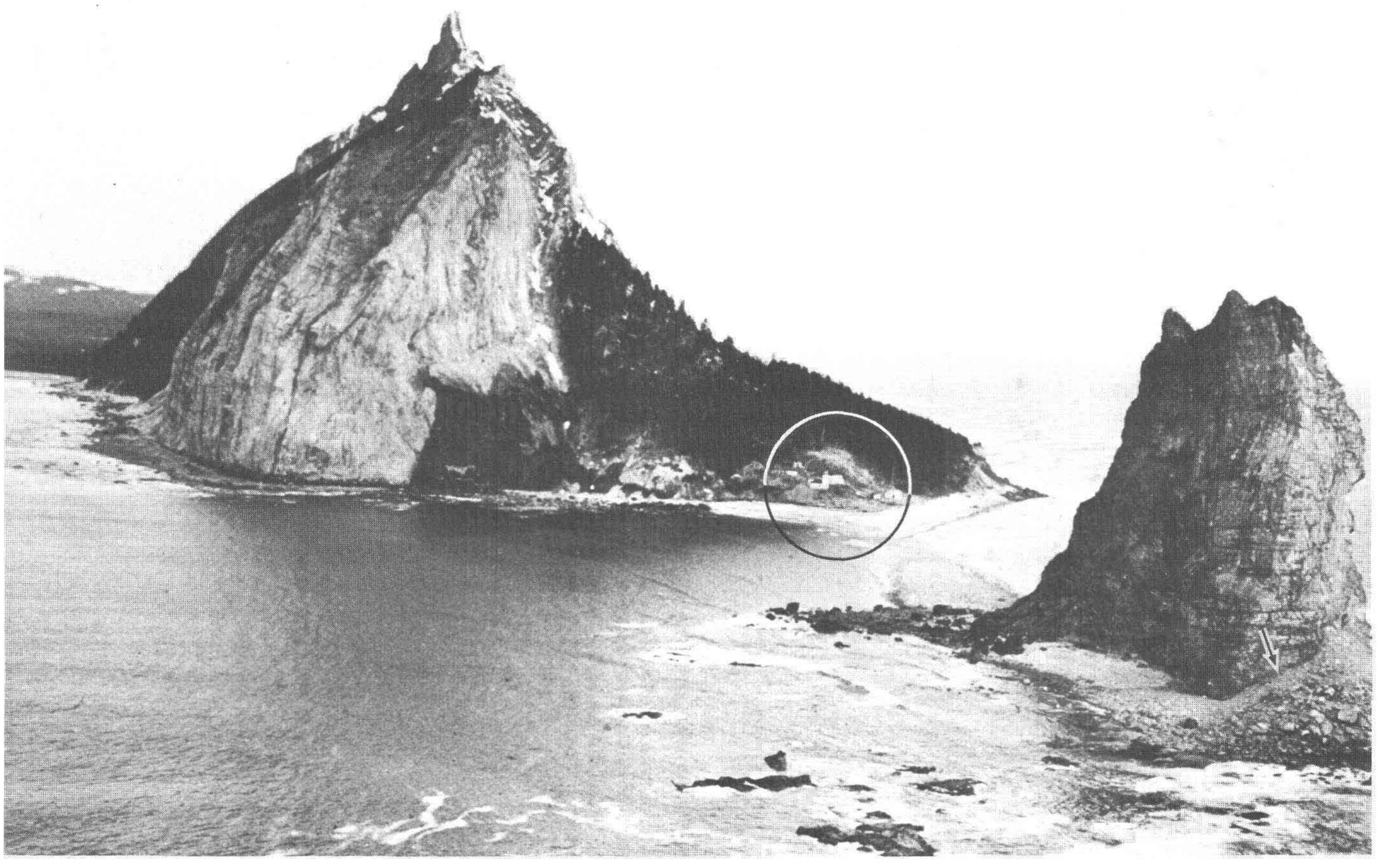
Cape Saint Elias is the site of a Coast Guard light station on the southwestern tip of Kayak Island, just off the Bering Glacier on the north-central coast of Prince William Sound. Pinnacle Rock, a rugged rock promontory, off the tip of Kayak Island, was accessible from the light station at low tides prior to the earthquake (see fig. 23). The promontory at the base of which the station is located and Pinnacle Rock consist of a massive porphyritic intrusive rock of middle Tertiary age.

21 (upper left).—Linear fissures and extensive areas of ejected mud (dark) in the tidal flats along the shore of Controller Bay.

22 (lower left).—Fissured and slumped fluvioglacial deposits bordering a kettle lake at the eastern margin of Bering Glacier.

According to William B. O'Neal, one of the station crew of four men, the fast jarring motion of the earthquake lasted about 5 minutes. There was no damage to the station except for displacement of a few small articles. Tectonic uplift at Cape Saint Elias was about 6 to 8 feet.

Within seconds after the initial shock, however, a massive rockfall was triggered at Pinnacle Rock (fig. 23). One of the crew members who was photographing sea lions at the pinnacle had a leg broken by the falling rock. Later, as he was being carried back to the station by the other three crew members, a series of seismic sea waves that flooded over the low-lying gravel bar drowned the injured man and nearly drowned his companions. These waves reportedly struck at about 6:15 p.m., almost an hour after the start of the earthquake. The first wave, which reportedly came from the southeast, overtopped the tectonically elevated gravel bar to a depth of about 4 feet; it was immediately followed by a second and higher wave from the northwest that swept the men into the sea.



23.—Aerial view of Cape Saint Elias (left) and Pinnacle Rock (right) at the southwestern tip of Kayak Island. A portion of the earthquake-triggered rock fall from Pinnacle Rock is in the lower right corner (arrow); the Cape Saint Elias Coast Guard station is circled.

MIDDLETON ISLAND

Middleton Island, 80 miles southwest of Cordova in the Gulf of Alaska, is the site of an FAA navigation facility and emergency airfield. The island is underlain by poorly indurated sedimentary rocks of late Cenozoic age.

Earthquake tremors on the island, described as moderately strong, caused a few small items to be moved about in buildings. The only noteworthy damage was that to oil lines from the fuel storage tanks; these broke and nearly all of the oil was lost.

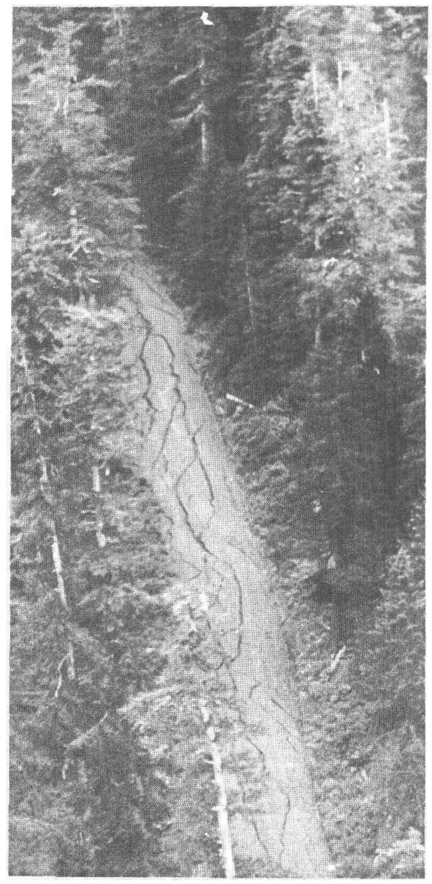
Tectonic uplift associated with the earthquake was roughly 11 feet, but the movement caused no damage because there are no dock or harbor facilities. According to Dwight Meeks, a seismic sea wave which struck the island from the west an estimated 20 minutes after the start of the earthquake, did not reach to the tectonically elevated high-tide level, and consequently caused no damage.

YAKATAGA

Yakataga is a small community on Cape Yakataga along the Gulf of Alaska coast, about 200 miles east of the earthquake epicenter and 100 miles west of Yakutat. It consists mainly of an FAA station, a communications facility, and dwellings of a few trappers and prospectors. The FAA facility and airstrip are built on fluvioglacial outwash deposits, whereas the communications facility and other homes are on the late Tertiary sedimentary rocks that form Cape Yakataga. Earthquake damage in the area was confined to fissuring of roads that extend from Yakataga across the coastal lowland to the west.

