The Alaska Earthquake
March 27, 1964

Effects on Communities

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

Seward

GEOLOGICAL SURVEY PROFESSIONAL PAPER 542-E

This page intentionally left blank

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

Effects of the Earthquake Of March 27, 1964, At Seward, Alaska

BY RICHARD W. LEMKE

A description and analysis of the damage resulting from submarine landsliding, seismic sea waves, and oil-tank fires in one of the most devastated cities in Alaska

GEOLOGICAL SURVEY PROFESSIONAL PAPER 542-E

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1967

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

EFFECTS OF THE EARTHQUAKE OF MARCH 27, 1964 AT SEWARD, ALASKA

Fishing boat beached several hundred feet inland from the head of Resurrection Bay by seismic sea waves.

THE ALASKA EARTHQUAKE SERIES

The U.S. Geological Survey is publishing the results 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: Anchorage (542–A), Whittier (542–B), Valdez (542–C), Homer (542–D), and Seward (542–E); other chapters are in preparation on Kodiak and on several smaller communities. Other professional papers describe the regional effects of the earthquake; the effects on the hydrologic regimen; the effects on transportation, communications, and utilities; and the history of the field investigations and reconstruction effort.

CONTENTS

ILLUSTRATIONS

PLATES

[In pocket]

FIGURES

EFFECTS OF THE EARTHQUAKE OF MARCH 27, 1964, AT SEWARD, ALASKA

By Richard W. Lemke

ABSTRACT

Seward, in south-central Alaska, was one of the towns most devastated by the Alaska earthquake of March 27, 1964. The greater part of Seward is built on an alluvial fan-delta near the head of Resurrection Bay on the southeast coast of the Kenai Peninsula. It is one of the few ports in south-central Alaska that is ice free all year, and the town's economy is almost entirely dependent upon its port facilities.

The Alaska earthquake of March 27, 1964, magnitude approximately 8.3–8.4, began at 5:36 p.m. Its epicenter was in the northern part of the Prince William Sound area; focal depth was 20–50 km.

Strong ground motion at Seward lasted 3–4 minutes. During the shaking, a strip of land 50–400 feet wide along the Seward waterfront, together with docks and other harbor facilities, slid into Resurrection Bay as a result of large-scale submarine landsliding. Fractures ruptured the ground for several hundred feet back from the landslide scarps. Additional ground was fractured in the Forest Acres subdivision and on the alluvial floor of the Resurrection River valley; fountaining and sand boils accompanied the ground fracturing. Slide-generated waves, possibly seiche waves, and seismic sea waves crashed onto shore; wave runup was as much as 30 feet above mean lower low water and caused tremendous damage; fire from burning oil tanks added to the destruction. Damage from strong ground motion itself was comparatively minor. Tectonic subsidence of about 3.5 feet resulted in low areas being inundated at high tide.

Thirteen people were killed and five were injured as a result of the earthquake. Eighty-six houses were totally destroyed and 269 were heavily damaged. The harbor facilities were almost completely destroyed, and the entire economic base of the town was wiped out. The total cost to replace the destroyed public and private facilities was estimated at $22 million.

Seward lies on the axis of the Chugach Mountains geosyncline. The main structural trend in the mapped area, where the rocks consist almost entirely of graywacke and phyllite, is from near north to N. 20° E. Beds and cleavage of the rocks commonly dip 70° W. or NW. to near vertical. Locally, the rocks are complexly folded or contorted. No major faults were found in the mapped area, but small faults, shear zones, and joints are common.

Surficial deposits of the area have been divided for mapping into the following units: drift deposits, alluvial fan deposits, valley alluvium, intertidal deposits, landslide deposits, and artificial fill. Most of these units intergrade and were deposited more or less contemporaneously.

The drift deposits consist chiefly of till that forms moraines along the lower flanks of the Resurrection River valley and up tributary valleys. The till is predominantly silt and sand and lesser amounts of clay-size particles, gravel, cobbles, and boulders. Glacial outwash and stratified ice-contact deposits constitute the remainder of the drift deposits.

Fans and fan-deltas have been deposited at the valley mouths of tributary streams. Some, including the one upon which Seward is built, project into Ressurrection Bay, and deltaic-type deposits form their distal edges. The larger fans—composed chiefly of loosely compacted and poorly sorted silt, sand, and gravel—form broad aprons having low gradients. The fan deposits range in thickness from about 100 feet to possibly several hundred feet and, at least in some places, lie on a platform of compact drift. Smaller fans at the mouths of several canyons have steep gradients and considerable local relief.

Valley alluvium, deposited chiefly by the Resurrection River, consists mostly of coarse sand and fine to medium gravel. In the axial part of the valley it is probably more than 100 feet thick. Near the head of Resurrection Bay, the alluvium is underlain by at least 75 feet of marine deltaic sediments, which are in turn underlain by 600 or more feet of drift in the deepest part of the bedrock valley.

Beach, deltaic, and estuarine sediments, deposited on intertidal flats at the head of the bay and along fan margins that extend into the bay, are mapped as intertidal deposits. They consist mostly of silt, sand, and fine gravel, and lesser amounts of clay-size particles.

The earthquake reactivated old slides and trigged new ones in the mountains. Rock and snow avalanches, debris flows, and creep of talus deposits characterized slide activity on the steeper slopes.

The Seward waterfront had been extended before the earthquake by adding artificial fill consisting of loose sand and gravel; part of the lagoon area had been filled with refuse. After the earthquake, fill, consisting of silt and sand dredged from the head of the bay, was pumped onto part of the lagoon area and also on land at the northwest corner of the bay.

Response to the disaster was immediate and decisive. City, State, and Federal agencies, as well as other or-

232-728 O—67——2

ganizations and individuals, gave unstintingly of their time and facilities. Within a few days, there was temporary restoration of water, sewerage, and electrical facilities.

The U.S. Army Corps of Engineers was authorized to select sites and construct a new dock for the Alaska Railroad, a new small-boat basin, and related facilities. The firm of Shannon and Wilson, Inc., under contract to the Corps of Engineers, investigated subsurface soils extensively to determine the factors responsible for the sliding along the Seward waterfront and to assist in site selection for reconstruction of the destroyed harbor facilities. Borings were made along the Seward waterfront and at the head of the bay, and laboratory tests were conducted on pertinent samples. These studies were augmented by geophysical studies both on land and in the bay. In addition, the Corps of Engineers made shallow borings on the intertidal flats at the head of the bay and performed pile-driving and load tests. Borings also were drilled and test pits were dug in the subdivision of Forest Acres.

Sliding along the Seward waterfront markedly deepened the water along the former shoreline. Postearthquake slopes of the bay floor immediately offshore also are steeper in places than before the earthquake. The strong ground motion of the earthquake triggered the landsliding, but several factors may have contributed to the magnitude and characteristics of the slides. These factors are: (1) the long duration of strong ground motion, (2) the grain size and texture of the material involved in the sliding, (3) the probability that the finer grained materials liquefied and flowed seaward, and (4) the added load of manmade facilities built on the edge of the shore. Secondary effects of the slides themselves—sudden drawdown of water, followed by the weight of returning waves—also may have contributed to the destruction.

Submarine sliding at the northwest corner of the bay occurred in fine-grained deltaic deposits whose frontal slopes probably were in metastable equilibrium under static conditions. Uplift pressures from aquifers under hydrostatic head, combined with the probable liquefaction characteristics of the sediments when vibrated by strong ground motion, probably caused the material to slide and flow seaward as a heavy slurry.

Under static conditions, no major shoreline or submarine landsliding is expected in the Seward area; in the event of another severe earthquake, however, additional sliding is likely along the Seward waterfront and also in the deltaic deposits at the northwest corner of the bay. Fractured ground in back of the present shoreline along the Seward waterfront is an area of incipient landslides that would be unstable under strong shaking. For this reason the Scientific and Engineering Task Force placed the area in a high-risk classification and recommended no repair, rehabilitation, or new construction in this area involving use of Federal funds; it was further recommended that the area should be reserved for park or other uses that do not involve large congregations of people. The deltaic deposits at the head of the bay probably also would be susceptible to sliding during another large earthquake. This sliding would result in further landward retreat of the present shoreline toward the new railroad dock. Specifications for the new dock, whose seaward end is now approximately 1,100 feet from the back scarp of the subaqueous landslide, require design provisions to withstand seismic shock up to certain limits.

Earthquake-induced fracturing of the ground in the subdivision of Forest Acres was confined to the lower part of a broad alluvial fan. There, sewer and water lines were ruptured and the foundations of some homes were heavily damaged. Landsliding, such as occurred along the shoreline of the bay, was not a contributing cause of the fracturing. Two hypotheses are offered to explain the fracturing:

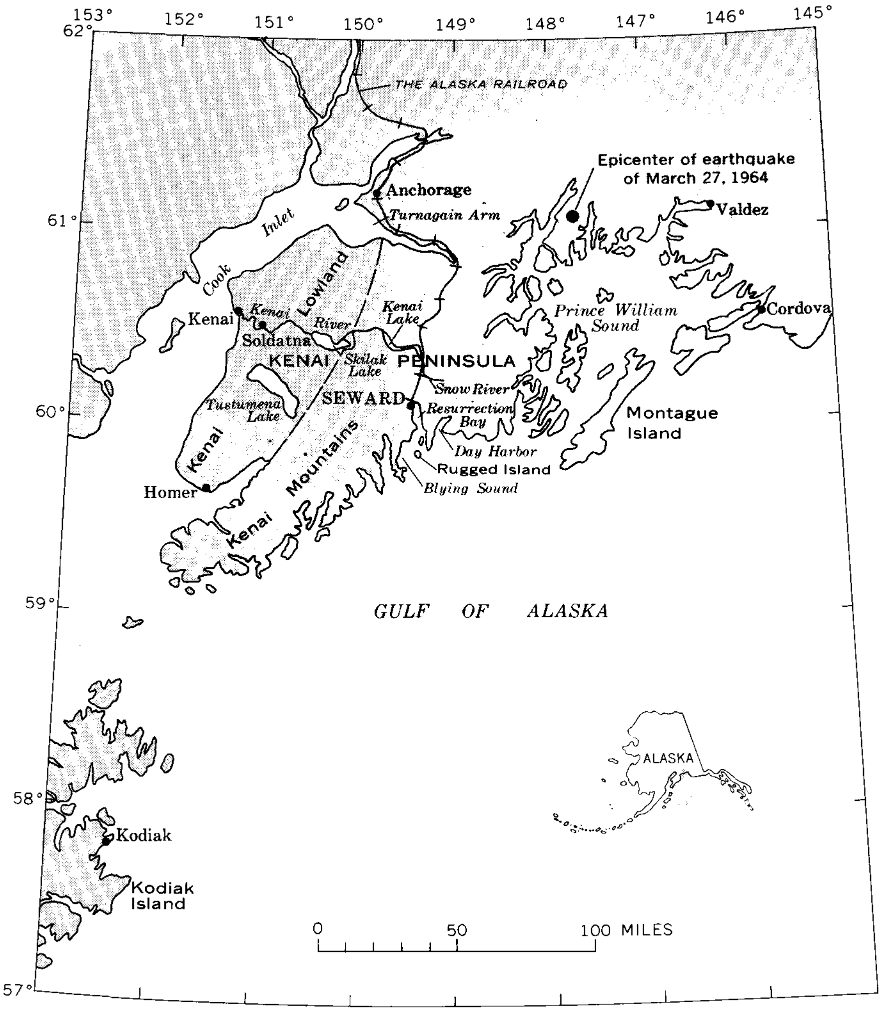
1. Seismic energy was transformed into visible surface waves of such amplitude that the strength of surface layer was exceeded and rupturing occurred; tensional and compressional stresses alternately opened and closed the fractures and forced out water and mud.
2. Compaction by vibration of the fine-grained deposits of the fan caused ground settlement and fracturing; ground water under temporary hydrostatic head was forced to the surface as fountains and carried the finer material with it.

Water waves that crashed onto shore, while shaking was still continuing, were generated chiefly by onshore and offshore landsliding. Waves that overran the shores about 25 minutes after shaking stopped and that continued to arrive for the next several hours are believed to be seismic sea waves (tsunamis) that originated in an uplifted area in the Gulf of Alaska. During the time of seismic sea-wave activity and perhaps preceding it, seiche waves also may have been generated within Resurrection Bay and complicated the wave effects along the shoreline.

INTRODUCTION AND ACKNOWLEDGMENTS

Seward was one of the cities most heavily damaged by the great Alaska earthquake of March 27, 1964. The city is near the head of Resurrection Bay, on the southeast coast of the Kenai Peninsula, and about 75 airline miles south of Anchorage (fig. 1; pl. 1). The climate is mild and humid because of the influence of the Gulf of Alaska, and Seward is one of the few ports in south-central Alaska that is ice free the entire year. It therefore provides year-round access from the coast by railroad and highway to Anchorage and the interior of Alaska.

Before the earthquake of March 27, 1964, the economy of Seward was based mostly on shipping. Freighters, barges, tankers, and fishing boats docked regularly in the harbor. Most of the freight was transhipped to other communities by road or rail. Texaco, Inc., and the Standard Oil Co. of



1.—Index map, Seward and the Kenai Peninsula.

California had established large tank farms on the waterfront. Fishing boats unloaded their catch, and at least one cannery was in operation.

The entire economic base of the town was wiped out by the near-total destruction of harbor facilities during the earthquake. Damage was caused chiefly by shoreline and offshore landsliding and by locally generated waves, seismic sea waves, and fire. A tectonic downdrop of approximately 3.5 feet caused formerly dry low areas to be covered by water at high tide.

This paper describes the effects of the earthquake at Seward and relates them to engineering geologic applications. The physical properties of the geologic units, as they affect manmade structures, are emphasized. The aim of the paper, therefore, is not only to describe the geologic conditions that caused structures to fail during the earthquake but also to record other geologic conditions in the area so that future facilities can be so planned and located that they will undergo minimal damage in the event of another severe earthquake.

The writer gratefully acknowledges many sources of information. Federal, State, and City organizations, contractors, and many local individuals gave complete cooperation. One of the most helpful single sources of information was the consulting firm of Shannon and Wilson, Inc., (of Seattle, Wash.), which was under contract to the Corps of Engineers. Their report (Shannon and Wilson, Inc., 1964) on the subsurface investigation for the city of Seward and vicinity contains valuable data derived from borings, samplings, soil testing, test pits, and seismic surveys. The writer worked closely with representatives of this firm during their field investigations. Information and ideas, freely interchanged, permitted maximum and timely use of the information.

Information was also interchanged between representatives of the Corps of Engineers and the writer. The outstanding cooperation of John A. Spangler, Resident Engineer at Seward for the Corps of Engineers and of his staff is particularly acknowledged. Mr. Spangler provided office space and generous assistance in many other ways.

City officials of Seward, especially Perry Stockton, Mayor, J. W. Harrison, City Manager, and his successor, Fred Waltz, also cooperated in every way possible. In spite of extremely heavy demands upon their time, they willingly lent assistance whenever asked.

Many individuals provided their own observations of the earthquake. Without these accounts, the sequence of events during and after the earthquake could not have been reconstructed.

Robert D. Miller of the U.S. Geological Survey assisted the writer for a week when ephemeral earthquake-produced features were being mapped.

THE EARTHQUAKE AND ITS EFFECTS

The Alaska earthquake of March 27, 1964, began at 5:36 p.m., local time. The epicenter of the main shock was determined as lat 61.1° N. and long 147.7° W. ±15 km (U.S. Coast and Geodetic Survey, written commun., 1965), near Unakwik Inlet in the northern part of Prince William Sound, and approximately 95 airline miles northeast of Seward (fig. 1). A Richter magnitude of approximately 8.3–8.4 has been assigned, and the focal depth has been calculated as 20–50 km.

The events that took place during and immediately after the main shock at Seward were reconstructed from eyewitness reports. The writer interviewed more than 100 individuals and studied written accounts that had already been obtained by others; the report by Lantz and Kirkpatrick (1964) was especially useful. The chronology of events, however, must be regarded as approximate because few individuals looked at their watches until late that night or the following day. In an attempt to determine this chronology as accurately as possible, the writer estimated how long it would take an individual to complete various actions, such as running three blocks or driving a car a certain distance, that observers did between the occurrences of reported events.

Strong ground motion at Seward, which was in a north-south direction at least part of the time, lasted 3–4 minutes. Nearly all accounts indicate that the shaking started gently but increased markedly in a few seconds and continued to grow in violence until people could hardly stand without support. Reportedly the ground rose and fell like waves, trees bent in unison, and buildings swayed back and forth. Two gantry cranes at The Alaska Railroad dock bounced off their tracks and into Resurrection Bay, and automobiles rocked from side to side. Several chimneys fell, windows were broken, and foundations were cracked in various parts of the city. The Seward city hall was damaged beyond repair by shaking, but the building is said to have been in poor condition before the earthquake. Some other public buildings were damaged to some extent by shaking. Material on shelves tumbled to the floor, and glassware breakage, in such places as bars and liquor stores, was heavy. Water and sewer lines were ruptured in several parts of the city and in Forest Acres subdivision.

Almost as soon as shaking started, rocks began falling from some of the steeper valley walls. As shaking continued, rock slides were triggered in Jap Creek canyon and Box Creek canyon. Snow avalanched down the walls of Lowell Creek canyon and of several tributary valleys.

The more extensive and spectacular effects of the earthquake, however, were along the Seward waterfront. Between 30 and 45 seconds after violent shaking began, the distal part of the Seward fan, an area extending from the Standard Oil Co. dock to beyond the San Juan dock, began sliding seaward as a result of large-scale offshore landsliding. Slice after slice of ground along the shore slid progressively as shaking continued, until a strip of harbor area 50–500 feet wide had disappeared into the bay (fig. 2, p. 6). Large fractures broke the ground surface behind the slide area and extended several hundred feet inland as shaking continued (figs. 3, 4, p. E8, E10). Some fractures near the Texaco tanks reportedly opened and closed repeatedly during the shaking; some were at least 20 feet deep. They filled quickly with water and, as the shaking continued, spewed muddy water at intervals. When the shaking ceased, fracturing had reached its maximum extent and the shoreline had receded to the position shown in figure 2 (bottom).

Pipes and valves of the tanks at the Standard Oil Co. dock began rupturing 30–45 seconds after shaking started, and fuel poured from the tanks. As the tanks began to overturn and slide into the bay, they exploded with a roar, and flames leaped 200 feet into the air. Water, displaced by landsliding, receded rapidly from the shore carrying burning fuel on its surface. A tanker unloading at the Standard Oil Co. dock reportedly hit bottom when the water level suddenly dropped 15–20 feet. In the small-boat harbor north of San Juan dock, the *Unga* also hit bottom; from the known former depth of water in the harbor and the draft, the withdrawal there must have been at least 7 feet vertically.

As the water was displaced suddenly from the shore, a large mound of water formed several hundred yards out in the bay and in line between the Standard Oil Co. tanks and Fourth of July

Point. Waves radiated in all directions from this mound, but predominantly in two directions: one toward the Seward waterfront and Lowell Point, the other toward the head of the bay. Both caused much damage.

