The Alaska Earthquake
March 27, 1964

Regional Effects

Ground Breakage in the Cook Inlet Area

GEOLOGICAL SURVEY PROFESSIONAL PAPER 543-F

THE ALASKA EARTHQUAKE, MARCH 27, 1964:
REGIONAL EFFECTS

Ground Breakage and Associated Effects in the Cook Inlet Area, Alaska, Resulting from the March 27, 1964, Earthquake

By HELEN L. FOSTER and THOR N. V. KARLSTROM

A description of the ground cracks and deposits from ground-water eruptions and crustal changes, particularly in the Kenai Lowland

GEOLOGICAL SURVEY PROFESSIONAL PAPER 543-F

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1967

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

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 history of the field investigations and reconstruction effort; the effects of the earthquake on communities; the effects on hydrology; and the effects on transportation, communications, and utilities.

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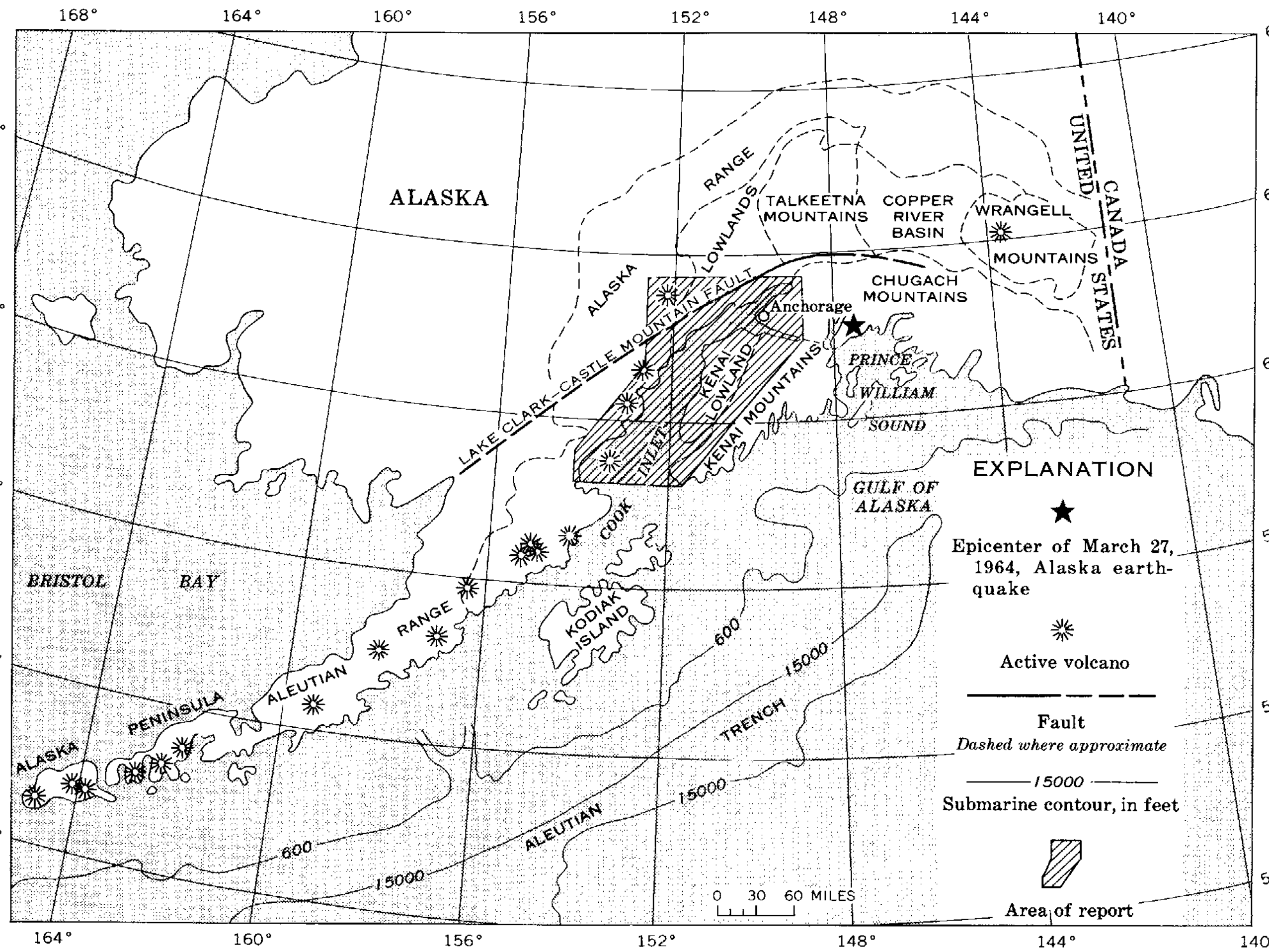


1.—Index map showing location of Cook Inlet area.