Ground motion in an east-west direction was strongly felt in the Yakataga area for durations estimated to be from 4 to 8 minutes long. Small objects in some buildings reportedly were thrown off shelves or tables, water sloshed out of an emergency water tank 14 feet in diameter, and some fissures formed in the gravel airstrip. There was no structural damage. Two trappers, Clarence Tarbelt and Steve Smas, said the ground motion on the broad foreland west of Yakataga was so violent they were thrown to the ground. Within 1½ minutes after the earthquake began, they observed fissures forming in the frozen ground and a sound "like an awful rush of water". According to these 2 observers, individual fissures laced the area and some zones of fissures could be traced for a mile or more. Collapse pits along some of the fissures were as much as 9 feet in diameter and 14 feet deep. Water with mud or fine silt was ejected from some ground fissures intermittently, for a few seconds at a time, to an estimated height of 8 to 10 feet. Streams in the vicinity that were dry at the start of the shaking "were running in torrents" within a few minutes because of the vast amount of water poured out of the ground fissures, and perhaps, because of cracking of ice-dammed lakes upstream. The high water lasted for 11 days. In spite of the strong shaking, Tarbelt reports, damage in his cabin consisted of only one spice can shaken from the shelves.

The main damage in the area consisted of extensive fissuring of abandoned oil-exploration access roads (fig. 24) and buckling of some bridges due to lateral movement of the banks inward toward the channels. Horizontal displacement across some fissures was as much as 10 feet, and pressure ridges formed from ½ to 8 feet high. Tarbelt observed that a ⅝-inch steel cable which had frozen into the ground surface was



24.—Intensely fissured road at the crest of an elevated beach ridge west of Yakataga.

cleanly parted in five places where it was crossed by fissures. The casing of a nearby abandoned oil well sheared off near the surface with a "pop like a rifle shot" a few seconds after the shaking stopped, presumably because of horizontal movement of the frozen ground.

Shortly after the earthquake ended, seismic sea waves in the form of erratic tides and swift currents were observed along the shore of Cape Yakataga. Charles Bilderback, a long-time resident of the cape, noted that the sea was calm at the time and almost at zero tide stage. The first water movement was a withdrawal that reached a low of about −6 feet at 6:25 p.m., almost 1 hour after the start of the earthquake. By using rocks on the reef as a reference for estimating tide levels, he recorded the following sequence of wave heights (relative to mean lower low water) during the evening after the earthquake:

Alaska standard time (p.m.)	*High water (feet)*	*Low water (feet)*
6:25		−6.0 to −8.0(?)
6:35	10	
6:45		0
6:55	12	
7:05		0
7:18		−1 (surge)
7:30		−6.0
7:45	8	
7:50		0
7:55	10	
7:58		0
8:07	13 (followed by 6-ft surge)	
8:16	12	
8:40		0 (followed by surge)
8:50		−4
9:20	10 (followed by surge)	
10:50	14	

The waves were followed by surges of 1 to 3 feet every few hours for about 5 days after the earthquake. No damage was caused by the waves, the highest of which reached approximately to the normal extreme high-tide level of about 15 feet.

YAKUTAT

Yakutat is the site of a native fishing village and cannery near the mouth of Yakutat Bay about half way between Juneau and Cordova, and almost 300 miles west of the earthquake epicenter. A large airfield and FAA facility are just east of the village, and a Coast Guard loran station and a microwave relay facility are along the coast nearby. Inhabited areas are on a low-lying coastal plain, the Yakutat Foreland, which is bounded on the northwest by rugged foothills of the Saint Elias Mountains. The village is on a late Holocene end moraine, the airfield is on an extensive thick deposit of fluvioglacial outwash, and the facilities along the coast are on moraine or marine beach deposits.

The earthquake was strongly felt throughout the Yakutat Foreland as an east-west rolling or swaying motion that built up to a peak in about 30 seconds and lasted a total of 6 minutes (timed), according to A. T. Gorman of the U.S. Weather Bureau. Some individuals reported a feeling of motion sickness during the earthquake. Small items were thrown from shelves in stores and in some homes, but there was no structural damage. Ice on many lakes was broken and some lakes drained. The ground movement caused trucks parked on the airfield ramp to roll back and forth as much as 10 feet, and caused roller-mounted doors of the large FAA hangar, which are oriented northwest-southeast, to alternately open and slam closed. Rumbling noises were heard during the earthquake and a series of loud noises described as similar to "cannon shots" were heard for about 20 minutes afterward. The noises reportedly came from the vicinity of Khantaak Island, a few miles northwest of the village.

Slight damage to the concrete runway and parking ramp at the airfield resulted from vertical movement of concrete slabs and cracking of some of the slabs. According to Mr. Gorman, damage to the runway and parking ramp was somewhat greater than that which occurred during the July 10, 1958, earthquake that centered about 100 miles southeast of Yakutat (Davis and Sanders, 1960, p. 237–238).

Although ground motion was strongly felt throughout the Yakutat Foreland, two seal hunters (Jack Williams and Sam Dick) who were camping on a bedrock site near the head of Yakutat Bay were completely unaware that an earthquake had occurred until they returned to Yakutat later in the evening. A significant difference in ground response to the passage of seismic waves in the bedrock as compared to the thick unconsolidated deposits of the foreland is thus reflected.

A single wave was observed along the shore at the village during the earthquake. The roiled and muddy water reported in the vicinity the next day suggests the possibility that a submarine slide occurred in the Khantaak Island area, the site of a disastrous slide that killed three people at the time of the 1958 earthquake (Davis and Sanders, 1960, p. 242–246). Erratic tides were observed after the earthquake and were presumably associated with passage of seismic sea waves. None of them reached above extreme high-water level or caused damage in the vicinity of the village. However, the two seal hunters at the head of Yakutat Bay reported that tide level there reached approximately 6 feet above normal highest water at about 11:00 p.m.; apprehension caused by the abnormal tides prompted them to leave their camp hurriedly and return to Yakutat by boat that evening.

KENAI PENINSULA COMMUNITIES

This section discusses only the smaller communities on the Kenai Peninsula that were damaged by the earthquake; it does not include the following towns which have already been described in the Geological Survey's Professional Paper series on the earthquake: Whittier (Kachadoorian, 1965), Seward (Lemke, 1967), Homer (Waller, 1966a), Lawing and Moose Pass (McCulloch, 1966).

Port Nellie Juan, along the shore of Prince William Sound, was discussed on page G24.

People in all the communities on the peninsula felt the earthquake of March 27, 1964. Major damage by seismic shaking occurred at Portage, at the docking facility of Nikiski, and at the military installation of Wildwood Station. Seismic sea waves inundated the waterfront of Seldovia and logging camps at Puget Bay and Whidbey Bay. The chief cause of damage to the coastal communities by the earthquake was tectonic and local surficial subsidence. English Bay, Port Graham, Girdwood, Hope, Kenai, Portage, Rocky Bay and Seldovia all subsided. Three of these—Girdwood, Hope, and Portage—were partially or completely inundated by extreme high tides after the earthquake.

COOPER LANDING

Cooper Landing is at the west end of Kenai Lake, whose outlet forms the head of Kenai River. As described by McCulloch (1966), seismic vibration was severe in this vicinity, ground fissures were very numerous, and the land surface was warped by vertical tectonic displacements.

Despite the relatively heavy shaking, damage to structures, other than the highway bridge (Kachadoorian, 1968), was relatively light. Several concrete porch slabs and foundations were cracked where fissures intersected them, cinder-block chimneys fell, and plumbing fixtures were broken. Dishes and glassware, of course, were smashed, and several small fuel-oil and propane-gas tanks broke open when their supports collapsed. Some buildings continued to settle and to develop new cracks for several days after the earthquake.

The nearby Cooper Lake hydroelectric plant was undamaged, partly because it shut down automatically when troubled plants in Anchorage tripped overload switches on the entire power system (Eckel, 1967, p. B20).

ENGLISH BAY

English Bay, formerly called Alexandrovsk, is a fishing village on English Bay about 10 miles southwest of Seldovia. As at Seldovia and Port Graham, the only damage done by the earthquake was by tectonic subsidence of about 5 feet. A few houses that were partly flooded at high tides were torn down and replacements were built on higher ground by the Red Cross.

GIRDWOOD

The small town of Girdwood, about 55 miles west-southwest of the epicenter of the earthquake, is on a gently sloping alluvial fan where Glacier Creek flows into Turnagain Arm. The town is bordered on the east, west, and north by mountains, and on the south by Turnagain Arm.