The wave moving toward Lowell Point overran the northeast corner of that fan approximately 1 minute and 15 seconds after shaking started, or about half a minute after the landsliding started in the Standard Oil Co. dock area. It was estimated to be 30 feet high, as it approached Lowell Point, and was free of debris until it hit the shore, where it churned up much sand and silt; burning oil covered its surface halfway to Lowell Point. The wave swept several hundred feet inland and caused much destruction, totally demolishing a nearly completed marineway and smashing heavy earthmoving equipment, trucks, and other objects against trees or twisting them into wreckage.

The water surged back from the mound toward the southwest part of the Seward waterfront also. A large swell broke over The Alaska Railroad dock area (fig. 5, p. 12), lifting flat cars off the tracks and picking up several vehicles. Its crestline at Railroad Avenue was nearly as high as that of any later wave. As this wave hit the shoreline at the Standard Oil Co. tanks, burning oil was carried back onto shore. An 80-car freight train on the tracks between the Standard and Texaco tanks was just ready to start moving north. Its last 40 cars were filled oil tankers and as the fire swept onto shore, the tankers caught fire in a chain reaction of exploding cars down the track toward the Texaco yard. Reportedly several minutes elapsed before the Texaco tanks caught fire, even though oil from ruptured tanks had already spread over the surrounding area.

While this large wave was moving toward the Seward waterfront and Lowell Point, the other large wave from the mound of water offshore from the Standard Oil Co. tanks swept toward the head of the bay, swirling and boiling as it moved. As it neared shore, it broke up into several secondary waves, and much sand and silt were churned to the surface. This complex wave pattern was presumably due not only to the sliding along the edge of the Seward fan but also to sliding of deltaic deposits at the head of the bay. As wave crests reached the small-boat harbor, moored boats were lifted over the breakwater. A few were carried over the railroad embankment into the lagoon area, but most were first driven wildly to-and-fro in the northwest corner of the bay and then beached at the head of the bay. At about the time the first returning wave hit the small-boat harbor, the Army dock was lifted by a wave and then dumped into the bay. Although these early waves caused heavy damage, they did not attain the heights reached by later waves that arrived after the shaking stopped. Many people, who left the downtown area as soon as the shaking ceased, were able to travel on the highway across the lagoon and they noted only small amounts of debris on and adjacent to the road. Later the road was completely blocked by houses, boats, railroad cars, and other debris carried in by subsequent waves.

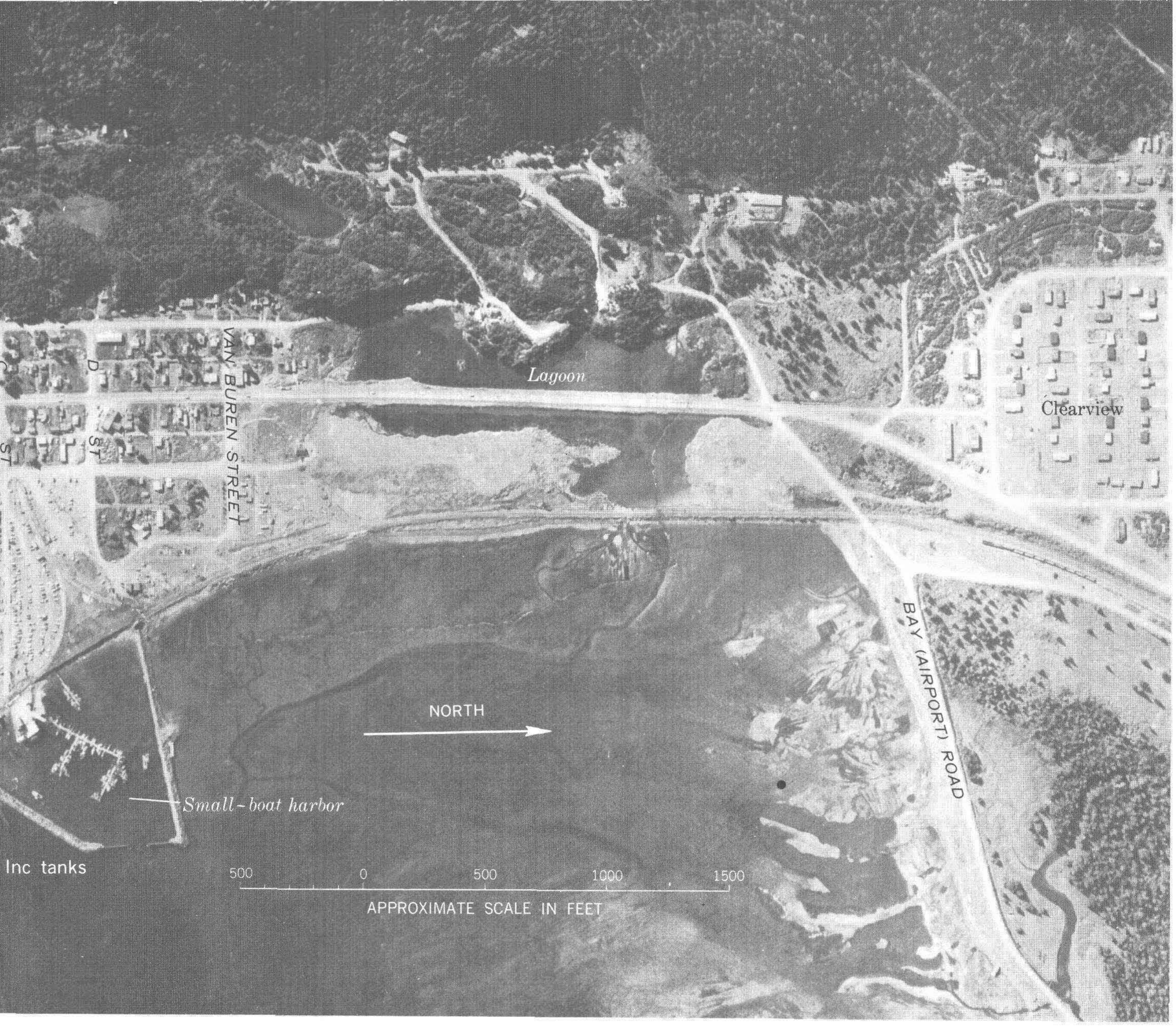
After strong ground motion had ceased and before the first seismic sea wave arrived, at least two additional waves swept the Seward waterfront. Water continued to slosh back and forth in the bay for at least 15 minutes following the quake. Near the head of the bay, swirling and boiling continued, actuated either by continued submarine sliding of deltaic deposits or possibly by seiche action. Some boats, which had been lifted out of the small-boat harbor by the first waves, are reported to have been quiet for as long as a minute as the water calmed, only to be driven wildly about as the water again began to churn. This pattern was repeated many times before the boats were finally driven onto land.

Fires ignited during the shaking continued to burn intensely after shaking had ceased, and new ones were started as explosions periodically ripped the waterfront. Burning oil and combustible debris covered most of the water surface from beyond the south end of Seward to the head of the bay. Without water (because of broken mains), the efforts of firemen and volunteers were largely futile. Had not a gentle wind been blowing eastward across the bay, the entire town probably would have burned. Most people thought the town was doomed either by fire or by expectable "tidal" waves. Some rushed in cars across the lagoon area, but most made their way to the hospital, which was at the head of the fan, on the highest ground they could reach.

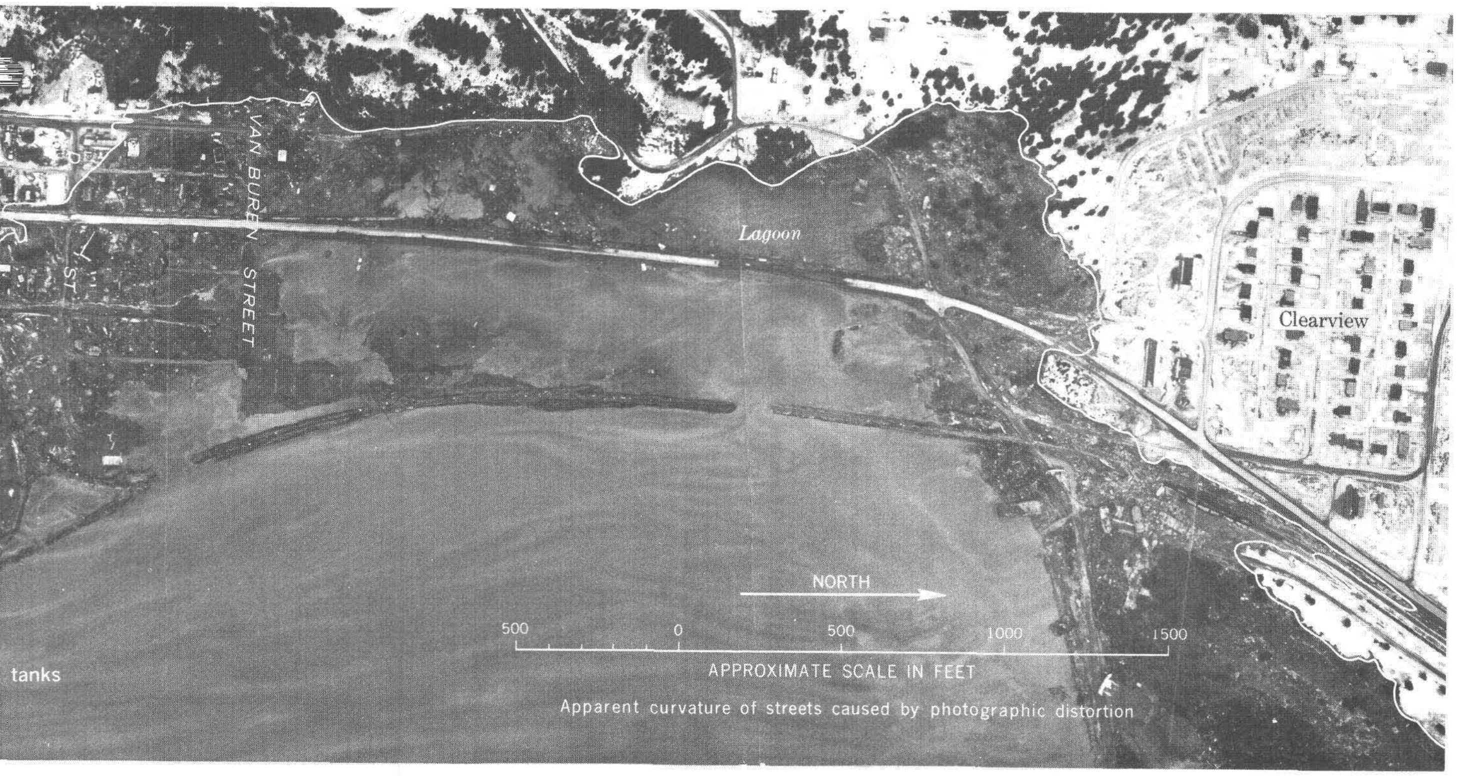
The arrival time of the first seismic sea wave from outside the Seward area is conjectural. Several people witnessed the wave's arrival, but none noted the time. By estimating the time that it would take these observers to perform a series of activities after shaking stopped and before the wave hit, it is concluded that the wave arrived between 20 and 30 minutes after shaking stopped; 25 minutes is the closest approximation that can be made.

The first seismic sea wave is reported to have spanned the width

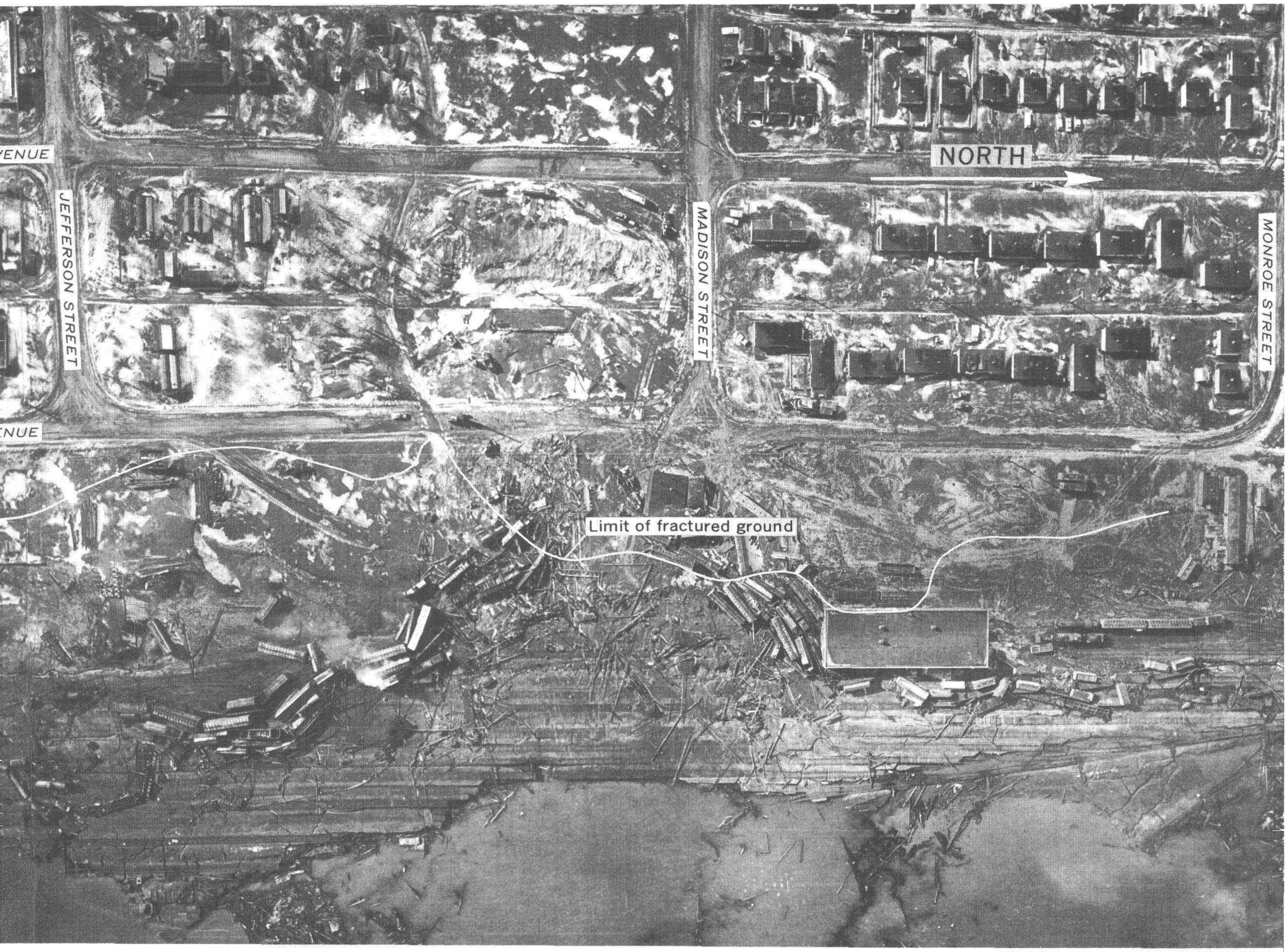
2. Seward before and after the earthquake. Top, before the earthquake of March 27, 1964. Bottom, 1 day after the earthqu



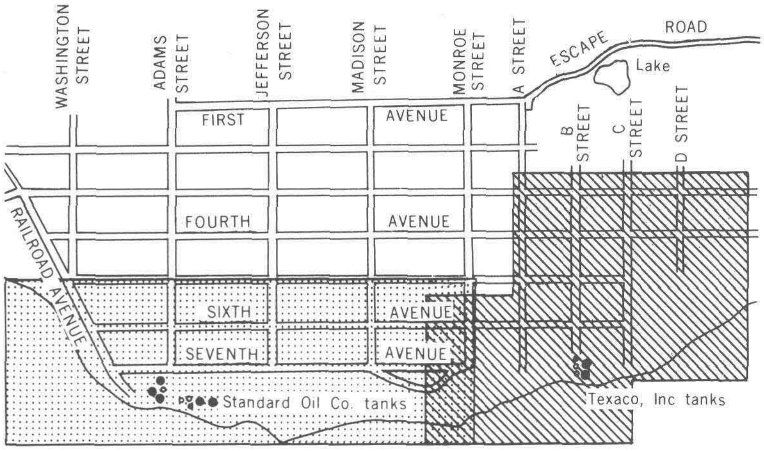
rch 27, 1964. Photographs by the U.S. Army, Corps of Engineers; mosaicked by the U.S. Geological Survey.



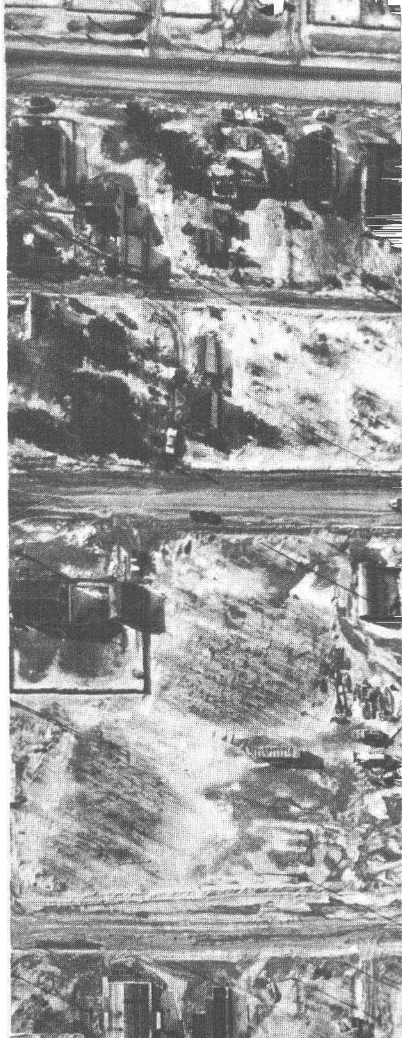
3. Aerial view of the southern part of the Seward waterfront showing extent of ground fracture and earthquake damage. Photogr



y U.S. Army; mosaicked by U.S. Geological Survey. See figure 4 (next page) for view of northern waterfront and index map.



Index map showing relation of figures 3 and 4. Stippled area is figure 3, hachured area figure 4.



4. Aerial view of the northern part of the Seward waterfront showing extent of fractured ground and earthquake damage. Photograph by U.S. Army; mosaicked by U.S. Geological Survey. Index map (upper left) shows relation of figures 3 and 4.

of the bay as it entered the Seward area and to have been 30–40 feet high as it neared the head of the bay. Burning oil covered much of its surface. Carrying boats, houses, and railroad cars collected from the Seward waterfront area, the wave crashed over the railroad embankment into the lagoon area and moved inland at the head of the bay. Debris was piled so high on the road across the lagoon that it blocked all motorized exit from town. At the airport, a wall of water rushed part way up the airstrip at an estimated speed of 50–60 miles per hour. The wave was reportedly accompanied by a rumbling sound like the noise of a fast-moving freight train and by a terrific rush of air at its front as it overran the land. There is general agreement that this wave extended farther inland at Seward and at the head of the bay than any of the earlier locally generated waves; it also inundated a larger part of Lowell Point than earlier waves. Its maximum runup, however, apparently was not as great as that of at least one of the later waves.

