The Alaska Earthquake
March 27, 1964

Regional Effects

Kodiak and Nearby Islands

GEOLOGICAL SURVEY PROFESSIONAL PAPER 543-D

THE ALASKA EARTHQUAKE, MARCH 27, 1964:
REGIONAL EFFECTS

Geologic Effects of the March 1964 Earthquake And Associated Seismic Sea Waves on Kodiak And Nearby Islands Alaska

By GEORGE PLAFKER and REUBEN KACHADOORIAN

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THE ALASKA EARTHQUAKE SERIES

The U.S. Geological Survey is publishing the results of investigations of the earthquake in a series of six Professional Papers. Professional Paper 543 describes the regional effects of the earthquake. Other Professional Papers describe the effects of the earthquake on communities; the effects on hydrology; the effects on transportation, communications, and utilities; and the history of the field investigations and reconstruction effort.

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GEOLOGIC EFFECTS OF THE MARCH 1964 EARTHQUAKE AND ASSOCIATED SEISMIC SEA WAVES ON KODIAK AND NEARBY ISLANDS, ALASKA

By George Plafker and Reuben Kachadoorian

ABSTRACT

Kodiak Island and the nearby islands constitute a mountainous landmass with an aggregate area of 4,900 square miles that lies at the western border of the Gulf of Alaska and from 20 to 40 miles off the Alaskan mainland. Igneous and metamorphic rocks underlie most of the area except for a narrow belt of moderately to poorly indurated rocks bordering the Gulf of Alaska coast and local accumulations of unconsolidated alluvial and marine deposits along the streams and coast. The area is relatively undeveloped and is sparsely inhabited. About 4,800 of the 5,700 permanent residents in the area live in the city of Kodiak or at the Kodiak Naval Station.

The great earthquake, which occurred on March 27, 1964, at 5:36 p.m. Alaska standard time (March 28, 1964, 0336 Greenwich mean time), and had a Richter magnitude of 8.4–8.5, was the most severe earthquake felt on Kodiak Island and its nearby islands in modern times. Although the epicenter lies in Prince William Sound 250 miles northeast of Kodiak—the principal city of the area, the areal distribution of the thousands of aftershocks that followed it, the local tectonic deformation, and the estimated source area of the subsequent seismic sea wave, all suggest that the Kodiak group of islands lay immediately adjacent to, and northwest of, the focal region from which the elastic seismic energy was radiated. The duration of strong ground motion in the area was estimated at 2½–7 minutes. Locally, the tremors were preceded by sounds audible to the human ear and were reportedly accompanied in several places by visible ground waves.

Intensity and felt duration of the shocks during the main earthquake and aftershock sequence varied markedly within the area and were strongly influenced by the local geologic environment. Estimated Mercalli intensities in most areas underlain by unconsolidated Quaternary deposits ranged from VIII to as high as IX. In contrast, intensities in areas of upper Tertiary rock ranged from VII to VIII, and in areas of relatively well indurated lower Tertiary and Mesozoic rocks, from VI to VII.

Local subsidence of as much as 10 feet was widespread in noncohesive granular deposits through compaction, flow, and sliding that resulted from vibratory loading during the earthquake. This phenomenon, which was largely restricted to saturated beach and alluvial deposits or artificial fill, was locally accompanied by extensive cracking of the ground and attendant ejection of water and water-sediment mixtures.

Numerous landslides, including a wide variety of rockfalls, rockslides, and flows along steep slopes, were triggered by the long-duration horizontal and vertical accelerations during the earthquake. The landslides are most numerous in a narrow belt along the southeast coast of Kodiak Island and the nearby offshore islands. Their abundance appears to be related to an area underlain predominantly by Tertiary rocks.

Temporary and permanent changes of level occurred after the earthquake in some wells, lakes, and streams throughout the area; ice was cracked, and the salinity of a few wells increased. Permanent change of water level at some localities appears to be related to readjustments of fracture porosity by earthquake-induced movements of bedrock blocks. Increased salinity of wells in coastal areas resulted from encroachment of sea water into aquifiers after subsidence during the earthquake, and to flooding of watersheds by seismic sea waves.

Vertical displacements, both downward and upward, occurred throughout the area as a result of crustal warping along a northeast-trending axis. Most of Kodiak and all of Afognak, Shuyak, and adjacent islands are within a regional zone of subsidence whose trough plunges gently northeastward and approximately coincides with the mountainous backbone of Kodiak Island. Subsidence in excess of 6 feet occurred throughout the northern part of the zone—a maximum subsidence of 6½–7 feet having occurred on Marmot and eastern Afognak Islands. Southeast of the axis of tectonic tilting, uplift of at least 2½ feet occurred in a narrow zone that includes most of the southeasterly capes of Kodiak Island, the southeastern half of Sitkalidak Island, and Sitkinak Island. The uplift is inferred to extend offshore over much or all of the continental shelf adjacent to the Kodiak group of islands. Within the affected area, tectonic subsidence, which was locally augmented by surficial subsidence of unconsolidated

deposits, caused widespread inundation of shorelines and attendant damage to intertidal organisms, nearshore terrestrial vegetation, and salmon-spawning areas.

The most devastating effect of the earthquake on Kodiak Island and nearby islands resulted from seismic sea waves that probably originated along a linear zone of differential uplift in the Gulf of Alaska. A train of at least seven seismic sea waves, having initial periods of 50–55 minutes, struck along all the southeast coast of the island group from 38 to 63 minutes after the earthquake. The southeast shores were repeatedly washed by destructive waves having runup heights along exposed coasts of perhaps as much as 40 feet above existing tide level, and of 8–20 feet along protected shores. Runup heights of the waves were much less on the northwest and southwest sides of the islands, and no wave damage was incurred there. Locally, high-velocity currents that accompanied the waves caused intense erosion and redistribution of unconsolidated natural and artificial shore deposits and of shallow sea-floor deposits.

The Alaska earthquake was the greatest natural catastrophe to befall the Kodiak Island area in historic time. The combination of seismic shock and the earthquake-related tectonic deformation and seismic sea waves took 18 lives, destroyed property worth about $45 million, and resulted in estimated losses of income to the fishing industry of an additional $5 million.

Most of the damage and all of the loss of life were directly attributable to the seismic sea waves that crippled the city of Kodiak, wiped out the village of Kaguyak, and destroyed most of the village of Old Harbor and parts of the villages of Afognak and Uzinki. Bridges and segments of the highways in the vicinity of the city of Kodiak were washed out, and parts of the Kodiak Naval Station were inundated and damaged. Especially serious to all the damaged communities was the loss of fishing boats, seafood processing plants, and other waterfront installations, which had been the mainstay of the economy.

Additional heavy losses resulted from the combined regional tectonic and local surficial subsidence that occurred during the earthquake. Widespread shoreline flooding by high tides necessitated raising, protecting, or removing many installations otherwise undamaged by the earthquake or waves.

Structural damage attributable to seismic shock during the earthquake was relatively light and was restricted to areas underlain by saturated unconsolidated deposits. The chief structural failure in the area as a result of shaking was the collapse of part of a cannery built on saturated beach deposits that were partially liquefied during the earthquake. Minor structural damage resulted from differential settlement and cracking of the ground on natural granular deposits and artificial fills. The overwhelming majority of structures are constructed on indurated bedrock; none of these sustained damage other than small losses resulting from shifting about and breakage of their contents.

INTRODUCTION

The great earthquake of March 27, 1964 was strongly felt throughout Kodiak Island and the nearby islands. Earth tremors triggered numerous landslides and avalanches, caused the ground to crack and subside in some areas of unconsolidated deposits, and affected water levels of streams, lakes, and wells. The earthquake was accompanied by regional tectonic warping that resulted in both extensive subsidence and local uplift of the land relative to sea level. It was followed after about half an hour by a train of at least seven destructive large-amplitude seismic sea waves that repeatedly inundated low-lying segments of the shore.

The loss of 18 lives and most of the property damage were due to seismic sea waves that battered the southeastern coast of the islands. Additional heavy losses resulted from inundation of coastal lowlands and waterfront installations as a result of the combined tectonic and local subsidence. Structural damage directly attributable to seismic shock during the earthquake was light and was largely due to foundation failure of varying degrees. Total earthquake-related property damage in the area is estimated at about $45 million (table 1), and income losses to the fishing industry amount to an additional $5 million.

PURPOSE AND SCOPE OF INVESTIGATION

This report presents the results of a reconnaissance study of the earthquake effects over the vast uninhabited parts of the islands. The regional setting of the islands, and the effects of the earthquake at localities other than the urban areas are described. Detailed accounts of specific damage at the communities will be given in a separate volume of this series on earthquake effects on Kodiak and other communities on the Kodiak Islands.

An effort was made to evaluate the local geologic factors that control the distribution and character of the shock-induced effects because these factors have potential significance in the design and construction of engineering works in seismically active areas. A reconnaissance of the tectonic changes in land level was made to delineate the areal extent and nature of these movements on the islands, and their relationship to the deformation that occurred elsewhere in south-central Alaska. These data are pertinent to any critical interpretation of the mechanics of the earthquake and

TABLE 1.—*Estimated property losses on Kodiak and nearby islands*

Location	Nature of damage	Estimated replacement cost	Source of data
Kodiak City	Losses of private, commercial, and public property.	$24,746,000	Tudor (1964).
Afognak; village site abandoned.	Losses of private and public property.	816,000	Bur. Indian Affairs (written commun., Sept. 25, 1964).
Old Harbor	do	707,000	Do.
Kaguyak; village site abandoned.	do	321,000	Do.
Uzinki	do	49,800	Do.
Entire area except city of Kodiak.	Commercial	2,140,000	Alaska Dept. Fish and Game (1965).
Entire area	Vessels damaged and lost.	2,466,500	Do.
Kodiak Island exclusive of Kodiak Naval Station.	Bridge and highway damage.	3,359,000	Alaska Dept. Highways (written commun., April 1, 1964).
Kodiak Naval Station.	Structures and equipment including bridges and highway.	10,936,800	Tudor (1964).

to the origin of the seismic sea waves that followed. Incidental to the geologic studies enumerated above, information was also obtained on the arrival times, runup heights, and characteristics of the seismic sea waves and the damage caused by them.

The present report is based largely on studies made by Plafker from float-equipped fixed-wing aircraft and helicopter during the periods July 14–20, 1964, and July 15–21, 1965; on studies made by Kachadoorian at Kodiak and vicinity July 14–18, 1964; and on observations on earthquake effects made by G. W. Moore May 13–21, 1964. Moore also provided unpublished data on the geology of the islands. These observations were supplemented with studies of U.S. Coast and Geodetic Survey vertical aerial photography by the writers and W. H. Condon. Additional data was obtained from the numerous individuals and organizations listed in the acknowledgments. Kachadoorian wrote the section on damage to the highways; the remainder of the report was written by Plafker.

ACKNOWLEDGEMENTS

We are greatly indebted to numerous individuals who provided us, in interviews and on form questionnaires, with eyewitness accounts of their experiences during and immediately after the earthquake.

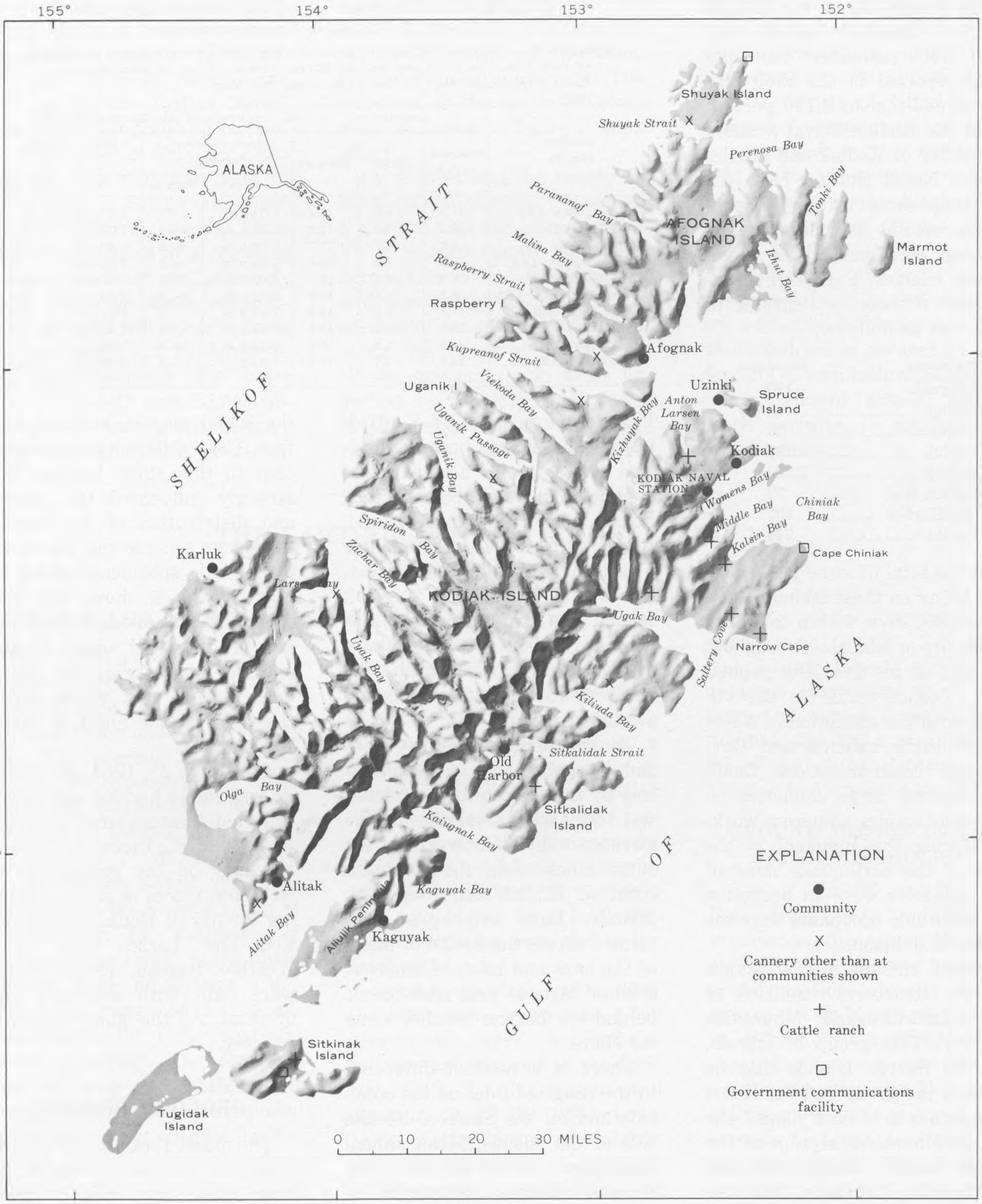
Personnel of the Fleet Weather Central, Kodiak Naval Station (Comdr. A. L. Dodson, Commanding Officer), obtained critical data on the seismic sea-wave sequence and the change in tide levels at the Naval base in Womens Bay and furnished helicopter transportation to an otherwise inaccessible area of Narrow Cape. Dexter Lall and other biologists of the Alaska Department of Fish and Game provided unpublished data and numerous photographs of the earthquake effects on coastal lakes and streams. June Brevdy of the U.S. Navy Radiological Laboratory furnished photographs, newspaper clippings, and published data on structural damage from seismic sea waves in the Kodiak area. Lt. Comdr. W. D. Barbee, of the U.S. Coast and Geodetic Survey, provided tide records and data on changes in land level at tide-gage stations on Kodiak Island. The U.S. Coast and Geodetic Survey and the U.S. Army furnished postearthquake aerial photographs. Pierre St. Amand, of the U.S. Naval Ordnance Test Station, made available data obtained during an aerial reconnaissance of the area immediately after the earthquake. Fred O. Jones, consulting geologist, provided photographs and data on earthquake effects in the Terror River drainage basin.

Pilots Bob Leonard and Al Cratty flew Plafker around the islands and freely shared with him their intimate knowledge of the Kodiak Islands area and of earthquake-induced changes that had occurred there.

GEOGRAPHIC SETTING

The group of islands described in this report, of which Kodiak Island is the largest, lies at the western border of the Gulf of Alaska in the north Pacific Ocean between lat 56°30′ and 58°40′ N. and long 150°40′ and 154°50′W. (fig. 1). The group has an aggregate land area of 4,900 square miles, extends for a distance of 177 miles in a northeast direction, and is 67 miles wide at its greatest width. The largest islands of the group are shown on figure 2.

1.—Physiographic map of south-central Alaska showing location of the Kodiak group of islands with respect to the epicenter of the March 27 earthquake and its zone of major aftershocks (lined pattern). Submarine contours in meters.