GROUND BREAKAGE AND ASSOCIATED EFFECTS IN THE COOK INLET AREA, ALASKA, RESULTING FROM THE MARCH 27, 1964, EARTHQUAKE

By Helen L. Foster and Thor N. V. Karlstrom

ABSTRACT

The great 1964 Alaska earthquake caused considerable ground breakage in the Cook Inlet area of south-central Alaska. The breakage occurred largely in thick deposits of unconsolidated sediments. The most important types of ground breakage were (1) fracturing or cracking and the extrusion of sand and gravel with ground water along fractures in various types of landforms, and (2) slumping and lateral extension of unconfined faces, particularly along delta fronts.

The principal concentration of ground breakage within the area covered by this report was in a northeast-trending zone about 60 miles long and 6 miles wide in the northern part of the Kenai Lowland. The zone cut across diverse topography and stratigraphy. Cracks were as much as 30 feet across and 25 feet deep. Sand, gravel, and pieces of coal and lignite were extruded along many fissures. It is suggested that the disruption in this zone may be due to movement along a fault in the underlying Tertiary rocks.

The outwash deltas of Tustumena and Skilak Lakes in the Kenai Lowland, of Eklutna Lake and Lake George in the Chugach Mountains, of Bradley Lake in the Kenai Mountains, and at the outlet of upper Beluga Lake at the base of the Alaska Range showed much slumping, as did the delta of the Susitna River. Parts of the flood plains of the Skilak River, Fox River, and Eagle River were extensively cracked.

A few avalanches and slumps occurred along the coast of Cook Inlet in scattered localities. Some tidal flats were cracked. However, in view of the many thick sections of unconsolidated sediments and the abundance of steep slopes, the cracking was perhaps less than might have been expected.

Observations along the coasts indicated changes in sea level which, although caused partly by compaction of unconsolidated sediments, may largely be attributed to crustal deformation accompanying the earthquake. Most of the Cook Inlet area was downwarped, although the northwest side of Cook Inlet may have been slightly unwarped. Maximum change in the Cook Inlet area was probably less than 6 feet. Little or no regional tilting was detected in the lake basins of Tustumena and Skilak Lakes.

INTRODUCTION

The great 1964 Alaska earthquake caused considerable ground breakage in the Cook Inlet area of south-central Alaska. Cook Inlet is the major marine reentrant of the Gulf of Alaska; it extends inland between the Kenai and Chugach Mountains and the Alaska Range (fig. 1). It is bordered by extensive lowlands on the east, northwest, and north. The epicenter of the earthquake (fig. 1) was to the east and northeast of Cook Inlet and separated from it by part of the Chugach Mountains and the Kenai Mountains. The greatest ground breakage outside of the Anchorage and Portage areas was in the Kenai Lowland, about 115 air miles west of the epicenter.

SCOPE OF REPORT AND SOURCE OF DATA

This report is concerned primarily with the ground breakage and related phenomena in the lowland areas of Cook Inlet—particularly the more populated and accessible Kenai Lowland. Descriptions of the damage in the Anchorage and Portage areas are available in previously published reports (Grantz and others, 1964; Hansen, 1965). Some observations of ground breakage in the northwestern part of the Chugach Mountains are included here.

Most of the information on earthquake effects presented in this report is based on field observations made by Karlstrom between May 10 and July 15, 1964, and by Foster from May 10 to the end of May. Ground observations were made in the parts of the Kenai Lowland accessible by road and along beaches. Karlstrom made boat traverses along the shores of Tustumena Lake, Skilak Lake, and Lake George. The ground observations were supplemented by reconnaissance from fixed-wing planes and by the study of aerial photographs made after the earthquake by the U.S. Army, the U.S. Coast and Geodetic Survey, and the U.S. Geological Survey. Localities near the head of Cook Inlet were checked primarily by road traverses. On the west side of Cook Inlet only one ground traverse was made near Tyonek. Other observations there were from fixed-wing planes.

Ground breakage is difficult to detect from the air, especially in wooded areas. Consequently, some localities with ground breakage undoubtedly have been overlooked, particularly west of Cook Inlet.

ACKNOWLEDGMENTS

Special acknowledgment is due Mr. David M. Spencer, Mr. Robert Ward, Mr. Avery Thayer, and Mr. Will Troyer of the U.S. Fish and Wildlife Service in Kenai, Alaska, who provided essential logistic support and supplied personal observations on changes in areas not visited by U.S. Geological Survey personnel. Thanks are also due Mr. Joe Magargl and Mr. George Calvin of Kasilof for their assistance during the boat traverse around the shores of Tustumena Lake, and to numerous members of the U.S. Geological Survey stationed in Anchorge and Palmer, who supplied critical information based on personal observations of the earthquake effects. George Plafker, David McCulloch, Roger Waller, and Reuben Kachadoorian, all of the U.S. Geological Survey, made their unpublished data available and gave assistance during the preparation of the manuscript.