5.—Damage caused by water waves to old Alaska Railroad dock and facilities. Photograph by U.S. Army.

Several other large waves followed the first seismic sea wave. Information on the number, height, and periodicity of these waves is fragmentary. There are accounts of waves arriving at about half-hour intervals until 11:00 p.m.; the last wave in the Seward area, however, was reported to have arrived at about 4:20 a.m., March 28. The third seismic sea wave was probably the largest, but most of the destruction had already been done by he earlier waves. Fires burning on the surface of the bay were extinguished several times by incoming waves, only to start anew as burning oil poured out along the waterfront.

Water apparently withdrew from the shores in the intervals between the seismic sea waves, but there is no indication that the water receded immediately before the first wave. According to one report, at approximately 9:45 p.m. the surface of the bay near the site of a former cannery (on the road to Lowell Point just south of the railroad dock) was 40 feet below mean lower low water. The floor of the bay at the end of the cannery dock was reported to have been exposed.

The maximum extent of the waves in Seward and at the head of the bay shown in figure 2 and on plate 1 represent the maximum runup reached by one or more waves and, therefore, represent the composite pattern of the wave action. Eyewitnesses agree generally that the third seismic sea wave was the highest, but other waves may have been locally higher.

Heights of wave runup in different parts of Seward are shown below. The altitudes, based upon a detailed topographic map made after the earthquake, are in feet above mean lower low water; however, the preearthquake datum, approximately 3.5 feet higher than present land level, was used on plate 1.

Wave runup (feet)	*Location*
24	First St., south end.
25	Depot, Railroad Ave.
26	Fifth St., south end.
28	Adams St., east end.
31	Jefferson St., east end.
31	Madison St., east end.
29	Monroe St., east end.
28	A St., east end.
28	B St., east end.
29	C St., east end.
26	D St., east end.
30	Second St., north end.

At Lowell Point the position of scars on trees and the directions in which debris was carried inland indicate that at least three waves from three different directions ran up onshore. The first wave, generated by landsliding offshore from the Standard Oil dock, hit the northeast corner of Lowell Point. Debris carried by this wave was lodged several hundred feet inland and approximately 30 feet above mean lower low water. A second wave hit the southern end of Lowell Point and carried debris in a northerly direction to approximately the same altitude. A third wave overran the shore at the eastern end of Lowell Point and moved westward. It apparently did not move inland as far as the other two waves, but heavy tree growth may have dissipated the wave's energy. Whether more than one wave hit the shore in each direction cannot be ascertained. One eyewitness account states that a larger second wave hit Lowell Point less than an hour after the first wave, but exactly where is not made clear.

Debris lines several hundred feet or more inland marked the limit reached by waves on Fourth of July Point. The number of waves and the direction they traveled onto this fan are difficult to reconstruct. Manmade structures or other points of reference are largely lacking. Debris brought in by waves was found, however, at a height of 25 feet above mean lower low water, and in places waves may have reached greater heights.

LOSS OF LIFE AND DAMAGE TO MANMADE STRUCTURES

Thirteen people were killed and five injured in and near Seward as a result of the earthquake. Most of the 13 were killed by wave action. One man was killed by an incoming wave about 10:30 p.m. as he was helping to clear debris off the highway in the lagoon area to open an escape route out of town. Three bodies were never found.

6.—Earthquake damage along Seward waterfront in area of Texaco, Inc., tanks. Photograph by U.S. Army.

Harbor facilities in the waterfront area between the Standard Oil and Texaco tanks were almost completely destroyed, and other parts of the waterfront were heavily damaged (fig. 6). The Standard Oil dock, 13 oil tanks, the Army dock, and the San Juan dock, on which a cannery was located, disappeared completely into the bay. Several Texaco tanks were destroyed by fire.

The Alaska Railroad dock at the south end of town was almost totally destroyed by wave action and shaking (fig. 5). Sheet piling cells, upon which the main dock was constructed, split open and dropped the front of the dock into the bay. Much of the adjacent auxiliary dock and the warehouse on it were also destroyed, chiefly by waves. A cannery and small dock just to the south along the road to Lowell Point were crushed by one of the first waves and disappeared into the bay.

The railroad marshalling yards were left a tangled mass of wreckage by wave action and fire (fig. 7, next page). Railroad cars, many of them filled with cargo, were moved at least 100 feet and heaped in windrows by the waves. Twisted rails and overturned locomotives attested to the energy of the waves.

Eighty-six houses were totally destroyed and 269 were heavily damaged (James W. Harrison, Mayor, oral commun., 1964); water waves caused nearly all the destruction. Homes in the area between the Texaco tanks and the lagoon were swept completely off their foundations, and most were washed into the lagoon (fig. 8, p. 15).

Earthquake damage in the outlying areas was less severe. There was little damage in the Clearview subdivision except at the Jesse Lee Home where shaking toppled a chimney and damaged a large building reported to have been in poor structural condition before the quake. In Forest Acres, sewer and water mains were broken by ground fracturing. Foundations and floor joists of several homes were heavily damaged, but most of the structural elements were repairable. At Lowell Point, a nearly completed marineway and its construction equipment were totally destroyed. The few houses that were in the path of the water waves on that fan also were completely demolished. The old freight-line dock and warehouse

7.—Wave damage in the area of railroad marshalling yards.

on the east side of the bay across from Seward were heavily damaged. A lumber mill at the northeast end of the bay was heavily damaged by wave action, as were all the houses in the Crawford subdivision just north of the old Signal Corps building (still largely intact). Several ground fractures cut the airstrip, but it was used immediately even though one end, lowered by tectonic subsidence, was washed by high tides. Damage was fairly heavy to railroad embankments, highway bridges, and areas of road fill outside the town.

Total damage in Seward and vicinity to public and private facilities, based upon cost of restoration, was estimated at $22,363,349 (Alaskan Construction Consultant Comm., 1964, p. 44).

SLIDES AND OTHER CHANGES IN NATURAL FEATURES

Snow avalanches were the most conspicuous type of slides triggered by the earthquake in Lowell canyon. Two of three snow avalanches in the lowermost mile of Lowell canyon reached the creekbed and piled up snow, rock fragments, and broken trees as high as 30 feet. Several talus deposits were also activated by the shaking. There was a general creep of material downslope, and in places small debris flows formed near the bottom of the slopes.

A fairly large rock and debris slide was triggered by the earthquake near the mouth of Jap Creek canyon. A projecting ledge of

8.—Houses and other debris carried by waves into the lagoon area at the north end of Seward. Main road leading north out of town shown in right-hand part of photograph. Photograph by U.S. Army.

bedrock 200–300 feet above the floor of Jap Creek was dislodged, and a near vertical back scarp about 80 feet high was left. The slide toe extended across Jap Creek and was 15–25 feet thick in the creekbed.

A small rock slide also was triggered by the earthquake a short distance upstream from the large slide. A snow avalanche, which contained some rocks and other debris, moved downslope across Jap Creek a few hundred feet downstream from the major rock slide and continued a short distance up the opposite valley wall. In both places, Jap Creek continued to flow under the slide masses and no water was impounded.

Rock and debris slides were activated by the earthquake in Box Creek canyon. The largest slide extended entirely across the valley front and blocked the creek channel. Small-scale sliding occurred intermittently during the summer, apparently triggered at least in part by aftershocks.

On part of the Jap Creek fan, as well as on much of the valley bottom of Resurrection River, the frozen ground was conspicuously fractured during shaking. Water spouted from many of the fractures. The ejected water pulsated in height and volume as the fractures opened and closed and commonly fountained to heights of 3–6 feet. Some early phases of fountaining were clear and were muddied later when much silt and sand was ejected; other fountains were muddy from the beginning.

Effects of the earthquake on water wells in and near Seward were moderate. Seward's main source of water is Lowell Creek, and neither this supply nor the storage tank in Lowell canyon was adversely affected. However, casings and pump collars were bent or broken to such a degree in three supplemental wells between Clearview and Forest Acres that it was necessary to drill two new wells (Waller and others, 1965). A circular pattern of fractured ground, downthrown about 6 inches, around one of the wells suggested that there was considerable differential subsidence of material around the hole. A well 47 feet deep in alluvium, 4.5 miles north of Seward, was flowing before the earthquake, but no water was obtainable from it after the quake, perhaps owing to a broken casing. The water surface in a second nearby well, which was 22 feet deep, was about 6 feet from the top of the well before the earthquake. Immediately after the quake, the well became artesian and gushed 2 feet into the air. It was still bubbling at the surface a week later, but by August 22, 1964, the well was at its preearthquake level. Additional information on earthquake effects on the hydrologic regimen is discussed by Waller (1966).

TECTONIC LAND CHANGES

Regional tectonic deformation that accompanied the 1964 Alaska earthquake has been described by Grantz, Plafker, and Kachadorian (1964), U.S. Coast and Geodetic Survey (1964), Plafker (1965), and others. During the summer of 1964 the U.S. Coast and Geodetic Survey reestablished vertical and horizontal control and added new controls designed to link the earthquake-disrupted geodetic net with the undisturbed portion of the net near Fairbanks. The surveys furnished much valuable information on the amount of vertical and horizontal land movements.

On the basis of first-order leveling by the U.S. Coast and Geodetic Survey (1965, p. 29), the landmass in the Seward area subsided approximately 3.5 feet. Low areas which were above higher high tide (10.6 feet above lower low tide) before the earthquake are now covered by water. High tides now advance several hundred feet to nearly half a mile farther inland at the head of the bay. Likewise, part of the lagoon area, the distal edge of Lowell Point (where residential development was underway), and a strip of land at Fourth of July Point are now covered by water during high tides. The airstrip must be reconstructed, the road around the head of the bay must be relocated, and other land has lost its private-use potential.

As part of the geodetic surveys conducted by the U.S. Coast and Geodetic Survey after the earthquake, a horizontal control survey was extended southward from Anchorage to Seward. The results of this survey, when compared with the original third-order survey made by the U.S. Army Corps of Engineers in 1942, indicate that the landmass on the west side of the Resurrection River valley north of Seward moved 5 feet north with respect to the landmass on the east side of the valley (U.S. Coast and Geod. Survey, 1965, p. 18). This indicated 5-foot shift extends northward past Kenai Lake to Turnagain Arm south of Anchorage.

It is not clear whether the translation between opposite sides of the valley reflects tectonic displacement or instrumental differences in the two survey nets used for comparison. In the mapped area at Seward the writer found no surface evidence of ground breakage related to faulting; the intricate fracturing in surficial deposits is attributed to landsliding and other nontectonic causes. On the other hand, Rusnak (oral commun., 1965; and in Corwin and Bradley, 1965) believes that large-scale rock movements along preexisting faults and folds that parallel the configuration of the bay contributed to submarine sliding of the overlying sediments. This interpretation is based on data he obtained from geologic samples and subbottom profiles of Resurrection Bay.

GEOLOGIC SETTING

Seward lies on the axis of the Chugach Mountains geosyncline (Payne, 1955). Sedimentary rocks of Jurassic and late Cretaceous age were highly deformed and partly metamorphosed during post-Paleocene time (Payne, 1955). Graywacke and phyllite predominate in the Seward area. Extrusive igneous rocks are interstratified with the sedimentary rocks in some places and some granitic rocks are also present; these rocks are outside the mapped area of plate 1. During the Tertiary Period and continuing into the Quaternary Period, the area was uplifted and eroded several times.

Unconsolidated glacial and fluvial deposits now overlie the bedrock in most places except on the steep higher slopes.

The business district and most of the residential district of the city are on the alluvial fan of Lowell Creek near the northwest corner of Resurrection Bay. The area of about 8 square miles north of the bay that was annexed to Seward shortly after the earthquake includes the Forest Acres subdivision on the distal edge of the alluvial fan of Jap Creek, and the sites of scattered homes in part of the valley of Resurrection River and some of its tributaries. The population of Seward at the time of the earthquake was slightly more than 1,900.

Most of the surrounding region is very rugged and is characterized by numerous glaciers (pl. 1). The Kenai Mountains rise steeply above Resurrection Bay and the valley of Resurrection River. Iron Mountain, Marathon Mountain, and Bear Mountain—the highest peaks on the west side of the bay and the valley—attain altitudes of 4,274, 4,603, and 4,003 feet, respectively.

Jap Creek, Lowell Creek, and Spruce Creek are the chief streams on the west side of the Resurrection River valley; all three are fed by cirque glaciers at their heads. The large Harding Icefield lies only a few miles to the west of the bay, but its drainage flows to Resurrection River.

Resurrection Bay is a deep fiord about 25 miles long and 3–5 miles wide. Its maximum depth is 978 feet, in the vicinity of Thumb Cove approximately 8 miles south of the head of the bay. Near Seward, the bay is 2–3 miles wide and about 500 feet deep. Except at the head of the bay and near some alluvial fans, the water is deep immediately offshore.

Engineering properties of graywacke

[Data provided by the U.S. Army Corps of Engineers (written commun., 1964)]

Location	Specific gravity (CRD–107–60)	Los Angeles abrasion (CRD–117–56) (percent)	Soundness, magnesium sulphate (CRD–137–62) (percent)
1. Old quarry near high school, Seward	2.71	15.6	------------
2. West end of lagoon area, Seward	2.69	16.7	------------
3. North end of Lowell Point	2.73	17.2	------------
4. Lowell canyon, about ½ mile west of Seward	2.74	24.2	0.69

BEDROCK

Alternating units of graywacke and phyllite constitute virtually all of the bedrock in the immediate vicinity of Seward (pl. 1). Each unit is commonly tens to hundreds of feet thick. In places, however, the graywacke and phyllite are in thin interbeds only 1–4 inches thick. In still other places, all gradations in composition and texture exist between the two rock types.

On the west side of Resurrection Bay, from the northern end of Seward to Lowell Point, nearly all the bedrock below an altitude of about 1,000 feet consists of graywacke, whereas phyllite predominates above this altitude. On the east side of the bay, phyllite is almost continuously exposed in sea cliffs from near the head of the bay to Fourth of July Point. Phyllite predominates over graywacke in the higher parts of the mountains on the east side of the bay and along the valley walls north of the head of the bay.

The graywacke is medium to dark gray, fine to medium grained, generally massive, and indistinctly bedded. It commonly forms ledges that have slopes ranging from about 45° to more than 70°. It is well indurated and slightly metamorphosed.

Engineering properties of the graywacke, based upon analyses from four locations, are shown in the table above. The tests were made by the U.S. Army Corps of Engineers, during a postearthquake search for armor rock to construct breakwaters for new harbor facilities; the rock chosen for the breakwaters was from location 3 at the north end of Lowell Point where a large quarry was opened. The data obtained are believed to be fairly representative of the more massive graywacke of the area.

The phyllite originally was a shale that has been subjected to low-grade metamorphism. It is dark gray to nearly black and fine grained and has a well-developed cleavage parallel to the bedding in most places. On steep weathered slopes, it commonly splits into sheets from less than an inch to several inches thick and from less than a foot to several feet across. The cleavage surfaces have a lustrous sheen produced by flakes of mica and chlorite. Some less metamorphosed rocks, more nearly slate, are also present, and shale that has undergone little or no metamorphism has been found in a few outcrops.

The main structural trend of the rocks in the Seward area is from near north to approximately N. 20°

232-728 O - 67 - 4

E. Beds and cleavage commonly dip 70° W. or NW. to near vertical. Locally the rocks are complexly folded and contorted, and Moffit (1906, p. 18) reported that about 2 miles east of Resurrection Bay near Godwin Glacier (pl. 1) the beds lie in immense folds slightly overturned to the east. Smaller folds in the vicinity of Seward also appear to be slightly overturned to the east.

No major faults have been identified in the mapped area, but the rectilinear pattern of the major valley system extending northward from Seward into the central part of the Kenai Peninsula strongly suggests that this valley system is at least in part fault controlled. If so, the trough extending south from Kenai Lake and continuing along the long axis of Resurrection Bay may reflect a fault valley scoured by glacial erosion. Rusnak (oral commun., 1965; and in Corwin and Bradley, 1965) believes that during the earthquake of 1964 there was large-scale rock movement in Resurrection Bay along preexisting faults and folds that parallel the configuration of the bay. The writer, however, has found no evidence to support this view.

Small faults, shear zones, and joints are common in the mapped area. The rocks are commonly offset vertically a few inches to several feet along these faults. The shear zones, mostly less than 5 feet wide, commonly are made up of angular pieces of graywacke or phyllite a few inches to a few feet long, though some are composed of finely ground rock fragments or a bluish-gray clayey gouge. The more massive graywacke is characterized in many places by a major and a secondary joint system. North of Lowell Point, where the joints are well exposed, the major set strikes N. 60°–70° W. and dips approximately 85° NE., and the secondary set trends northeastward. Most of the joints are filled with quartz but some are filled with calcite.

SURFICIAL DEPOSITS

Surficial deposits in the Seward area are both glacial and nonglacial in origin and generally are intermixed in the valley of Resurrection River.

The surficial deposits, of Pleistocene and Recent age, are divided on the basis of land form and origin into six units: glacial deposits, alluvial fan and fan-delta deposits, valley alluvium, intertidal deposits, landslide deposits, and artificial fill. Most of the units are gradational and were deposited more or less contemporaneously. Marine deposits are known only from the subsurface (pl. 1) and are not discussed separately.

GLACIAL DEPOSITS

Remnants of lateral moraines flank the main valley of Resurrection River and extend up the sides of the tributary valleys to a maximum altitude of about 1,500 feet. In a few places, as directly west of Seward, the original form is still well preserved, and the ridges are 25–75 feet high and fairly sharp crested. Many ridge crests slope downvalley rather steeply from individual tributary valleys; these steep slopes suggest that the ridges are lateral moraines of tributary glaciers. The tributary glaciers, which flowed from large icefields in the higher mountains, probably coalesced in the main valley to form a large trunk glacier whose terminus is not known, although it must have been some miles or tens of miles south of the present head of Resurrection Bay.

The lateral moraines are heavily vegetated in most places. In the few places exposed, however, they consist chiefly of rather loose gray till, which oxidizes to a yellowish gray. The till consists predominantly of silt, sand, and gravel, and smaller amounts of clay-size particles, cobbles, and boulders. A sample from a roadcut just west of the lagoon area at the north end of Seward consists of about 10 percent clay-size particles, 20 percent silt, 40 percent sand, and 30 percent gravel. The finer material is derived largely from phyllite bedrock, and the material of gravel size and larger is mostly graywacke. The cobbles and boulders are generally sharply angular.

About 50 feet of loose sand, gravel, and cobbles is exposed along the road about 4 miles northeast of Seward in what may be a kame terrace. Bedding in the lower part of the deposit dips as much as 20° SE.; the upper part is more lenticular and consists chiefly of poorly sorted gravel with boulders as much as 1.5 feet long.