2. — Physiographic map of Kodiak and nearby islands.

The population of the Kodiak group of islands is sparse, only about 3,600 permanent residents being reported in the 1960 census, in addition to 2,160 personnel at the Kodiak Naval Station.

The city of Kodiak and nearby Kodiak Naval Station have the only large concentrations of population on the islands. The remaining settlements are small fishing villages. Permanent population of these settlements in 1960 was as follows:

Community	*Population*
Afognak	190
Akhiok	72–75
Kaguyak	36
Karluk	129
Kodiak	2,628
Larsen Bay	72
Old Harbor	193
Uzinki	214

Of the total of some 5,700 persons living on these islands, more than 5,300 live within 20 miles of the city of Kodiak. Throughout the rest of the area the population is concentrated in the villages with the exception of a few remote cattle ranches and Government communications facilities. Several large canneries on the island employ numerous workers during the summer; at the time of the earthquake none of the canneries were in operation and their only occupants were the winter watchmen.

Kodiak and the nearby islands are the structural extension of the Kenai-Chugach Mountains (fig. 1). This group of islands, and the Barren Islands that lie between the group and the Kenai Mountains, have been named the Kodiak Mountains section of the Pacific Border Ranges province (Wahrhaftig, 1965, p. 39). As a whole, the islands are mountainous, being lowest on the islands at the extreme north and south and highest in the middle (fig. 2).

TABLE 2. — *Tidal constants at selected stations along the coasts of Kodiak and nearby islands*

[Station: A, on the Gulf of Alaska; B, on Shelikof Strait. Predicted time and height of tides from U.S. Coast and Geodetic Survey (1964a). Local (Alaska standard) time; tide measurements in feet above lower low water]

Station (fig. 2)	Annual tide			Predicted tide, March 27–28, 1964			
				Low, evening, March 27		High, morning, March 28	
	Diurnal range	Mean	Highest	Time	Height	Time	Height
Perenosa Bay (A)	11.3	5.9	13.4	7:34 p.m.	0.1	1:29 a.m.	11.4
Izhut Bay (A)	8.9	4.5	11.0	7:16 p.m.	−.2	1:13 a.m.	10.0
Kizhuyak Bay (A)	9.6	4.9	11.7	7:06 p.m.	−.2	1:07 a.m.	9.7
Kodiak Harbor (A)	8.5	4.3	10.6	6:52 p.m.	−.3	0:57 a.m.	8.6
Ugak Bay (A)	8.4	4.3	10.6	6:35 p.m.	−.1	0:32 a.m.	8.6
Sitkalidak Island (A)	8.3	4.4	10.6	6:49 p.m.	−.1	0:43 a.m.	8.6
Alitak Bay (AB)	11.7	6.2	14.9	7:10 p.m.	.1	0:59 p.m.	10.1
Uyak Bay (B)	13.8	7.3	13.8	7:23 p.m.	−.4	1:24 a.m.	15.2
Uganik Bay (B)	14.6	7.6	17.7	7:22 p.m.	−.3	1:25 a.m.	15.8
Malina Bay (B)	14.5	7.7	17.7	7:24 p.m.	−.3	1:26 a.m.	16.0

The western part of Kodiak Island has many broad alluviated valleys and coastal lowlands that are underlain by thick glacial deposits. Sitkinak Island, at the south end of the group, has a maximum altitude of 1,470 feet. The surface of nearby Tugidak Island is a marine terrace that rises only about 100 feet above sea level. Shuyak Island and the northern part of Afognak Island are hilly lowlands.

The coastline is extremely steep and irregular and is characterized by many deep narrow fiords and rocky islets. Narrow marine terraces occur at intervals on the outer capes along the southeast coast of Kodiak and Sitkalidak Islands. Bars and spits have formed across the mouth of many of the bays and inlets. Numerous shallow lagoons and lakes occur behind low barrier beaches along the shore.

There is a marked difference in the range of tides on the ocean side and on the Shelikof Straits side of the islands. Mean annual tide range is 13 to 14½ feet along Shelikof Strait in contrast to 8.2 to 11.3 feet at most places on the ocean coast. Furthermore, the difference in maximum annual tide height on the two sides of the island may be as much as 7 feet. These differences are significant to this study because they strongly influenced the amount and distribution of the damage caused by seismic sea waves and by tectonic subsidence along the coast. Table 2 shows the tidal constants at selected localities, and the time and height of high and low tide during the period when seismic sea waves struck the coast on the night of March 27.

On March 27, 1964, the weather was mild; highest and lowest reported temperatures were 37° F. and 20° F.; there was little or no snow on the ground at sea level, but traces of snow fell during the day at Kodiak Naval Station and Larsen Bay (U.S. Weather Bureau, 1964). Winds were light with scattered high overcast. All the lakes were frozen over.

GEOLOGIC SETTING

The oldest rocks in the area lie along the northwest coast of Kodiak Island and consist chiefly of metavolcanic and marine sedimentary rocks of Triassic and Jurassic age that are cut by mafic intrusives. Younger Mesozoic marine sedimentary rocks of probable Cretaceous age, complexly deformed and extensively intruded by granitic rocks, underlie the axial part of the Kodiak Mountains. Northeast-trending belts of downfaulted lower Tertiary rocks make up the southeast side of Kodiak Island, Sitkalidak, Tugidak, and Sitkinak Islands. These belts are composed of a sequence of highly inclined and intensely folded sandstone, shale, conglomerate, and altered volcanic rocks that are locally cut by felsic intrusives. Overlying the older rocks are poorly consolidated upper Tertiary marine sedimentary rocks that have been gently to moderately folded. Fold axes and major faults strike northeast, the northwest blocks of the faults generally being upthrown. Distribution of the major lithologic units is shown in figure 3 (next page).

On Kodiak and the nearby islands, unconsolidated deposits as a rule are thin and discontinuous. They consist mainly of glacial debris, alluvial and delta deposits, and beach deposits. Local thick accumulations of colluvium occur along the bases of the steeper slopes, particularly in areas underlain by Tertiary rocks. Most of the coast consists of rugged rocky bluffs; extensive and well-developed beaches are uncommon.

A significant proportion of the alluvial deposits in an east-west belt across the central part of the islands consists of virtually uncompacted volcanic ash and pumice deposited in the spring of 1912 during the eruption of Katmai Volcano, on the Alaska Peninsula to the west (Capps, 1937, p. 170–171).

The thickest and most extensive alluvial and glacial deposits are delineated on figure 3. Areas where bedrock is covered by thin deposits of soil, colluvium, glacial debris, stream gravel, marine beach deposits, or artificial fill are not shown.

THE EARTHQUAKE AND ITS AFTERSHOCKS

LOCATION AND MAGNITUDE

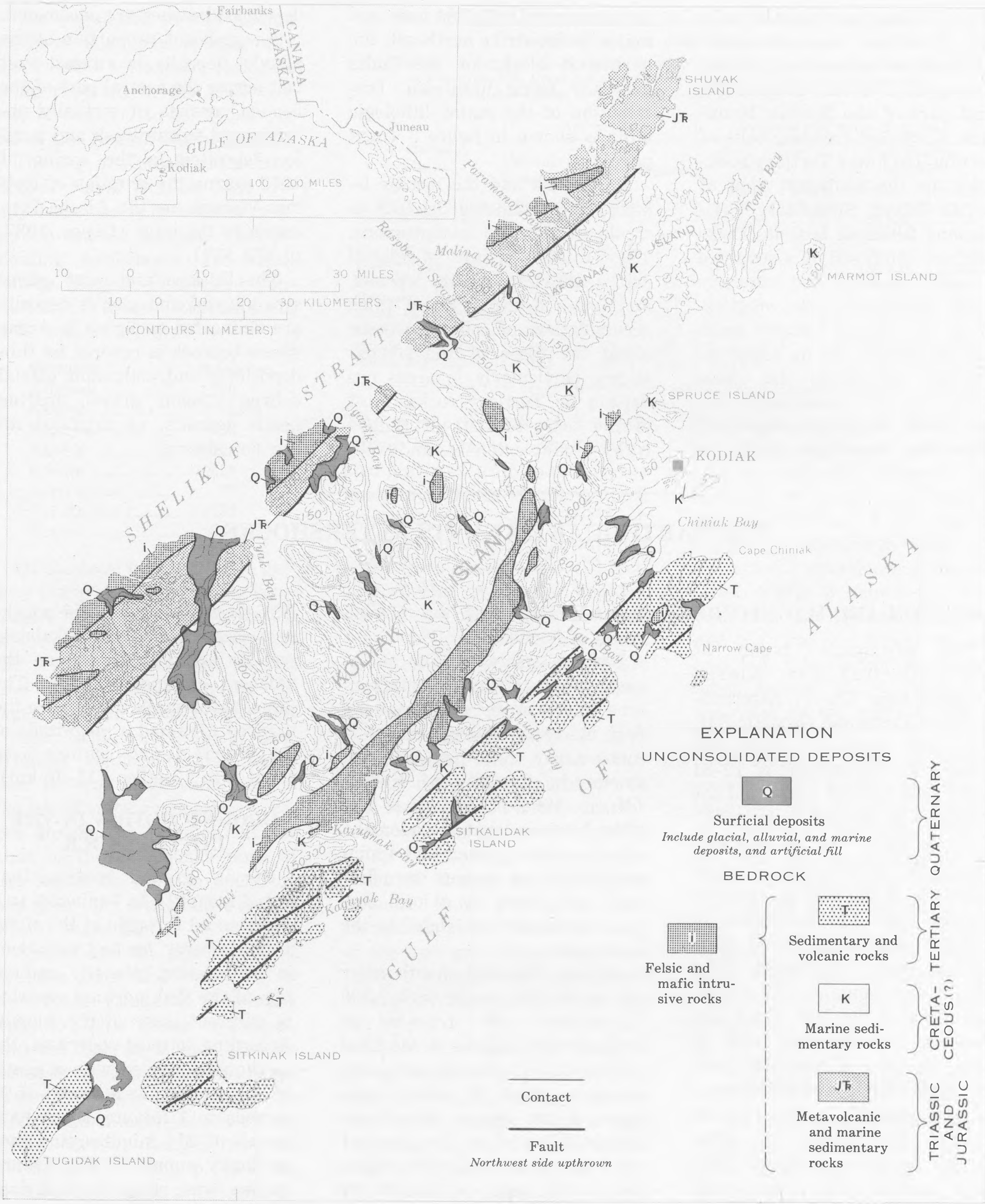
The earthquake began at 5:35:12.15±0.25 p.m. Alaska standard time (S. T. Algermissen, U.S. Coast and Geodetic Survey, oral commun., April 22, 1965); its hypocenter is 12–31 miles deep (20–50 km); and the epicenter is located at lat 61.1° N., long 147.7° W. in northern Prince William Sound, 250 miles northeast of the Kodiak group of islands (fig. 1). Estimates of Richter magnitude, based upon surface wave amplitudes (M_s) are in the range of 8.4 to 8.5 according to the U.S. Coast and Geodetic Survey. The focal region, or zone of probable fault breakage during the earthquake, is approximately outlined by the spatial distribution of aftershocks. As shown by figure 1, this zone extends 400 miles southwestward from the epicenter in a broad belt that includes much of the continental shelf and southeastern margin of the Kodiak group of islands.

Perhaps related to the earthquake was an apparent instantaneous increase in the magnetic field by about 100 gamma on a continuously recording magnetometer in the city of Kodiak (Moore, 1964, p. 508). It is possible, however, that the anomaly, which occurred 1 hour and 4 minutes before the tremors were first felt, was caused by a local surface disturbance unrelated to the earthquake.

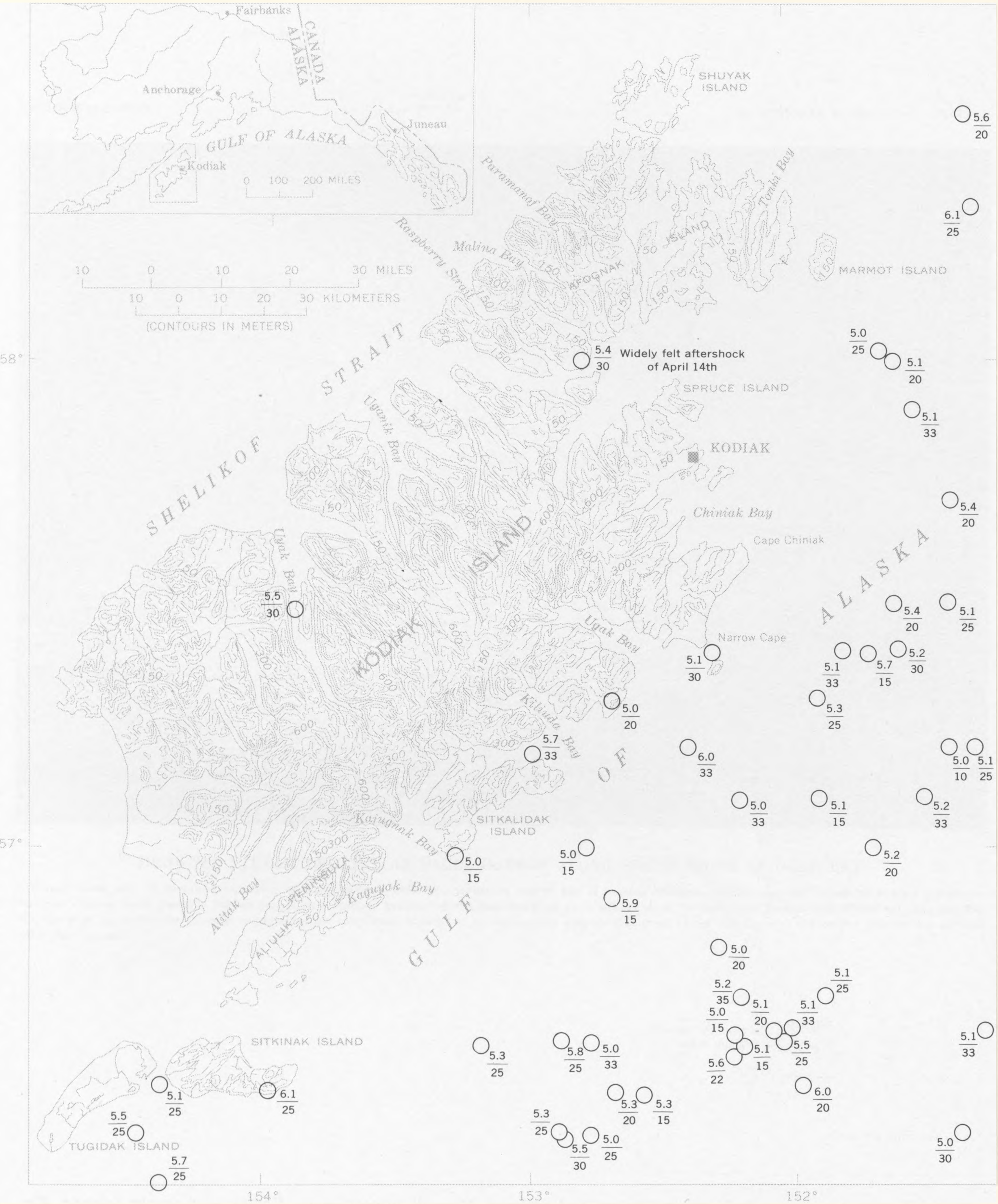
During the first month after the earthquake, more than 7,500 aftershocks were recorded at seismograph stations in the focal region (S. T. Algermissen, oral commun., April 22, 1965). Locations of the larger aftershocks (magnitudes of 5.0 or greater) with epicenters in the vicinity of the Kodiak group of islands are indicated on figure 4. Except for two aftershocks centered in the western part of the islands (p. D9) they all lie along the southeast coast of Kodiak, Sitkalidak, and Sitinak Islands and on the adjacent continental shelf. The largest aftershock recorded in the mapped area had a magnitude of 6.1. Focal depths range from about 9 to 19 miles (15–30 km).

GROUND MOTION IN THE INITIAL SHOCK

Strong ground motion that lasted from 2½ to 7 minutes was experienced throughout the study area. However, marked variations in the duration, intensity, and nature of the shaking were reported in different parts of the islands. According to most observers, the earthquake started with a gentle rolling motion for a period of 20 seconds to 1 minute, shook hard for about 2½ minutes, and then gradually subsided. The ground motion was generally described as rolling like sea waves, or as a strong horizontal oscillation. The jarring motion that was felt in



3. — Geologic sketch map of Kodiak and nearby islands. Geology generalized after Capps (1937) and from unpublished data by G. W. Moore.