REGIONAL GEOLOGIC SETTING

The Cook Inlet area is near the juncture of the western Pacific island arc system and the orogenic belts of the western part of North America. Just northeast of Cook Inlet the trends of the mountain ranges abruptly change from northwest to southwest and extend in broad subparallel arcs (fig. 1). Near the apices of these arcs the granite-cored Talkeetna Mountains separate the Chugach Mountains from the Alaska Range and form the divide between the head of Cook Inlet and the intermontane Copper River basin to the east. Several arcuate fault zones have been mapped in central and southern Alaska; these in part follow and in part transect the mountain-range structures. One of the faults, the Lake Clark-Castle Mountains fault, cuts the Alaska Range just north of Cook Inlet (Dutro, 1957), there having a northeasterly trend. A belt of high seismicity, coincident with the apical zone of the arcuate mountain structures, extends from Prince William Sound beyond Fairbanks north of the Alaska Range and includes the epicenter of the main shock of the 1964 earthquake.

GEOLOGIC HISTORY AND LOCAL GEOLOGIC SETTING

The geologic structure of the Cook Inlet area is highly complex. The rocks of the region record a history of repeated geosynclinal sedimentation, deformation, and intrusion beginning in Paleozoic time and extending through the Tertiary. Near the end of the Cretaceous, there was downwarping and subsidence of the Cook Inlet trough and, in the Tertiary, rocks that are now locally more than 15,000 feet thick were deposited. By the end of Tertiary time, the major topographic elements of the area were established. The subsequent geologic history has consisted largely of erosion and modification of the mountainous areas during repeated glacial-interglacial cycles and of partial filling of lowland areas and valleys with glacial drift and associated deposits (Karlstrom, 1964). Offsets of surficial deposits, along preexisting faults in bedrock, indicate continuing sporadic tectonism in the region through the Quaternary and to the present. In the Cook Inlet area, it was primarily the thick unconsolidated deposits of Quaternary age that locally failed by fissuring, slumping, and subsidence during the 1964 Alaska earthquake.

The Kenai Lowland part of the Cook Inlet area had the most ground breakage and therefore was examined in more detail; it is a broad low shelf 20 to 50 miles wide and 106 miles long. Most of the lowland is less than 400 feet above sea level, surfaces are flat to undulating, and local relief varies from a few feet to more than 200 feet. The Caribou Hills, a broad glaciated upland north of Homer, rise abruptly 1,000 to 2,000 feet above the general lowland surface. Remnants of this same upland surface occur as piedmont slopes adjacent to the Kenai Mountains between Skilak and Tustumena Lakes (Karlstrom, 1964, p. 12).

Drainage in the Kenai Lowland is poorly integrated, and numerous lakes, marshes, and muskeg areas make up more than a third of the total surface. Two major lakes, Tustumena and Skilak, occupy glacially scoured and moraine-dammed troughs and are drained respectively by the Kasilof and Kenai Rivers, which empty into Cook Inlet. Along the shoreline of Kenai Lowland are wave-cut cliffs that range in height from 800 feet in the Kachemak Bay area to less than 50 feet near the mouths of major drainage lines (Karlstrom, 1964, p. 12). Tertiary bedrock is exposed locally beneath glacial deposits in the cliffs, especially along the northwest shore of Kachemak Bay and along the Cook Inlet shoreline south of Kasilof.

A complex of Quaternary moraines and associated drift and outwash deposits of several ages covers the greater part of the Kenai Lowland (pl. 1). Locally, the deposits are more than 400 feet thick. The moraines have been modified to different degrees by erosion, by an irregular cover of loess, and by mantling with proglacial lake sediments. Other proglacial lake sediments underlie terraced and channeled surfaces between major morainal belts on coastal lowlands and in mountain valleys. The lacustrine sediments range in thickness from a few inches to at least 100 feet. Many of the streams have built large deltas; other smaller streams have deposited sediments to form alluvial fans and alluvial fan deltas. Thick and extensive elevated tidal-flat and beach deposits occur in places along the coasts (pl. 1), particularly near Kenai and Kasilof.

GROUND BREAKAGE

TYPES OF BREAKAGE

Ground failures in the Cook Inlet area include most of the types that occurred elsewhere during the 1964 earthquake and that are described in detail from adjoining regions in other chapters of the U.S. Geological Survey 1964 Alaska earthquake series. Types of failure include (1) rock falls and avalanches resulting from dislodgement of bedrock, colluvium, and snow on steep rocky slopes; (2) landslides on moderate to gentle slopes with downslope migration of surface materials giving rise to tensional cracking and folding (pressure ridges); (3) slumping and lateral extension of surficial deposits toward steep unconfined faces (river banks, lake shores, delta fronts, and sea bluffs) that cause tensional and rotational fracture patterns; (4) transverse and longitudinal tensional cracking of surface gravel in valley flood plains and valley trains; and (5) concentric and transverse cracking of frozen surface layers of muskeg and elevated tidal flats resulting largely from differential compaction and downslope movements of underlying water-saturated fine-grained deposits.