ALLUVIAL FANS AND FAN-DELTA DEPOSITS

Alluvial fans and fan-deltas have been deposited at the mouths of several tributary valleys. Some fans extend into Resurrection Bay and deltaic deposits form their distal edges. Most of the others have spread out onto the alluvial floor of the Resurrection River valley. The four largest fans, composed chiefly of silt, sand, and gravel, form broad aprons having low gradients.

SEWARD FAN-DELTA

The fan-delta on which the town of Seward is built is at the mouth of Lowell Creek canyon and projects into Resurrection Bay. It is approximately 1¼ miles long in a north-south direction and half a mile wide, and rises from sea level to an altitude of 130 feet at the mouth of the canyon—an average gradient of about 3°, or about 275 feet per mile.

Data from drill holes, backhoe

9.—Seward alluvial fan in 1939 showing torrential-type deposition from Lowell Creek after a flood. Photograph by Robert Zentmeyer.

trenches, and excavations for sewer and water lines indicate that the fan-delta deposits are predominantly very loosely compacted and nearly unstratified sand and gravel together with smaller amounts of clay-size particles, silt, cobbles, and boulders. The sand is mostly medium to coarse and consists chiefly of flat chips of phyllite; the gravel is generally subangular to subrounded and is mostly graywacke. Light-gray silt is rather evenly disseminated throughout the deposits. Cobbles and boulders, nearly all subangular to angular pieces of graywacke, generally are locally concentrated. They are most abundant toward the head of the fan and along the former channel of Lowell Creek where the boulders are as much as 2.5 feet long. Before construction of a diversion tunnel (2,000 feet long and 10 feet in diameter) from Lowell canyon a quarter of a mile west of Second Street to the bay at the southern end of Seward, Lowell Creek flowed in a channel approximately coincident with the present Jefferson Street (pl. 2). Floods pouring down this channel periodically spread deposits of sand and gravel over much of the fan during historic time. One such flood in 1939 dumped considerable debris at and near the mouth of the creek (fig. 9).

The thicknesses of the fan deposits were determined from three holes (S–100, S–105, and S–106) drilled after the earthquake along the Seward waterfront (pl. 2), from the log of a water well drilled near the hospital at the west end of Jefferson Street, and from seismic studies across the fan along Jefferson Street and offshore from the fan (pl. 2).

These data indicate that the fan deposits generally are approximately 100 feet thick but are considerably thicker along the distal edge. The deposits can be divided into three subunits on the basis of seismic velocities (pl. 2): (1) an upper unit, approximately 25 feet thick, having a seismic velocity of 1,600 fps (feet per second); (2) an intermediate unit, 10–90 feet thick, having a seismic velocity of 2,800 fps; and (3) a wedge-shaped unit underlying the others along the distal edge of the fan and extending beneath the bay, which has a seismic velocity of 6,100 fps. The log of drill hole S–100 indicates that the velocity differences in the three subunits are primarily due to the degree of compaction rather than grain size or composition. The uppermost unit is very loose material, deposited partly in historic time, and includes some loose artificial fill. The two more compact underlying units may represent deposits laid down during two distinct phases of glaciation in the mountains to the west.

The fan deposits intertongue with marine sediments along the frontal scarp of the fan from the vicinity of the Standard Oil Co. tanks to somewhat north of the Texaco, Inc., tanks. Drill hole S–100, at the eastern end of Adams Street (pl. 2), penetrated 292 feet of fluvial deposits and then about 15 feet of marine sediments before passing into a probable till. Drill hole S–105, near the former Army dock, penetrated several layers or stringers of marine sediments interbedded with fluvial deposits in the upper 312 feet of hole. In drill hole S–106, just north of the Texaco tanks, much of the material penetrated between depths of 80 and 313 feet is marine sediments.

The fan deposits are believed to lie on a platform of till and associated compact glaciofluvial deposits. Seismic studies (pl. 2, SL–1 and SL–2) show that the drift has a velocity of 7,200–7,500 fps. In drill hole S–100, which penetrated this unit from 306 feet to the bottom of the hole at 333.4 feet, the material is a compact mixture of sand and gravel and minor silt—probably a till partly reworked by water. A more silty or clayey till containing large boulders was penetrated between depths of 25 and 78 feet (bottom of the hole) in a water well dug before the earthquake at the apex of the fan near the hospital (Tryck, Nyman, and associates, 1961, app.). After the earthquake this hole was deepened to 118 feet; bedrock was penetrated at about 113 feet (J. C. Ireton, Corps of Engineers, written commun., 1966) and till presumably was penetrated between 78 feet and 113 feet.

The bedrock that forms the valley walls along the western margin of the fan probably extends beneath the fan deposits at about the same slope as above the fan, 30°–45°, and beneath most of the fan is probably more than 1,000 feet deep. Bedrock was not detected in seismic surveys in which depth of penetration ranged from 600 to 1,200 feet.

JAP CREEK FAN

At the mouth of Jap Creek canyon, a broad fan, 1½ miles long (north-south) and 1 mile wide, extends onto the alluvial floor of the Resurrection River valley. It rises from an altitude of about 25 feet along its outer margin to approximately 300 feet at the mouth of the canyon—an average gradient of 3.3°, or about 285 feet per mile. Most of the surface of the fan, however, is below an altitude of 100 feet.

The composition and thickness of the fan deposits have been determined primarily from logs of water wells and test holes and exposures in test pits and water and sewer lines, mostly in the subdivision of Forest Acres. The fan deposits are chiefly sand and gravel, in general progressively finer grained from the head of the fan to its outer margin. In a few exposures along the creek banks where Jap Creek emerges from its canyon, the deposits are mostly medium to coarse gravel, cobbles, and boulders of graywacke as much as 5 feet long; near the outer margin of the fan, they are chiefly silt, sand, and fine gravel. Most of the fine-grained material has been derived from phyllite. Considerable fossil wood was exposed in waterline trenches along Diamond Boulevard and Evergreen Street in Forest Acres. Fossil tree trunks as much as 1 foot in diameter were fairly abundant at a depth of 7–8 feet. Most were embedded horizontally in a slightly plastic silty layer, but others, which also had their roots in the silty layer, were upright and extended in some places to the surface soil—conditions that indicate rapid deposition of the upper sand and gravel.

The Jap Creek fan deposits in the Forest Acres area are generally more distinctly bedded than the Seward fan deposits. Lenses or beds of clean sand, 1–5 feet thick, commonly intertongue with units of poorly sorted sand and gravel. Here and there, lenses of silt, generally less than 2 feet thick, are intercalated in the sand layers. The mixed sand and gravel units are very loose and tend to slump on near vertical slopes. All the deposits slump when excavated below the water table on steep slopes.

The thickness of the fan deposits is not known, but it is probably more than 200 feet in most places. A water well near the outer margin of the fan between the Forest Acres and Clearview subdivisions penetrated 310 feet of sand and gravel (Tryck, Wyman, and Associates, 1961, app.). Whether all the sand and gravel are part of the fan deposits or whether all or some of the lower part of the section are alluvial deposits of Resurrection River cannot be determined. Morainal deposits probably underlie the fan deposits, at least near the head of the fan, as they do the Seward fan. Bedrock probably lies from several hundred feet to possibly more than 1,000 feet beneath the fan, except immediately adjacent to the valley wall.

LOWELL POINT FAN-DELTA

The Lowell Point fan-delta, 1½ miles south of Seward at the mouth of Spruce Creek canyon, extends into Resurrection Bay for nearly half a mile. All the fan is below an altitude of 100 feet and much of it is below 50 feet. By local usage, the entire fan area is known as Lowell Point, the official designation of the easternmost point of the fan (pl. 1).

The fan deposits have been laid down by Spruce Creek, which is fed in part by glacial melt waters. From late May until October, Spruce Creek is a fast-flowing stream about 50 feet wide and 3–4 feet deep. The stream, which in the past has migrated across the fan, will cut new channels during large floods. Cobbles and boulders, as much as 2 feet long, form the channel floor.

In most places the fan deposits appear to consist chiefly of fine gravel and coarse sand, minor amounts of coarser gravel, and cobbles, and a few boulders mostly about 1 foot in maximum dimension; from the vicinity of Spruce Creek to the southern end of the fan, they consist mostly of coarse sand. The sand contains little or no intermixed silt or clay-size material and consists almost entirely of flat chips of phyllite.

Depth to bedrock beneath the fan is unknown. Projection of the bedrock profile from the slope of the adjacent mountains would place it several hundred feet below the surface of most of the fan and perhaps more than 1,000 feet beneath the distal edge. No data are available to indicate if there are morainal deposits between the fan deposits and bedrock.

FOURTH OF JULY FAN-DELTA

On the east side of Resurrection Bay, Fourth of July Creek has built a triangular-shaped fan about 2½ miles long in an east-west direction and 1½ miles wide along its distal edge. Unlike the three fans previously described, it projects into the bay only a short distance beyond the mountain front and most of it forms the valley floor of the lower reaches of Fourth of July Creek. The fan in most places is nearly flat with a gradient of only about 1°, or 90 feet per mile. Fourth of July Creek, which is fed in part by melt water from Godwin Glacier, flows in several bifurcating channels across the fan.

Sand and gravel constitute most of the fan deposits in the vicinity of the bay. Toward the head of the fan, the deposits are coarser, and cobbles and boulders are more abundant. Thicknesses of the fan deposits are not known but probably exceed several hundred feet along the edge of the bay.

OTHER FANS

Small fans also are present at the mouths of several canyons. Most have fairly steep gradients and considerable local relief. Exposures are rare because of a heavy tree cover, but the presence of large isolated boulders and a general hummocky topography on many of the fans, especially those along the valley wall between the northeast corner of Resurrection Bay and Bear Lake, suggest that morainal deposits underlie the surfaces at shallow depth. It is likely that the morainal deposits are being partly reworked by stream action and that the fluvial deposits themselves are thin and patchy. Some mudflow and other types of mass-wasting deposits probably constitute parts of some of the fans.

VALLEY ALLUVIUM

Resurrection River is a wide, braided, and low-banked stream. During alternate accretion and erosion the channel has migrated laterally across a wide flood plain. The flood-plain deposits of this stream and those of tributary streams are described as valley alluvium.

The flood-plain deposits of Resurrection River consist mostly of coarse sand and fine to medium gravel. Medium to coarse gravel and small cobbles form lag concentrates along some of the abandoned stream courses. Like the fan deposits, the gravel-size material is predominantly graywacke, and the sand is chiefly flat chips of phyllite. However, the larger size fractions are somewhat more rounded probably because of a greater transport distance, than those of similar size in the fan deposits. The alluvium deposited along the lower reaches of Salmon Creek consists chiefly of medium to coarse sand and fine gravel. The deposits that underlie the north-trending valleylike trough south of Bear Lake (pl. 1) are of composite origin and, therefore, differ considerably in grain size from place to place. No stream flows the entire length of this trough at the present time although it probably was used as a melt-water channel during one phase of deglaciation. Streams at the north and south ends of this trough have deposited sand, gravel, cobbles, and some boulders on their flood plains. Swamp deposits in the SE¼ sec. 24, T. 1 N., R. 1 W., consist largely of organic debris and sand.

In the main part of the Resurrection River Valley, the alluvium probably is more than 100 feet thick in most places. At the head of the bay, at least 75 feet of deltaic sand and gravel overlies about 100 feet of marine sand and silt (pl. 1). It is not known how far upvalley the marine deposits extend. However (as shown on pl. 1) 600 feet or more of till and other glacial drift have been deposited in a deep bedrock valley that entered the northwest corner of the bay and probably extended for some miles northwestward under the recent alluvial deposits of Resurrection River. The continuation of this deep bedrock valley beneath Resurrection Bay is reflected as a trough on the bay floor offshore from Seward (pl. 2).

INTERTIDAL DEPOSITS

Beach, deltaic, and estuarine sediments, deposited on intertidal flats at the head of the bay and along the margins of fans extending into the bay, are referred to here as intertidal deposits. The deposits mapped (pl. 1) are those that were exposed between mean lower low water and mean higher high water before the earthquake. Some of the tidal flats formerly exposed at lower low water are now inundated because of tectonic subsidence of approximately 3.5 feet, probable compaction of the sediments, and some sliding along the front of the deltaic deposits during the earthquake. Furthermore, low areas bordering the shore that formerly were above tidal range are now covered by water at high tide.

Borings near the new railroad dock (pl. 2) show that the grain size of the intertidal deposits decreases with depth. The upper 5–20 feet consists chiefly of silty sandy gravel in which most of the pebbles are less than 1 inch long. Underlying this unit to a depth of about 60 feet are beds that consist chiefly of gravelly silty sand, which in turn is underlain by silty sand to sandy silt. Between 85 and 100 feet, clay-size material predominates in some beds.

Holes drilled near the outlet of the lagoon in the small-boat harbor show that the intertidal deposits are somewhat finer grained there than in the vicinity of the new railroad dock. Silty sand and minor quantities of fine gravel predominate in approximately the upper 25 feet of the sediments. Below, to a depth of at least 40 feet, sandy silt is more abundant.

In holes drilled on the intertidal flats near the northeast corner of the bay, the sediments, ranging in grain size from silty sand to silty gravel, are approximately 60 feet thick and are underlain by compact till. Small cobbles, gravel, and coarse sand form a beach shingle on the higher parts of the intertidal area.

Intertidal deposits form comparatively narrow bands, in most places not more than 500 feet wide, around the distal edges of the alluvial fans at Lowell Point and Fourth of July Point. The washed surfaces are characterized by a thin veneer of cobbles, gravel, and sand, except at the south end of Lowell Point where sand predominates. Underlying the washed surfaces to an unknown depth are deposits chiefly of coarse sand and fine gravel. The surfaces generally are firm even when covered with water and can support heavy loads such as large tractors.

LANDSLIDE DEPOSITS

The earthquake reactivated some old landslides and triggered new ones. Rock and snow avalanches, debris flows, and talus creep characterized slide activity on steep mountain slopes. The large-scale shoreline and submarine sliding, which occurred in places along the bay, are described on page E26.

In Lowell Canyon, several talus deposits, whose unvegetated slopes were at the angle of repose (about 32°), were activated during the earthquake, and in places small debris flows formed near the bottoms of the slopes. Open fractures at the heads of a few talus deposits, some present before the earthquake and some formed by the earthquake, attest to the present instability of these steep talus slopes. Talus deposits having slopes of less than 32° generally are covered by grass, shrubs, or trees that show no evidence of recent disturbance and appear to be fairly stable.

Rock and debris slides also were actuated by the earthquake in Box canyon, a steep-walled valley just north of sec. 22, T. 1 N., R. 1 W. In the largest slide area, boulder- and cobble-size material extended entirely across the valley floor to a height of 10–15 feet and blocked the creek channel. A channel was bulldozed through the slide mass to allow the stream to resume its former course and to prevent impoundment so that large discharges would not flow down Clear Creek, which heads at this point. Excessive flows down Clear Creek would inundate residential areas downstream.

A fairly large rock and debris slide was triggered by the earthquake near the mouth of Jap Creek canyon (see p. E14). Cobbles and boulders as much as 5 feet long form the slide material in the Jap Creek area. Because of the coarseness of the material, Jap Creek was not impounded behind the slide but flowed through it during the period observed (April–September 1964). There appears to be little or no danger that the slide mass will suddenly break and release large quantities of water downstream. The available impoundment area above the slide is small and, should the stream top the slide, the rate of downcutting to its original bed will probably be slow. Small-scale sliding of this mass continued intermittently during the summer of 1964. A second but smaller rock slide also was triggered by the earthquake a short distance farther upstream; there was no impoundment of water.

Talus deposits form steep slopes on the east flank of Iron Mountain about one-third mile north of the mouth of Jap Creek canyon, and have been shown on the map as landslide deposits. Although there apparently was little movement of the deposits as a result of the earthquake, the upper slopes are mostly unvegetated and slow creep is indicated. Adjacent talus deposits are vegetated and appear to be fairly stable.

Several small landslides are present on steep slopes bordering the bay between Seward and the Lowell Point fan. These occupy V-shaped drainage courses whose slopes generally exceed 40°. Boulders, as much as 6 feet long, and cobbles constitute most of the slide material. In general, the slides are fairly stable and only minor quantities of material moved downslope during the earthquake. However, considerable material was removed from the toes of the slides during road construction after the earthquake, and some sliding can be expected in the future whether or not strong ground motion occurs.

An inactive rock slide is present along the base of the mountain front at the north edge of the Lowell Point fan and about 500 feet back from the shoreline. It is about 200 feet across its outer margin and probably about 30 feet thick. A bedrock outcrop approximately 200 feet upslope from the toe of the slide indicates that little or no slide material is present above this exposure. The slide material consists chiefly of graywacke in blocks as much as 5 feet long and 3 feet wide. A surface cover of vegetation, including unbent trees 1 foot in diameter, indicates that the slide is inactive. The slide material is a small potential source of large-size riprap.

ARTIFICIAL FILL

The chief areas underlain by artificial fill (not shown on geologic map) are along the Seward waterfront, in the abandoned part of the channel of Lowell Creek, in the lagoon area, and in the area at the northwest corner of Resurrection Bay.

During the years prior to the earthquake, additional space for the Seward waterfront facilities was provided by artificial fill along the shoreline. In places, such as in the area of the old railroad docks at the south end of town, a strip of fill 200–300 feet wide and as much as 15 feet thick (seaward edge) was emplaced. Fill also was used to extend the shoreline between the former Standard Oil Co. dock and the San Juan dock to afford additional space for railroad tracks and other facilities. Comparison of a 1939 photograph (fig. 9) with a mosaic of photographs (fig. 2, top) made a few years before the 1964 earthquake shows the extent of fill. Poorly sorted sand and gravel, taken chiefly from overflow deposits of Lowell Creek during flooding (fig. 9), constitute most of the fill material. However, wood cribbing, which helped support the railroad tracks near the water's edge before the tracks were raised, also is incorporated in the sand and gravel.

After Lowell Creek was diverted through a diversion tunnel and no longer flowed across the Seward alluvial fan, the abandoned channel (pl. 2) was filled with sand and gravel. The width of the fill probably does not exceed 150 feet in most places and its maximum thickness in the bottom of the channel is probably less than 10 feet. Water and sewer trenches dug across the fill indicate that the fill material is nearly identical in grain size and other characteristics to the deposits of the adjacent alluvial fan.

Early maps show that the lagoon at the north end of town formerly was larger than it was at the time of the earthquake. Reportedly, the south end of the lagoon, in the vicinity of Van Buren Street and east of Third Avenue, was used as a garbage dump for a number of years and then was covered with soil. After the earthquake, the lagoon area east of Third Avenue was filled to a height of several feet with sand and silt dredged from the new small-boat basin (pl. 2).

During construction of the new railroad dock and marshalling yards after the earthquake. sand and silt was dredged from the area in front of the dock and pumped onto the intertidal flats and land at the head of the bay (pl. 2). This fill, which is 500–600 feet wide, ranges in thickness from about 15 feet near the shoreline to less than 5 feet about 3,000 feet inland from the shore.