Girdwood is underlain by silt, sand, and gravel deposits which become coarser grained from the toe toward the apex of the alluvial fan. The water table varies in depth; it is near the surface at the coastline of Turnagain Arm and becomes progressively deeper inland toward the apex of the fan.

Seismic motion at Girdwood was northwest-southeast and lasted for about 4 to 5 minutes. One person who was driving a car on the Seward-Anchorage Highway at Girdwood reported that the motion was so violent that he could not control the vehicle. When one of his passengers got out of the car she was thrown to the ground.

Many fissures developed on the lower lying areas underlain by the finer grained deposits. Water and mud were ejected from some of the fissures. Reports on homes and other structures in Girdwood are scarce, but those obtained indicate that seismic shaking did not directly damage any structure. However, seismic shaking did generate numerous fissures throughout the town. Locally, some slight displacement downslope occurred in the water-soaked fine-grained unconsolidated sediments. Damage was widespread on the railroad grade and highway roadbed.

Five feet of regional subsidence and an additional 3 feet of local subsidence occurred at Girdwood. This total 8-foot subsidence was enough to put much of the lower lying areas of the town under water during high tides. During the high tides of April 14, 1964, all of the highway, much of the railroad west of the railroad depot, and all of the town between the railroad and highway were inundated. Water was as much as 3 feet deep in some of the buildings, and subsequently the buildings were moved to higher ground or placed on stilts.

HOPE

Hope is a small mining and fishing community on the south shore of Turnagain Arm at the mouth of Resurrection Creek. Surrounded on three sides by the rugged Kenai Mountains, the town itself is on the gently sloping surface of the creek's delta. It is underlain by relatively coarse gravel and sand, probably less than 150 feet thick. Before the earthquake the water table was less than 15 feet below the surface.

Residents of Hope reported that seismic motion started suddenly, was east-west, and lasted about 4½ minutes. They thought that the earthquake was a minor one and did not realize its severity until later. Calvin Drier, a resident of Hope since 1921, stated that the

1964 Alaska earthquake was much less intense than the one that occurred in 1936.

Most of the relatively minor earthquake damage was caused by subsidence rather than by vibration. Seismic shaking toppled one concrete-block chimney and knocked off some shelf goods. Mr. Drier's home, a log cabin resting on fine gravel, sand, and silt, settled about a foot into the ground. Seismic shaking also formed many ground fissures, the largest about ½ mile long with a maximum width of 6 inches. Water spouts, one of which was reportedly 8 feet high and lasted for 4 minutes, occurred during the earthquake.

The primary cause of damage at Hope was not seismic shaking but the effects of regional and local subsidence. Tectonic subsidence of about 5 feet and local surficial subsidence of as much as 1 foot was sufficient to flood some houses during high tides. In others, basements only were flooded. The encroaching saline water of Turnagain Arm raised the water level in many wells and made the water somewhat salty.

KENAI AND VICINITY

Kenai is on the west coast of the Kenai Peninsula, at the mouth of the Kenai River. The city is a fishing and farming center as well as a supply point for much of the Kenai Lowland. Wildwood Station, 5 miles to the north, is an Air Force base, and Nikiski, 10 miles to the north, is a shipping terminal for petroleum products from the nearby Swanson River oil field. The Kenai area is underlain by glacial till and outwash on an extremely thick sequence of poorly consolidated continental sediments of late Tertiary age. Nearly all of the relatively minor damage in the Kenai area was caused by strong seismic shaking, though a small amount of tectonic subsidence caused accelerated erosion of natural bluffs and of a manmade embankment along the Cook Inlet side of the town.

Ceiling tiles and some light fixtures fell in the newly built Kenai Central High School, and a wall in one room parted from the floor slab but there was no other structural damage. Minor cracks formed in numerous other public and commercial buildings, but the greatest damage occurred to their contents, displaced by the shaking.

Wildwood Station, with an estimated complement of 700 men, experienced relatively severe damage from seismic vibrations. Greatest damage was to an elevated steel water tower which collapsed. The rush of released water struck the Officer's Club about 200 feet west of the tower, broke several windows, and injured one man. All power and other utilities were disrupted temporarily, but an emergency source of power supplied some electricity and steam and pumped water while main lines and facilities were under repair.

The water tower was an all steel structure supported by six posts, with an elevated tank which was full to within 5,000 gallons of its 150,000-gallon capacity. During the earthquake the tank began to sway. About halfway through the earthquake, the manhole cover at the top blew off and water spouted out of the manhole. Then the tower split in two pieces and failed; one half fell against the petroleum-oil-lubricants building southwest of the tower center and the second half fell northwest of the tower center. Figures 25 and 26 are photographs showing the destroyed water tower. Note that the tank broke across the welds rather than along them.

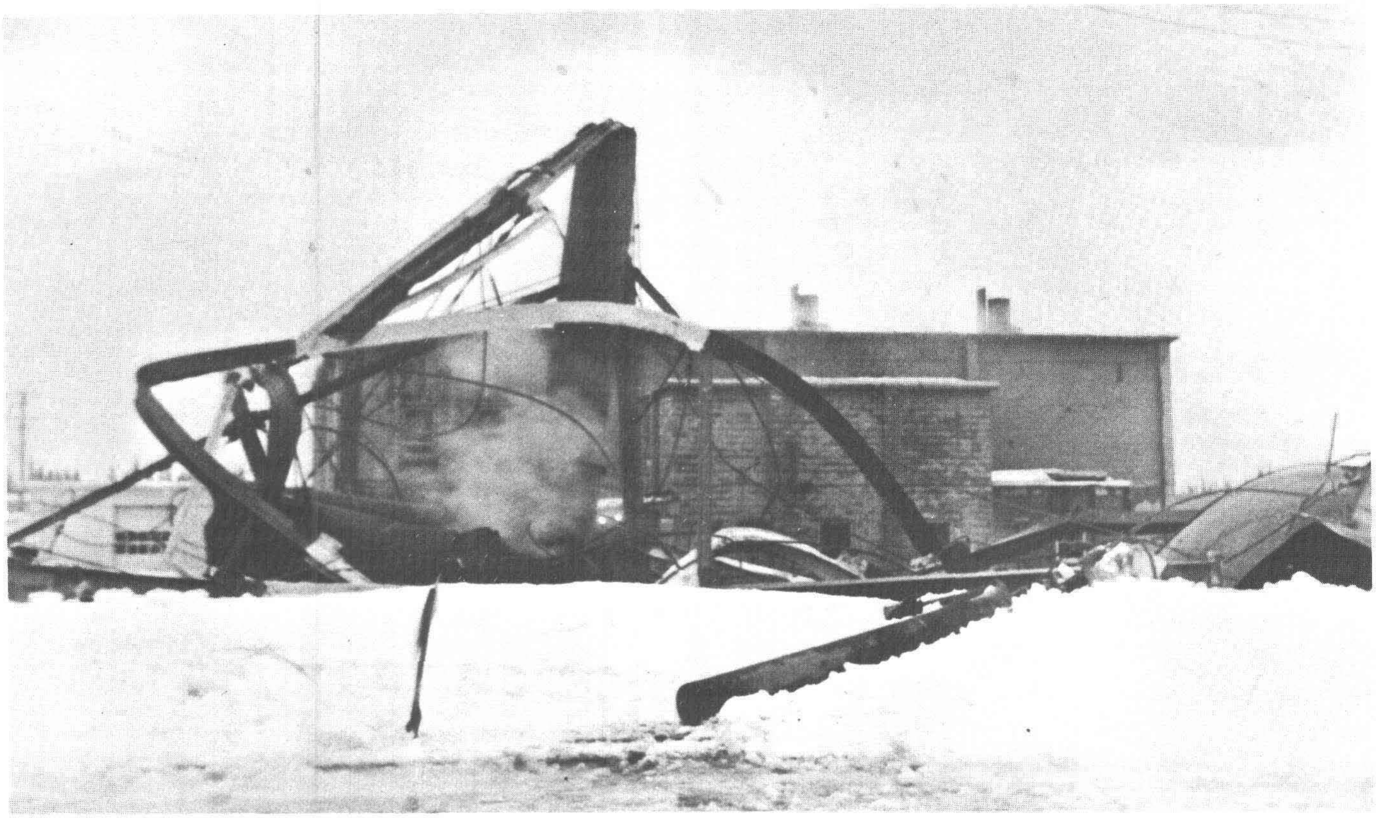
The pipeline that transports petroleum southward from the Swanson River oil field to loading and refinery facilities at Nikiski was not damaged, nor were any of the producing wells. The catwalk over the pipeline between the shore and the offshore loading terminal collapsed during the shaking, but the pipelines themselves remained intact (fig. 27). A tanker that was loading fuel oil at the time of the earthquake pulled away from the terminal until the tremors subsided, then was able to resume loading (Cheechako News, Kenai, April 3, 1964).