There was also extensive ground breakage and extrusion of sand and gravel along fractures which cut across the topography and so seem, at least in part, unrelated to it.

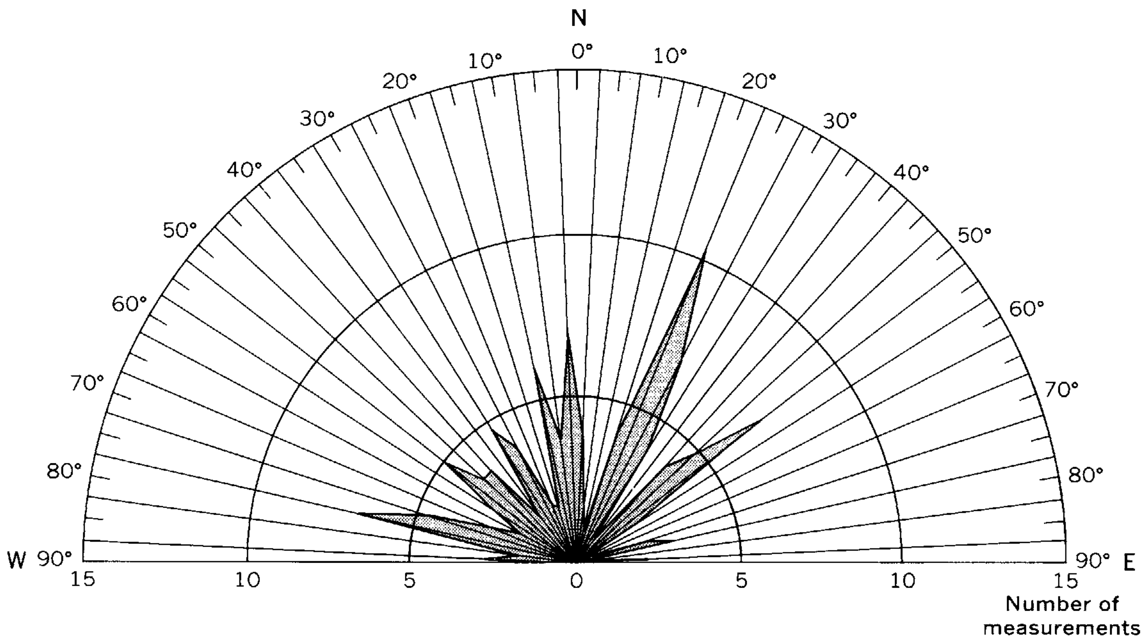
KENAI LOWLAND

NORTHEAST-TRENDING ZONE

Most localities of major ground breakage in the Kenai Lowland are roughly alined northeast-southwest in a zone 60 miles long and 6 miles wide which extends from Kasilof on the east shore of Cook Inlet to Chickaloon Bay on the south shore of Turnagain Arm (pls. 1, 2).

The zone of ground breakage crosses an area of diverse landforms underlain by Quaternary surficial deposits of differing origin and age (Karlstrom, 1964). Included are elevated tidal flats of Recent age, end moraines of Knik (preclassical Wisconsin) age near Kasilof and Chickaloon Bay, and an interlobate moraine of Eklutna (Illinoian?) age in the central part of the zone (pl. 1). The moraines are mantled by a variable thickness of proglacial lake silt, sand, and gravel of Naptowne (classical Wisconsin) age. The proglacial lake deposits are thinner and coarser on the flanks of the moraine and become thicker and finer grained in the intermoraine areas of the lowland. Interbedded glacial, glaciolacustrine, and glaciofluvial deposits, generally hundreds of feet thick, underlie the surface drift units and overlie bedrock of Tertiary age.

The intensity of ground cracking and ground-water eruption varies within the zone. The areas of broken ground are separated by large areas in which surface cracks are inconspicuous or absent. No consistent relationship is apparent between ground cracking and either the local topography or the underlying stratigraphy. Within the zone the ground-cracked localities occur (1) on terraced morainal slopes and crests underlain by thick sections of compact till mantled by thin sand and gravel deposits, (2) on channeled plains bordering moraines and underlain