4. — Aftershock distribution (magnitude greater than 5.0) in the Kodiak Island area. Numbers indicate Richter magnitude (above) and focal depth in kilometers (below). Data after U.S. Coast and Geodetic Survey, Preliminary determination of epicenter cards, 1964.

5.— Reported ground motion, sounds, ground waves, and assigned Mercalli intensities on Kodiak and nearby islands. The directions of reported ground motion are shown by arrows; localities at which sound was reported are shown by solid circles, localities at which ground waves were reported by open circles, and assigned Mercalli intensities by Roman numerals.

DROWNED STREAM ESTUARY AT EAGLE HARBOR ALONG SOUTH SHORE OF UGAK BAY

Extensive brown area of terrestrial vegetation has been killed by salt-water immersion after 4 feet of tectonic subsidence and an unknown amount of surficial subsidence. The gray ridge of beach gravel in the left part of view (arrows) has been eroded back and built up in adjustment to the new higher base level of deposition. The fact that the effects of inundation are scarcely visible along the steep bedrock shore in the background suggests that much of the subsidence at the estuary deposits was surficial rather than tectonic.

DEBRIS AVALANCHE ON THE PENINSULA BETWEEN UGAK AND KILIUDA BAYS

A slide of Tertiary rocks from the 1,500-foot-high peak at upper right flowed into the uninhabited valley below at about 300-foot altitude where it spread out as a debris lobe roughly 1,500 feet across. The narrow streak of light-colored debris in the lower right corner is part of the slide mass that overflowed the near flank of the landslide scar.

6. — The Kadiak Fisheries cannery site in Shearwater Bay along the north shore of Kiliuda Bay. Cannery buildings in the foreground were split during the earthquake and the seaward parts of the structures were later washed away by seismic sea waves. The former locations of the buildings and dock are outlined by timber pile foundations in the beach and water. The entire beach is now inundated at high tide as a result of about 4 feet of tectonic subsidence and 2-10 feet of surficial subsidence of the beach deposits. The barge behind the cusp is a floating cannery that replaces the destroyed facility on land. Location of cannery shown on figure 5.

some areas closer to the epicenter was not experienced on Kodiak or the nearby islands during the initial shock, although it was reported in some of the larger aftershocks. A local resident, Mr. Rudy Lorensen, timed the duration of the strongest ground motion as 2½ minutes on a bedrock site near the city of Kodiak.

Reports of the directions of vibrations show a wide variation. The apparent variations may be in part due to the difficulty in determining the direction from which a shock comes during such a distressing experience. In part they may result from a change in the source of the vibrations as the rupture propagated southwestward from its epicenter in Prince William Sound or to local variations in ground conditions. Figure 5 shows that the reported vibration directions were mostly northeast-southwest to north-south, although in a few instances they were northwest-southeast.

The intensity, or the destructive potential, of the vibrations in the area varied markedly from place to place and appeared to be closely controlled by the local geologic environment. The generalization that both the intensity and duration of earthquake vibrations are enhanced in unconsolidated ground, particularly on water-soaked unconsolidated deposits (Gutenberg, 1957), is strikingly borne out by the distribution of vibration-induced damage in the area.

The most severe shaking occurred in areas of thick saturated unconsolidated Quaternary deposits throughout the islands. In these areas, structural damage resulted mainly from foundation failure attributable to partial liquefaction, differential settlement, and cracking of unconsolidated deposits and artificial fill. The sole structural failure reported in the area was the partial collapse of the main building of the Kadiak Fisheries cannery located on a beach cusp on Shearwater Bay along the north shore of Kiliuda Bay. The structure split in half when it was shifted off its piling foundation according to the cannery watchman, Mr. Sergei Pestrikoff. The piling was driven into beach gravel that was partially liquefied during the earthquake (fig. 6). The fallen section was later washed away by the seismic sea waves.

SURFACE WAVES

Reliable data on the amplitude and period of the ground waves that accompanied the earthquake in the area are unavailable. Long-period surface waves set bodies of surface water, trees, radio antennas, and hanging objects such as lighting fixtures and wall pictures into violent oscillation throughout the islands but caused only minor damage to manmade structures. The period of an oscillating antenna pole about 50 feet high on a bedrock site was timed by one observer as "slightly less than one second."

Visible traveling undulations of the ground surface in areas underlain by unconsolidated deposits were reported at the villages of Uzinki and Afognak. The wavelength at Uzinki was described as 30 feet; estimates of amplitude could not be made. Similar progressive linear earth waves having estimated amplitudes as great as 3 feet were observed at numerous localities underlain by unconsolidated deposits in the part of south-central Alaska where the earthquake was strongly felt. Such waves have been frequently noted in comparable geologic environments during other great earthquakes throughout the world. The waves may correspond to the large amplitude "hydrodynamic" waves discovered by Leet (1946, p. 209–211) on seismograph recordings of underground explosions. It is conceivable that such waves, which have particle orbits comparable to those of water waves, may be propagated in ground that has become semifluid as a result of ground vibration.

Elsewhere in areas underlain by consolidated deposits and in areas of poorly consolidated Tertiary rock, there was minor cracking of interior plaster, concrete and concrete-block walls and floors, and a few concrete-block chimneys, and rupture of buried pipelines. In some of these areas slight damage was incurred when heavy objects such as generators, appliances, and furniture were shifted about or overturned. In areas underlain by unconsolidated deposits it was generally difficult or impossible for people to stand or walk during the earthquake.

Ground motion in areas of pre-Tertiary bedrock or bedrock mantled by thin unconsolidated deposits—areas where most communities and canneries of Kodiak and the adjacent islands are located—was not strong enough to cause structural damage. Some small light objects or heavier objects in precarious positions were thrown down, although in most places inanimate objects were not disturbed. People report that, although difficult, it was possible to stand and move about during the earthquake.

Estimates of the Mercalli intensity of ground shaking in the area, based on the reported effects on people and inanimate objects, are shown on figure 5. Ground-water effects, landsliding, and avalanching, which were widely distributed and bore no clearcut relationship to structural damage, were not considered as suitable criteria for intensity estimates. Except as noted, assigned intensity ratings are according to the abridged Modified Mercalli Intensity scale of 1931, in which the violence of ground motion is separated into 12 categories of increasing destructiveness from I to XII (Hodgson, 1964, p.58-59).

With one exception, assigned Mercalli intensities range from VI to VIII throughout the area. They are lowest in areas of pre-Tertiary bedrock or bedrock mantled with thin well-drained unconsolidated deposits and highest in areas of poorly consolidated Tertiary rocks and thick unconsolidated deposits. Significantly, the highest intensity experienced, which is estimated as VIII to IX on the scale, was at the Kadiak Fisheries cannery—the only large structure in the entire area that is founded wholly on unconsolidated, saturated, granular deposits.

AFTERSHOCKS

Many of the numerous aftershocks that followed the main shock were felt as short, sharp, jarring shakes. They reportedly occurred at intervals of a few minutes to an hour throughout the night of the earthquake and at increasingly longer intervals for a period of several weeks thereafter. One aftershock, at 12:55 p.m. on April 14th, was especially noted throughout the islands. Its epicenter was about 20 miles northwest of the city of Kodiak (fig. 4), the magnitude is given as 5.4, and the focal depth as about 19 miles (30 km). Oddly enough, although this aftershock was the strongest one felt in the area, its magnitude was less than many of the other nearby aftershocks. It reportedly hit with a short jarring motion equal to the intensity of the main shock, after which it quickly subsided. Although it caused major consternation, it resulted in no noteworthy damage on Kodiak Island except for three broken pipelines at one cannery on the northwest coast of Kodiak Island, and a cracked roof at another cannery in Alitak Bay on the southwest coast of the island.

SOUNDS

The initial shock was heard as a low-pitched rumble by two individuals in the area. One of them reportedly heard the rumbling an estimated 5 seconds before the tremors were felt. During the weeks after the earthquake, many people heard aftershocks as deep rumbles a second or so before they were felt. Some individuals, both in the area and elsewhere in south-central Alaska, said they heard warning rumbling sounds before every felt aftershock. Richter (1958, p. 128) postulated that such noise may be produced during passage of the body waves, but that the shaking is felt only upon arrival of the slower moving surface waves.

SURFICIAL SUBSIDENCE AND ASSOCIATED GROUND CRACKS

Vibratory loading of noncohesive granular deposits during the earthquake resulted in local surficial subsidence through compaction, flow, and sliding. Areas of greatest subsidence were in thick, unconsolidated, saturated marine or lacustrine deposits and uncompacted manmade fills. Subsidence in some of these areas was accompanied by cracking of the ground and ejection of water or water-sediment mixtures. By the time this reconnaissance study was initiated 4 months after the earthquake, however, much of the evidence of ground cracking was obliterated.

Surficial subsidence of unconsolidated beach and delta deposits along the coast was most clearly manifested in the relatively greater amount of inundation of shoreline areas as compared to nearby rock outcrops. Virtually all areas underlain by such deposits, both in the zone of tectonic subsidence and slight uplift, show some indication of salt water immersion in the form of dead brown terrestrial vegetation (pl. 1).

BEACH DEPOSITS

At the Kadiak Fisheries cannery along the north shore of Kiliuda Bay, local subsidence of beach deposits was 2–10 feet more than that of the adjacent bedrock areas. The cannery is on a broad, roughly triangular cusp that juts out into Shearwater Bay—a small bay on the north side of Kiliuda Bay (figs. 5, 6). Before the earthquake, the buildings shown in the foreground of figure 6 extended on piling slightly beyond the water's edge, as shown in the photograph. Beyond this was a pier 170 feet long. The piling had been driven to refusal, that is, 10–15 feet into the beach deposits. The piles were originally vertical and the tops were level.

After the earthquake, measured subsidence was $5\frac{1}{3}$ feet at the shipway piling to the right (north) of the cannery buildings. This subsidence, 2 feet more than that at a bedrock site 1 mile to the south, indicates surficial settlement of about 2 feet relative to bedrock. Furthermore, measurement of the difference in height of the tops of the piling that previously supported the destroyed part of the cannery indicates that an additional 7.8 feet of surficial settlement occurred towards the tip of the cusp (fig. 7).

7. — Timber pile foundation at Kadiak Fisheries cannery site. Pronounced tilting of unbroken piling is indicative of lateral motion of the piling through 10–15 feet of beach gravel. Piling tops formerly level are now 7.8 feet lower at the seaward end of the cannery site than in the foreground owing to local settlement of the distal part of the beach cusp. Bent drift pins in the piling tops indicate that the cannery moved southward (away from the observer) off the piling.

8.— Road near the head of Lake Rose Tead submerged by about 5 feet of surficial subsidence of inlet-stream deltaic deposits. Ugak Bay is visible in the background. Photograph by Alaska Department of Fish and Game.

The site is now submerged at high tides, and the facilities have been replaced by a floating cannery. Ground cracks as much as a foot wide reportedly criss-crossed the cusp after the earthquake. Mr. Edward Pestrikoff, the cannery watchman, saw cracks form in the ground during the earthquake and saw water ejected as high as 6 feet. Reduction of shear strength of the unconsolidated deposits through partial liquefaction is suggested by the manner in which the foundation pilings shown in figure 7 were tilted without being broken when the cannery building collapsed.

Elsewhere, local differential subsidence of unconsolidated beach deposits relative to nearby bedrock amounted to an estimated 1–2 feet at Old Harbor and perhaps 5 feet near the McCord cattle ranch on Sitkalidak Island.

ALLUVIAL AND LACUSTRINE DEPOSITS

Mr. Joe Beaty, a long-time cattle rancher at Narrow Cape, observed that during the earthquake his truck and other heavy machinery settled as much as 2 inches into alluvial deposits on the flood plain of a small stream on the cape. He also noted much cracking at a bog between two lakes near the tip of the cape, and extrusion of gravel that had been buried beneath 20 feet of fine-grained surficial alluvial deposits; thus the cracks evidently extended to at least that depth.

Local subsidence of lacustrine delta deposits was noted at three localities by personnel of the Alaska Department of Fish and Game who carried out studies of the earthquake's effects on salmon spawning and sport fishing (Alaska Dept. Fish and Game, 1965, p. 3–21). Several feet of subsidence occurred on deltas of three streams that enter Buskin Lake near the city of Kodiak and at the inlet stream deltas of two large lakes—Lake Rose Tead and Saltery Lake—along the north shore of Ugak Bay. Surficial subsidence has resulted in local flooding of shoreline vegetation of these lakes and inundation of a segment of road along the shore of Lake Rose Tead (fig. 8). Mr. Ron Hurst, a rancher at Saltery Lake, reports that several acres along the lakeshore sank as much as 3 feet, and large amounts of subsurface pumice was pumped up into Saltery Lake and caused excessive turbidity early in the summer of 1964.

Slumped lake deltas, ground cracks, and spectacular sand-vent deposits were examined and photographed by F. O. Jones, consultant geologist to the Chugach Electric Association, in the upper Terror River drainage, on Kodiak Island between Ugak and Viekoda Bays at about 1,250-1,400 feet altitude. The inlet delta of Terror River at the head of Terror Lake slumped and subsided during the earthquake; near-shore vegetation there was put under 2–3 feet of water (fig. 9, next page). Lateral extension of the slumped delta margin caused it to be cut by a system of rectilinear cracks as much as 1 foot wide (fig. 9). Large volumes of light-colored fine- to medium-grained pumice were ejected to the surface from many of these cracks, and the pumice forms clastic dikes that fill the cracks below the surface (fig. 10 p. D17). Jones noted similar slumped and cracked deltas elsewhere along the margin of Terror Lake and saw from the air an extensive area of reticulate cracks and sand-vent deposits in a partially filled lake basin 3 miles upstream from Terror Lake.

Drowning of shoreline vegetation was noted from the air along the margins of numerous lakes throughout the area. Undoubtedly shoreline subsidence, cracking of the ground, and extrusion of sediment similar to that noted above also occurred in comparable geologic environments at the numerous other lakes on the island that were not examined in detail.

ARTIFICIAL FILLS AND EMBANKMENTS

In addition to the subsidence of natural unconsolidated deposits, damage was caused to engineering works by surficial subsidence and cracking of filled ground and by settling of engineered fills and breakwaters into underlying unconsolidated natural deposits. Most of these effects, which occurred in the Kodiak area and along the highway east of Kodiak, will be discussed separately in the section of this report that describes effects on highways and in the companion report on damage to communities. The only other noteworthy examples of subsidence of artificial fill occurred at the U.S. Coast Guard Loran facility on Sitkinak Island where measured differential settlement of $4\frac{7}{8}$ inches occurred at one corner of a reinforced-concrete structure that was reportedly built on a 12-foot-thick fill. At Narrow Cape the approach fill of a ranch road on alluvial deposits sank about 2 feet below the level of a bridge deck.

CAUSES OF SURFICIAL SUBSIDENCE

From the foregoing descriptions it should be apparent that surficial subsidence of unconsoli-

9.—Inlet delta at the head of Terror Lake showing inundation of slumped and cracked delta margin and linear cracks defined by light-colored pumiceous ejecta. Photograph by F. O. Jones.

10.—Sectioned extension crack 1 foot wide at head of Terror Lake showing light-colored fine- to medium-grained pumiceous sand ejecta at surface and subsurface clastic dike. Photograph by F. O. Jones.

dated deposits and attendant ground cracking occurred under a variety of geologic conditions over a vast area. Causes of the subsidence are probably diverse and are related to the physical properties of the materials composing each deposit, as well as to the configuration of the deposit.

Subsidence of natural granular materials and uncompacted fills under vibratory loading may result from: (1) compaction, or volume reduction due to closer packing of the grains that compose the deposit; (2) varying degrees of liquefaction of saturated incoherent material with resultant lateral spreading through flow or sliding; (3) shear failure causing downward and outward movement of the slide mass; and (4) combinations of (1), (2), and (3).

Details of the physical properties and configuration of the affected materials before and after the earthquake are unavailable so that the specific cause, or causes, of subsidence are generally not known. Compaction of some of the deposits is suggested by surface ejection of water and water-sediment mixtures. Reduced shear strength through liquefaction is indicated at the Kadiak Fisheries cannery, where piling embedded 10–15 feet in beach deposits was dragged laterally and tilted to angles of as much as 20° without failure. Reduced bearing strength and compaction of some ground is suggested by the mass sinking of compacted fills, breakwaters, structures, and heavy objects into underlying alluvial deposits and artificially filled ground.