ENGINEERING GEOLOGY AND THE RECONSTRUCTION EFFORT

Response to the earthquake disaster at Seward was immediate and effective. The townspeople, together with city, State, and Federal officials swung into action at once. For many individuals and groups the arduous work continued for several months or more.

Preservation of life and property was the first order of business. All night after the earthquake the search went on for the dead and injured. Volunteer guards blocked off streets leading to the waterfront to keep people out of the area imperiled by incoming sea waves and the oil tank explosions. The city was fortunate in having a highly trained Civil Defense organization, which had been established to cope with emergencies. Large stockpiles of food, clothing, and medicine thus were available for immediate use. On the evening of the earthquake, an Alaskan Air Command plane from Elmendorf Air Force Base at Anchorage delivered an additional 10,400 pounds of relief cargo (U.S. Army Alaskan Command, 1964, p. 51).

Army personnel already on special duty at Seward, together with women and girl volunteers, set up and operated messhalls in the high school and at the Jesse Lee Home. Nearly all the citizens of Seward were fed at these messhalls during the first few days after the quake. Much of the frozen and refrigerated food supplies in town had to be cooked immediately to prevent spoilage.

Saturday morning, March 28, the first mail (no stamps required) left Seward on a military plane. As soon as weather permitted on Saturday, Army Mohawk aircraft from Anchorage flew photoreconnaissance missions. The high-quality photographs vividly portray the destruction at Seward (fig. 2, bottom). Later, the Strategic Air Command photographed several additional areas. Also on Saturday 175 Army officers and men arrived at Seward. Their equipment included a radio teletype, which gave Seward its first fast communications link with the outside world (U.S. Army Alaskan Command, 1964, p. 50). Guard posts were established along the waterfront and in the business district, and a patrol was detailed to assist city police. A water purification system that treated 10,000 gallons of water daily was set up by Army personnel at a small lake at the edge of town; water was distributed by six water trailers. Army and Civil Air Patrol personnel established a field control center at the airport to unload the many supplies coming into the city. In a 24-hour period, March 30–31, 168 passengers and 59,120 pounds of cargo were delivered to Seward; in the following 24 hours, 127,700 pounds of cargo and 198 passengers were unloaded (U.S. Army Alaskan Command, 1964).

City officials worked "around the clock" to cope with the emergency. At the time of the quake, Perry Stockton, Mayor, and James W. Harrison, City Manager, were in Anchorage to plan the forthcoming celebration of Seward's All America City Award for 1963. Acting Mayor Delmar Zentmeyer thus had the responsibility of making the many decisions for the city during the next 24 hours. For many months, problems arrived in endless succession. The sustained efforts of individuals and the teamwork of groups produced results far beyond what might have been predicted.

The Corps of Engineers participated fully both in the temporary restoration of public facilities and in the permanent reconstruction program. Demolition experts razed dangerous buildings, blasted pits for sanitary use, and did other jobs that required the use of explosives. In less than a week, temporary water and sewer services were restored and, with the help of the Chugach Electric Association, electric power was brought back into the city.

One of the first large programs started by the Corps of Engineers after the earthquake was the massive cleanup job along the Seward waterfront, at the head of the bay (fig. 10), and in the bay itself. Onshore, what was salvageable was

10.—Wrecked boats and other debris beached by waves at the northwest corner of Resurrection Bay. Photograph by U.S. Army.

saved; the rest of the debris was burned or otherwise disposed of. In the bay, hazards to navigation, such as boxcars, tankers, oil tanks, piling, rails, and remains of buildings, were removed to a minimum depth of 40 feet; this work was done in two stages: (1) cleanup of the lagoon area and the land area at the head of the bay and (2) cleanup of the railroad area and the bay. Not long after the initial cleanup was completed, reconstruction of public facilities was undertaken by the Corps of Engineers (George and Lyle, 1966).

On April 13 and 14, the U.S. Coast and Geodetic Survey, using the ship *Pathfinder*, made soundings and tidal measurements in Resurrection Bay. This work was augmented by detailed soundings along the Seward waterfront by the Corps of Engineers. The combined data provided bathymetry for navigational purposes, for locating and studying submarine landslides, and for underwater cleanup work. Tidal observations permitted an estimate of the amount of tectonic subsidence. During the summer, a first-order level line run into the city from Fairbanks gave additional data on land-level changes.

The Urban Renewal Administration of the U.S. Housing and Home Finance Agency, acting through the Alaska State Housing Authority, authorized a city plan and an urban renewal study. The plan was developed by City Planning Associates, of Mishawaka, Ind. In order to plan for best land use and to attempt to minimize damage from future earthquakes in connection with ground stability, this firm based its plan in large part on geologic information supplied by the U.S. Geological Survey, the Scientific and Engineering Task Force, and the Corps of Engineers. Private individuals were assisted through disaster loans from the Small Business Administration.

Many nongovernmental organizations and groups provided assistance. The American Red Cross and the Salvation Army gave food, clothing, household necessities, and money. Church groups, the American Legion, and other organizations contributed in many ways. A large van of furniture was sent from Allentown, Pa., to replace furnishings destroyed by the sea waves. A shipload of lumber donated from the Portland, Oreg., area was unloaded at Seward and distributed to people who had lost their homes. These responses are only a few examples.

It was early recognized that to be sound the reconstruction plan must be based on a thorough understanding of what had happened during the earthquake.

METHODS OF STUDY

Geologic investigations were conducted by the writer at Seward from April to October 1964. Early emphasis was directed toward assessing and mapping the surface geologic effects of the earthquake. During the summer, subsurface studies were coordinated with an extensive program of subsurface exploration by the U.S. Army Corps of Engineers and by Shannon and Wilson, Inc., who performed most of the soil analyses. In addition, consulting advice was given to the Field Team, Scientific and Engineering Task Force of the Reconstruction Commission, in regard to designating high-risk areas along the waterfront area of Seward and in part of Forest Acres (see Eckel and Schaem, 1966). In late summer and fall the writer mapped the geology of Seward and adjacent areas and collected and analyzed additional information made available during reconstruction.

High-quality low-altitude postearthquake aerial photographs were used for detailed mapping. Where aerial photographs were not available, mapping was done on an enlarged topographic sheet of the Seward A-7 quadrangle, published scale 1:63, 360.

Pre- and postearthquake hydrographic charts prepared by the U.S. Coast and Geodetic Survey were used for offshore studies. In addition, a detailed hydrographic chart, prepared by the Corps of Engineers after the earthquake, was most helpful in the study of landslides in the harbor area.

The Alaska District, Corps of Engineers, undertook a comprehensive study of subsurface conditions, in part by contract with Shannon and Wilson, Inc., of Seattle, Wash., that included test drilling, field and laboratory studies of soil samples, seismic surveys, and pile-driving tests. The soils investigation by Shannon and Wilson was undertaken primarily to determine the factors probably responsible for the submarine landslide along the Seward waterfront and to evaluate the stability of the area under static and dynamic (earthquake) conditions. Test borings and seismic surveys were also made at the head of Resurrection Bay to evaluate the stability of that area for possible new harbor facilities. This phase of the work was supplemented by offshore borings made by the Corps of Engineers. The heavily damaged part of Forest Acres subdivision also was studied.

During field investigations that were made between May 11 and July 25, 1964, 10 holes were drilled (locations shown on fig. 15, p. E36; pls. 1, 2): 3 along the Seward waterfront, 5 at the head of Resurrection Bay, and 2 in Forest Acres. Those along the Seward waterfront and at the head of the bay ranged in depth from 165 to 481 feet except the hole at the northeast corner of the bay which reached a depth of only 83 feet after penetrating 14 feet of bedrock.

The first six holes were drilled with a rotary rig. Drilling fluid, a thick mixture of bentonite and water, was used to remove cuttings and granular material and to maintain the uncased hole. Below the depth of 100 feet, drilling was continuous to minimize collapse of the hole. Drive samples were obtained at 5- or 10-foot intervals using a standard 2-inch sampler driven by a 140-lb hammer. Selected undisturbed samples were taken in 3-inch Shelby tubes pushed into the soil by a mechanical chain drive on the drill.

Because rotary drilling made it difficult to obtain representative samples, and because the mud masked artesian conditions, a churn drill was used to drill the last four holes. These holes were cased. Drive samples were obtained at 10-foot intervals using a 4-inch split barrel sampler. All samples were classified in the field before being sealed in glass jars and sent to the Shannon and Wilson, Inc., laboratory in Seattle for testing.

Five test pits were dug with a tractor-mounted backhoe: three along the Seward waterfront (pl. 2) and two in Forest Acres (fig.

15, p. E36). All were in areas of fractured ground and were intended to provide information on depositional and structural relations not obtainable from drill holes.

Ground-water levels and artesian pressures were measured or approximated in most borings and test pits. The first confirmation that artesian pressures existed at the northwest corner of the bay was found in hole S–101 when water began flowing at the surface a day after completion of the hole. The rate of flow was measured and related to tide levels. Direct readings of artesian pressure in the rotary-drilled holes could not be made because the holes were uncased and drilling mud was used. Large artesian flows developed in some of the churn-drill holes. Artesian conditions were observed as the holes were advanced; measurements were made using a Bourdon-type pressure gage. After completion of the holes, attempts were made to locate artesian zones that had been sealed off by the casing. The bottoms of the holes were sealed with grout, and the casing was perforated at points where considerable heaving, noted during drilling, indicated probable artesian pressures.

Selected samples from the onshore drilling program were subjected to standard laboratory tests by Shannon and Wilson, Inc. (1964). Most of the samples were necessarily of the finer grained materials; both disturbed split-spoon drive samples and relatively undisturbed Shelby-tube samples were taken. The laboratory test program by Shannon and Wilson included visual classifications of split-spoon samples and visual classification, mechanical and hydrometer analyses, water content, Atterburg limits, organic content, density, and triaxial strength determinations for the Shelby-tube samples.

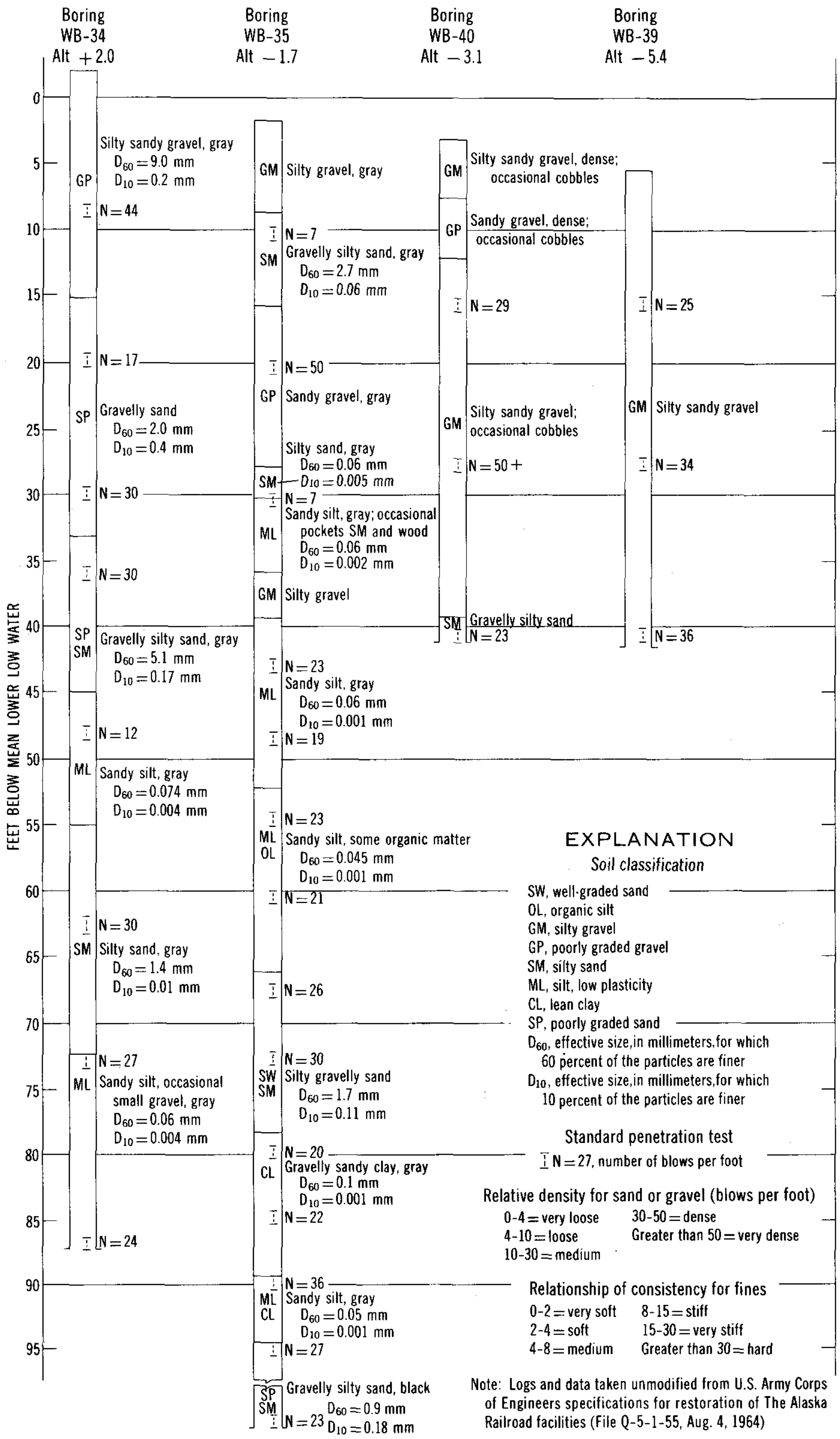
Two types of soil predominated in the Shelby-tube samples. One was black uniform medium to fine sand, composed of black phyllite particles, usually of medium density, and having wet unit strengths of about 130 lbs per cu ft. Triaxial tests on the sand showed an effective (drained) θ (angle of friction) of approximately 35°–39° and a total (undrained) θ of 32°–40°. Pore pressures at failure were low. The other predominant soil material tested was organic sandy to slightly clayey silt, which had an organic content of less than 5 percent. The plasticity index ranged from nonplastic to 13, and liquid limits from 21 to 34. Natural water contents ranged from 20 to 32 percent, and clay-sized particles made up 10–30 percent of the material. Drained triaxial tests showed positive pore-water pressure at failure. Effective (drained) θ's ranged from 35°–38°. The undrained θ's were lower, ranging upward from 21° for a consolidation pressure greater than the effective overburden pressure and averaging 26° for consolidation pressures equal to the effective overburden pressure.

To supplement the data obtained from the holes drilled on land and to obtain needed offshore information, 15 refraction seismic traverses (see pls. 1 and 2 for locations) were made by Geo-Recon., Inc., under subcontract to Shannon and Wilson, Inc. Profiles (pl. 2) indicated the nature and thicknesses of geologic units at depths considerably greater than were penetrated by the drill holes.

Seventy-one borings, mostly on the intertidal flats at the head of the bay, were made by the Seattle District, Corps of Engineers, to provide information on the subsurface conditions needed for planning restoration of harbor and railroad facilities. Offshore in the area of the new small-boat basin, 21 borings were made: 12 in the vicinity of the new Alaska Railroad dock and 9 near the northeast corner of the bay; on land north of the railroad dock, 27 borings were made.

None of the bore holes were more than 100 feet deep and most were less than 50 feet deep. Those on land were 4–9 feet deep. The borings were water-jet holes made by using a pump that developed 450 psi (pounds per square inch) at approximately 20 gallons a minute (Robert H. Moran, U.S. Army, Corps of Engineers, written commun., 1964). The sampler was a 1-inch split spoon on a 2-inch drill rod inside a 4-inch casing. All work was done at the higher stages of the tide when the tidal flats were covered by water. Samples were classified in the field. According to Moran, this method of investigation is both economical and time proven and gives sufficiently accurate information for assessment of dredging character and design of structures. Logs and test data from four offshore borings (fig. 11, next page) show subsurface conditions in the area of the new Alaska Railroad dock.

Pile tests were conducted offshore from the new railroad dock by the Corps of Engineers. Several steel H-piles were driven into the bay sediments to determine the rate of penetration and bearing strength. One pile, driven 64.25 feet into the ground near the offshore end of the planned dock, also



11.—Offshore borings in the vicinity of the new Alaska Railroad dock. See plate 2 for locations.

underwent a static loading test. Results of these tests have not been published but are available in the files of the Corps of Engineers.

LANDSLIDES

SEWARD WATERFRONT AND HEAD OF RESURRECTION BAY

Both onshore and offshore deposits slid into the bay along the Seward waterfront. Near the northwestern and central parts of the head of the bay, sliding was mostly submarine.

Along the Seward waterfront, a strip of land approximately 4,000 feet long and 50–500 feet wide slid into the bay concomitantly with offshore submarine landsliding. Behind the scarp marking this large submarine slide, the ground was intricately fractured for distances of 100–800 feet (figs. 3, 4). Near the northern end of the landslide scarp, some of the fractured ground subsided several feet and rotated as landslide slump blocks (fig. 12).

The submarine sliding along the Seward waterfront resulted in marked deepening of the water in the vicinity of the former shoreline. Cross sections *B–B′* and *C–C′* of plate 2 show the pre- and postearthquake profiles of the bay floor in the vicinity of the former Standard Oil Co. dock and the San Juan dock. Water that before the earthquake was 35 feet deep (mean lower low water) off the end of the Standard Oil Co. dock is now 160–180 feet deep; water that was approximately 35 feet deep off the end of the San Juan dock is now 140–150 feet deep. Immediately offshore from the Standard Oil Co. dock area, the average slope of the preearthquake profile to a depth of about 160 feet was about 20°, though locally the slope exceeded 35°. The slope of the postearthquake profile is 25°–30° to a depth of about 180 feet. Between 500

12.—Incipient landsliding along northern part of Seward waterfront. Fractured ground has subsided and rotated as landslide slump blocks.

and 600 feet from the present shoreline, both pre- and postearthquake profiles flatten rather abruptly to slopes of less than 5° and continue as nearly coincident surfaces for 2,300 feet. Beyond this point the profiles again steepen for a few hundred feet before reaching the relatively flat trough of the bay bottom. However, even there at a depth of about 500 feet, the bay floor appears to be lower than before the earthquake in spite of a layer of landslide debris. Near the former San Juan dock, the upper parts of the pre- and postearthquake profiles both slope about 10°, much flatter than near the former Standard Oil Co. dock.

There was little or no recession of the shoreline by landsliding in the area of the former Alaska Railroad docks at the southern end of town. Comparison, however, of pre- and postearthquake soundings indicates that submarine sliding deepened the bay floor a maximum of about 40 feet between present depths of 100 and 250 feet, but that the postearthquake deepening probably diminishes to zero at the shoreward end of the dock. According to J. C. Ireton, U.S. Army Corps of Engineers (written commun., 1966), sliding probably did not contribute to the dock failure. The material that did slide was probably in large part fine-grained marine sediments deposited on the steep frontal slope of the fan deposits. A sample of the marine sediments from this area, collected on the bay bottom at a depth of 75 feet by divers, comprised nearly 50 percent clay-size sediments, 40 percent silt size, and nearly all the remainder, sand size.