At the Nikiski tank farm a small water tank collapsed, a fuel storage tank was buckled at its base, and several floating roofs on storage tanks were damaged by earthquake-generated seiche waves in the containers (Rinne, 1967). Some fire bricks were also knocked out of the refinery burner wall.

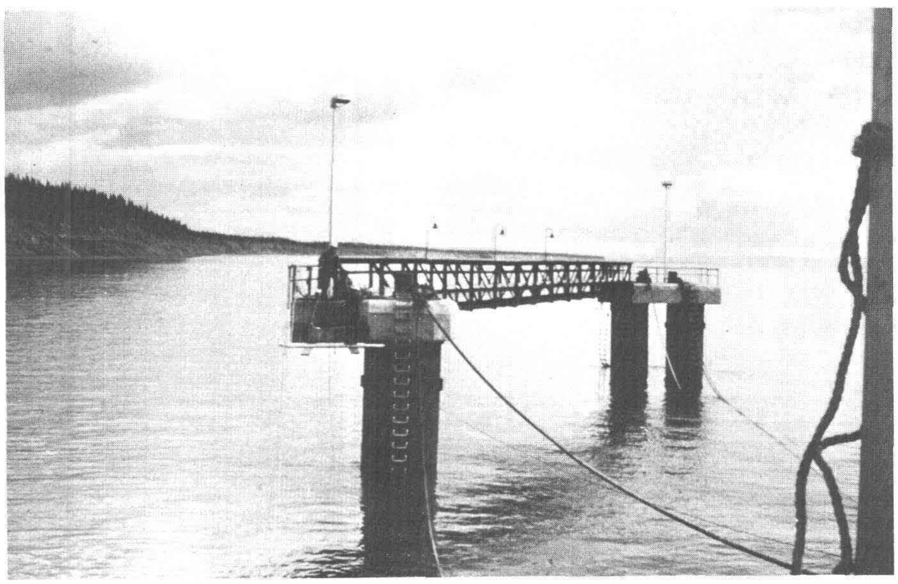
PORT GRAHAM

Port Graham is a fishing village on the south side of English Bay. It is on metamorphosed bedded rocks of Mesozoic age. As at Seldovia, 7.5 miles to the northeast, virtually all of the damage done by the earthquake was caused by tectonic subsidence of about 3 feet. According to Mrs. Vern Rimling and Mickey Moonan, a gentle swaying motion, mostly in an east-west direction, lasted from 3 to 4 minutes; a few articles fell from shelves, boats on ways swayed moderately, and trees rustled, but there was no property damage from the earthquake vibrations. Minor ground cracks appeared in unconsolidated deposits, and numerous rockfalls and rockslides were triggered in the surrounding mountains. One relatively low wave came in about 9 minutes after the earthquake but it reached only to about half-tide level and did no damage. During the night after the earthquake, erratic tides reached to the approximate ex-

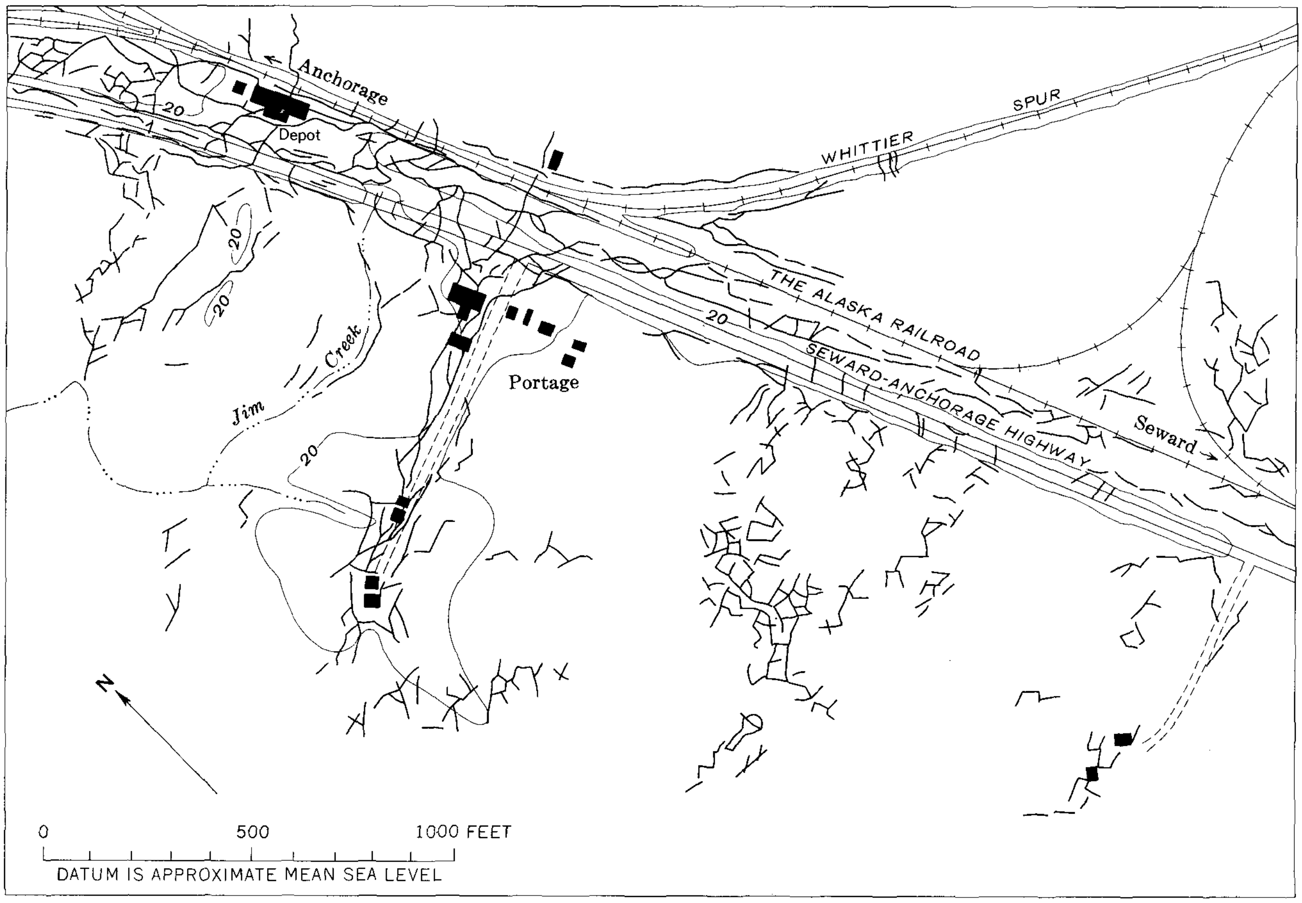
25.—View westward showing southwest half of collapsed water tower at Wildwood Station. Officers' club in background. Photograph by U.S. Air Force.



26.—Northeast half of collapsed water tower at Wildwood Station. Photograph by U.S. Air Force.



27.—Collapsed catwalk at Nikiski refining facility.



Base map by Walker & Whiteford, Inc., Seattle, Wash. from photographs taken June 4, 1964 for Alaska Department of Highways
Datum: Horizontal, U.S. Geological Survey; vertical, U.S. Coast and Geodetic Survey (as of April 17, 1964)

Fractures mapped by D. S. McCulloch

28.—Major earthquake-induced fissures in Portage area. The entire area shown was inundated by high tides on April 14, 1964.

treme high-tide level. Tectonic subsidence of about 3 feet caused flooding of the cannery by high tides, and some waterfront structures were partly damaged by high tides during the winter of 1964–65. By the spring of 1965 a new and higher beach berm had been built by natural processes and has since protected the waterfront area from flooding.

PORTAGE

The small town of Portage, about 40 miles southwest of the epicenter, is on the Seward-Anchorage Highway at the head of Turnagain Arm. The town is on a flat surface underlain by fine-grained silt, sand, and gravel. Locally, the water table is within a foot and generally not more than 3 feet from the surface.