LANDSLIDES

Long-duration horizontal and vertical accelerations during the earthquake triggered numerous landslides and avalanches on the slopes of Kodiak and the adjacent islands. The landslides included a wide variety of falls, slides, and flows involving bedrock, unconsolidated deposits, and snow in varying proportion.[1] Landslides of rock and soil presumably loosened by shaking during the initial shock were unusually abundant in the months after the earthquake. Some of them may have been triggered by the larger aftershocks or by summer thaw of frozen ground. None of the landslides or avalanches in the area caused property damage or human casualties.

The following general descriptions of the distribution and nature of the landslides and avalanches are based almost entirely on aerial observation, interpretation of postearthquake aerial photographs, and accounts by local residents. Only a few of these features were examined on the ground.

[1] The classification and nomenclature for landslides used herein correspond to those of Varnes (1958).

DISTRIBUTION AND NATURE

Most of the landslides occurred along the southeast coast of Kodiak Island and on the islands offshore from Kodiak Island. A few other landslides—mainly large rockfalls—occurred at widely scattered sites on Kodiak Island and on Afognak and Marmot Islands. The generalized areal distribution of the larger landslides that occurred during or after the earthquake and before August 1964 is shown in figure 11. Many of these slides were reactivated older slides. In some places—most notably along steep coastal bluffs—rockfalls are so closely spaced that a single symbol on figure 11 necessarily represents several slides. No attempt was made to map the smaller rockfalls and soil slips, although, as might be expected, their frequency is roughly proportional to that of the large slides.

Numerous snow avalanches and debris avalanches of snow-rock mixtures are visible on aerial photographs of the steep slopes at higher altitudes along the rugged backbone of Kodiak Island. They are not shown on figure 11 because the postearthquake aerial coverage was inadequate to permit photogeologic mapping of their distribution. Furthermore, most of the avalanches at high altitudes were obscured by new snowfall by the time this study was initiated 3½ months after the earthquake.

In approximate order of abundance, the landslides in the area may be divided into the following general categories: (1) rockslides and rockfalls in areas of consolidated rock, (2) debris slides and avalanches of Tertiary and Quaternary deposits, (3) earthflows and soil slips of unconsolidated surficial materials, and (4) rotational slumps in both consolidated rock and soil. Many of the landslides observed are complex features that probably

11. — Generalized distribution of the larger landslides and soil slips triggered by the March 27, 1964, earthquake on Kodiak and nearby islands. Areas underlain by rocks of Tertiary or probable Tertiary age are shaded.

12. — Rockslides in tightly folded blocky sandstone along north shore of Ugak Bay, Kodiak Island. Bluff is about 1,000 feet high and is exposed to surf from Gulf of Alaska.

13. — Reactivated large debris slide in sedimentary rocks of middle Tertiary age along the south shore of Sitkinak Island. Note the characteristic steplike transverse scarps, displacing surface vegetation at head of the slide. A small rockfall covers part of the beach in lower left of photograph. Vertical height of slide mass is approximately 300 feet.

involve varying combinations of falling, sliding, and flowage, but in the descriptions that follow they have been classified on the basis of their most characteristic features as interpreted mainly from the aerial photographs and from aerial observation.

Rockfalls and rockslides are locally very numerous along steep coastal bluffs (fig. 12). Commonly, the bluffs are partially undercut by wave erosion and have surf-cut sea caves near the high-tide line that lead to precipitous failures of large rock masses. The rock falls and slides are particularly numerous where blocky massive sandstone and basalt of Tertiary age, or older igneous intrusive rocks, form the steep bluffs along the shore. They are relatively rare in areas underlain by the well-indurated bedded and slaty rocks of pre-Tertiary age that compose the central part of Kodiak Island and most of Afognak and Shuyak Islands (fig. 3). Many rockfalls, too small to be plotted on the landslide distribution map, were seen in areas underlain by the blocky granitic rocks that compose much of the rugged drainage divide on Kodiak Island.

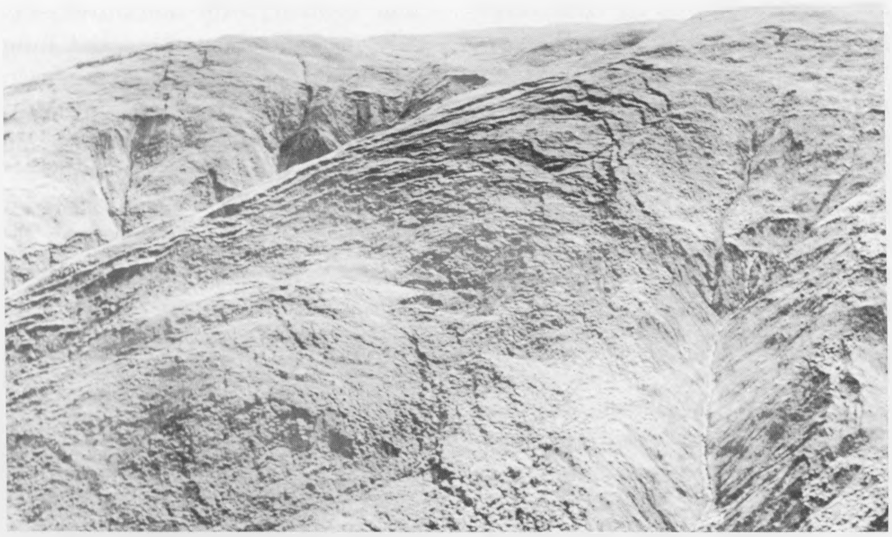
Debris slides and debris avalanches were sporadically distributed along the southeastern coast of Kodiak Island, on Sitkalidak Island, and on Sitkinak Island. They apparently occurred mostly in areas underlain by bedded rocks of Tertiary age or by Quaternary deposits. Such slides are especially numerous on deeply weathered, moderately steep slopes underlain by rocks of middle to late Tertiary age. The debris slide shown in figure 13 is typical of many throughout the area.

The slide illustrated on plate 2 is probably the largest that occurred in the area and is anomalous in that it spread as a relatively thin sheet over the valley below the slide source. The areal distribution and irregular surface characteristics of the slide debris suggest that it was emplaced by high-velocity viscous flow.

Earthflows and soil slips of unconsolidated materials occurred throughout the area, but were especially common along the moderately steep slopes that were deeply weathered and mantled with thick deposits of one or more of the following: (1) glacial till, (2) volcanic ash, (3) colluvium. Typically, the flows and slips are manifested at the head as a series of transverse "wrinkles" or scarps stepped downslope, below which is a subtle bulge of debris (fig. 14). All gradations occur between the earthflows and soil slips that involve thin surficial layers of unconsolidated debris and the debris slides that are characterized by relatively coherent slide units.

Rotational slumps were rather rare in the study area. This type of landslide was recognized only at Narrow Cape on Kodiak Island and along the southeast cape of Sitkalidak Island. Pierre St. Amand of the U.S. Naval Ordnance Test Station and George W. Moore of the U.S. Geological Survey directed our attention to these features, which were studied with special care because their long linear scarps bore a superficial resemblance to fault breaks.

The Narrow Cape landslide involved moderately dipping, poorly indurated sedimentary rocks of late Tertiary age. It occurred on slopes of 15°–35° along a structurally controlled northeast-trending linear valley that is incised 125–150 feet into a flat-lying erosion surface. The main scarp of the slide (fig. 15) broke at the top of the southeast valley wall along a distance of roughly 1,400 feet. The slide mass slumped down on the northwest side as much as 15 feet with headward tilting along a surface of rupture that intersected the surface on the valley floor 125–150 feet be-



14. — Earthflow resulting from soil slip or slump in deeply weathered Tertiary sedimentary deposits along the north shore of Sitkinak Island. The head of the slide is marked by numerous small scarps; the foot is the hummocky bulbous mass in the lower left corner.

15. — Main scarp at the head of a large rotational slump in Tertiary deposits on Narrow Cape, Kodiak Island. The landslide is approximately 1,400 feet long and 125–150 feet high. The rock mass at the left slid 8–15 feet downslope along a surface of rupture, the main scarp of which trends diagonally across the photograph. Note the headward tilt of the original surface on the upper part of the slide mass and draping of the vegetation mat over the crown of the main slide.

low. Open tension cracks and shallow grabens are abundant on the erosion surface headward from the main scarp. The slide toe is characterized by transverse pressure ridges and small overthrusts in the surface mat of muskeg vegetation. The brush-covered hummocky topography of the lower part of the slide surface and the chaotic internal structure suggest that earlier gravity movement has taken place.

At the southeast end of Sitkalidak Island, a discontinuous zone of landslides occurs along the base of a moderately steep southeast-facing ridge that fronts on a broad, gently sloping terrace. The landslides have exposed a series of southeast-facing scarps that can be traced along the base of the ridge for about 1½ miles. They die out both to the northeast and the southwest. As seen from the air, the freshly exposed scarps are estimated to be as much as 15 feet high and appear to be largely in unconsolidated deposits. The slide masses consist of both headward-tilted blocks and irregular hummocky earthflows along the downslope sides of the scarps.

The relatively straight and abrupt break in slope along which the sliding occurred on Sitkalidak Island strongly suggests the possibility that the topographic feature is controlled by a preexisting fault and that the line of slumps may have been related to renewed displacement along this inferred fault during the earthquake. Fortunately, it was feasible to check this possibility by measuring vertical displacement of the shore relative to sea level both to the northeast and southwest of the line of landslides. No changes indicative of vertical fault displacement during the earthquake were detected within the limits of precision of the method (estimated to be ±1½ ft in this area). On the contrary, the measurements showed a slight northwest tilting of the island which is opposite in sense to the down-to-the-southeast movement along the landslide scarps.

CAUSES

Elastic ground vibrations during the 1964 earthquake triggered most of the fresh landslides (and avalanches), or so loosened large masses of rock that they slid shortly thereafter. A contributory factor may have been ground accelerations related to the observed permanent vertical displacements, together with possible horizontal displacements, that occurred during the earthquake. The effect of transitory horizontal accelerations is to increase temporarily the shear stress on slope-forming materials; this increase may result in failure (Varnes, 1958, p. 43). In some instances slope failure may have occurred because of loss of shear strength through partial liquefaction of saturated granular materials below the layer of seasonal frost.

Although the earthquake was clearly the trigger, it was not the ultimate cause of the slides. In a topographically rugged and geologically complex area such as Kodiak and the nearby islands, many rock masses are in a state of unstable equilibrium as a result of local topography, lithology, structure, weathering, and water saturation. Even without earth shocks to act as a trigger, numerous landslides continually occur.

Of particular interest is the concentration of earthquake-induced slides along the southeast coast of Kodiak Island and the nearby offshore islands (fig. 11), in contrast to their relative scarcity elsewhere. This distribution appears to be controlled primarily by local lithology and structure but may also be related to proximity to the earthquake focal region. Steepness of slope probably is not an important factor in controlling the overall distribution, inasmuch as maximum slope angles in the area of few slides are, in general, equal to, or greater than, those in the zone of many landslides.

The strong coincidence of maximum landslide frequency and outcrop areas of bedded Tertiary rock is shown in figure 11. It is also noteworthy that the landslides in Tertiary rock are exceedingly diverse and complex in character and include all the types that were described above, whereas those in pre-Tertiary outcrop areas are almost exclusively rockfalls.

The predominance of landsliding in areas underlain by Tertiary rock seems to be largely controlled by the physical properties of the rocks in at least five ways: (1) The Tertiary sequence locally contains inherently weak materials such as clay, siltstone, and tuff along which sliding may occur. ((2) The rocks, as a rule, are complexly folded and are broken by numerous discontinuities such as faults, joints, and bedding planes, which reduce shear strength. (3) The relative ease of weathering has resulted in local thick accumulations of landslide-prone soil and colluvium. (4) More rapid erosion has produced numerous steep-sided stream valleys and wave-cut cliffs, and attendant slope instability has resulted from removal of lateral support. (5) Intensity of the tremors during the earthquake (fig. 5) suggests that the horizontal ground accelerations and amplitudes in some areas underlain by Tertiary rock were greater than in areas underlain by pre-Tertiary rock. Such differences in intensity would result in proportionately larger transient increases in shear stress and attendant reductions in shear strength of slope-forming materials in the Tertiary outcrop belt during the earthquake.

In summary, the distribution of landsliding shown in figure 11 appears to be closely related to local geologic conditions, the slides being most abundant in areas underlain by the least competent Tertiary rocks, and relatively few and widely scattered throughout the remainder of the region. The five factors enumerated above apply especially to units of middle and late Tertiary age. Rocks of early Tertiary age, as a rule, are well indurated, can be distinguished from pre-Tertiary bedded rocks only with difficulty, and probably have physical properties and susceptibility to sliding that are intermediate between those of the late Tertiary and pre-Tertiary sequences.

Although it appears that landslide frequency is largely controlled by the underlying rock units, the possibility must also be considered that proximity of the southeastern coast to known faults (fig. 3) or to the focal region (as defined by aftershock distribution shown on figs. 1 and 4) may have resulted in a higher intensity of ground motion and attendant susceptibility to sliding. The limited available data, however, do not indicate that either proximity to faults or to the focal region had a discernible influence on landslide distribution. Geologic study of the deformation in the area of highest landslide frequency failed to reveal active faults having significant surface displacement along which landslides might be concentrated. Furthermore, if the landsliding were controlled mainly by proximity to the focal region rather than by lithology and structure, there should be a progressive decrease in landslide frequency northwestward, away from the focal region, instead of the abrupt change that occurs between the belt of Tertiary rocks and the remainder of the area studied.

EFFECTS ON GROUND AND SURFACE WATER

Earthquake-induced fluctuations in level and (or) flow of some wells, lakes, and streams occurred at numerous localities throughout Kodiak and the adjacent islands. Temporary and permanent fluctuations of water level and flow that were recorded after the earthquake throughout much of Alaska, Canada, and conterminous United States, Hawaii, and Puerto Rico (Waller and others, 1965) are to be detailed in a separate volume of this series of reports that deals with earthquake-induced changes in the hydrologic regime and, consequently, will be described only briefly in the following paragraphs.

OBSERVATIONS

Reported effects of the earthquake on the few water-supply wells on the islands varied markedly. Some wells went dry or decreased yield and a few had increased yield, but most reportedly had no perceptible change. Many wells were muddied, and some along the coast became saline. Because none of the wells on the islands were equipped with water-level recorders, all the available data on earthquake-induced changes are, of necessity, based on observations by local residents reported in questionnaires and personal interviews.

The only wells in the area known to have gone completely dry during the earthquake were shallow hand-dug wells on a small island near the Port Bailey cannery on the south side of Kupreanof Strait (fig. 2). A cannery worker, Mr. Rudy Lorenson, reported that after the earthquake the wells were dug 2 feet deeper without finding water. The wells were still dry 4 months later. Ranch wells at Narrow Cape (fig. 2) became muddy immediately after the earthquake. Although the yield of some wells reportedly increased, it is not known whether this increase was accompanied by a permanent change of level. Wells along the shore at Afognak village were also muddied after the earthquake. These wells, and the school well at Old Harbor, became salty and unusable. There was no change in quality or level of water at the Coast Guard station near Cape Chiniak on Kodiak Island, or at the Federal Aviation Agency radio station at the north end of Shuyak Island.

Observers throughout the area report that ice on virtually all lakes and reservoirs at low altitudes was cracked during the earthquake—particularly around the margins. At higher altitudes pilots noted cracking of ice on some large lakes, but many of the smaller lakes showed no perceptible changes. A small cabin along the shore of a pond near Cape Chiniak was destroyed when seiching drove the ice cake over the bank and into the structure. According to eyewitnesses at Afognak village, ice on the lakes began cracking as soon as the earthquake was felt. Marginal cracking of lake ice probably can be attributed to the inertial effect of the water and ice cakes in resisting horizontal ground oscillations during the earthquake. In other parts of south-central Alaska it was noted that pressure ridges built up in the ice and snow along the shorelines in response to repeated pounding of the ground against the ice cakes. Although similar pressure ridges undoubtedly formed along lakeshores in the area, they were not specifically noted by local residents.

In general, lake levels were either unaffected by the earthquake or were lowered. R. M. Waller has pointed out that erroneous reports of lowered lake levels may have been made in places where earthquake-induced seiching stranded cracked ice along the shore, or where the tremors have caused collapse of peripheral ice and snow bridges that commonly form by normal lowering of lake levels during the winter. Two shallow lakes between 3 and 3½ feet deep on Shuyak Island reportedly went dry during the earthquake. One filled up soon afterward but the other remained dry. Numerous shallow lakes on Kodiak Island that had gone dry during the earthquake were still dry or had lower water levels 4 months afterward. A cirque lake 2,000 feet long by 1,000 feet wide, at an altitude of 500 feet 5 miles northwest of Narrow Cape, reportedly was lowered 20 feet during the earthquake, although nearby lakes showed no perceptible change of level.