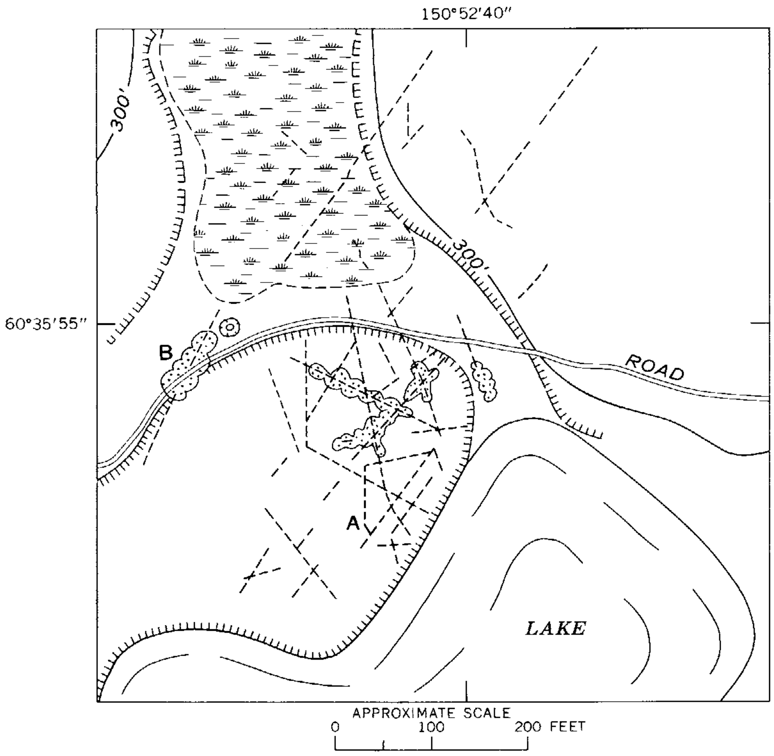
2.—Azimuth-frequency diagram showing dominant trend of ground cracks in the Kenai Lowland resulting from the 1964 Alaska earthquake. Includes measurements of 139 cracks in the central part of the northeast-trending zone of ground breakage in the Kenai Lowland.

by thick sections of predominantly fine- to medium-grained sand, (3) in intermoraine depressions underlain by sand and silt, and (4) on elevated tidal flats underlain by estuarine silt and sand. The cracks cut undeflected across small hills and depressions in morainal topography.

The broken ground is characterized by a mosaic of ground cracks that trend in many directions. Locally the cracks show topographic control by slumping on slopes, but in many places no such control is evident. In all localities observed on the ground, the northeast-trending cracks were the most persistent and in many places could be traced diagonally across slopes and ridges without apparent deflections in trend. Measurements of the most conspicuous crack directions in the southern half of the zone suggest preferred fracture trends of N. 50°–55° E. (parallel to the zone itself), N. 20°–25° E., N. 0°–5° W., N. 10°–15° W., N. 30°–35° W., N. 50°–55° W., and N. 75°–80° W. (fig. 2). Examples of broken ground patterns within the zone are shown in figures 3 and 4. In forested areas, cracking of the ground split numerous trees (fig. 5).

Most of the cracks within the zone ranged in width from knife edge to a foot (fig. 6). They were generally very sharp, vertical, and straight with abrupt angular changes in direction and sharp angular intersections with other cracks (fig. 7). Major cracks had many smaller branch cracks that intersected the main cracks at sharp acute angles or sometimes at right angles. In places, major cracks abruptly changed direction at crack intersections. Vertical and horizontal displacements occurred along some cracks; most were less than a foot but a few were as much as 2 feet (fig. 7). Most displacements appeared to be primarily the result of adjustments in the surficial materials by slumping and differential compaction, or of removal of underlying materials by ground-water eruption.

Features associated with ground-water eruptions were common throughout the zone. These features included ridges and mounds of sand alined along cracks (fig. 8); sand sheets as much as 2 feet thick, locally covering acres of ground associated with the cracks (fig. 9); vents from which erupted sand either spread in all directions or was extruded primarily in one direction—and made a sand apron extending from the vent; collapse pits, as much as 30 feet in diameter; and fissures as much as 20 feet wide and 25 feet or more deep (figs. 9, 10), resulting from the removal of material by copious outpouring of ground water. In a few places great outpourings of sand were followed by small extrusions of watery silt which formed low (2 to 3 inches high) silt ridges and mounds and irregular microrelief features on the surface of the sand (figs. 11, 12). These silt extrusions must have occurred in the very last stages of the ground-water eruptions and after the main shaking



EXPLANATION

Terraced and channeled sand plain

Muskeg

Ground-water eruptive deposits of sand and silt with pebbles of clastic coal and lignite