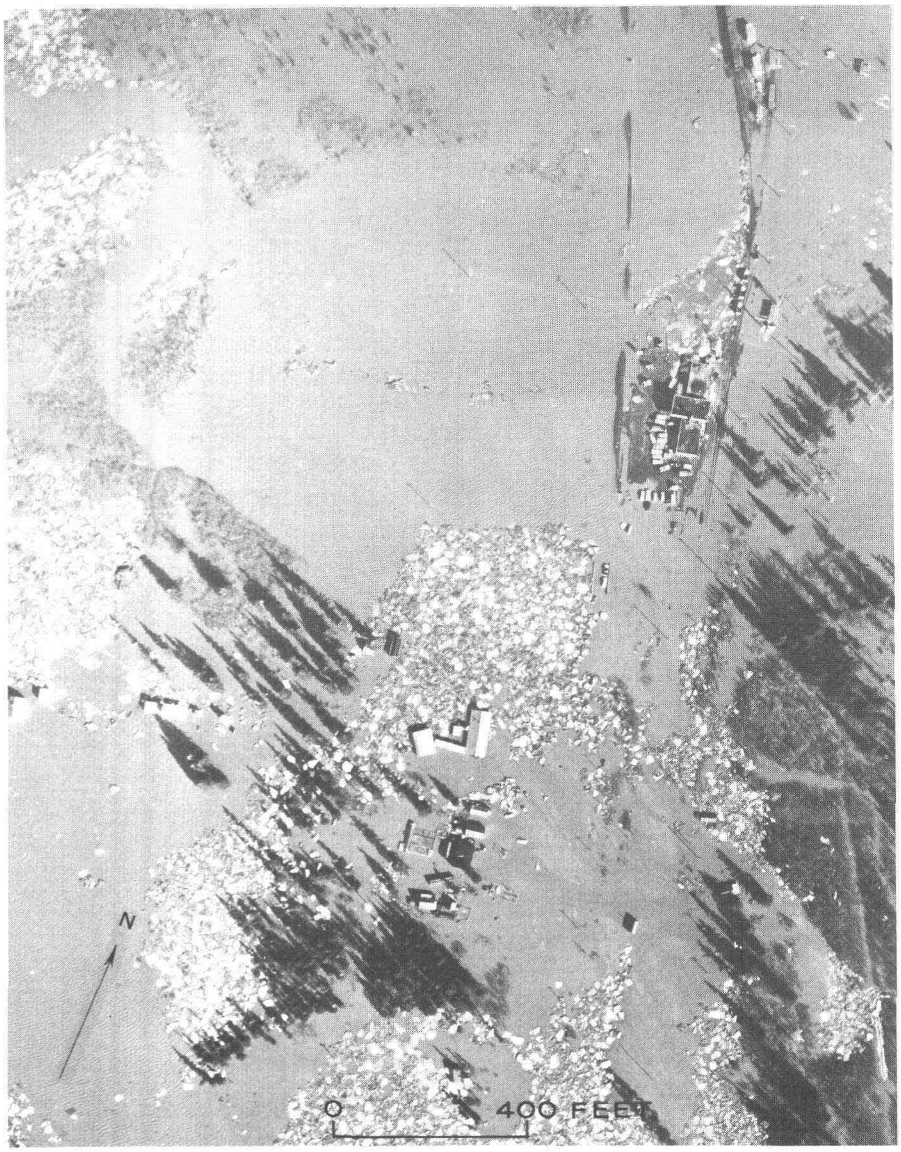
Seismic motion at Portage was northwest-southeast and lasted for 5½ to 6 minutes. As in other localities, the motion started gently, but at Portage it became violent within a few seconds after it started. Vibration caused structural damage to several buildings in Portage and generated numerous cracks or fissures in the ground. George Larson, of Portage, reported that during seismic shaking the chimney at a gasoline station was destroyed; one-half of it fell into the building and the other half fell outside. Most of the buildings in town were damaged to some degree by the seismic motion. In addition, further damage was caused by ground fissures that formed beneath the buildings during the earthquake. The largest of the fissures was 4 feet wide; their average width was only 2 feet.

Figure 28 shows the major patterns of fissures that developed in the ground at Portage. Some buildings are astride fissures that disturbed foundations and in some instances damaged the buildings. None of the buildings, however, were damaged beyond repair.

Numerous water spouts, some 25 to 30 feet high, occurred in the town during the earthquake. Mr. Larson reported that the water spouts continued for about 2 minutes after the earthquake. The ejected water contained a large amount of silt and sand which mantled the highway and other surfaces after the water had drained away.

Although seismic shaking and resultant ground fissures damaged buildings, the highway, and The Alaska Railroad grade, the subsidence had the most damaging effect. The Portage area had a regional subsidence of slightly more than 5 feet and, in addition, local subsidence of 1½ to 2 feet. Local subsidence was greatest in areas underlain by thick fill, such as the highway roadbed which, in places, subsided more than 3½ feet.

All the area on the map (fig. 28), which prior to the earthquake was above high-tide level, was inundated by the post earthquake high tides. Figure 29, a photograph taken on April 14, 1964, shows the extent of the flooding. Once it became evident to local residents that the town would be flooded continually during extreme high tides, they moved many of the buildings to higher ground—some were moved to Indian, about 20 miles northwest of Portage, on the Seward-Anchorage Highway.



29.—Vertical aerial photograph of Portage area showing extent of inundation by high tides of April 14, 1964. Photograph by Air Photo Tech., Anchorage, Alaska.

PUGET BAY

A small logging camp at the head of Puget Bay on the rugged south coast of the Kenai Peninsula was severely damaged by destructive seismic sea waves that followed the earthquake. The earthquake caused no damage to the cabins at the camp although it broke off the tops of many dead trees, opened numerous fissures across an airstrip built on the outwash train at the bay head, and produced mud spouts, estimated to be 20 to 30 feet high, all along the beach flats near the camp. Numerous landslides and avalanches were triggered on the nearby mountain slopes. One gigantic slide which traveled about 1¼ miles from a 3,931-foot-high peak just west of the camp to sea level with a "deafening roar," partially filled the northwest end of the bay. Sam Hatfield described the shaking as being so violent that he could not walk inside his house trailer, and could only walk with difficulty outside. Streams in the area went dry for about 3 days. Tectonic uplift during the earthquake elevated the land about 5 feet relative to sea level.

According to Mr. Hatfield, a series of waves struck the head of the bay about 20 minutes after the earthquake began. The first wave reached 18 feet above preearthquake mean lower low water on the tectonically raised shoreline; the second one, 10 to 15 minutes later, was a "little smaller"; the third and highest wave, which caused all the damage, came in about 2½ hours after the earthquake. The highest wave reached to an estimated 28 feet above mean lower low water, flooded the entire camp area, and washed away or destroyed about $8,000 worth of logs and machinery.

ROCKY BAY

Rocky Bay is a shallow irregular embayment near the southwestern tip of the Kenai Peninsula. A small logging camp, located on the west side of the bay, is underlain at shallow depth by crystalline rocks, of probable early Mesozoic age.

Strong shaking at Rocky Bay lasted only 1½ minutes and is described as a slow north-south rolling motion with a definite dropping or sinking sensation toward the end of the shake, "as when a plane hits an air pocket" (Guy Branson, oral commun., 1964). The shaking triggered a few avalanches in the surrounding hills but did not even shift the contents of cabins. It "didn't amount to very much," according to Mr. Branson, and was considerably less severe than shaking during an earthquake that was felt for about 1 minute in July 1963. At a cattle ranch on Perl Island, about 12 miles southwest of Rocky Bay, Harley Hess also reported relatively mild tremors with an estimated duration of only 15 seconds.

The earthquake was accompanied by tectonic subsidence of 5 feet at Rocky Bay. The lowered land level adversely affected the logging operations by changing the beach configuration and removing almost all of the beach storage area for logs.

A series of seismic sea waves, described as "fast and quiet tidal surges," without breakers, washed the tectonically lowered shores of the bay. The first wave was about 9 feet high and was preceded by a withdrawal estimated to be about 18 feet. Mr. Branson believes that the first wave crested about half an hour after the earthquake began, although he was not paying much attention to the time of these tidal fluctuations. The highest wave, which came after midnight at about high tide, reached 19½ feet above postearthquake mean lower low water, or about 5 feet above extreme high-tide level. About 70,000 board feet of logs stored on the beach were washed away by the first wave. On nearby Perl Island, the waves inundated low-lying parts of a ranch, drowned nine head of cattle, and washed out some range fencing.