A few local changes in streamflow—involving both decreases and increases in volume—were reported in the area after the earthquake. Abnormally reduced water flow at two important salmon-rearing streams was noted by Dexter Lall of the Alaska Department of Fish and Game.

A particularly interesting sequence of changes was noted by Mr. Rudy Lorensen in a small stream that flows across Mesozoic bedrock near the Port Bailey cannery on northern Kodiak Island. According to Mr. Lorenson, the creek flow was reduced to about half its normal volume after the earthquake. The remaining flow was cut off entirely during the jarring aftershock of April 14th, the epicenter of which was located within 10 miles of the cannery (fig. 4). The stream remained dry for two months until another sharp aftershock in June started the normal volume of flow once again.

The flow of streams at Afognak village and springs at a ranch on the north shore of Ugak Bay on Kodiak Island reportedly increased for a period of one week after the earthquake. Four larger streams on which U.S. Geological Survey water-level recording gages were installed showed no significant flow changes following the earthquake.

CAUSES OF FLUCTUATIONS

Lack of detailed data on the pre- and postearthquake flow records of wells, streams, and springs for which earthquake-induced changes are reported precludes analysis of the origin of these changes.

Elsewhere in the part of Alaska strongly affected by the earthquake, where adequate data are available, the widespread lowered well and lake levels and reduced streamflow in granular materials has been attributed by H. E. Thomas of the U.S. Geological Survey to temporary increases in the porosity of saturated materials (in Grantz and others, 1964, p. 10). This mechanism could be the reason for lowered well levels in the islands, and, in conjunction with increased opportunity for water seepage from lakes and streams into earthquake-cracked frozen banks, and through cracked ice dams at lake outlets, could also explain some of the lowered lake and stream levels.

In many places, however, lowered water levels in wells, streams, and lakes appear to be permanent. The reported sequence of abrupt changes in discharge of the small stream near Port Bailey suggests that, in areas underlain by bedrock, fracture porosity may be abruptly increased or decreased by slight shock-induced adjustments of bedrock blocks. Similar changes may have resulted from tectonic deformation within the area, especially if significant horizontal extension accompanied the vertical subsidence. Retriangulation within the zone of subsidence near Anchorage has revealed horizontal extension roughly normal to the trend of the zone amounting to as much as 8×10^{-5} or roughly one-half foot per mile (U.S. Coast and Geodetic Survey, 1965, p. 17). If comparable extension occurred on Kodiak and the nearby islands, where subsidence is equal to or greater than that of the Anchorage area, near-surface fracture porosity may have increased sufficiently to cause some of the reported changes in water regimen, and particularly in areas of fracture porosity.

The permanently increased salinity of a few wells in highly permeable beach and alluvial deposits at Afognak and the school well at Old Harbor probably was the result of encroachment of sea water into aquifers after tectonic subsidence. Temporarily increased salinity of most of the shallow dug wells, however, resulted from flooding of watershed areas by the seismic sea waves.

VERTICAL TECTONIC DEFORMATION

The March 27 earthquake was accompanied by tectonic deformation that resulted in vertical crustal movements, both upward and downward throughout the report area. Anomalous tide levels soon after the earthquake made coastal residents aware of the vertical displacement of the land.

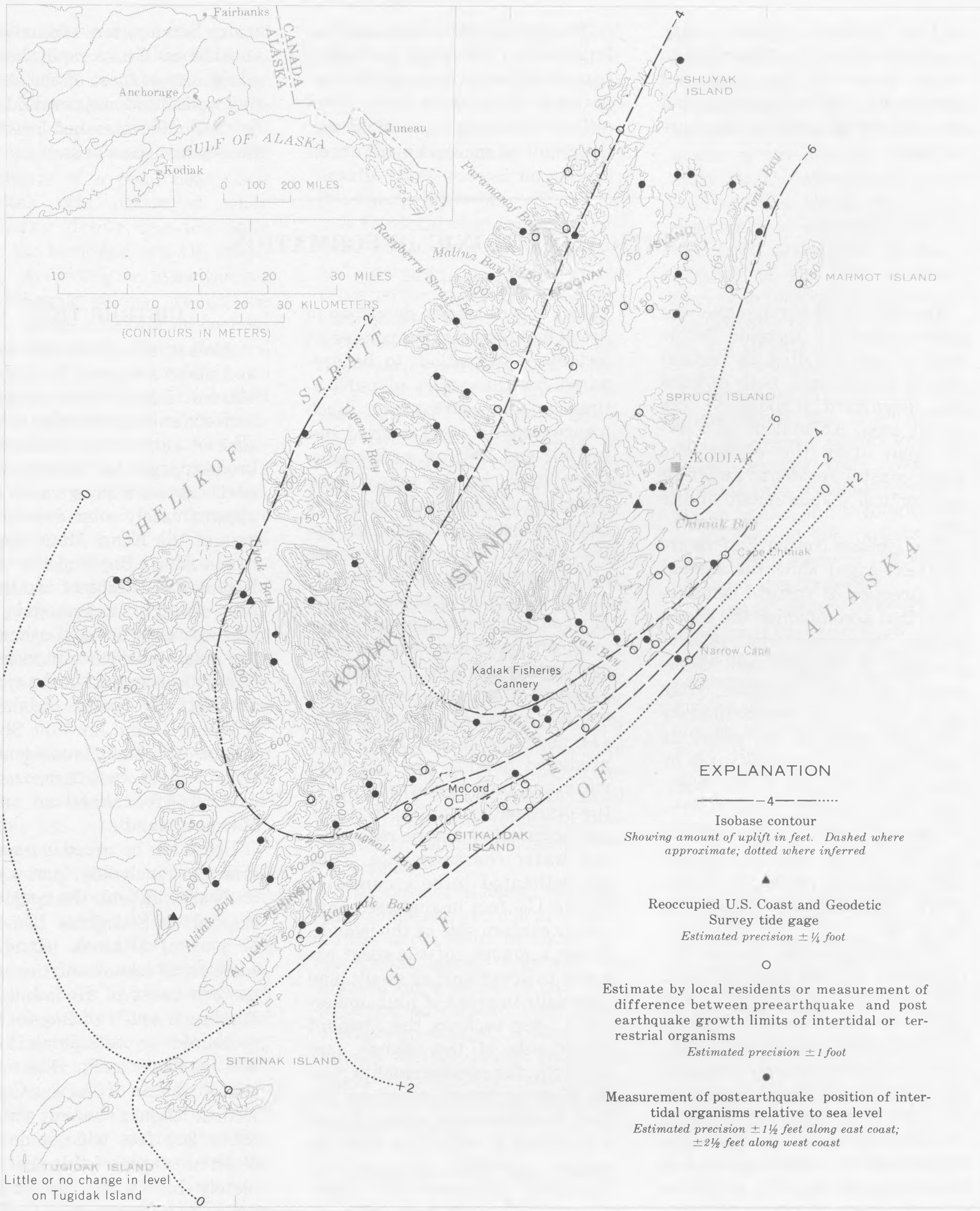
The isobase contours of figure 16 (next page) show the amount and direction of vertical displacement that accompanied the earthquake. Directions and relative amounts of change were determined at four localities from coupled pre- and postearthquake tide-gage readings, at about 25 localities from estimates made by local residents, and at 95 localities from measurements of the displacement of the upper growth limit of sessile intertidal organisms along the seashore. Data-point locations are shown on figure 16.

Determinations of vertical displacement at tide gages is probably accurate to within a few tenths of a foot. Most of the estimates made by fishermen, mariners, and other coastal residents who have had long experience with the local tides are probably correct to within a foot. The technique used for estimating vertical displacements from the height of the upper growth limit of marine organisms above tidal datum planes has been outlined elsewhere (Plafker, 1965, p. 1675-1679.) It will also be described in detail in a forthcoming volume on tectonic deformation, to be prepared for this series of publications on the earthquake. Such measurements were carried out in 1964 and 1965 on a reconnaissance basis in the area. Those based on difference in pre- and postearthquake altitudes of upper growth limits of barnacles and algae are thought to be generally accurate to about 1 foot. Most of the measurements, however, are based only on the postearthquake altitude of these organisms above sea level; they contain inherent errors due to (1) deviation of sea level from predicted heights and (2) local variations in the growth limits of the organisms resulting from local factors of exposure, rock type, and water characteristics. They are estimated to be accurate to within 1½ feet in sheltered bays on the eastern side of the islands. Along segments of the coast exposed to heavy surf or swells, and especially in areas of high and erratic tides such as the Shelikof Strait side of the islands (see table 2), the measurements may be in error by as much as 2½ feet. In these areas, more reliance was placed on estimates made by coastal residents and on the measured difference in upper growth limits of pre- and postearthquake organisms than on those measurements that require use of tide level as a datum.

DISTRIBUTION

Almost all of Kodiak Island, and all of Afognak, Shuyak, and Marmot Islands have undergone tectonic subsidence (fig. 16). The zone of subsidence consists of a broad trough that plunges gently northeastward along an axis that approximately coincides with the axis of the Kenai Mountains between Alitak Bay and the city of Kodiak. The limbs of the trough are strongly asymmetric, the steepest limb being southeast of the axis. Subsidence in excess of 6 feet has occurred in the vicinity of northern Kodiak Island, on Afognak Island, and on Shuyak Island. Maximum subsidence of 6½–7 feet was measured on eastern Afognak Island and on Marmot Island.

Uplift has occurred in a narrow zone that includes Narrow Cape on Kodiak Island, the southeastern half of Sitkalidak Island, all or part of Sitkinak Island, and some small islands off the southeastern coast of Kodiak Island. Maximum uplift of 2½ feet was measured on Sitkalidak Island. Mr. Joe Beaty (see p. D15) reports that at the tip of Narrow Cape on Kodiak Island a surf-cut platform about 200 feet wide is now exposed at stages of tide that completely inundated the platform before the earthquake. Uplift of at least 2 feet, and possibly in excess of 3 feet, is suggested near this locality by postearthquake



16. — Areas affected by tectonic deformation on Kodiak and nearby islands.

incision of streams and the consequent partial draining of two small beach-barred lakes. However, the outlet streams may have become incised through scouring action of the seismic sea waves that entered the lakes after the earthquake. At Sitkinak Island, another rancher, Mr. Hal Nelson, noted 1–2 feet of shoaling at the entrance to a lagoon immediately after the earthquake—probably the result of a slight crustal uplift. Evidence of as much as 2 feet of uplift in the coastal area and small offshore islands between Narrow Cape, Sitkalidak Island, and Sitkinak Island suggests that the zone of uplift is probably continuous beneath intervening water-covered areas.

As far as could be determined during the brief reconnaissance of the area, changes of land level associated with the earthquake resulted from regional warping rather than faulting. A diligent search was made for surface faults, particularly in the vicinity of the zero isobase between the areas of uplift and subsidence, a zone roughly paralleling numerous known faults (fig. 3). No evidence of significant surface faulting was found, nor were there any anomalous abrupt changes in amounts of uplift or subsidence along the coast suggestive of measurable displacement along concealed faults.

Past movements on the major faults in this zone have been mainly dip slip with the northwest blocks upthrown (fig. 3). Consequently, if any of these faults were reactivated during the earthquake only a reverse displacement could produce the observed pattern of deformation along the southeast coast of the islands.

EFFECTS ON SHORELINES

Tectonic subsidence, augmented locally by surficial subsidence of unconsolidated deposits, has had a profound effect on shoreline morphology, intertidal marine organisms, and terrestrial vegetation. Virtually all shorelines that subsided more than 3 feet show clear physical evidence of the change, and the changes were locally noticeable where the subsidence was as little as 1 foot.

The effects were most pronounced in areas of lowest mean annual tidal range (table 2), inasmuch as both the frequency and duration of shoreline immersion for a given amount of subsidence vary inversely with the tidal range. The conspicuous effect of subsidence is the fringe of dead brown terrestrial vegetation along the shore that has been killed by salt-water inundation at periods of high tides (pls. 1, 3).

Beach berms and stream deltas in subsided areas are shifted landward and are building up to the new higher sea levels. The lower reaches of streams are now inundated by tides for distances of as much as 4,500 feet inland (table 3). The striking effect of subsidence in the estuarine part of Olds River at Kalsin Bay is illustrated by plate 3. Many former beach-barred lakes at stream mouths or bay heads have become tidal lagoons. Wave action at the higher sea levels is rapidly eroding shorelines composed of poorly consolidated deposits that are now brought within reach of the tides (pl. 4). An irreparable loss resulting from accelerated erosion of such deposits is the destruction of many coastal archaeological sites situated on them. Former reefs and low-lying islands along the coast are now submerged, and some tombolo-tied points or capes have become islands.

Effects of the small and localized uplift along the shore are minor compared to those due to subsidence. At Narrow Cape a new surf-cut rock terrace 200 feet wide reportedly is exposed at zero tide, and nearby beach-barred lakes have been partially drained by incision of the outlet

TABLE 3.—*Tidal inundation resulting from tectonic and surficial subsidence*

Stream	Location (fig. 2)	Approximate tectonic subsidence (feet)	Length of stream newly inundated by tides (feet)[1]
	Afognak Island		
Danger Bay Creeks	14 miles northeast of Afognak.	5½	865
Marka Creek	5 miles northeast of Afognak.	4–5	2,600
Back Bay Creeks	5 miles north of Afognak	3½–5	605
Afognak River	4½ miles north-northeast of Afognak.	3½–5	825
	Kodiak Island		
Kiliuda Creeks	Kiliuda Bay	4–5	1,900
Eagle Harbor Creek	Ugak Bay	4	850
Saltery Cove Creek	do	5	570
Olds River	Kalsin Bay	4½	4,500

[1] Alaska Department of Fish and Game (1965, p. 5).

streams. Elsewhere a few new reefs are exposed at stages of tide when they formerly were under water. Lowered tide levels in lagoons in the area with attendant reduced volume and velocity of diurnal flow through the outlets may eventually result in the barring of the lagoon outlets and subsequent conversion of the lagoons to fresh-water lakes.

REGIONAL SETTING OF THE CHANGES

The 4,900-square-mile land area of Kodiak and the nearby islands within which vertical displacements were measured is but a part of a regional zone of tectonic deformation associated with the earthquake. An area of at least 70,000 square miles, and possibly 110,000 square miles or more of south-central Alaska, is involved (Plafker, 1965). The zone, which is more than 500 miles long and as much as 200 miles wide, is roughly parallel to the Gulf of Alaska coast from the Kodiak group of islands northeastward to Prince William Sound and thence eastward to about long 143° W. It consists of a major seaward zone of uplift bordered on the northwest and north by a major zone of subsidence (fig. 17). These two zones are separated by a line of zero land-level change that trends northeastward from Sitkinak Island along the seaward sides of Sitkalidak and Kodiak Islands (fig. 16). From Kodiak Island, the line trends northeastward to intersect the mainland between Seward and Prince William Sound. It then curves eastward through the western part of Prince William Sound to the vicinity of Valdez and crosses the Copper River valley about 50 miles above the mouth.

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

In the northern part of the deformed area, uplift in excess of 6 feet occurred over a wide area including part of Prince William Sound, the mainland east of the sound, and offshore islands on the continental shelf as far southwest as Middleton Island. Along surface faults on Montague Island, the uplift locally exceeded 30 feet (Plafker, 1965, fig. 7). Southwest of Montague Island the sea bottom may have been uplifted more than 50 feet (Malloy, 1964, p. 1248), where pre- and postearthquake bottom soundings show seaward continuations of new fault scarps along preexisting fault lines. Large-scale uplift of the continental shelf and slope southwest of Montague Island is inferred from the trend of isobase contours in the northeastern part of the deformed area, and from the presence of the fringe of uplift along the outer coast of the Kodiak Island area (fig. 16). The minimum extent of this inferred offshore zone of uplift is thought to be roughly outlined by the earthquake focal region, or belt of major aftershocks, shown on figure 1.

The major zones of vertical tectonic displacement and the belt of aftershocks, which lie within and parallel to the Aleutian Trench and the Aleutian volcanic arc, are inferred to have resulted from displacement along a fault or zone of faulting that dips at a moderate angle northward from the Aleutian Trench beneath the continent (Grantz and others, 1964, p. 2). Neither the orientation nor the sense of movement on the primary fault (or faults), along which the earthquake presumably occurred, is certain, inasmuch as the primary fault or zone of faulting is not known to intersect the surface on land.