Trends of main ground crack sets

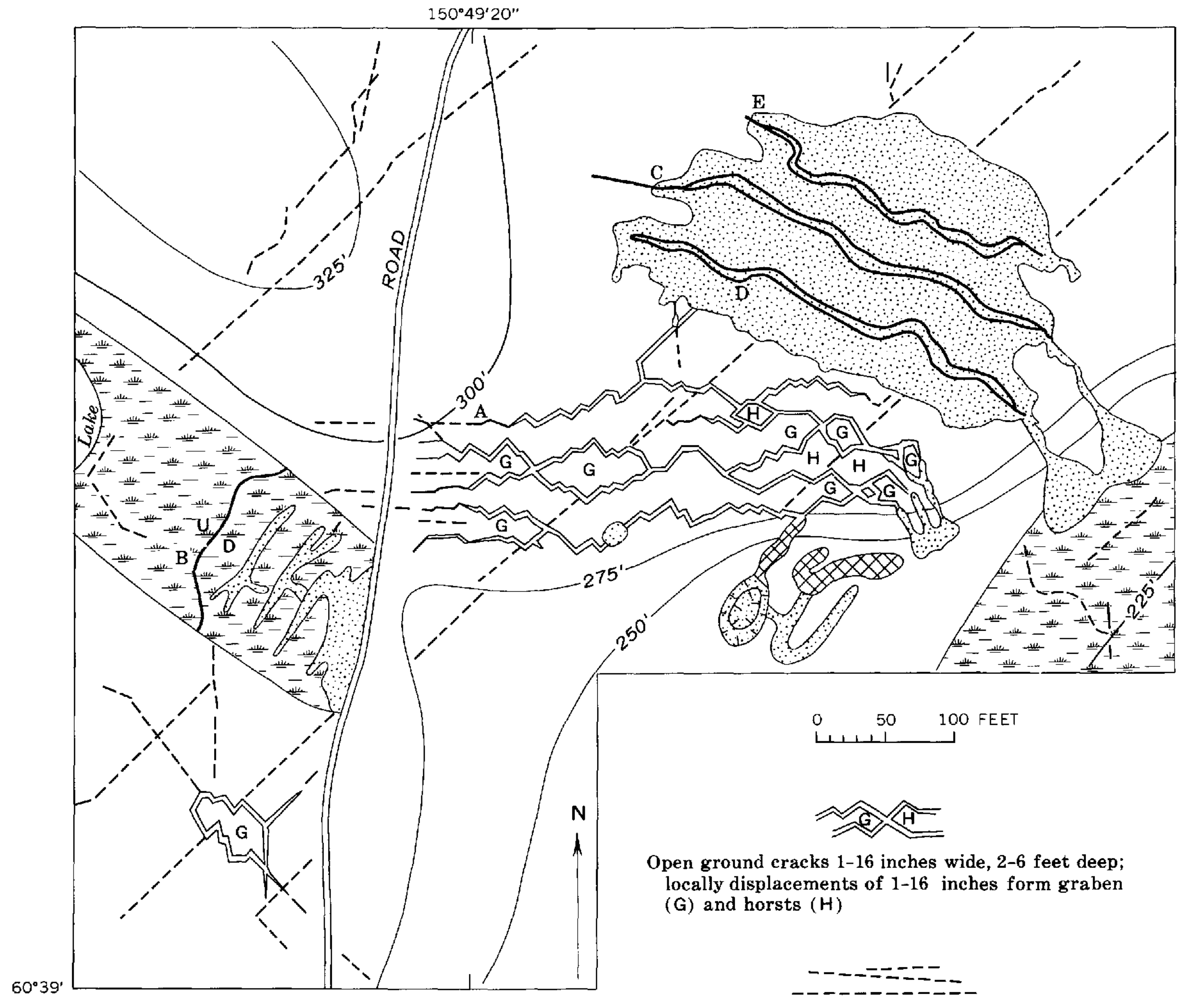
Margin of well-drained ground

Craterlet which erupted ground water and sand

B

Letter indicates location of photograph

3.—Ground cracks (loc. 1, pl. 1), Kenai Lowland.



EXPLANATION

Forested, terraced, and channeled moraines underlain by variable thickness of stratified silt, sand, and gravel over till

Muskeg underlain by 6-20 feet of peat and organic silt

Ground-water eruptive deposits of sand and silt with pebbles of clastic coal and lignite

D
U
Fault
U, *upthrown side;* D, *downthrown side*

Open ground cracks 1-16 inches wide, 2-6 feet deep; locally displacements of 1-16 inches form graben (G) and horsts (H)

Thin ground cracks cutting forest turf and peat deposits

Pressure ridges of forested turf and peat formed by landsliding

Collapse pits and fissures associated with erupted sand deposits

Open ground cracks with associated eruption of sand and ground water

250'
Topographic contour

B
Letter indicates location of photograph

4.—Ground cracks (loc. 2, pl. 1), Kenai Lowland.

5.—Tree split by ground cracking (loc. 2, pl. 1), Kenai Lowland. The ground crack which trends into the split in the tree (loc. A, fig. 4) cuts across the top of a small knoll in moraine.

6.—Typical large ground crack (loc. 1, pl. 1), Kenai Lowland. Crack was 4 inches to 1½ feet wide; it cut a sand plain. Sand was not extruded along this crack (loc. A, fig. 3).