Large-scale landsliding of deltaic deposits offshore from the northwest corner of the bay shifted bathymetric contours several hundred feet landward. Water that was 20 feet deep before the earthquake is now about 130 feet deep. In both pre- and postearthquake profiles across a typical part of the slide area (pl. 2, section *A—A′*) the underwater face of the delta slopes approximately 15°, though after sliding the average slope steepens locally to approximately 20°.

Submarine landsliding of the deltaic deposits extended at least as far east as the mouth of Resurrection River. The extent of sliding east of that point cannot be detemined because of insufficient preearthquake bathymetric control. However, if there was submarine sliding, it probably was of smaller magnitude.

Submarine landsliding also occurred offshore from Lowell Point and Fourth of July Point (G. A. Rusnak, written commun., 1965) although there was no sliding of the land above water. Rusnak noted that offshore material at Lowell Point slid in large masses and is now at the toe of the point. Investigations made from the research vessel, the *Don J. Miller*, by G. A. Rusnak and others (1966, written commun.) provide additional information on submarine slides in Resurrection Bay.

MECHANICS AND CAUSES OF LANDSLIDING

Strong ground motion during the earthquake triggered the sliding along the Seward waterfront and elsewhere in the bay, but several factors contributed to its magnitude.

The long duration of strong ground motion was a major factor. All evidence indicates that sliding took place progressively throughout the approximately 4 minutes of heavy shaking. Eyewitnesses state that strip after strip of land disappeared into the bay until the earthquake ceased. A strip of land marginal to the present slide scarp is heavily fractured into incipient landslide blocks, and divers reported that the underwater slope in the area of the San Juan dock was also deeply fissured. Because much of the sliding at the head of the bay took place underwater, no one saw the progressive sliding in that area, but the intermittent churning and boiling of the waves indicate that sliding there also continued throughout the earthquake and perhaps even for several minutes afterwards.

The configuration of the pre-earthquake underwater slopes and the nature of the materials forming these slopes also favored large-scale sliding. Data from borings and from geophysical profiles show that loose, generally fine-grained materials were involved in the sliding. These materials, laid down as deltaic deposits and forming steep underwater slopes, probably were metastable under static conditions; under dynamic conditions of continued seismic shock, they failed readily.

In choosing the location for the new railroad dock and facilities, sites at both the northwest and northeast corners of the bay were considered. On the basis of offshore and onshore borings and geophysical data, the subsurface conditions at the northeast corner appeared to be superior to those at the northwest corner. As stated by Shannon and Wilson, Inc. (1964, p. 25), "In the northeast corner the subsurface conditions are considered to improve with bedrock exposed on shore [east valley wall] and at depths of the order of 100 feet over a substantial area. There are indications that dense glacial till may be present at relatively shallow depth over some of the area. Subaqueous landslides apparently did not occur. Hence it would appear that portions of the northeast corner, on the basis of limited data, are more stable and offer foundation conditions superior to those which may be obtained elsewhere." The writer fully agrees with these conclusions.

In final selection of the dock site at the northwest corner of the bay, however, economic and logistical considerations overrode the indicated differences in geologic suitability. A site at the northeast corner of the bay would have been approximately 7 miles from downtown Seward by the present road system. In addition to time and cost of travel, accessibility would be difficult in winter. Furthermore, The Alaska Railroad would have had to extend its trackage and acquire additional land for marshalling yards. Other facilities, now in Seward, would also have required relocation.

Conditions for failure probably were nearly optimum along the Seward waterfront, where, as shown diagrammatically in cross sections *C–C′* and *B–B′* of plate 2, loose sand and gravel in the distal edge of the alluvial fan intertongue and interlense with marine clay, silt, and sand. Torrential flooding from Lowell Creek canyon has periodically dumped sand and gravel off the distal edge of the fan (fig. 9); during the relatively long intervening periods when only minor quantities of fluvial deposits reached the bay, fine-grained marine sediments were deposited along the steep underwater face of the fan. Drill-hole data indicate that some of the foreset beds along the distal edge of the fan dip as steeply as 30° and that the chips of phyllite constituting nearly all the sand-size particles are oriented with their flat sides parallel to the bedding.

Vibration of the ground during the earthquake may well have been of sufficient duration and critical frequency to produce liquefaction of the finer grained sediments, particularly the sand, silt, and clay constituting the intertongued marine sediments. If so, there was a sudden but temporary increase in pore water pressure, and the saturated sediments were transformed into a concentrated suspension with minimal shear strength (Terzaghi and Peck, 1948, p. 100–101). The seaward-dipping tongues of sand, silt, and clay, as well as fine-grained lenses intercalated with the coarser fan materials, would furnish optimum conditions for seaward flowage of material as sliding advanced progressively landward. The structure of the deposits, particularly those deposits forming steep slopes, would collapse, and part of the material would be transformed into a slurry. This suspended material would tend to travel toward the deeper part of the bay and would be dispersed in turbidity currents. Where material was less susceptible to liquefaction and slopes were flatter, discrete blocks consisting of coarser disaggregated particles would tend to slide. In support of this supposition, G. A. Rusnak (written commun., 1965) concluded from his work, done in the fall of 1964 on the research vessel *Don J. Miller*, that landslide debris was deposited in part by mass movement and in part by turbidity currents. Thickness of slide debris, as shown on the cross sections of plate 2, is largely conjectural. Further studies of the bay floor in 1965 by G. A. Rusnak and others have provided much additional data on the thickness of the slide debris and on the total extent of submarine sliding. On the basis of preliminary analyses of these data, Rusnak (oral commun., 1965; and in Corwin and Bradley, 1965) believes that large-scale rock movement along preexisting faults and folds in Resurrection Bay contributed to the sliding of the overlying sediments. As stated previously, however, the writer has found no evidence on the adjacent land to support the supposition that there was fault movement in the Seward area that was related to the earthquake.

According to eyewitnesses, there was a sudden drawdown in water level along the waterfront shoreline during the early part of the strong ground motion. In places, such as near the Standard Oil dock, the water level may have been lowered as much as 20–25 feet. In addition, the water was nearly at low tide. The combined conditions would tend to increase markedly the shearing stresses in the saturated deposits owing to loss of support of the water along the free face of the fan. Slide activity, which initially caused the drawdown, would be increased.

Another factor probably contributing to sliding is the effect of added load of manmade facilities. The docks, which extended out to the steep slopes of the fan, in addition to their own weight, were heavily loaded with filled oil tanks, warehouses, and heavy equipment. Numerous other filled oil tanks, as well as the railroad marshalling yards and associated facilities, were close to the shore. Many of these facilities had been extended seaward by adding artificial fill, as much as 15 feet thick, to the distal edge of the fan. At the time of the earthquake, a fully loaded freight train of 80 cars and a locomotive, stood on the tracks between the Standard Oil dock and the Texaco, Inc., tanks. The combined weight of all these objects must have been considerable. Slopes, which had been built out at the natural angle of repose, may well have been unable to accommodate this additional surcharge under seismic conditions.

Closely related to the manmade surcharge is the possible effect of the added weight of water from the wave that overran the Seward waterfront area after the drawdown of water but while the ground was still in motion. The limit of ground fracturing, which is believed to represent the limit of incipient landsliding, is nearly coincident with the maximum runup of the waves. It seems reasonable to assume that the added weight of water from the first wave, plus the seaward pulling effect as it receded rapidly from the land, was a contributing factor during the later stages of the landsliding. So far as can be determined, however, no further sliding continued during runups of the later seismic sea waves when ground shaking had subsided.

Onshore drilling at the northwest corner of the bay and near the mouth of Resurrection River shows that several aquifers under hydrostatic head intersect the slides in that area. These artesian conditions probably contributed to the sliding in the deltaic deposits. Uplift pressures would tend to create a buoyant effect upon the fine-grained material when vibrated and to decrease the stability and bearing capacity of the slope. This factor, when combined with the probable liquefaction characteristics of the sediments, probably would cause the material to flow seaward as a suspended sediment.

FUTURE SLOPE STABILITY

STATIC CONDITIONS

Under static conditions, there seems little likelihood of major shoreline or submarine sliding in the Seward area. In the year after the earthquake, no recession of the shoreline occurred along the Seward waterfront other than local minor slumping and erosion from wave action. During the first few months apparently minor offshore adjustments of slopes took place; tank cars, railroad ties, and other debris that had been entrapped on the bay floor floated to the surface.

The average underwater slope to a depth of about 180 feet in the vicinity of the former Standard Oil Co. dock is now somewhat steeper than the average preearthquake slope. However, the preearthquake slope exceeded the present slope in places. The present slope will not be further steepened by deposition of alluvium off the edge of the fan, as happened periodically before Lowell Creek was diverted through the diversion tunnel. Moreover, the absence of docks will lessen the possibility that these slopes will become catchments for large accumulations of littoral sediments, which would oversteepen the slopes. Probably even more significant, the landsliding stripped the more slide-prone material from the face of the fan. Subsurface data indicate that the tongues of marine sediments wedge out landward into the more stable fan deposits.

One small area where some submarine landsliding or slumping may occur during static conditions is the cove near the old railroad dock at the southwest end of town. Here a considerable volume of alluvium debouches from the diversion tunnel during times of high streamflow and is deposited on an already steep slope (pl. 2). Conceivably, the underwater slope can be oversteepened to the point of failure. Before construction of any docks in the area, this possibility should be investigated. Farther south, the west shoreline is mostly bedrock and sliding is unlikely.

Offshore slopes at the northwest corner of the bay are approximately the same as they were before the earthquake, and it is unlikely that large-scale sliding will occur under static conditions. The same statement probably holds true for the area to the east. Deltaic and marine deposits will gradually accumulate to establish profiles similar to those that existed before the earthquake. Whether the 3:1 slope formed by dredging at the end of the new railroad dock (pl. 2) will be stable under static conditions is unknown. There is little doubt, however, that periodic dredging will be necessary in the area in front of the dock and at the entrance to the small-boat basin. Sediment brought in by the Resurrection River and by creeks will continue to accumulate in this area as it has in the past. Tides and offshore currents will tend to spread this material into the dredged areas.

DYNAMIC CONDITIONS

In the event of another large earthquake, additional onshore and submarine landsliding can be expected along that part of the Seward waterfront that slid during the earthquake of 1964. As discussed previously (p. E29) the area of fractured ground back of the present shoreline (figs. 3, 4) is believed to represent incipient landslides. Had shaking continued longer during the 1964 earthquake, a large part of this area would have slid into the bay. Thus, sliding of similar extent can be expected during a future large earthquake.

Because of the potential instability of the Seward waterfront area, the Scientific and Engineering Task Force of the Reconstruction Commission, which based its decision upon the investigations of Shannon and Wilson, Inc., the Corps of Engineers, and the U.S. Geological Survey, placed a large part of this area in a high-risk classification. A map depicting the extent of this area is shown by Eckel and Schaem (1966). In general, the limits of the area shown as high risk include the area of fractured ground (figs. 3, 4). The Task Force recommended that the high-risk part of the waterfront area should be reserved for park or other uses that do not involve large congregations of people. Shannon and Wilson (1964, p. 23) further stated that "The stability of the waterfront could be improved by flattening the underwater slopes and buttressing the toe of the slide with fill. However, due to the great depth we doubt that slope flattening and toe buttressing are practicable." The writer concurs in both statements.

The remaining part of downtown Seward was classified by the Task Force as nominal risk—risk no greater than is normally expected in the construction industry. However, one must consider whether fracturing would extend into the eastern part of the nominal-risk area if an additional strip of shoreline should slide into the bay. This possibility cannot be discounted, but the geologic environment indicates that it would, at most, be of small extent. The thickest part of the fan deposits and probably all the intertongued marine sediments lie between Seventh Avenue and the bay (section *C-C′*, pl. 2). West from Seventh Avenue toward the business district, the fan deposits become progressively coarser, are probably only 100–150 feet thick, are nearly horizontally bedded, and lie on a fairly flat platform of compact stable till. It is therefore probable that fracturing, at least west of Sixth Avenue, would be minor.

The earthquake triggered small-scale landsliding offshore from the old railroad dock, and another severe earthquake could cause additional sliding. The relatively shallow depth to bedrock and the possibility that only thin deposits of fluvial material rest on a stable platform of till probably explain why this area was less susceptible to sliding than other parts of the waterfront.

Additional submarine landsliding can be expected along the present face of the deltaic deposits in the northwest corner of the bay in the event of another large earthquake. The present landslide scarp has about the same slope as the preearthquake foreset bedding. The material back of the scarp has virtually the same physical properties as that involved in the sliding, and landward retreat of the landslide scarp can be expected. Shannon and Wilson, Inc. (1964, p. 25), estimated that "additional sliding may be expected to envelop an area to the north of the present scarp for a distance of some 600 feet." They further stated that "It would be prudent in our opinion to site the proposed improvements [new Alaska Railroad dock] so that an adequate set-back from this zone of potential sliding is maintained." The end of the new railroad dock is approximately 1,100 feet from the edge of the scarp (pl. 2). In the writer's opinion, the amount of scarp retreat will depend in part on the intensity of shaking, but even more on the duration of future shaking. Strong ground motion during the 1964 earthquake lasted approximately 4 minutes. During this period, there was a landward retreat of the delta face of 400–500 feet. If the materials are liquefied during shaking, as believed, then the accumulation of debris at the toe of the slide will not be a deterrent to further sliding. Provided there is no change in the characteristics of the materials involved, slumping will continue landward at about the same slope angle for as long as strong ground motion continues.

In order to provide sufficient depth for ocean-going ships to reach the new railroad dock, it was necessary to dredge a swath, 35 feet deep, 1,700 feet long, and 500–900 feet wide. The sides of the dredged area were constructed on 3:1 slopes, largely in loose fine gravel and sand. A future earthquake as severe as the one of 1964 will probably cause some failure of these slopes and partial filling of the dredged area. Shannon and Wilson, Inc. (1964, p. 24–25), stated "Dredging for ocean ships probably will remove the sand and gravel which overlies the marine sediments, thus structures will obtain their support in these [marine] sediments. Notwithstanding the removal of weight by dredging, significant area subsidence should be anticipated in the event of another great earthquake. Heavy structures, such as earthfills will experience subsidence of the order of several feet and perhaps as much as 10 feet or more whereas lighter structures are expected to subside significantly less. It is possible that piles imbedded in the marine sediments may lose their support in localized areas due to liquefaction during an earthquake." Later, offshore pile-driving tests by the Corps of Engineers showed negligible pile settlement under static loads. However, no dynamic (vibratory) load tests were conducted to simulate the effect of strong ground motion.

To minimize future earthquake damage to the new railroad dock and related facilities, the structures were designed by the Corps of Engineers to withstand seismic shock up to certain limits. In instructions (Warren George, Chief, Engineering Division, written commun., July 14, 1964) to those responsible for design, it was specified that "Your analysis specifically must consider earthquake dynamic effects on the soils such as liquefaction of sands and silts and inertia forces on the soils and structures thereon. Use a strong motion design for an earthquake of the order of a Richter magnitude of 7.5, a maximum horizontal ground acceleration of 0.15 to 0.20 gravity and a duration above two percent gravity of 3 minutes and an epicenter within 30 miles. Select a group of response spectra reflecting the interrelation of local stratigraphy and formation densities on the structure vibrations and motions."

POTENTIAL LANDSLIDES AND AVALANCHES IN ADJACENT MOUNTAIN AREAS

The earthquake of 1964 triggered several landslides and snow avalanches in steep-walled tributary valleys in the mountains flanking Seward; if there is another large earthquake, additional landsliding and avalanching can be expected.

Future earthquake-induced snow avalanches and rock and debris slides along Lowell canyon could impound sufficient water to flood Seward if there were a sudden rupture of the slide dam. This possibility would be markedly increased if tree trunks and other debris were washed into the diversion tunnel and plugged the intake. To help obviate this last possibility, as well as the possibility of large rocks being stream-carried into the tunnel, at any time, a trash rack could be constructed upstream from the tunnel intake to catch any large material washed downstream.

Additional earthquake-induced rock slides and snow avalanches also can be expected in Jap Creek canyon, but unless the slides are very large, little damage from flooding is likely downstream if the dams formed by slides are suddenly breached. Additional slides can also be expected in other scattered areas. Further slides in Box canyon, similar to those triggered by the earthquake of 1964, could divert a large discharge of water down Clear Creek that would inundate residential areas downstream. Some talus slopes, already weakened by the 1964 earthquake, may become even less stable. Rock talus slopes, whose toes have been excavated during road construction along the steep cliffs between Seward and Lowell Point, are particularly susceptible to sliding whether an earthquake occurs or not.

FRACTURED GROUND

SEWARD WATERFRONT AREA

Ground fracturing along the Seward waterfront (figs. 3, 4) is believed to be closely related to onshore and offshore landsliding in that area. Horizontal translation and vertical displacement of the ground seaward, as sliding progressed, apparently was the dominant cause of fracturing.

The total amount of horizontal and vertical displacement in the area of fractured ground could not be determined accurately. It undoubtedly was greatest in the area of the Texaco tanks and became progressively less toward the Standard Oil Co. tanks. Two weeks after the earthquake, the fractures in the area of the Texaco tanks were commonly 0.5–2 feet wide, and a few were as wide as 4 feet. In general, the dominant fracture systems were roughly parallel to the shore. Intersecting transverse fracturing commonly produced a roughly polygonal pattern (fig. 4). In most places, the decreasing width of the fractures

13.—Ground fracture near east end of A Street, about 100 feet from present shoreline, showing vertical displacement of about 4 feet. Downthrown side is toward Resurrection Bay.

away from the shore reflected a decrease of lateral spread of the ground in that direction. Where the fractures were offset vertically, the downthrown side was generally toward the bay (fig. 13). Vertical offsets were confined largely to the near-shore area and to the fractures paralleling the shore. Along the shore at the eastern extension of Monroe Street, vertical offsets of as much as 5 feet marked margins of blocks tilted with their surfaces sloping landward. In most places, however, there was no evidence of rotation of the ground between fractures. Vertical offset decreased southward so that in the vicinity of the Standard Oil tanks little or no vertical displacement was discernible. The sharpness and linearity of fracturing probably can be attributed to the fact that the ground was frozen to a depth of about 0.5 foot. Such a rigid blanket would tend to fail along sharp, straight fractures.

Near the Texaco tanks and northwest toward the lagoon area, sand was ejected from some of the fractures and deposited as a thin skim on the surface, generally less than 1 inch thick and less than 6 inches wide, bordering the fractures. No conspicuous sand boils or vents, such as characterize the Forest Acres subdivision, were apparent. Eyewitnesses reported that the fractures opened and closed and ejected muddy water during the shaking.

Probably other factors beside lateral translation of the landmass were involved in the area where the sand was pumped from the fractures. In the area of pumping, the near-surface material is generally loose fine-grained silt, sand, and gravel and the water table is within a few feet of the surface. Such materials are susceptible to compaction when vibrated. During compaction of these saturated deposits, water would be forced from the voids to the ground surface, carrying fine material with it. Whether or not other factors, such as seismic waves reaching critical amplitudes, rupturing the surface, and pumping out sand contributed cannot be properly evaluated for this area. These factors are considered in more detail in the following discussion of Forest Acres and adjacent areas where pumping of water and sand was prevalent.