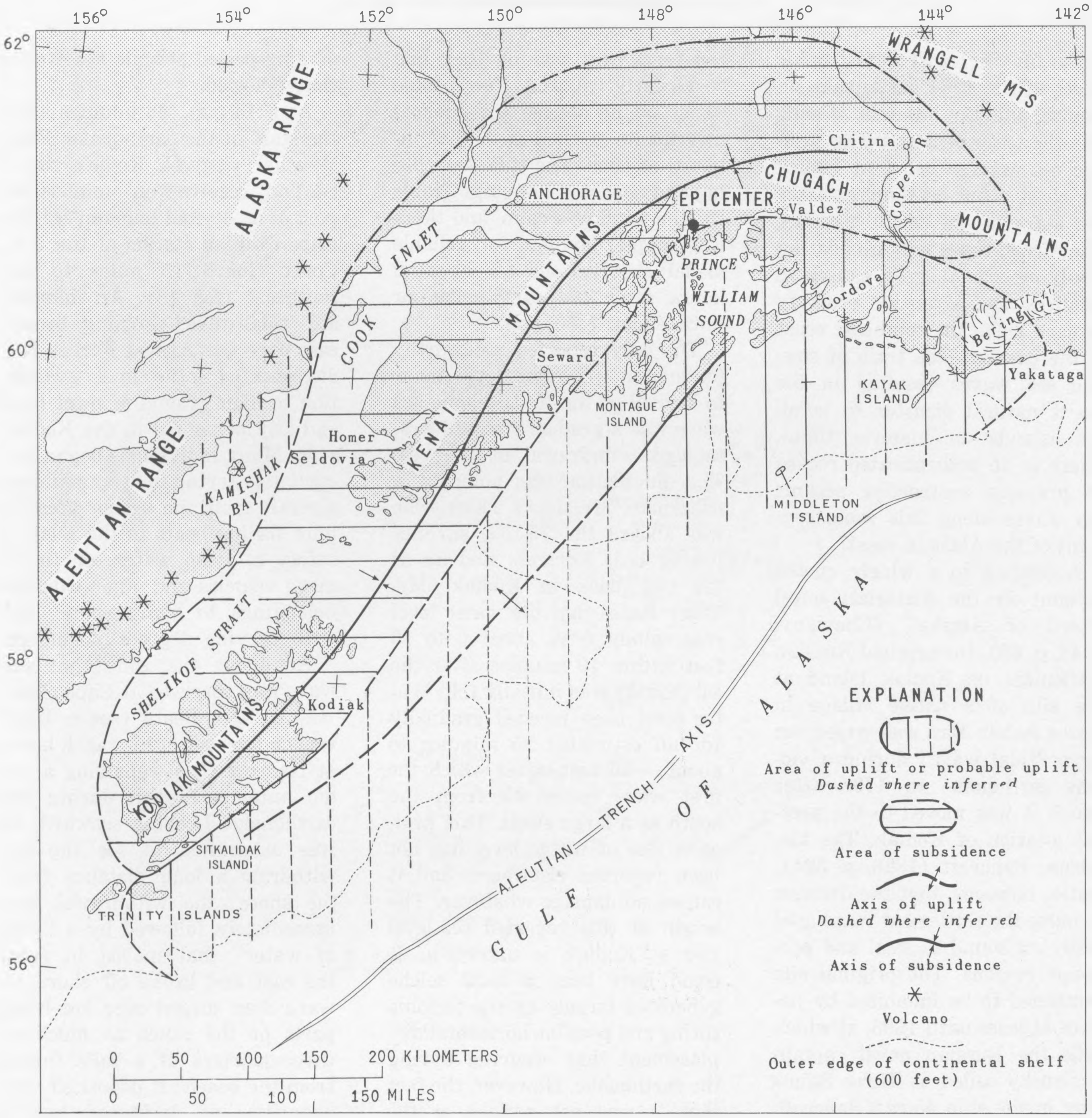
The two known surface breaks, which occurred on preexisting faults on Montague Island along the axis of maximum uplift, are clearly within and subsidiary to the zone of regional uplift. The faulting on Montague Island is known to extend offshore southwestward at least 15 miles, and comparable fault displacements probably occurred along this trend or elsewhere on the sea floor of the continental shelf within the focal region of the earthquake. Indeed, the direction of travel and reported arrival times of the initial wave crest in the area (p. D30–D39) suggest that the axis of maximum uplift (fig. 17), along which faulting occurred on Montague Island, may extend southwestward perhaps to the latitude of Sitkalidak Island (Plafker, 1965, p. 6; Plafker and Mayo, 1965, fig. 12).

SUBSIDENCE AT MIDDLE BAY

Extensive inundation at the head of Middle Bay resulting from 5 feet of tectonic subsidence and an unknown but substantial amount of surficial subsidence. Arrows indicate the approximate location of remnants of the Kodiak-Chiniak highway. Dashed line shows the approximate preearthquake mean high-water shoreline which has been shifted about half a mile landward.

UNDERMINED TREES ON BARRIER BEACH IN IZHUT BAY, AFOGNAK ISLAND

Accelerated wave erosion in an area of about 5 feet of tectonic subsidence caused this damage. Foliage of trees along shore has turned brown from salt-water immersion of the roots.



17. — Setting of the observed and inferred vertical displacements of the Kodiak group of islands with respect to regional tectonic deformation in south-central Alaska.

SEISMIC SEA WAVES

By far the most catastrophic effect of the 1964 earthquake on Kodiak and the adjacent islands was the train of destructive seismic sea waves that first struck the coast about 38 minutes after the start of the earth tremors. The waves, repeatedly inundating low-lying coastal areas, caused 18 fatalities and extensive property damage along the southeast coast of the islands. This train of seismic sea waves resulted in the worst natural disaster to befall the islands in historic times. There is no authenticated record of previous destructive seismic sea waves along this same segment of the Alaskan coast.

According to a widely quoted account in the historical novel "Lord of Alaska" (Chevigny, 1942, p. 63), the original Russian settlement on Kodiak Island at the site of a native village in Three Saints Bay was wiped out by a "tidal wave" during a violent earthquake in 1792 after which it was moved to the present location of Kodiak. The historian, Bancroft (1886, p. 324), states, however, that the decision to move the settlement was based solely on sound tactical and economic reasons. The original site continued to be inhabited by natives at least until 1805, at which time the Russian naval captain Lisiansky called at Three Saints Bay in the ship *Neva* (Bancroft, 1886, p. 434-435).

CHRONOLOGY

For a period of about half an hour after the earthquake, most residents were busily assessing the relatively light earthquake-induced damage and discussing the terrifying shaking they had so recently endured. Few people recall having noticed any unusual movements of the sea in that interval of time. The tide was ebbing and nearly at low stage (table 2), the wind was calm, and there was ample daylight for reliable visual observations for about 2 hours after the earthquake, or until about 7:30 p.m.

The only reported noteworthy fluctuation of water level prior to arrival of the first seismic sea wave was a gradual rise and subsequent withdrawal of the sea. This fluctuation was noted by a fisherman, Mr. Jerry Tilley, who was aboard the 75-foot shrimp-fishing boat *Fortress* tied up at the city dock in Kodiak. Mr. Tilley states that the water level rose calmly from about 0 to 13 feet within 10 minutes after the earthquake was initially felt. Water level then receded gradually for an estimated 25 minutes to about —10 feet, after which the first wave moved in from the south as a large swell. This first, calm rise of water level has not been reported elsewhere, and it caused no damage whatever. The origin of this reported sea-level rise at Kodiak is uncertain. It could have been a local seiche generated largely by the tectonic tilting and possible horizontal displacement that occurred during the earthquake. However, the fact that it was not noticed at the nearby Naval station, which underwent approximately the same amount of subsidence, argues against this possibility. In any event, the limited data available on this initial sea-level rise suggest that it was a local phenomenon, rather than part of the train of long-period seismic sea waves that followed.

At 6:14 p.m., 38 minutes after the start of the earthquake, Fleet Weather Central, Kodiak Naval Station, received an ominous report of a "30-foot tsunami" at the Cape Chiniak station of the U.S. Coast Guard 15 miles to the southeast (fig. 18). An immediate "tidal-wave" warning, broadcast over the Armed Forces Radio, resulted in the timely evacuation to high ground of most base and city personnel in the Kodiak area. Many individuals began immediately trying to fly amphibious aircraft from the harbor area, to pilot fishing boats to the relative safety of deep water, or to remove vehicles and other valuable belongings to high ground, but with varying degrees of success.

At about the time that the wave was observed at Cape Chiniak, Mr. Joe Beaty (see p. D15) was on the roof of his ranch home at Narrow Cape repairing a radio antenna broken during the earthquake. Looking seaward, he was astonished to see the sea withdraw a long distance from the shore; the withdrawal was immediately followed by a "wall of water" that moved in from the east and broke off shore. A wave then surged over low-lying parts of the ranch as much as three-quarters of a mile inland from the beach; it deposited vast quantities of driftwood but it stopped just short of the house and outbuildings. Seven head of cattle were drowned, contrary to one journalist's account which claimed that the animals somehow sensed the oncoming wave in time to move to the safety of high ground.

18. — Localities on Kodiak and nearby islands at which waves caused major property damage (black circles), shorelines showing physical evidence of wave damage (x), shorelines reportedly inundated by runup (open circles), and U.S. Geological Survey streamflow gages on which waves were recorded (triangles). Numbers indicate approximate highest runup in feet above existing tide level; plus sign following numeral indicates that tide stage is unknown and maximum runup shown is minimum value assuming coincidence of wave with high tide. Lined pattern offshore indicates inferred position of the northwest and southwest margins of the wave-crest source.

19. — Seaplane ramp at Kodiak Naval Station along shore of Womens Bay showing approximate high-water level reached by first wave. Note calm water surface. Aircraft parked in front of hangar at left center were later moved to high ground and saved. Photograph by U.S. Navy.

Shortly after the initial wave struck the outer coast from Cape Chiniak to Narrow Cape, inhabitants elsewhere along the southeast coast between Kaguyak and Afognak noticed rapid rises of the sea, accompanied in some places by dull rumbling sounds. By 6:35 p.m., 63 minutes after the start of the earthquake, the initial wave was cresting at the city of Kodiak, nearby Kodiak Naval Station, and other points along the shore of Chiniak Bay, and was inundating low-lying coastal areas. Everywhere except at Cape Chiniak and Narrow Cape, the first waves were described as a gentle gradual flood with swirls resembling riverflow that rose at estimated rates of as much as 3 feet per second. Figure 19 shows part of the airport at Kodiak Naval Station as the first wave crested. At Kodiak and Old Harbor, gradual withdrawals of about 10 feet reportedly preceded the initial wave, but no withdrawal in Womens Bay was observed at the Kodiak Naval Station.

The initial wave was followed everywhere by a turbulent swirling retreat of water from the shore, during which segments of the sea floor were bared far below the level of the extreme low tides. Much of the fishing fleet at Kodiak was left grounded, but some boats were swept offshore and caught in whirlpool-like eddies or high-velocity currents that accompanied the withdrawal. The water withdrew to about 10 feet below the postearthquake mean lower low water at the Kodiak Electric Association powerhouse in Kodiak. At the Kodiak Naval Station, the water withdrew to about 11½ feet below the postearthquake mean lower low water.

Approximately at 7:40 p.m., as darkness was falling and the tide beginning to flood, a second wave that was the largest and most destructive of the train in the Chiniak Bay area struck the coast. It swept away docks, houses, and vehicles along the shore and drove flotsam and fishing vessels inland as battering rams, causing much destruction of property previously undamaged by the high water.

The withdrawal that followed the second wave was extremely turbulent and rapid. Swirling currents with velocities variously estimated at 20–25 knots flowed through the straits near Kodiak. The water was choked with debris, and vessels that were unable to steer against the swirling erratic currents were carried on its flood.

The third wave, which struck the southeast coast of the area between 8:30 and 9:30 p.m., was slightly lower than the second wave in Chiniak Bay, but because it came in on a rising tide it reached almost the same altitude along the shore as the previous wave, adding substantially to the damage. It was the highest and most destructive wave witnessed at the villages of Afognak, Old Harbor, and Uzinki; numerous homes and other structures were washed to sea, and fishing vessels were sunk or beached. At the widely spaced villages of Afognak and Old Harbor, the arrival time of the wave crest was recorded on clocks that were stopped by the inundation almost simultaneously—at 9:27 p.m. and 9:28 p.m., respectively. By this time virtually everyone along the southeast coast except those aboard boats and personnel at Fleet Weather Central had evacuated to higher ground, and it was too dark in most places to permit reliable observations on the nature and sequence of waves.

The instrumental records and the record kept at the Kodiak Naval Station show that waves continued to inundate the shoreline with progressively decreasing amplitude until early the next morning. However, the highest runup in some localities, including Womens Bay near Kodiak Harbor, coincided with high tide shortly after midnight (table 2).

The greatest observed withdrawal of water occurred at the Kodiak Naval Station a few minutes after midnight. At that time, water level fell some 24 feet from a plus 8-foot tide to 16 feet below mean lower low water.

Along the Shelikof Strait side of the group of islands, no wave action or water motions were noted, aside from minor local turbulence, until about 90 minutes after the earthquake. Water fluctuations there consisted of rapid low-amplitude tide changes accompanied by swift and erratic currents. The shoreline was inundated a few feet above normal preearthquake highest tide levels only by the waves that occurred between 11:30 p.m. and 1:00 a.m., within an hour of high tide (table 2). The last recorded anomalous tide rise on the Shelikof Strait side of the island that could be attributed to wave action was at about 5:00 a.m. on the morning after the earthquake.

CREST HEIGHTS

Locations of coastal areas on Kodiak and nearby islands that were affected by the seismic sea waves are shown on figure 18. Also shown are maximum runup heights recorded at shore stations and the inferred source area of the waves.

The sole operative tide gage on Kodiak and the nearby islands was at the Kodiak Naval Station in Womens Bay. It was put out of action by the earthquake tremors and was subsequently inundated by the waves; the marigram for March was lost. Observations of water-level changes at the Naval Station were made by Fleet Weather Central personnel throughout the night of March 27 and the early hours of March 28. It is the most complete record available of the seismic sea waves in the area or elsewhere along the Gulf of Alaska coast in the region strongly affected by the earthquake.

Unique instrumental records of arrival times and maximum runup heights of the higher waves were obtained from three U.S. Geological Survey streamflow gages at localities shown on figure 18. The three gages were situated at sites near stream mouths that subsided sufficiently during the earthquake to bring them within reach of the highest seismic sea waves; the two gages on the Shelikof Strait side of the island are low enough to record the higher astronomical tides since the earthquake. Arrival times, crest heights, and runup altitudes of the waves at Womens Bay and at the three streamflow gages are given in table 4 (next page).

With the exception of the four localities enumerated above, all data on wave-arrival times were obtained through conversations or written communications with eyewitnesses. Most are little more than rough estimates of elapsed time beween start of the tremors and the wave-crest arrivals. Few observers had the opportunity or presence of mind under the prevailing conditions to record the time at which the waves struck, and in any given locality opinions varied considerably.

The maximum heights to which the waves rose along the shore at localities other than Womens Bay and the sites of the streamflow gages could be readily ascertained from the strand lines of seaweed and driftwood, waterstains on buildings, and abraded bark or broken branches in trees and brush along the shore. Heights were measured by hand level and stadia rod above prevailing sea level and later reduced to mean lower low water. At most localities measured heights were substantially lower than those indicated by eyewitnesses or estimated by some investigators who visited the area after the earthquake.

Because much of the land area had been lowered or uplifted by the tectonic deformation that presumably occurred during the earthquake (Plafker, 1965, p. 1680) and because the wave train struck the coast at stages of tide ranging from low to high, appro-

TABLE 4.—*Heights (in feet) and arrival times of seismic sea-wave crests at Womens Bay, Myrtle Creek, Terror River, and Uganik River on Kodiak Island*

[Local (Alaska standard) time. MLLW, postearthquake mean lower low water]

Wave	Womens Bay[1] (Kodiak Naval Station)			Myrtle Creek[2]			Terror River[3]			Uganik River[4]		
	Time	Crest height		Time	Crest height		Time	Crest height		Time	Crest height	
		Above tide level	Above MLLW		Above tide level	Above MLLW		Above tide level	Above MLLW		Above tide level	Above MLLW
	March 27											
1	6:35 p.m.	10.8	10.6	6:45 p.m.	15.2	15.0	11:15 p.m.	8.0	18.2	11:00 p.m.	6.2	15.2
							March 28					
2	7:40 p.m.	12.8	12.8	7:40 p.m.	18.6	18.8	1:15 a.m.	1.8	17.0	1:15 a.m.	0.9	16.0
3	8:30–8:44 p.m.	8.6	9.7	8:30 p.m.	17.2	18.4	1:50 a.m.	2.6	17.7	2:32 a.m.	4.9	18.5
4	10:00 p.m.	9.4	13.7	9:45 p.m.	14.3	18.4	3:00 p.m.	8.6	21.1	....	....	....
5	11:16–11:34 p.m.	11.6	18.8	11:15 p.m.	13.2	20.3	4:20 a.m.	9.2	18.2	....	....	....
	March 28											
6	0:47 a.m.	3.2	11.6	2:40 a.m.	7.3	13.9	....	....	....	....	....	....
7	1:54 a.m.	6.4	13.8	....	....	....	....	....	....	....	....	....
8	2:20 a.m.	3.0	10.0	....	....	....	....	....	....	....	....	....
9	2:58 a.m.	2.2	7.2	....	....	....	....	....	....	....	....	....
10	3:20 a.m.	1.6	5.6	....	....	....	....	....	....	....	....	....