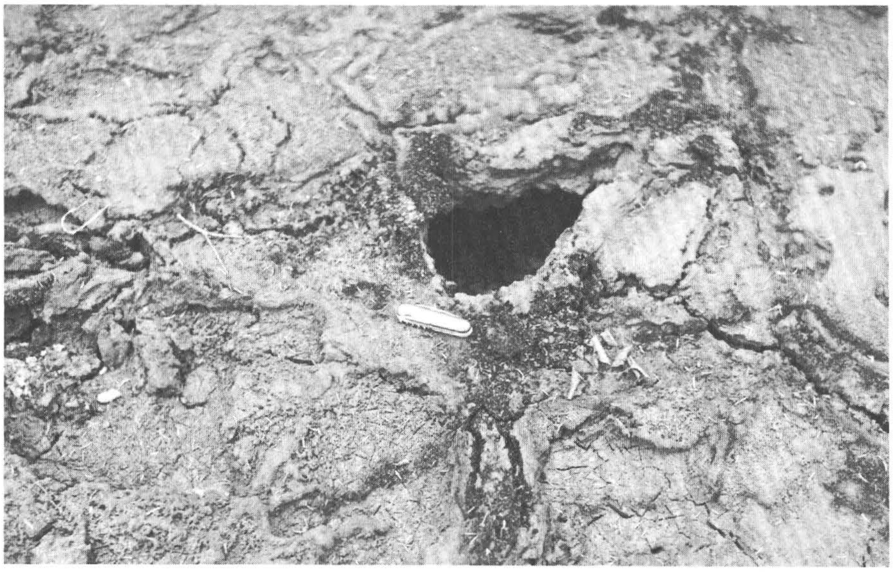
7.—Vertical displacement (loc. 2, pl. 1). A scarp more than 200 feet long and 2 to 3 feet high was produced in a thick section of frozen peat and organic silt (loc. B, fig. 4). Crack at the base of the scarp was 6 inches to 1 foot wide. Another crack intersects scarp at right angles; this displacement probably resulted from differential compaction and downslope extension of silty deposits in a muskeg bordering a small lake.

8.—Sand ridges deposited along a ground crack (loc. 2. pl. 1) by eruption of ground water during the earthquake. A sand ridge on the right side of the picture intersects the main ridge at nearly right angles. Person has right leg in deep crack (loc. C, fig. 4).

9.—Large fissure at locality 2 (pl. 1). This fissure was 25 or more feet deep and as wide as 20 feet in places. A thickness of 2 or more feet of sand which was extruded from the fissure can be seen around the tree. Photograph was taken at locality D (fig. 4).

10.—Large ground crack with vertical displacement (loc. 2, pl. 1). Thick deposits of sand border the left side of the crack. Photograph was taken near E (fig. 4).

11.—Microrelief features formed in extruded silt (loc. 2, pl. 1). Area pictured is about 48 inches wide) 3-inch-long jackknife is slightly above center of picture). The delicate silt mounds and ridges were formed in the last stages of ground-water eruption on the surface of previous sand extrusions.



12.—Small vent which extruded watery silt (loc. 2, pl. 1). Jackknife is 3 inches long. Near locality D (fig. 4), watery silt from small vents such as this was extruded in the last stages of eruption and spread out over the top of previously erupted sand.

had ceased, otherwise the small delicate microrelief features would not have been so well preserved. Although the greatest outpourings of sand were in relatively flat areas or depressions, some sand was extruded from cracks extending up the sides of small morainal hills.

The deposits laid down by ground-water eruption within the zone are predominantly fine- to medium-grained sand. In most localities the sand contains scattered pebbles and cobbles of detrital coal and lignite as much as 6 inches long (fig. 13). The largest amounts of sand and much of the coal were commonly concentrated at the intersection of two or more major cracks or at the intersection of a wide and a narrow one. Many, if not all, of the coal fragments carried to the surface during the earthquate by ground water could have been derived from near-surface deposits that contain detrital coal originally derived from underlying Tertiary coal beds. However, derivation of some of the coal from the Tertiary coal beds at depths of several hundred feet, though unlikely, is not excluded as a possibility by present evidence.

The quantity of sand deposited locally indicates copious ground-water discharge during the earthquake and suggests the tapping of large reservoirs. Sand and silt deposited on tree branches indicate that water was ejected out of some cracks to a height of at least 20 feet. Ground-water supplies in the general area of the central part of the zone are obtained from gravel aquifers under hydrostatic head. The aquifers are 100 to 200 feet below the surface and beneath the surface till units. It is probable that ground cracking penetrated through the surface till units at many places and tapped these deep ground-water reservoirs.

In several, but not all, places where the northeast-trending zone crossed roads, cracks were found. The zone crossed the paved Sterling Highway east of Soldatna, and several cracks in the pavement were noted together with minor slumping in fill. Large cracks and large outpourings of sand occurred where the zone crossed the oil-well access road and several of the side roads connecting with it (pl. 1).

Although this zone of ground breakage passed along the southern margin of the Swanson River oil field, no ground breakage was noted or reported from the field itself. Apparently the oil wells were not damaged or significantly disturbed by the earthquake.

In the spring-fed Finger Lakes (about one-half mile southwest of loc. 2, pl. 1), there was a gradual lowering of water during the summer following the earthquake, an occurrence which had not been observed in previous summers. It was suggested that the lowering might be due to fissures in the lake bottoms or to a restriction of the flow of spring water as a result of the compaction of sediments (Alaska Dept. Fish and Game, 1965, p. 29). The lakes are in glacial moraine and the earthquake caused slumping on the sides of the moraines along the margins of the lakes.