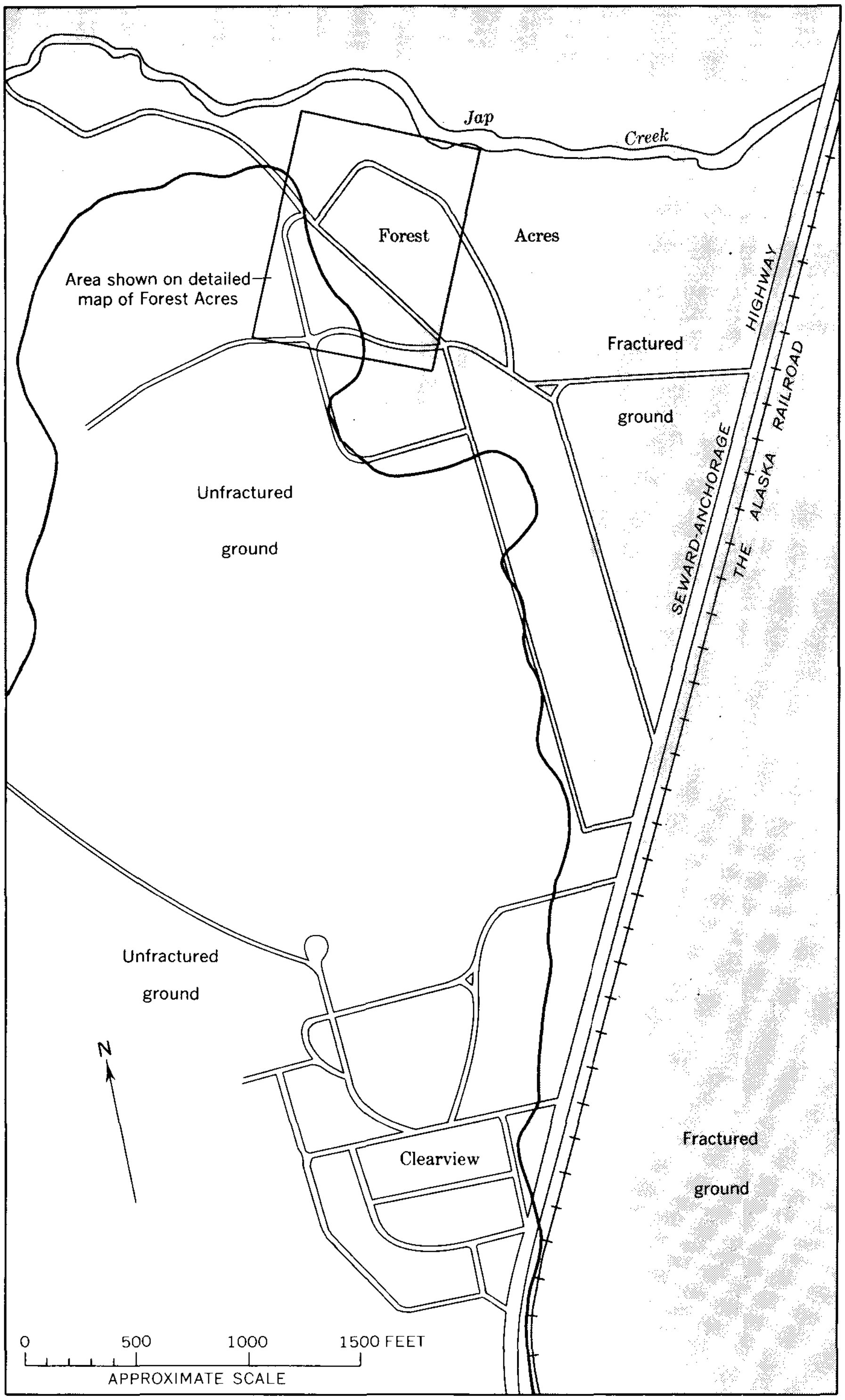
FOREST ACRES AND ADJACENT AREAS

The conspicuous fracturing of the Jap Creek alluvial fan and of much of the alluvial floor of the Resurrection River valley cannot be directly related to major landsliding. Limited lateral movement of the ground may have been involved in the process, but the area of fracturing is relatively flat and there are no large free faces toward which the materials could be laterally translated except near the head of the bay itself; therefore, the fracturing must be attributed largely to other causes.

Fracturing on the Jap Creek alluvial fan was confined to the distal part of the fan. A fairly distinct scarp, 10–15 feet high, marks the northern margin of the fan, but the much wider eastern margin slopes gradually down to the valley alluvium without a clearly defined boundary. Figure 14 shows the upslope limits of fracturing in this area, and figure 15 (next page) depicts the pattern of fracturing of an area in Forest Acres where there was greatest damage to manmade structures.

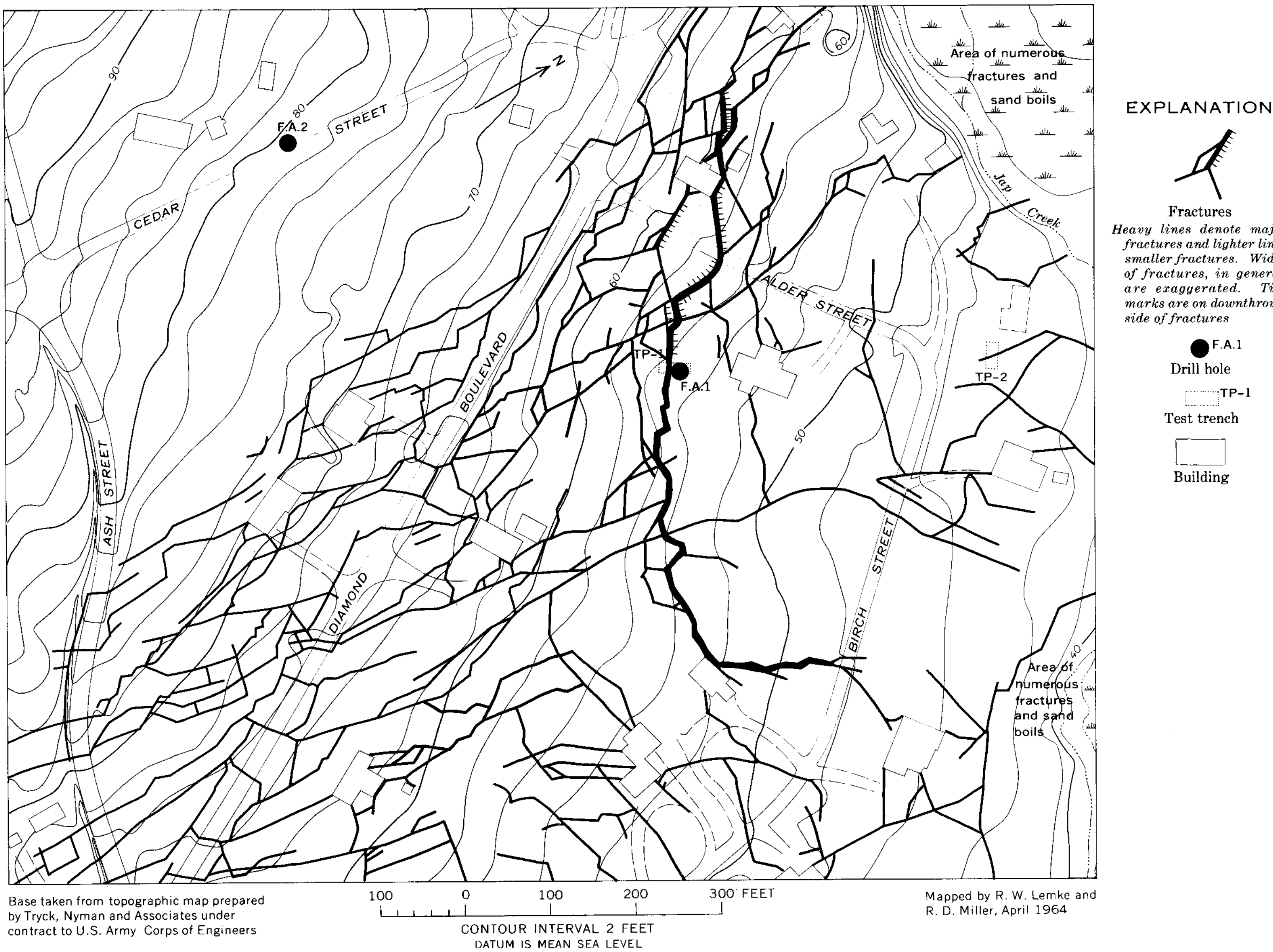
In many places the relatively flat alluvial floor of the Resurrection River valley was more intensely fractured than was the outer margin of the Jap Creek fan. Particularly in the lower lying swampy areas and along river bars, fractures were so closely spaced and sand ejected from the fractures was so abundant that individual fractures were commonly obscured. A heavy tree and brush cover over much of the area severely limited detailed ground study and interpretation from aerial photographs. In general, the fracture pattern and geologic environment appear to be similar to that in Forest Acres except along the streams where many of the larger fractures roughly parallel the banks of the drainage courses. There lateral spreading toward a free face is indicated.

The fracture pattern in Forest Acres is different from that along the Seward waterfront in several respects, as can be seen on figure 15,



Culture adapted from an aerial mosaic photograph

14.—Map of general area of Forest Acres and Clearview subdivisions of Seward showing extent of ground fractured as a result of the earthquake of March 27, 1964.



15.—Map of the Forest Acres subdivision showing fractures induced by the earthquake of March 27, 1964.

although in both places the major fracture system (heavy line on fig. 15) and many other long linear fractures roughly parallel the contours. In general, the fracture-bounded areas in Forest Acres are more elongate in plan. Many fractures die out along their extensions (fig. 16). Several fractures intersect at right angles to each other, and otherwise remarkably linear fractures commonly make right-angle turns. Only a few are arcuate in plan. Many fractures extend diagonally from corners of buildings and die out in a short distance; most of these do not extend under the buildings. Fractures commonly follow the bottoms of the shallow ditches bordering the streets and other manmade excavations where the depth of frozen ground was less than elsewhere.

Along the main fracture system shown on figure 15, the fractures commonly were 2–3 feet wide at the surface at the time of mapping (Apr. 20–24, 1964). The greatest width was 4.2 feet. Some caving beneath the frozen surface layer, a peaty gravelly soil about 1.5 feet thick, had already occurred, but the frozen layer itself remained intact; hence the dimensions at the time of mapping closely approximated the width of the fractures immediately after the earthquake. Loose sand and gravel, caved from the walls, has filled the fractures so that most were 3–5 feet deep at the time of mapping; the greatest

16.—Ground fracture in Forest Acres area. Fracture is about 2 feet wide in the foreground. Photograph by R. D. Miller. April 1964.

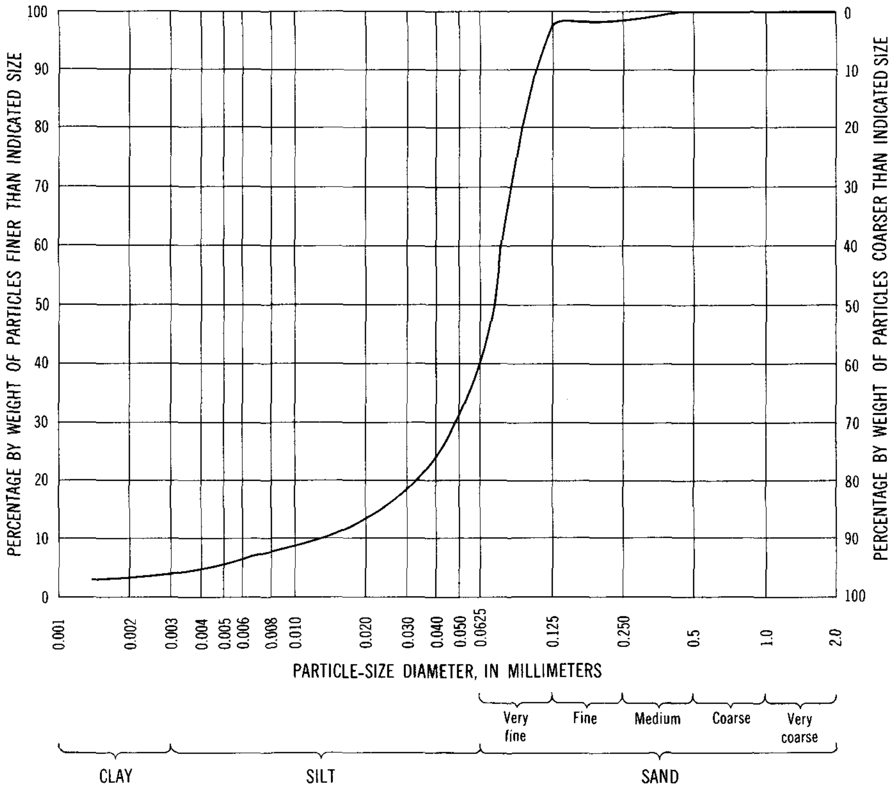
depth observed was 11 feet. The widths of the fractures in general decrease upslope toward Diamond Boulevard from the main fracture system. Widths of 3–4 inches were common, and many fractures were only hairline cracks that broke the hard-packed snow, which covered much of the area to depths of 1–3 feet. West (upslope) from Diamond Boulevard, the fractures became progressively narrower and finally died out entirely. No fractures were found above the 80-foot contour line in this area.

Some fractures, particularly those along the major system, are offset vertically as much as 1.5 feet, but the displacement is generally only a few inches. In places, the downthrown side of a fracture may be on one side along part of the length and on the other side along another segment. In a few places, small grabens were formed where parallel fractures were downthrown in opposite directions.

In places where the ground was fractured beneath large trees, the tree trunks were cracked. In one place on the alluvial floor of the Resurrection River valley, two trees were split to a width of 1 foot at their bases and to a height of 30–40 feet. If the trees were frozen at the time of the earthquake, as they may have been, splitting would have been facilitated.

Sand boils were formed along part of the major fracture system, particularly in the downslope area. Only a few small sand boils were formed southwest of the major fracture system, and none west of Diamond Boulevard in the area shown on figure 15. Where only a small quantity of water and sand was ejected to the surface, the sand spread out on the snow-covered surface as subcircular or oval patches, 10–30 feet in diameter and 1–4 inches thick. Where fountaining was more pronounced and the volume of pumped sand was greater, as in the low area east of Birch Street, sand from individual vents coalesced and formed aprons as much as 1 foot thick. Many of these larger sand areas nearly obscured the underlying fractures. Here and there tabular ridges of sand 3–6 inches wide reflected the location of the underlying fractures. These ridges were accumulations of sand ejected into the fractured overlying snow and left standing in relief after the snow melted.

The ejected material was everywhere remarkably uniform in size and consisted of a dark-gray, very fine sand (0.0625–0.125 mm),



17.—Grain-size analysis of material from a sand boil, Forest Acres area. Analyst George S. Erickson; sample 4–346.

lesser quantities of silt, and minor clay. Figure 17 shows a grain-size analysis of a typical sample taken near trench TP–2.

No well-developed cones of sand surrounding exit vents, such as have been described from other earthquake-affected areas (Fuller, 1912, p. 79–80; Segerstrom and others, 1963), were found. Presumably the ejected material had sufficient fluidity to spread out everywhere as a thin blanket. Only a few surface vents were detectable, and these consisted for the most part of a slight circular enlargement of the fracture walls, open at the time of mapping to a depth only slightly deeper than that of the fracture. In several places, venting appears to have taken place simultaneously along a 25- to 75-foot segment of a fracture.

COORDINATE CAUSES OF FRACTURING

In order to determine the causes and mechanics of the ground fracturing and of the associated sand-boil activity, the subsurface conditions under the fractured area were studied extensively and compared with the sediments underlying the nearby unfractured area (fig. 15). Drill holes F.A. 1 and F.A. 2, bored to depths of 50.0 feet and 69.5 feet through fractured and unfractured ground, respectively, furnished a comparison of the composition and characteristics of the materials. Trench TP–1, dug to a depth of 12.5 feet across the major fracture system, furnished information on bedding and sorting, depth of fracturing, material found in the fractures, and depth to the water table. Trench TP–2, dug farther downslope and to a depth of 7.3 feet, supplemented this information.

All subsurface data indicate that the fan deposits, in general, become progressively finer grained downslope. Drill hole F.A. 2 penetrated poorly sorted sand and gravel to a depth of approximately 60 feet and then bottomed in silt and sand. In drill hole F.A. 1, poorly sorted sand and gravel also were penetrated to a depth of 50 feet, but intercalated sand and silt layers were fairly abundant, particularly in the upper part of the section. Hammer blow counts, taken at both holes, also showed generally much more difficult penetration of materials in drill hole F.A. 2 and doubtless reflected larger size fractions. In trench TP–2, as well as in sewer and water trenches along Birch Street, the near-surface deposits were chiefly sand and silt. Gravel, where present, was fine grained.

The water table also comes progressively closer to the surface in a downslope direction. The depth to the water table in drill hole F.A. 2 could not be determined at the time of drilling because of drilling mud. However, 2 weeks later the water level in the hole was at a depth of 22.0 feet; whether the water was under hydrostatic head is not known. The surface of this hole is 25 feet higher than the surface of TP–1, where water entered the trench at a depth of 12.5 feet. In TP–2, downslope from TP–1, a copious volume of water entered the trench from the northeast at a depth of 6.3 feet, approximately the same elevation as the surface of the water in nearby Jap Creek.

Caved material filling the fractures was so nearly identical in appearance to the loose material forming the walls of the fractures that, generally, a well-defined fracture on the surface could not be recognized more than 2–3 feet below the caved material. A notable exception to this, however, was found in TP–1. Here, a fracture 1–2 feet wide at the surface, at a point where a sand boil had formed, was open to depth of 2 feet. Between depths of 2 and 7.7 feet, the fracture was filled with loose sand and gravel that had caved from the adjacent walls. Between 7.7 feet and the bottom of the trench (12.5 feet), the fracture, which was vertical and approximately 1 foot wide, was filled with sand identical in appearance to the sand forming the sand boil at the surface. This sand dike was obviously part of the ejecta that did not reach the surface and, therefore, the bottom of the trench (12.5 feet) provides a minimum depth of sand source for the boil.

The mechanism of ground fracturing on the outer margin of the Jap Creek fan and on the alluvial floor of the Resurrection River valley is not clear. Evidence is strong that differences in the properties of materials and the heights of the water table determined to a large degree the areal extent and magnitude of fracturing and the related sand-boil activity. Two hypotheses present what seem to be the most plausible causes of the fracturing; it is conceivable that both are correct.