[1] Data from Fleet Weather Station, U.S. Navy, Kodiak.
[2] Data recorded on U.S. Geological Survey streamflow gage about 1 mile above preearthquake stream mouth.
[3] Data recorded on U.S. Geological Survey streamflow gage 0.7 mile above preearthquake stream mouth.
[4] Data recorded on U.S. Geological Survey streamflow gage 0.5 mile above preearthquake stream mouth.

priate corrections for vertical displacement and tide stage had to be made at each locality to obtain the actual runup heights shown in figure 18 and table 4. Where wave-crest arrival times were known, corrections were made by subtracting from the measured runup heights (1) the amount of subsidence, if any, at the shore station, and (2) the predicted tide height above lower low water at the time the wave crested. Where runup heights were measured from swash marks or other evidence left along the shore at unknown stages of tide, corrections could be made for vertical displacement but not for tide stage. In these localities, the height indicated on figure 18 is a minimum value (indicated by a plus sign following the numeral) that assumes coincidence of the highest wave with high tide on the morning of March 28 (table 2). Along the ocean side of the islands the highest waves apparently occurred between low and half tide, so the runup heights of the highest waves most probably were 4–8 feet higher than those shown on figure 18.

RUNUP HEIGHTS

In general, the waves were high and destructive only along the exposed ocean coast. They barely inundated shorelines above normal highest tide levels along the Shelikof Strait side of the islands and the straits between the larger islands. The waves were too low to flood above the shoreline along the southwest shore of Kodiak Island or at Sitkinak Island.

As indicated by figure 18, maximum runup heights of the waves around the islands ranged from a minimum of 5 feet or less to at least 31½ feet. Large local variations in runup heights occurred around the islands—apparently controlled by the highly irregular configuration of the coastline, differences in offshore bottom topography, and length of wave travel path. The highest recorded runups were along exposed beaches and bluffs on southeastward-facing shores of Kodiak and Sitkalidak Islands, whereas runup heights in adjacent sheltered embayments and segments of coast protected by offshore reefs were substantially lower.

The highest measured runup was at an uninhabited locality between Cape Chiniak and Narrow Cape, where trees were damaged 31½ feet above predicted astronomical high tide on the night of the earthquake; however, the highest wave probably coincided with the first large wave at low tide that was witnessed at Narrow Cape and Cape Chiniak. If it did, runup above existing tide level would have been almost 40 feet. Runup of 24½ feet above the March 28 high-tide level was measured on an eastward-facing beach at Sitkalidak Island, and driftwood deposited on a terrace at the south end of the island is estimated to be at least 15 feet higher. Wave-deposited driftwood was also seen from the air at high altitudes on bluffs along the north coast of Marmot Island.

In sheltered embayments along the ocean coast, runup heights ranged from 12 to 17 feet. The highest runup of 17+ feet occurred at Kaguyak which is situated at the head of a large, deep bay that opens into the Gulf of Alaska. The rather low measured runup of 8 feet at Afognak village and at other localities on Afognak Island that face the open ocean are suggestive of rapid dissipation of wave energy with distance from the inferred offshore-source area, especially in areas of shoal waters and shallow reefs such as extend several miles offshore from Afognak village.

On the Shelikof Strait side of the islands, maximum runup heights generally range from 5 to 6 feet. A lone exception is at the Terror River streamflow gage site, where, as described in the following section, seiching caused anomalous water-level rises of as much as 10 feet above tide level at 3:00 a.m. and 4:00 a.m. on the morning of March 28.

Other than at the Terror River gage site, maximum recorded runups above tide level occurred during the first three waves. The highest runups above predicted postearthquake astronomical tides recorded at Kodiak Naval Station and at the Myrtle Creek streamflow gage (12.8 and 18.4 ft, respectively) occurred during the second wave. At Cape Chiniak and Narrow Cape the first wave (at least 31½ and possibly 40 ft) reportedly was the highest. At Afognak and Old Harbor the third wave (8 and 13 ft above tide level, respectively) was the highest. The maximum runup altitude in these areas, however, did not necessarily coincide with the highest wave, inasmuch as the maximum was the resultant of both wave height and the stage of postearthquake astronomical tide at any given locality. As shown by table 2, the tides on which the seismic sea waves were superimposed ranged from slightly less than 0 to 16.0 feet. Consequently, the highest recorded runup at many localities, including those stations indicated on table 4, coincided with wave arrivals close to midnight at about high tide, rather than with the larger early waves that arrived at lower tide stages.

PERIODS

The first three seismic sea waves as recorded at Womens Bay and the stream gage at Myrtle Creek had periods of 50–55 minutes (table 4). This period probably most nearly approximates that of the waves at their source. Later irregularities in the interval between successive waves at these places and at the two stream gages on the Shelikof Strait side of the islands may reflect superposition of local seiches upon the wave train. Such superposition may in part explain the inconsistencies in the reports by eyewitnesses at different localities on the number and arrival times of wave crests.

The anomalous increase in wave height recorded at the Terror Bay streamflow gage (table 4) is suggestive of a longitudinal seiche excited in Terror Bay through approximate coincidence between the natural oscillation period of the bay and that of the seismic seawave train. That the anomalous high waves in the bay were purely of local origin is clearly demonstrated by the record of successive waves of declining amplitude during the same period on the Uganik River gage and at inhabited areas nearby. The Terror River gage is at the head of a nearly rectangular fiord about 14 miles long, less than 1 mile wide, and with an average depth of roughly 270 feet. The natural period of oscillation for the fundamental mode of open-sided bays, such as Terror Bay, is given by the formula:

$$Tn = \frac{4l}{\sqrt{gd}}$$

where Tn is the natural period in seconds, l is the length of the bay in feet, g is the gravitational constant, and d is the water depth in feet (Ruttner, 1953, p. 43). The fundamental mode of oscillation is that in which the first node is situated at the mouth of the bay. By use of this formula and the dimensions and depth indicated above, the period for the fundamental mode of water in the fiord is about 53 minutes, which coin-

20.— Opening torn by seismic sea waves in the barrier beach of a large lake along the shore of Izhut Bay on Afognak Island. Channel scour and subsidence of at least 6 feet permit sea water to enter the basin at all stages of tide. Note partially submerged trees along inner margins of the beach spits, and small new rockslide along bluff in background. Photograph by Alaska Department of Fish and Game.

cides almost too closely with the period of 50–55 minutes indicated for the initial waves. Consequently, the anomalously high wave recorded at the stream gage may have resulted from resonant amplification of a longitudinal seiche that was excited by the train of seismic sea waves.

EFFECTS ON SHORELINES AND SEA BOTTOMS

High-velocity currents associated with the repeated ebb and flood of the waves resulted in extensive damage through erosion of artificial fills and unconsolidated deposits along the coast. The effect of the surges may be compared to erosion during extreme flood conditions of rivers. At several places, barrier beaches damming coastal lakes were breached by the waves, and the lakes were thereby converted to lagoons, as illustrated in figure 20.

Stream gravel was removed from the bed and banks of Olds River at the head of Kalsin Bay along a length of at least 400 feet of the estuary (Alaska Dept. Fish and Game, 1965, p. 6). Mud was eroded from tidal flats along the shore at Kodiak to a depth of 10 feet. Bottom changes off shore from Kodiak at a depth of 75 feet were reported by a scuba diver, Mr. Jerry Tilley, who noted that the channel had been scoured clean of mud and that thousands of clams were thereby exposed on the sea floor.

The combination of swift currents and the buoyant effect of large-amplitude waves moved several navigation and mooring buoys in the Chiniak Bay area, and dragged the navigation buoy in Shuyak Strait off station. Undoubtedly the 20- to 25-knot currents associated with the waves caused intensive scouring of sediment from shorelines and narrow straits and deposition of the eroded material in deeper quieter water. Few such effects, however, have been documented along the shores of Kodiak and the nearby islands because of the general scarcity of preearthquake reference marks in coastal areas and the complicating factor of widespread postearthquake subsidence.

At uninhabited capes and embayments along the ocean coast, wave inundation was evidenced by newly deposited driftwood and seaweed above the level of highest tides and by broken and scarred shoreline vegetation in timbered areas. Figure 21 illustrates the effects on a stand of spruce trees near Narrow Cape of a driftwood-laden surge of water that ran up to an altitude of 42 feet above lower low water.

21. — Shoreline damage between Narrow Cape and Cape Chiniak caused by driftwood-laden seismic sea wave. Spruce trees as much as 8 inches in diameter were broken off at about 30 feet altitude. Limbs were broken and trunks scarred to a measured altitude of 42 feet above lower low water. Crowns of downed trees point in direction of water movement.

ORIGIN

The seismic sea waves clearly were generated off shore from the Kodiak group of islands within the Gulf of Alaska, as shown by the arrival times of the initial waves, the distribution of wave damage, and the orientation of damaged shorelines. The distance traveled by the waves can be determined where wave velocity along the propagation path and travel time are known. Because the wave lengths are long, seismic sea waves move as shallow water waves even in the deepest ocean. As such, their velocity is controlled by the depth and conforms closely to LaGrange's equation (in Lamb, 1932, p. 257):

$$V = \sqrt{gh}$$

where g is the gravitational constant, and h is the water depth along the travel path (as determined from nautical charts). The travel time is taken as the elapsed time between arrival of the first wave crest at shore stations and the inferred time at which the waves were generated.

Calculations of the distance travelled by the first waves to the few stations where reliable data are available on arrival times defines a source area that trends northeastward at a minimum distance of 28 miles off Cape Chiniak and 17 miles offshore from Sitkalidak Island—assuming that the waves were generated at the time of the earthquake or shortly thereafter (fig. 18). A time delay between the beginning of the earthquake and generation of the waves would modify the position of the inferred source by shifting it shoreward. Thus, if as much as 5 minutes elapsed between the beginning of the earthquake in Prince William Sound and the generation of the waves offshore from the Kodiak area, the inferred source area would be 4–6 miles shoreward from the position shown on figure 18. The absence of large waves at Sitkinak Island and in Alitak Bay suggests that the wave source did not extend southwest of the general latitude of southern Sitkalidak Island. The anomalous lack of wave effects along the low-lying northeast shore of Sitkinak Island, which is ideally situated to receive heavy damage from northeasterly waves, further suggests that the waves were strongly directional—as might be expected from a linear northeast-trending source area.

Initial upward motion in the source area is suggested by (1) the distribution of measured land-level change along the adjacent coast and offshore islands, (2) the initial rise recorded on tide gages outside the immediate area affected by the earthquake (Van Dorn, 1964, p. 11), and (3) possibly by the unique atmospheric waves ("seismic air waves") recorded shortly after the earthquakes on microbaragraphs at both the University of California at Berkeley and the Scripps Institution of Oceanography at La Jolla (Van Dorn, 1964, p. 7; Bolt, 1964, p. 1096). The initial direction of water movement within the Kodiak islands area is less clear, however, because there were no operative tide gages, and in many localities water movement during and after the earthquake was complicated by land-level changes along the coast, and perhaps also by local waves generated by the ground tremors or by subaerial and submarine landslides. With a few notable exceptions, however, most observers along the coast of the Kodiak group of islands and elsewhere along the coast of the Kenai Peninsula and Prince William Sound area reported that the first strong surge of waves from the Gulf of Alaska was upward; this report tends to support the inference of vertical displacement in the source area.

The waves recorded on Kodiak and the nearby islands and those that struck the outer coast of the Kenai Peninsula (fig. 17; Plafker and Mayo, 1965, p. 10, fig. 12) appear to have originated along a linear axis of maximum uplift that extends about 350 miles between Sitkalidak Island in the Kodiak group and Montague Island in Prince William Sound. The discrepancy in the position of the inferred axis of maximum uplift offshore from the Kodiak Island area between figure 21 and that of a preliminary report (Plafker and Mayo, 1965, fig. 12) results from a previous error in calculating propagation velocities of the waves.

The axis of the inferred wave source as shown in figure 17 and as computed independently by Van Dorn (1964, figs. 8, 10) are in close agreement. At the north end of this axis near Montague Island there is clear evidence for significant upward displacement in a 6-mile-wide segment of the sea floor. Both extreme crustal warping and large fault dislocation must have taken place. The southwest tip of Montague Island was elevated as much as 33 feet relative to sea level; there was at least 18 feet of vertical offset on land along the Patton Bay fault (Plafker, 1965, p. 1132; Plafker and Mayo, 1965, p. 7). Furthermore, the fault has been traced as a prominent scarp in the ocean floor for at least 15 miles southwest of Montague Island towards the Kodiak group of islands. As much as 50 feet of net uplift of the sea floor along this line has been inferred from comparison of pre- and postearthquake bathymetric surveys made by the U.S. Coast and Geodetic Surveys southwest of Montague Island (Malloy, 1964).

The inferred source area shown on figure 18, from which destructive waves radiated northwestward to batter the coast of the Kodiak group of islands could be a southwestern extension of the axis of uplift and faulting in the Montague Island area. As in that area, it may represent a relatively narrow strip of extreme differential uplift and (or) faulting that is superimposed on the broad regional zone of uplift. The position of the inferred wave source is largely in an area of flat slopes and shoal water on the continental shelf; the possibility is thus virtually precluded that the waves result either from massive submarine landslides along the continental slope or from special resonant oscillations of water in the adjacent Aleutian Trench.

The low-amplitude dipole-type wave that Van Dorn (1964) considered to have been formed by tectonic warping of the broad zones of uplift and subsidence shown on figure 17 apparently did not adversely affect Kodiak or the nearby islands, although it may have contained much of the wave energy radiated out into the Pacific Ocean. No negative wave phase was recorded within the zone of subsidence along the shores of the islands, nor was a positive phase reported at any locality other than the city of Kodiak prior to the arrival of the initial wave crest. The tectonic warping did result, however, in almost immediate withdrawal of water from some tilted uplifted areas and in complementary rises of water level in depressed areas. The reported initial calm rise of water observed at Kodiak immediately after the earthquake may have been associated with this regional crustal tilting about the axis of zero land-level change.

The amount of uplift at the inferred wave source offshore from the Kodiak group of islands is not known and probably cannot be determined because the area had not been covered by detailed preearthquake bathymetric surveys. That the vertical seafloor displacements may be of the same order of magnitude as those in the Montague Island area is suggested by the similarity in the maximum runup heights of the seismic sea waves (35–40 ft) along physiographically comparable segments of coast both on the Kenai Peninsula opposite Montague Island (Plafker and Mayo, 1965, p. 10) and on Kodiak Island. Other factors, however, such as rate of uplift, initial slope at the wave source, and energy loss along the propagation path preclude direct correlation of runup heights with displacement at the source.

DAMAGE AND CASUALTIES

The earthquake and attendant subsidence and seismic sea waves severed the main coastal highways on Kodiak Island and caused extensive damage to the fishing, cattle ranching, and logging industries on Kodiak and the nearby islands. These industries constitute the main economic base for the region. The city of Kodiak also receives substantial revenue from the operation and maintenance of the Kodiak Naval Station that is about 6 miles south of the city.

The effects of the earthquake on the highway routes and on the various industries throughout the Kodiak Island region are described in the following section. The nature and cause of the extensive damage to public, private, commercial, and military property at population centers in the Kodiak region is discussed in a separate volume of this series of reports on earthquake effects on Alaskan communities. The estimated dollar value of damage by the earthquake is shown in table 1.