SELDOVIA

Seldovia is an important fishing and cannery center on Seldovia Bay, one of the few ice-free harbors along Cook Inlet, 16 miles southwest of Homer. A small airstrip is east of the city, along a tidal slough that connects Seldovia Lagoon with the bay. The city is built on metamorphosed lower Mesozoic bedrock, and most of the business buildings and docks were strung out along a mile-long boardwalk that skirts the harbor area (see fig. 30).

Virtually all the damage to Seldovia was caused by tectonic subsidence of about 3.5 feet. In contrast to that at many communities on the Kenai Lowland, the shaking at Seldovia was felt for only about 3 minutes and was described by local residents as "mild" or "moderate"; it toppled a few small objects in stores and homes but caused no structural damage.

The sea began to recede and fill erratically during the shaking, but seismic sea waves were not noticed until after 8:00 p.m., 2½ hours after the earthquake. There were several more waves during the night, with the highest, one of 26 feet, coming between 4:00 and 5:00 a.m. on March 28. One of the early waves carried away the floats of the small-boat harbor, and the highest wave inundated part of the boardwalk and damaged stock in a few store buildings.

Long-term damage caused by subsidence was far greater than that caused by seismic sea waves. The boardwalk and all buildings along it became subject to flooding at high tides, as did one end of the airport runway. Breakwaters had to be raised 4 feet to protect the small-boat basin, the damaged floats had to be repaired, and the airport runway raised (Eckel, 1967). Sandbags were used temporarily to protect the boardwalk, and the city dock was raised. Direct costs of compensating for the effect of subsidence amounted to slightly more than $1 million. Later, an urban renewal plan was adopted to restore the entire waterfront by building an extensive dike and filling the land behind it to levels above the postearthquake high tides.

WHIDBEY BAY

A small logging camp is located on a bay-head gravel bar at the head of Whidbey Bay on the south coast of the Kenai Peninsula. Damage there was entirely due to the train of seismic sea waves that followed the earthquake.

Bill Sweeney reported that he timed the duration of strong shaking as 8½ minutes. Seconds before he felt the earthquake, Mr. Sweeney heard the tanker *Alaska Standard*, then at Seward, radio that a violent "tidal" wave had struck the vessel. This report suggests that the submarine slide which generated destructive local waves at Seward was triggered almost instantaneously at the

30.—Seldovia as it appeared in March 1965, with restored inner harbor facilities and breakwaters, piers, and docks raised to compensate for the 3½-foot tectonic subsidence. Photograph by U.S. Army.

onset of the earthquake and that the vibrations were appreciably slower in reaching Whidbey Bay, even though the bay and Seward are about equidistant from the epicenter. The shaking opened fissures in the frozen ground around the camp with sounds described as "like rifle shots." Lateral movement of the beach bar caused a shallow graben 6 feet wide to open near the camp. The valley train at the head of the bay was extensively fissured and mud was ejected over large areas. Creeks reportedly went dry for about 10 days in the upper part of the valley train at the bay head and on the slopes. Numerous landslides and avalanches were triggered on the surrounding rugged mountains with "a noise like thunder." Tectonic uplift during the earthquake elevated the area between 1½ and 2 feet.

Immediately after feeling the earthquake, Sweeney and his family rode their tractor to the safety of nearby high ground in anticipation of seismic sea waves. From this vantage point they observed the first wave move rapidly into the bay and wash the shore to an estimated height of 35 feet above mean lower low water; Sweeney clocked its arrival at 19½ minutes after the initial shock was felt. Water then withdrew for 10 to 12 minutes; the bay bottom was exposed for an estimated mile from shore or about 50 feet below mean lower low water. A second, slightly higher wave then came in "like a big swell" with a loud rumble but no breakers. It washed over portions of the beach bar at the bay head, destroying the camp and everything in it. Smaller waves that came in on the rising tide throughout the night of March 27 and early morning of March 28 did not reach above the extreme high-tide line.

COMMUNITIES OF WESTERN COOK INLET AND THE ALASKA PENINSULA

Most of the communities on the remote Alaska Peninsula and in the northern Aleutian Range are small, widely spaced coastal fishing villages. The earthquake, which was strongly felt throughout the region, caused widespread ground breakage and cracking of ice on the coastal lowlands and in the larger river valleys as far southwest as Ugashik, on the Alaska Peninsula 430 miles southwest of the epicenter (pl. 1). A few small landslides, rockfalls, and avalanches occurred along the mountainous backbone of the Alaska and Aleutian Ranges, and at least one submarine slump was noted in a boat channel at Tuxedni Bay. Damage to structures, most of which are small single-story wood-frame buildings, was negligible. The only property damage reported was at Tyonek and King Salmon.

Vertical tectonic movements in the region, which amounted to less than 1½ feet along the Cook Inlet-Shelikof Strait coast and to no more than a few tenths of a foot on the Bristol Bay coast, caused no noteworthy shoreline changes or property damage. There were no destructive local waves along these coasts, and the seismic sea waves resulted only in erratic tides that nowhere reached above the level of extreme high water.

KING SALMON AND SOUTH NAKNEK

King Salmon, on the west coast of the Alaska Peninsula and nearly 400 miles west of the earthquake's epicenter, was the most distant community that sustained vibration damage. The community, with a population of about 220, is near the mouth of the Naknek River on Kvichak Bay, itself an arm of Bristol Bay. It is primarily a fishing village but is also the center for field stations of the Air Force, Fish and Wildlife Service, and the Federal Aviation Agency. It is chiefly underlain by several hundred feet of morainal and outwash deposits, some of which appear to be fine grained.

According to Wilkie Meleau of the King Salmon Inn, who timed a rolling motion of ground and buildings at 7 minutes, light fixtures swayed, one window and a sewerline were cracked, and a pinball machine registered "tilt," but the ground motion was not strong enough to displace anything from shelves. There reportedly was a temporary power failure at the King Salmon Air Force Base. In nearby South Naknek, pipes laid on the surface were buckled slightly and seiches splashed some diesel fuel from tanks. Little or no effect was noted at any water wells. The earthquake was also felt at numerous villages and canneries around the head of Bristol Bay where ice reportedly was cracked in many places and some ground fissures developed locally.

Residents in Naknek agreed that tides ran a few minutes earlier after the earthquake than before, but their estimates of change in height of tides vary enough to suggest that if there was any tectonic change in land level it amounted at most to a few inches.

TYONEK AND THE WEST COAST OF COOK INLET

Along the western shores of Shelikof Strait and the southern part of Cook Inlet, the mountains of the Aleutian Range and southern end of the Alaska Range rise steeply from the sea. From Tuxedni Bay northward, however, the west coast of Cook Inlet is similar to that of the Kenai Lowland on its east coast, with comparatively low bluffs cut along the edges of a low, nearly flat, fluvioglacial terrane. Seismic sea waves similar to those that wrought much havoc along the eastern shores of the Kodiak group of islands (Plafker and Kachadoorian, 1966) struck these westerly shores. The waves caused rapid tide changes and erratic currents but no damage.

The earthquake was felt at several villages along the coast, with timed durations of from 3 to 5 minutes, but there was little property damage. At Tyonek, Albert S. Kalea, Jr., chief of the village council, reported that the church bell rang upon passage of visible ground waves and that some people heard low rumbling sounds. Ice on a shallow lake oscillated, first in an east-west direction, then north to south. One waterline, buried 8 feet deep, was broken by ground fissures where it crossed swamp deposits near the lake. Unattached articles in homes were shaken, but there was no structural damage, no chimneys fell, and a large water tank on the hill above the village was unaffected. Tyonek is founded on a series of unconsolidated sedimentary deposits, mostly sand and gravel, but containing some clay and silt. The fact that the water table is unusually deep, 58 feet below the surface in the village well, probably accounts for the light damage from seismic vibrations.

In the vicinity of Tuxedni Bay, south of Tyonek, most structures are built on rock or on shallow alluvium over bedrock. At the large Chisik Island cannery and nearby homes, a few objects toppled from shelves but there was no other property damage. According to Joe Fribrock, cannery manager, part of the tidal flat slid into the deep channel, leaving steep scarps. Just south of Tuxedni Bay, the collapse of the roof of a small sawmill put the sawmill machinery out of operation. This property was the most seriously damaged of any along the west coast of Cook Inlet and Shelikof Strait. Mr. and Mrs. George Munger reported that about 40 percent of the beavers near Tuxedni Bay were lost when cracked pond ice pushed their food supply into the mud or actually crushed the animals. The short gravel road between Iliamna Lake and Iliamna Bay was temporarily blocked by a number of small earthquake-triggered landslides.