In one hypothesis, which Coulter and Migliaccio (1966) favored for explaining the longitudinal fractures that formed in alluvial fill at the head of the fiord at Valdez, seismic energy itself is the contributing cause for the fracturing. This hypothesis was first proposed by Oldham (1899, p. 89). According to Coulter and Migliaccio, seismic energy, transmitted into the thick unconsolidated deposits, is transformed into visible surface waves whose amplitude increases to the point where the strength of the surface layer is exceeded and rupture occurs. Furthermore, they believed that the ground was broken in areas where the frozen surface layer was the thinnest and that continued seismic-wave action subjected the underlying saturated materials to alternate compression and extension so that water containing suspended silt and sand was pumped up through the fissures onto the surface. A similar interpretation was made by Macelwane (1947, p. 17) who stated that "Another secondary effect of the earthquake motion is extrusion of sand or mud. The alternation tension and compression which is applied to the ground during the passage of earthquake waves opens fissures and sucks down the ground water, then closes them, violently forcing out the water and with it large quantities of sand or mud that lay in its path."

In several ways this mechanism is consistent with the physical conditions and the associated effects of fracturing noted in Forest Acres and adjacent areas. First, although ground waves of large amplitude were not reported in the Seward area, there were accounts of the ground moving in places like ocean waves. These ground waves may have been of sufficient size to break the ground where other conditions, such as the presence of a thick section of loose surficial deposits, favored breakage during alternate compression and extension. Secondly, the fact that the fountains accompanying the sand-boil activity pulsated in height during the shaking argues strongly that the fractures alternately opened and closed during the shaking. This alternation also was confirmed by eyewitnesses.

Finally, the surface layer, frozen to a depth of approximately 1.5 feet in the area of fracturing in Forest Acres, would act like a rigid, brittle pad; that is, it would break in a well-defined fracture pattern when subjected to compression or extension. The unfractured condition of ground above the 80-foot contour line in Forest Acres might be explained by the presence of a thicker frozen layer sufficiently competent to preclude breakage. The areal extent of fracturing might also have been limited by the characteristics of the materials underlying the frozen layer. Seismic energy tends to generate ground waves of larger amplitude and greater rupture strength in fine-grained deposits, particularly saturated deposits, than in coarser unsaturated material. Both types of materials are present in the Forest Acres area, and the effects of the earthquake on the two types can be explained by the hypothesis. The even greater amount of fracturing along the alluvial floor of the Resurrection River valley also would be explained because there the water table is generally within 5 feet of the surface and in places intersects the surface, and the area is underlain almost entirely by loose silt, sand, and fine gravel.

Coulter and Migliaccio (1966) stated that the depth of fracturing in the Valdez area could not be determined but that the fissures probably lost their identity as discrete voids at the water table. They also emphasize the fact that the ground at the time of the quake was frozen down to the water table at depths of 4–6 feet. In these respects, conditions at Forest Acres were not analogous to those at Valdez. In all places observed in Forest Acres the water table was well below the depth of frozen ground, and, as indicated by the sand dike which extends at least to the water table in trench TP–1, fracturing, at least in places, extended to and possibly below the water table. Whether fractures could be formed to this depth by compression and extension of the ground cannot be evaluated by the writer.

The second explanation of the fracturing and attendant effects in Forest Acres and vicinity involves compaction of the loose deposits under the frozen surface layer and consequent fracturing not only of the surface layer but also of the underlying deposits. The compaction of fine-grained materials during earthquakes has been well documented. As pointed out by Seed (1964, p. 37), "Earthquakes are a good source of vibrations and consequently we can get a great deal of compaction resulting from earthquakes. The decrease in volume of a soil due to compaction will cause settlement of the ground surface * * *. If the sediments which compact during an earthquake are saturated, then water from the voids is forced to the ground surface where it emerges in the form of sand spouts or sand boils."

The actual amount of vertical and horizontal compaction that may have taken place in the surficial materials in the Forest Acres area during the earthquake is not known, but the earthquake did produce substantial amounts of compaction in fine-grained sediments in other parts of Alaska. For example, at Homer, 2.5 feet of subsidence, presumably in near-surface fine-grained material, can be attributed to compaction (Grantz and others, 1964, p. 26). In the vicinity of Portage where there is a great thickness of silt and sand, 4–5 feet of subsidence is attributed to compaction (Seed, 1964, p. 37). Pre- and postearthquake vertical control across the Snow River valley, 18 miles north of Seward, where there was conspicuous bridge and highway failure, showed that the alluvial valley floor subsided 2–3 feet relative to the bedrock walls (M. Dickinson, Alaska State Highway Dept., written commun., 1964). The alluvium, at least to a depth of 100 feet, consists chiefly of sand and silt and has a high void ratio; the water table is within 2 feet of the surface. The alluvial surface is heavily fractured for a distance of several miles up the valley, and sand boils are very abundant. It should be pointed out that there was some lateral spreading toward the open face of the nearby delta of Kenai Lake and, therefore, the total amount of subsidence probably cannot be attributed solely to compaction. However, compaction probably was the main factor. The State of Alaska Department of Highways (written commun., 1965) stated that penetrometer logs indicate an increase in density after the earthquake, and it is their conclusion that the granular sediments at Snow River bridge now are more compact than before the earthquake.

Presumably, the deposits in Forest Acres and adjacent areas were also compacted to some extent. If so, the fracturing and associated effects might be explained as follows:

1. Thick loosely consolidated deposits, surficially nearly flat, resting on an irregular bedrock surface (see cross section *A–A′*, pl. 1) would be differentially compacted; that is, the thickest deposits would show the greatest amount of subsidence at the surface. The stretching effect from such differential compaction would tend to produce open tension fractures. This tensional effect also would explain the small grabens between some of the parallel fractures.
2. Concomitant with the differential compaction of the unfrozen deposits and the formation of tension fractures, the rigid frozen surface layer would also break in response to the tension and the loss of underlying support.
3. Fracturing would tend to die out upslope because of decreased compaction owing to increased grain size and perhaps to decreased depth to bedrock in the direction of the bedrock valley wall.
4. During compaction, water would be forced from the voids of the saturated sediments and, momentarily under considerable hydrostatic head, would spurt to the surface along the fractures. Sand, derived from the finer grained lenses and layers, would also be forced to the surface to form sand boils. The closer the water table to the surface and the finer the material, the greater the amount of fountaining and sand-boil activity one could expect. Both factors fit the geologic environment at Forest Acres.

STABILITY OF FRACTURED GROUND

The ground between the fractures appears to possess chiefly the same degree of static stability as before the earthquake. No collapse pits or other indications of further subsidence were noted in the months after the earthquake. Considerable sand was forced from the underlying deposits, but it apparently came from a large enough mass and from sufficient depth that it did not cause subsidence of the areas between the fractures.

Where the walls of the fractures were offset vertically, as in the graben areas, there was slight subsidence of the downthrown sides for a period of about 1 month after the quake. This movement was not detected after the frozen layer had thawed, and after the initial subsidence it did not exceed 3 inches. Apparently, the subsidence was confined to the frozen layer which adjusted to the configuration of the underlying material. Slumping of the walls of the fractures, of course, continued as the frozen layer melted, and by the fall of 1964 only the larger fractures could be detected on the surface.

What would happen in the fractured area in the event of another large earthquake is difficult to evaluate. Presumably the present fractures represent planes of weakness that could be reactivated by strong ground motion and, therefore, houses or other manmade facilities again would be susceptible to damage where intersected by fractures. However, unless the dynamic conditions were more severe than during the 1964 earthquake, fracturing probably would not extend into the presently unfractured area.

The Scientific and Engineering Task Force of the Federal Reconstruction and Planning Commission classified the area shown in figure 14 in two risk categories as reported in a news release of July 20, 1964. The classification "nominal risk" was applied to the unfractured area and "limited risk" to the fractured part. The limited-risk classification was defined as "ground susceptible to minor fracturing and differential subsidence in response to strong earthquake induced motion." It was further stated that "For this reason, risks are slightly greater than nominal. For construction of residential buildings the following construction practices are recommended: (1) all foundations must be reinforced concrete, and (2) all concrete and unit masonry must be reinforced and interconnected." Although these recommendations were confined to the subdivisions of Forest Acres and Clearview, they could be applied equally to other areas of fractured ground in the vicinity of Seward.

WATER WAVES IN THE SEWARD AREA

TYPES AND INTERPRETATION OF ORIGIN

Slide-generated waves, seismic sea waves, and possibly seiche waves overran the shores in the Seward area. Some were generated locally, others arrived from outside the bay. Whether this multiple wave source formed composite-type waves in the Seward area is not clear. If this condition did occur, then not only could a highly complex wave pattern be expected, but also the wave-arrival times would be erratic and anomalous. Unfortunately this aspect cannot be evaluated because the arrival times of the waves are known only in the most general way.

There is little doubt that the waves that hit the Seward waterfront, the head of the bay, and Lowell Point while strong shaking continued were generated chiefly by landsliding. Other than minor secondary slumping, sliding appears to have terminated at the end of the shaking and, therefore, this source of wave generation also ceased at that time. There are accounts of two local waves, occuring in the interval between the cessation of the shaking and the arrival of the first seismic sea wave about 25 minutes later, that might have been oscillation waves resulting from the first wave. They might, however, have been seiche waves formed as a response to vibratory action during the earthquake or caused by tilting of the bay floor.

The first large wave that arrived in the Seward area approximately 25 minutes after shaking stopped is believed to have been a seismic sea wave (tsunami). It is generally agreed that the seismic sea waves were generated by uplift of the sea floor in the Gulf of Alaska and that the wave crest was generated along one or more line sources within an elongate belt that extends southwestward from the axis of maximum uplift on Montague Island (Van Dorn, 1964; Plafker, 1965). The first seismic sea wave traveling from this source area toward the Kenai Peninsula arrived at Whidbey Bay and Puget Bay (25–30 miles northwest of the line source) approximately 20 minutes after shaking started (Plafker, oral commun., 1965) or approximately 16 minutes after shaking stopped. Arrival time of the seismic sea wave at the mouth of Resurrection Bay probably would be only slightly later than at Whidbey and Puget Bays, which are approximately 15 and 30 miles, respectively, to the east. Allowing for the additional 20 miles of travel up Resurrection Bay and the probable refraction of the wave off the shoreline and islands at the mouth of the bay, the expected arrival time of the wave at Seward would coincide closely with the reported arrival there of the first large wave after shaking stopped.

Other large waves continued to arrive fairly regularly in the Seward area until at least 11:30 p.m. on the night of the quake. The time intervals between waves can be estimated only very roughly on the basis of eyewitness accounts, which indicate that the waves had a periodicity of perhaps half an hour. According to Plafker (oral commun., 1965), the periodicity of the seismic sea waves in the Gulf of Alaska was about 55 minutes. Whether this periodicity would change substantially within the confines of the bay is not known. Also, if seiching developed in the bay, as indicated by Van Dorn (1964), the periodicity of the composite wave effect would be different. Complicated seiching in Kenai Lake about 20 miles north of Seward, due at least in part to westward tilt of that lake basin, has been well documented by McCulloch (1966). It seems reasonable that Resurrection Bay would act almost as a confined basin and that seiche waves could be formed by tilting of the surface in a manner similar to that at Kenai Lake. That the bay was tilted northwestward during the earthquake seems evident from the studies of Plafker (1965, p. 1677). This tilt would cause the first seiche wave to travel northwestward toward the head of the bay. Coincidence of a seiche wave along its travel path with a seismic sea wave might explain why the third seismic sea wave reaching Seward was reported to be one of the highest. Such a coincidence might also explain the reported high wave at 11:30 p.m. However, 11:30 p.m. was also the time of nearly high tide (10.5-foot tidal range), and wave runup would be correspondingly higher.

POTENTIAL WAVE DAMAGE

If a major earthquake in the future produces water waves of the size and energy induced by the earthquake of 1964, additional damage can be expected in the Seward area. Considerably less damage to manmade structures will occur, however, in the Seward fan area, if the area inundated by waves induced by the 1964 earthquake is reserved for parks or other uses requiring no major structures. The new railroad dock and associated facilities, on the other hand, as well as the new small-boat basin, are constructed in areas swept by earthquake-induced waves in 1964 and, therefore, are susceptible to damage from future waves of equal magnitude. Likewise, damage to the new marineway on Lowell Point as well as any other facilities built along the shores of this fan can be expected. However, because the docks and related harbor facilities must be built at the water's edge, the risk must be taken. Seward has few suitable sites for these facilities, and it is not feasible to locate them in more sheltered areas or to provide protection, such as breakwaters, to minimize the effects of the waves.

REFERENCES CITED

Alaskan Construction Consultant Committee [1964], Reconstruction and development survey of earthquake damages in Alaska: Prepared for and published by Federal Reconstruction and Development Planning Commission for Alaska; Honorable Clinton P. Anderson, U.S. Senator, Chairman, 98 p.

Corwin, Gilbert, and Bradley, Edward, 1965, Geological Survey's marine program: Undersea Technology, v. 6, no. 9, p. 35–37.

Coulter, H. W., and Migliaccio, R. R., 1966, Effects of the earthquake of March 27, 1964, at Valdez, Alaska: U.S. Geol. Survey Prof. Paper 542–C, 36 p.

Eckel, E. B., and Schaem, W. E., 1966, Work of the Scientific and Engineering Task Force, *in* The Alaska earthquake, March 27, 1964—Field investigations and reconstruction effort: U.S. Geol. Survey Prof. Paper 541. (In press.)

Fuller, M. L., 1912, The New Madrid earthquake: U.S. Geol. Survey Bull. 494, 119 p.

George, Warren, and Lyle, R. E., 1966, Reconstruction by the Corps of Engineers, *in* The Alaska earthquake, March 27, 1964—Field investigations and reconstruction effort: U.S. Geol. Survey Prof. Paper 541. (In press.)

Grantz, Arthur, Plafker, George, and Kachadoorian, Reuben, 1964, Alaska's Good Friday earthquake, March 27, 1964, a preliminary geologic evaluation: U.S. Geol. Survey Circ. 491, 35 p.

Lantz, Bill, and Kirkpatrick, Mildred, 1964, Seward quake; Good Friday 1964: Seward, Alaska, Kirkpatrick Printing Co., 56 p.

McCulloch, D. S., 1966, Slide-induced waves, seiching, and ground fracturing caused by the earthquake of March 27, 1964, at Kenai Lake, Alaska: U.S. Geol. Survey Prof. Paper 543–A, 41 p.

Macelwane, J. B., 1947, When the earth quakes: Milwaukee, Wis., Bruce Pub. Co., 288 p.

Moffit, F. H., 1906, Mineral resources of Kenai Peninsula; Gold fields of the Turnagain Arm region [Alaska]: U.S. Geol. Survey Bull. 277, p. 7–52.

Oldham, R. D., 1899, Report on the great earthquake of 12th June 1897: India Geol. Survey Mem., v. 49, 379 p.

Payne, T. G., 1955, Mesozoic and Cenozoic tectonic elements of Alaska: U.S. Geol. Survey Misc. Geol. Inv. Map I–84, scale 1:5,000,000.

Plafker, George, 1965, Tectonic deformation associated with 1964 Alaska earthquake: Science, v. 148, no. 3678, p. 1675–1687.

Seed, H. B., 1964, Soil engineering problems: California Resources Agency. Earthquake and Geologic Hazards Conf., San Francisco, Calif., Dec. 7–8, 1964, p. 37–43.

Segerstrom, Kenneth, Casertano, Lorenzo, and Galli O., Carlos, 1963, Eruptions of water and sand resulting from an earthquake near Concepción, Chile *in* Short papers in geology and hydrology: U.S. Geol. Survey Prof. Paper 475–B, p. B131–B134.

Shannon and Wilson, Inc., 1964, Report on subsurface investigation for city of Seward, Alaska, and vicinity, to U.S. Army Engineer District, Anchorage, Alaska: Seattle, Wash. [29 p.].

Terzaghi, Karl, and Peck, R. B., 1948, Soil mechanics in engineering practice: New York, John Wiley & Sons, Inc., 566 p.

Tryck, Nyman, and associates, 1961, City of Seward municipal water facilities: Anchorage, Alaska, 41 p., app.

[U.S. Army] Alaskan Command, 1964, Operation Helping Hand—The Armed Forces react to earthquake disaster: Seattle, Wash., Alaskan Command Headquarters, 83 p.

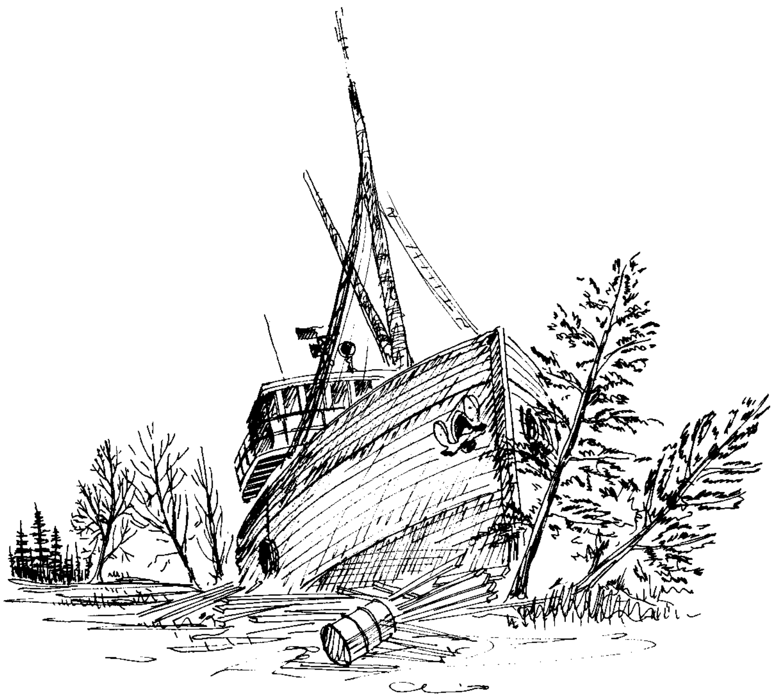
U.S. Coast and Geodetic Survey, 1964, Prince William Sound Alaskan earthquakes, March-April 1964: U.S. Coast and Geod. Survey, Seismology Div., Prelim. Rept., 83 p.

——— 1965, Assistance and recovery, Alaska, 1964; A report covering the activities of the U.S. Coast and Geodetic Survey in conjunction with the Prince William Sound, Alaska, earthquake of 1964 for the period March 27-December 31, 1964: U.S. Coast and Geod. Survey, 45 p.

Van Dorn, W. S., 1964, Source mechanism of the tsunami of March 28, 1964, in Alaska: Coastal Eng. Conf., 9th, Lisbon 1964, Proc., chap. 10, p. 166–190.

Waller, R. M., 1966, Effects of the March 1964 Alaska earthquake on the hydrology of south-central Alaska: U.S. Geol. Survey Prof. Paper 544–A, 28 p.

Waller, R. M., Thomas, H. E., and Vorhis, R. C., 1965, Effects of the Good Friday earthquake on water supplies: Am. Water Works Assoc. Jour., v. 57, no. 2, p. 123–131.



U.S. GOVERNMENT PRINTING OFFICE: 1967 O—232-728