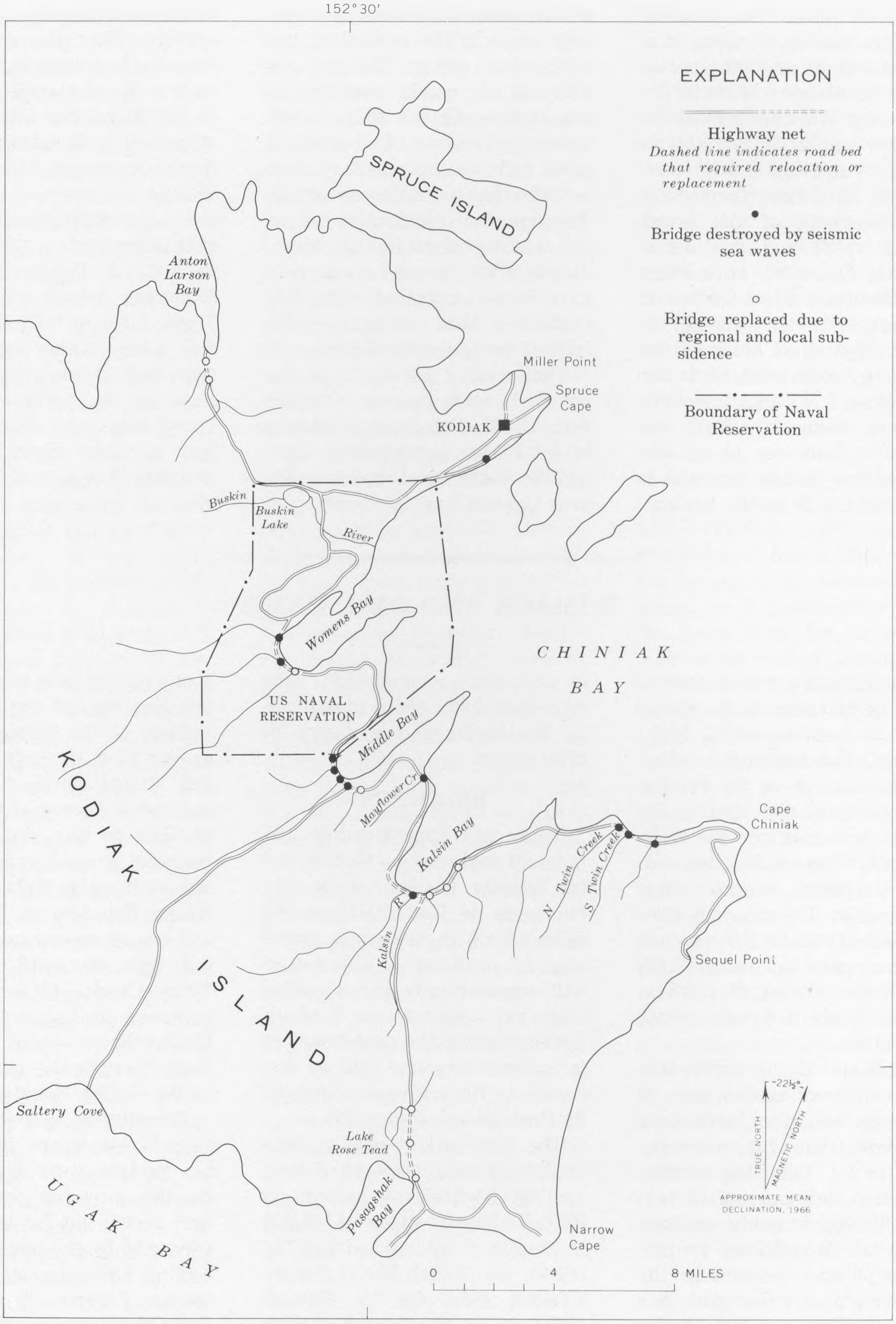
HIGHWAYS

There are approximately 125 miles of highway on Kodiak and the nearby islands; about 115 miles are on Kodiak Island—85 miles of which are rural routes (fig. 22, next page). This report will consider only the 85 miles of rural highway on Kodiak Island, because the remainder are in communities and will be discussed in the companion chapter in Professional Paper 542.

The earthquake caused approximately $5,036,000 worth of damage to the highway system on Kodiak Island—about $446,000 in the city of Kodiak and $1,677,000 in the Kodiak Naval Station (Tudor, 1964, fig. 3). Chiniak highway on the Naval Station was damaged from the station complex to Middle Bay, the southern boundary of the station.

Most of the damage occurred on the 47-mile route to Chiniak and Sequel Point. The seismic sea waves destroyed two bridges at Womens Bay, four in Middle Bay, one across Mayflower Creek, one across the Kalsin River at Kalsin Bay, two on Twin Creek, and one at an unnamed creek at mile 33.7, about 0.8 mile east of Twin Creek. (Mile posts are reckoned north and south of the Buskin River—mile 0.0—which flows through the main complex of the Kodiak Naval Station.)

Eyewitness accounts of the seismic sea waves indicate that the bridges were not destroyed by the incoming water of the first wave, but by the outgoing wave and by the more violent incoming and outgoing subsequent waves. Figures 23 and 24 (p. D41) show seismic sea-wave damage to two bridges.



22. — Earthquake damage to major highway routes on Kodiak Island.

23.—Bridge at Womens Bay destroyed by seismic sea waves. Deck of bridge collapsed owing to destruction of piles. Compare with fig. 24. Photograph by U.S. Navy, March 30, 1964.

24.—Deck of highway bridge at Womens Bay washed away by seismic sea waves. Photograph by U.S. Navy, March 30, 1964.

25. — Section of roadway along Chiniak highway at Womens Bay destroyed by seismic sea waves. Photograph by U.S. Navy, March 30, 1964.

In addition to those that were destroyed, five bridges on the Chiniak highway had to be replaced either because they were underwater during high tide or because their approaches needed realinement. The bridges that required replacement (indicated by open circles on fig. 22) are at Womens Bay, Middle Bay, and Kalsin Bay.

The seismic sea waves destroyed at least 13 miles of roadway on the highway to Chiniak. About 3 miles of road was destroyed at Womens Bay (figs. 22 and 25), 3 miles at Middle Bay (pl. 3), 1 mile at Mayflower Creek, and 4 miles at Kalsin Bay. The roads in these areas were not only destroyed but had to be realined because regional and local subsidence was so great that the pre-earthquake alinement left the roadway under water during high tides.

The Anton Larson highway spur, 9 miles long, starts near Buskin Lake on the Naval Reservation and runs west and then north to Anton Larson Bay. Damage occurred near the terminus of the road at the bay. One mile of roadway was destroyed and required replacing. In addition, two bridges near the bay required replacing.

The Saltery Cove spur road originates at the Chiniak highway at Middle Bay. It heads generally southeastward for 14 miles to Saltery Cove on Ugak Bay. Damage on this spur occurred near its point of origin at Middle Bay and at the divide between the Saltery Cove and Middle Bay drainage basins. Two miles of roadway were destroyed and one bridge had to be replaced.

The Narrow Cape spur road is 15 miles long; it originates at Kalsin Bay and heads south, where it skirts the east edge of Lake Rose Tead, then runs on to Pasagshak Bay. At the head of Pasagshak Bay, the road forks. One spur continues south about 2 miles to Pasagshak Point; the other spur heads east for about 5 miles to Narrow Cape.

Two miles of roadway of the Narrow Cape spur was damaged by the earthquake and attendant subsidence. At Kalsin Bay 1 mile of roadway had to be replaced. Another mile of roadway required replacement at Lake Rose Tead (fig. 8). In addition to 2 miles of roadway that was destroyed, three bridges had to be replaced on the Narrow Cape spur road. Two bridges at Lake Rose Tead and one on a small creek that flows into the head of Pasagshak Bay required replacement.

Along the 85 miles of rural highway on Kodiak Island, 18 miles of roadway, 22 bridges, and 1 culvert were either destroyed by seismic sea waves or had to be replaced because of regional and local subsidence. No bridges were destroyed by seismic shock even though some were on foundations of unconsolidated deposits.

FISHING INDUSTRY

The salmon, king crab, halibut, dungeness crab, shrimp, and clam fishing industry, upon which the economy of the area is almost en-

26. — Chaotic condition of the commercial section of the city of Kodiak following inundation by seismic sea waves. The small-boat harbor, which was in the left background, contained an estimated 160 crab and salmon fishing boats when the waves struck. Photograph by U.S. Navy, March 30, 1964.

tirely dependent, suffered devastating losses of processing facilities, vessels, and gear. Three canneries at Kodiak and one at Uzinki were destroyed by seismic sea waves, and one other cannery and a cold-storage plant at Kodiak were severely damaged. The Kadiak Fisheries cannery at Shearwater Bay was damaged by seismic shock during the earthquake, after which it was virtually destroyed by the waves. Estimated value of the structures and the finished products they contained is $2,610,000.

The total number of lost or damaged fishing boats is not known. In the vicinity of Kodiak alone, 13 vessels were lost and 19 others were swamped or run aground (fig. 26). Vessels underway in deep water were not damaged by the waves. One boat, a 38-foot seiner, went down with its crew of six when it either struck a wave-propelled log or was grounded between waves in shallow water near Spruce Cape, 8 miles northeast of Kodiak. Two other lives were lost on two fishing boats that sank in the Kodiak small-boat harbor. Replacement cost of vessels that were sunk, grounded, or otherwise damaged throughout the area has been estimated at $2,466,500.

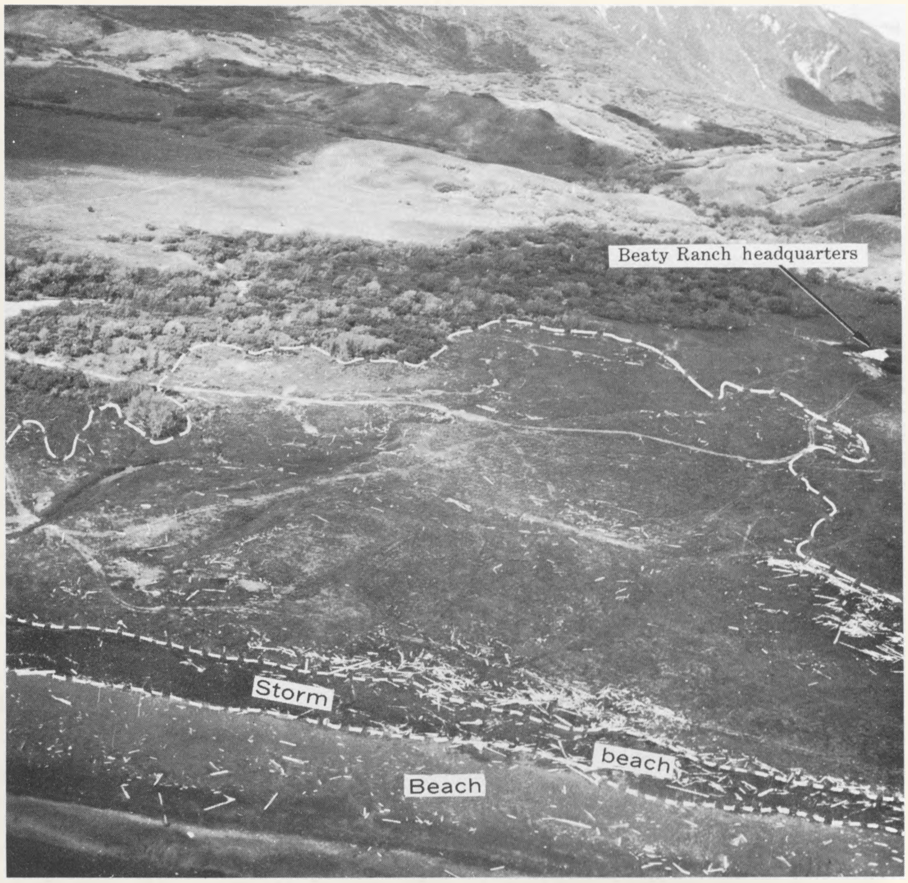
As a result of regional tectonic subsidence, three canneries and their facilities were made unusable by inundation, and four others sustained costly damage. The lost and damaged cannery facilities were valued at $1.3 million (Alaska Dept. Fish and Game, 1965, p. 21).

Studies of salmon habitat by the Alaska Department of Fish and Game (1965, p. 3) indicate that, because of subsidence, tides have made many previous intertidal salmon spawning areas nearly useless and have engulfed former fresh-water stream rearing areas. As shown by table 3, tidal inundation of streams extends as much as 4,500 feet farther inland than before the earthquake. According to the Department of Fish and Game, at least two important salmon fishing areas did not produce in 1964, even though it was a bumper salmon year elsewhere. Studies have been initiated to determine whether the poor catch was due to normal seasonal variations in salmon runs, or was in some way related to the earthquake.

Significant changes in currents and the time of tide changes have been reported by fishermen on the Shelikof Strait side of the islands since the earthquake. These changes are probably related to changes in water depth resulting from the tectonic deformation. The difference in tides and currents has required modification of fishing techniques and could have a detrimental long-term effect on the migration pattern of the salmon.

In Sitkalidak and Raspberry Straits (fig. 2) where subsidence amounted to about 1 and 3½ feet, respectively, local residents report not only higher high tides since the earthquake but also lower low tides. In these areas, clamming is reportedly better on minus tides than it was prior to the earthquake. These reports have not been confirmed or explained by the fisheries authorities.

Tectonic uplift and subsidence has changed the appearance of landmarks used by vessel operators along the treacherous rocky coast and has altered water depths. These changes have reportedly caused several vessels to be damaged or sunk since the earthquake by collision with submerged objects.



27. — Part of Beaty Ranch showing extent of wave inundation, as indicated by light-colored debris. Ranch buildings are a quarter of a mile from the shoreline.

CATTLE RANCHES

The earthquake was a near-disaster to several of the small cattle ranchers in the area who were struggling to develop sound and profitable operations.

Inundation by seismic sea waves caused extensive property damage at all the isolated cattle ranches along the southeast coast of Kodiak Island and on Sitkalidak Island. According to a U.S. Department of Agriculture report (Oliver, 1964), 175 cattle were drowned, 3 ranch houses and 20–25 outbuildings with their contents were swept away, and 25 miles of corral and range fencing was lost. In addition, several hundred acres of land used for hay production was littered with wave-borne debris (fig. 27).

Numerous beaches and deltas along the southeast coast of Kodiak and Sitkalidak Islands are now inundated by tides, and salt water has ruined several hundred acres of the best beach rye lands which were used for winter grazing.

LOGGING INDUSTRY

Logging in the area is carried on by small operators and is almost entirely for local consumption. One of the sawmills near Afognak village on southern Afognak Island was abandoned because seismic sea waves washed away most of the docking facilities and caused extensive damage to the mill. A second small mill near Uzinki sustained an unknown amount of wave damage to the dock.

CASUALTIES

In the Kodiak Island area the earthquake caused the loss of 18 lives through drowning, but the extent of wave damage and attendant loss of life would undoubtedly have been much greater had not the largest waves coincided with low, rather than high, stages of tide. Furthermore, the disaster would have been worse had the earthquake occurred during the summer when the population of the islands is substantially increased by large numbers of fishermen and cannery workers, many of whom normally live and fish along shores.

The toll of 18 dead, although relatively light, was to a considerable extent needless and was caused largely by public ignorance concerning the nature and destructive force of seismic sea waves. Especially serious is the prevailing mistaken belief that the first wave is necessarily the highest. As a consequence some individuals made the disastrous error of returning to low-lying coastal areas after the initial wave, and 10 of them were trapped and drowned by subsequent waves. Furthermore, the first wave did not reach any of the boat harbors until about an hour after the earthquake, and a local warning broadcast was issued half an hour earlier advising of the impending wave, yet few manned vessels were piloted to the safety of nearby deep water. All the vessels that were sunk, including three in which eight lives were lost, went down in shallow water.

Clearly, a better method of disseminating information is required as the key to minimizing loss of life from future seismic sea waves in coastal areas of the Kodiak group of islands, as well as elsewhere along coastal segments of the Gulf of Alaska that may be threatened by similar waves in the future. Evacuation procedures for the populace and for boats should be carefully worked out in advance, and it should be made clear that the danger from such waves may persist for several hours after the initial wave strikes. The Seismic Sea Wave Warning System operated by the U.S. Coast and Geodetic Survey can provide advance warning where destructive waves are generated by distant earthquakes in the Pacific Ocean basin. The present system, however, cannot assure warnings for locations closer to the wave source than about 1,000 miles because at least an hour may be required to locate the earthquake epicenter, determine its magnitude, and broadcast a warning (Spaeth and Berkman, 1965, p. 4–7). Consequently, in earthquake-prone areas—such as the Gulf of Alaska and Alaska Peninsula—where any strongly felt earthquake of long duration could be accompanied by destructive seismic sea waves, immediate evacuation of low-lying coastal areas is the only prudent course of action.

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