INLAND COMMUNITIES

The writers visited many of the inland communities after the earthquake, but only Fairbanks, Palmer and Matanuska Valley, and Sutton are discussed here. The other inland towns in which some damage occurred are in the Copper River Basin. Earthquake effects at these towns were summarized by Ferrians (1966).

FAIRBANKS

Fairbanks, the second largest city in Alaska, is in the interior of the State on a broad, flat surface along the Chena River. It is 275 miles north of the earthquake epicenter and predictably experienced only minimal damage.

Most of the Fairbanks area rests upon silt, sand, and gravel with local accumulations of loess and organic debris. Except along the Chena River and local small areas, the sediments are perennially frozen. The thickness of the sediments is unknown, but it may be as much as 300 feet locally. The water table lies close to the surface, and many of the shallow gravel pits contain water. Most small residential wells are no more than 25 feet deep.

Seismic motion at Fairbanks lasted from 4 to 5 minutes; more people reported the lesser figure than the greater one. Motion was of a rolling nature and was chiefly northeast-southwest. The intensity of seismic motion increased gradually and once at its maximum intensity did not vary much. The motion subsided abruptly.

Top Copeland reported seeing ground waves, 4 to 6 inches high, traveling about 10 miles an hour in a northeast direction. He also reported that a parked automobile rolled back and forth 1 to 1½ feet in the same direction.

Relatively little damage was reported at Fairbanks. Shelf goods were shaken, but not toppled. There were some fissures in the ground. At the Alaska Motel, fissures 2 inches wide and 40 feet long developed during the earthquake. One edge of the structure sank about 4 inches, and some slumping occurred in the excavation beneath the motel. Some damage to utilities and to a few concete structures at Fort Wainwright was reported. The water in one 23-foot-deep well in Fairbanks was muddy for about 2 days after the earthquake.

The very light damage experienced at Fairbanks is accounted for by the distance from the earthquake epicenter and by the fact that most of the city is underlain by permafrost, which responds to seismic vibrations much as does solid rock.

PALMER AND THE MATANUSKA VALLEY

Palmer is the principal supply point for the Matanuska Valley agricultural community. It is on the Glenn Highway and The Alaska Railroad, about 48 miles northeast of Anchorage and 75 miles northwest of the epicenter. Although Palmer and other towns in the valley, such as Wasilla, Matanuska, and Sutton, are about the same distance from the earthquake epicenter as is Anchorage, they were virtually undamaged as compared with Anchorage.

Nearly all of the valley is underlain by outwash sand and gravel laid down by the Matanuska River and its ancestral streams. Bedrock crops out in places, and there are some bedrock knobs within the town of Palmer itself; ground moraine forms the surface in places, especially along the sides of the valley. All the outwash material contains much sand and some of it becomes "quick" during well-drilling operations. Most of the gravel particles are pebble sized, with but few cobble-sized stones. The water table is everywhere 10 to several scores of feet beneath the surface of the highly permeable sand and gravel beds (Trainer, 1960).

Eyewitnesses report the earthquake motion in the valley as rolling, principally in northwest-southwest directions. They also report that the motion increased gradually but ceased rather abruptly. Seismic vibration, variously estimated in different towns to have lasted from 3 to 5 minutes, cracked ice on streams and ponds and caused some ground fractures in places. Damage to buildings was minimal. Electric power from the Eklutna hydroelectric plant was interrupted for a period of 18 hours immediately after the earthquake, but this interruption was caused by trouble at the generating plant and by an avalanche that cut the transmission line rather than by damage to the local distribution system (Logan, 1967). No airstrips were damaged. Effects on water wells, most of them minor, are described by Waller (1966b). All the relatively minor damage to manmade structures in Palmer and nearby farms and communities was caused by seismic vibration. The facts that all structures are on coarse gravelly sediments or on bedrock and that ground water is everywhere 10 or more feet beneath the surface probably explains the lack of more serious damage throughout the area.

SUTTON

Sutton, 65 miles northwest of the earthquake epicenter, sustained only slight damage from vibration. The town is about 50 miles northeast of Palmer, on the Glenn Highway and The Alaska Railroad, and is close to the Matanuska River. Its chief importance is as a shipping point for coal from the mines just north of the town.

Like Palmer, Sutton rests on an unknown thickness of outwash deposits consisting of sandy gravel with minor amounts of silt. The coal seams are in a series of conglomerate, sandstone, and shale of early Tertiary age.

The rolling northwest-southeast motion of the earthquake was felt for about 5 minutes; intensity increased with time, but even at its maximum, the vibration was less severe than that at Anchorage. River ice was cracked during the shaking, and some ground fissures formed. As at Palmer, vibration damage to buildings was slight because most of the materials beneath the town are coarse gravelly sediments and because ground water is 10 or more feet below the surface. Several people reported that water in their wells became muddy, and one man reported that the water level in his well fell an unknown amount. The nearby coal mines were virtually unaffected by the earthquake, probably because the coal beds are enclosed by well-indurated rocks.

SUMMARY AND CONCLUSIONS

All of the damage and casualties related to the 1964 Alaska earthquake resulted either directly from earth tremors and tectonic displacements or indirectly from water waves generated by them. Ground motion during passage of seismic waves caused damage to structures primarily through (1) triggering of numerous subaerial and subaqueous landslides, (2) widespread fissuring of underlying unconsolidated deposits caused by differential horizontal or vertical movements, and (3) shaking of some structures. Violent water waves that accompanied most subaqueous slides were a major indirect effect of the earth tremors. Regional vertical tectonic displacements, both upward and downward caused long-term damage to coastal communities and shoreline installations within south-central Alaska directly through changes in their positions relative to the sea and indirectly from the seismic sea waves they generated. In addition, large-scale horizontal tectonic movements may also have generated destructive local waves along the shores of many enclosed or semienclosed water bodies within the deformed region.

GEOLOGIC CONTROL OF VIBRATORY DAMAGE DISTRIBUTION

The intensity of seismic shock and attendant damage to structures varied markedly from place to place, and appeared to be more closely controlled by the local geologic environment than by proximity to the epicenter. In general, it was greatest in areas of thick, water-saturated unconsolidated deposits, least on well-indurated bedrock, and intermediate on Quaternary unconsolidated deposits with relatively low water table or on moderately indurated sedimentary rocks of late Tertiary age. As a consequence, meaningful isoseismal lines based on the Modified Mercalli Intensity scale cannot be drawn within the region of greatest earthquake-induced damage. The generalization that both the intensity and duration of earthquake vibrations are enhanced in unconsolidated ground, particularly in areas of high water table (Gutenberg, 1957), is strikingly borne out by the distribution of the vibration-induced damage.

Significantly, nowhere in the earthquake-affected region was there noteworthy damage to the numerous structures founded on indurated rock or bedrock veneered with thin unconsolidated deposits. At the communities described in this report, damage to structures founded on bedrock was very minor. It consisted of toppling or cracking of unreinforced brick chimneys at Sawmill Bay and Ellamar, a slight settling of one end of the bunkhouse into filled ground at Port Oceanic, and toppling of a stovepipe at Perry Island. Structural damage from seismic shock at Cordova was confined to areas east of the city on the Copper River Delta. No other damage, other than some slight breakage caused by moving about of the contents of buildings occurred at communities on bedrock sites anywhere else in the Prince William Sound epicentral region.

The habitation closest to the epicenter was the home and small hand cannery of Joe Clark at a bedrock site on Fairmont Island just 12 miles from the instrumental center of the earthquake. Yet the only effect of the vibrations there was the breaking of a few dishes that toppled from shelves and of glass ashtrays that were knocked off tables. At the home of Mr. and Mrs. Jerry Clock on Peak Island, only about 25 miles southwest of the epicenter, shaking merely threw three books from the overloaded top shelf of a ceiling-high bookcase and tipped one casserole off a tilted stove top.

Elsewhere in bedrock areas of the Chugach and Kenai Mountains and of the Kodiak group of islands, the effect of the tremors was comparable, even on large buildings of ferroconcrete. At the port of Whittier, 40 miles from the epicenter, there was no structural damage to the very large Buckner Building nor to a large modern steamplant, both of which are founded on bedrock (Kachadoorian, 1965). At other communities on bedrock sites in the southern Kenai Peninsula and the Kodiak group of islands, including the cities of Seldovia and Kodiak, direct vibration damage to structures was negligible. In all these bedrock areas the estimated Mercalli intensities, as based on effects to people and inanimate objects, probably did not exceed VI to VII.

In the Kenai Lowland, on the west shore of Cook Inlet, and in the Matanuska Valley, local structural damage was sustained from direct seismic vibrations at various communities located on late Tertiary sedimentary deposits having relatively low water tables. Thus, shaking in the vicinity of Kenai was strong enough to topple a water tank, to destroy part of the pier and to damage storage tanks at Nikishki, to crack concrete block structures, to topple some chimneys, and to knock items from shelves in almost all stores and homes. Similar minor damage was sustained at Portage, Lawing, Moose Pass, and Homer on the Kenai Peninsula. Most other communities in and around Cook Inlet on comparable foundations, such as Ninilchik, Kasilof, Soldotna, and Tyonek, were undamaged. Structures in Palmer, Wasilla, Sutton, and Matanuska in the Matanuska Valley were also undamaged. Mercalli intensities in such areas, although highly variable, were probably no more than VII, but may have reached VIII in the Kenai area.

The most severe direct vibratory damage to communities described in this report was sustained in areas of water-saturated alluvial deposits, such as the Copper River Delta area east of Cordova and at Girdwood, Hope, and Portage near the head of Turnagain Arm. At these communities, and in previously described communities in comparable geologic settings, damage resulted more from foundation failure than from vibration of structures. At the Cordova FAA station, Girdwood, and Portage, vibratory loading of noncohesive granular deposits during the earthquake resulted in local ground fissuring and foundation damage. Causes of the fissuring are probably diverse and are related to the physical properties of the materials composing each deposit, as well as to its configuration. Fissuring of natural materials and uncompacted fills under vibratory loading in these localities is most probably caused by (1) differential compaction or volume reduction due to closer packing of the constituent grains and (or) (2) varying degrees of liquefaction of saturated incoherent materials with resultant lateral spreading towards free faces. In Girdwood, Hope, Portage, and other coastal communities, additional damage resulted from inundation due to surficial subsidence that accompanied compaction and lateral spreading. The upper limit of Mercalli intensities due to seismic shaking effects on people and structures in areas of saturated unconsolidated deposits ranged between XIII and X.

Translatory block slides, such as the ones at Anchorage (Hansen, 1965) or subaqueous slides of the type that damaged the Homer Spit (Waller, 1966a), Whittier (Kachadoorian, 1965), Valdez (Coulter and Migliaccio, 1966), Lawing (McCulloch, 1966), and Seward (Lemke, 1967), did not cause direct damage at any of the communities discussed here. Waves generated by subaqueous slides, however, probably were the cause of damage and loss of at least one life at Anderson Bay in western Valdez Arm and may have caused some of the wave damage elsewhere in Prince William Sound.

VERTICAL TECTONIC DISPLACEMENTS AND SEISMIC SEA WAVES

Vertical displacements of the land relative to sea level during the earthquake caused extensive long-term damage at several coastal communities described in this report as well as in the Kodiak group of islands (Kachadoorian and Plafker, 1967), Whittier (Kachadoorian, 1965), Homer (Waller, 1966a), and Seward (Lemke, 1967). Tectonic subsidence of 5 to 6 feet, augmented by surficial subsidence of unconsolidated deposits, led to relocation or rebuilding of parts of Hope, Girdwood, and Portage and the transportation routes near these communities. At Seldovia, 3 feet of tectonic subsidence necessitated a costly compensating program of raising waterfront installations. Considerable damage from varying amounts of subsidence was also sustained at smaller coastal communities elsewhere along the coast of the Kenai Peninsula and on the Kodiak group of islands.

Tectonic uplift of the land, most notably in the eastern and southern parts of Prince William Sound and offshore islands of the Continental Shelf, necessitated dredging of harbors and waterways at Cordova and Tatitlek and lengthening of the pier at Cape Hinchinbrook Light Station. Uplift also reduced the usefulness of docks and piers at most smaller communities throughout the affected areas.

The most important and disastrous indirect effect of the vertical tectonic displacements was the generation of a train of destructive seismic sea waves. Of the communities described here, Seldovia, Whidbey Bay, Puget Bay, the Cordova area, and Cape Saint Elias sustained light to moderate property losses and two casualties from these waves. Most of the damage from seismic sea waves in Alaska, however, was to the various communities along the seaward coast of the Kodiak group of islands (Kachadoorian and Plafker, 1967) and at Seward (Lemke, 1967).

LOCAL WAVES AND SUBAQUEOUS SLIDES

Major damage and casualties to coastal communities resulted from violent local waves that struck during or immediately after the earthquake at numerous localities in Prince William Sound, Resurrection Bay, and Aialik Bay. Of the communities described here, local waves were the main cause of destruction at Anderson Bay, Chenega, Port Oceanic, Port Nellie Juan, Nowell Point, Perry Island, Sawmill Bay, and Latouche. Comparable waves, some of them clearly generated by subaqueous slides of unconsolidated deposits, also caused most of the damage at the ports of Valdez (Coulter and Migliaccio, 1966), Whittier (Kachadoorian, 1965), and Seward (Lemke, 1967), and at places along the shore of Kenai Lake (McCulloch, 1966).

Subaqueous slides and related destructive local waves are known or inferred to have occurred at localities along the shores of Prince William Sound, the southern Kenai Peninsula, and Kenai Lake (pl. 2). Another slide destroyed the boat harbor at Homer Spit in Kachemak Bay, but it was accompanied by only relatively minor water disturbances (Waller, 1966a). At Seward, Whittier, Valdez, and along the shore of Kenai Lake, subaqueous slides carried away segments of the waterfronts, and waves generated by the moving slide masses compounded the damage. The sequence of events reported by eyewitnesses at Seward and Thumb Cove in Resurrection Bay, at Lawing on Kenai Lake, and at Valdez clearly demonstrates (1) the instability of saturated unconsolidated deposits on steep slopes under seismic shock and (2) the ability of such slides to generate destructive waves.

Shoreline damage that occurred along uninhabited segments of the shore of Kenai Lake, Aialik Bay, Kings Bay, Blackstone Bay, and western Valdez Arm (pl. 2) is comparable in all major respects to that which accompanied known subaqueous slides. At these localities, subaqueous sliding is suggested by one or more of the following lines of evidence: (1) a pattern of wave damage that radiates outward from the vicinity of deltaic or morainal deposits, (2) subaerial scarps or oversteepened nearshore slopes on the unconsolidated deposits, and (3) differences between pre- and post-earthquake bathymetry indicative of removal of material from the upper portion of deltas or moraines and of deposition of slide debris in deeper water. Only the wave damage at Anderson Bay and adjacent shorelines in western Valdez Arm, of the communities discussed in this report, can be confidently attributed primarily to subaqueous slides on the basis of the criteria outlined above.

At all other communities where local waves were the major cause of damage, no subaqueous or subaerial slide source for the waves was identifiable. Conceivably, widespread damage along the shores of steepsided deep fiords such as at Chenega, Point Nowell, Port Nellie Juan, and Latouche could have been generated by sliding of submarine moraine-outwash complexes that may have been perched along fiord walls. However, wave damage at some of these communities, such as Sawmill Bay and Port Oceanic, which are situated in shallow embayments or semienclosed basins, are difficult to attribute to such an origin. Furthermore, although regional tilt, submarine faulting, or seismic vibrations may have contributed to the water disturbances, none of these phenomena either alone or in combination could have caused waves as large as those observed.

A possible alternative mechanism for at least some of the water disturbances is that they were generated by inertial effects of the water bodies as the landmass was tectonically displaced horizontally beneath them in a relative southward to southeastward direction (Plafker, 1969). The magnitude of such displacements in the Prince William Sound region, as indicated by retriangulation data, increases progressively from about 20 feet near Whittier in the northern part of the sound to more than 60 feet near Sawmill Bay and Latouche in the southern part. It is suggested that the horizontal movements, if they occurred fast enough, may have been either the primary or a contributing cause to local waves of unknown origin that devastated smaller communities and uninhabited shores around Prince William Sound and elsewhere in the earthquake-affected region. This suggested origin for the waves is consistent with (1) their sudden onset during or immediately after the earthquake, (2) the favorable orientation and configuration of affected shorelines, and (3) their occurrence in an area of large horizontal displacements.

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 542

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GEOLOGICAL SURVEY

William T. Pecora, *Director*

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[Letters designate the separately published chapters]

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