At several places within the zone, ancient collapse pits and linear troughs covered by mature forest vegetation record previous episodes of ground cracking and ground-water eruption.

COASTS

Much of the western coast of the Kenai Peninsula was examined, and few changes attributable to the earthquake were found. Although steep high bluffs of unconsolidated glacial deposits line much of the coast, there were no large landslides and very little slumping.

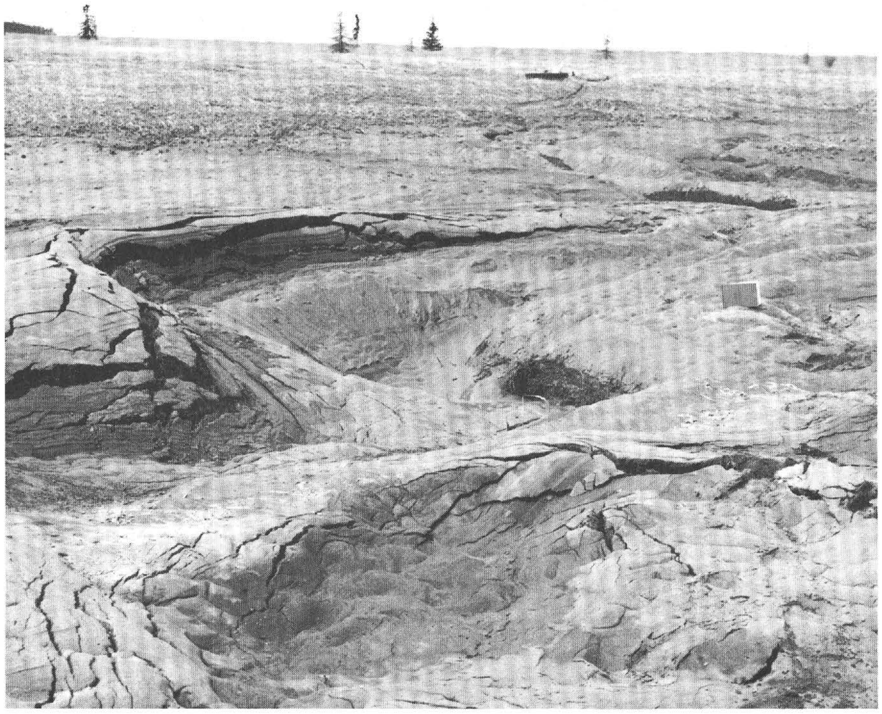
At Kasilof, which is approximately in line with the northeast-trending zone of ground breakage previously described (p. F3), cracks as much as 1 foot wide were formed. The cracks were traceable for several hundred feet and cut sand dunes and beach deposits at the coast (fig. 14). Crack walls were generally sharp—in fact, exceptionally sharp for occurrence in loose sand. Some had small vertical displacements as much as 10 inches high. They had the usual pattern of many branches and cracks intersecting from several directions. Collapse occurred along some cracks where large amounts of sand had been extruded (fig. 15). Pressure ridges a few inches high and 2 to 3 inches across were noted in silt on tidal flats; some radiated from a central point in several directions for distances of 25 feet or more.

At Chickaloon Bay a complex network of cracks extended seaward from the shore and perpendicular to it onto the tidal flats. Major crack systems also paralleled the shore, but these were observed only from the air. Although the tidal flats at Kasilof and Chickaloon Bay were considerably fractured, other tidal flats in similar geologic and topographic situations had no ground breakage. For instance, no ground cracking was observed on the tidal flats at Kenai, Moose Point, Point Possession, Stariski, or in the Ninilchick area.

On the mainland near Homer, ground fissures occurred in the bluff on which the U.S. Bureau of Land Management station is located. However, as elsewhere on the coast, ground breakage due to the earthquake was slight and less than might have been expected where steep slopes in materials

13.—Detrital coal extruded with sand (loc. 1, pl. 1). Copious amounts of sand were extruded from a fissure cutting a gravel road (loc. B. fig. 3). Pieces of coal and lignite as long as 6 inches (some indicated by arrows) were extruded with the sand.

14.—Ground cracks at Kasilof in elevated beach deposits. Cracks were as much as 1 foot wide. Vertical displacement is evident along crack near man. Considerable clastic coal was brought up from beneath the surface and deposited with the sand.



15.—Collapse pits at Kasilof formed after eruptions of ground water and sand. Pit in foreground is about 3 feet in diameter. Erupted sand covers the ground. A large crack extends from the pits in the middle background.

susceptible to sliding abound (Waller, 1966, p. D6–D7). Damage to Homer Spit, due largely to submarine sliding and flooding, has been described by Waller (1966).

LARGE LAKES

Tustumena Lake and Skilak Lake are the two largest lakes in the Kenai Lowland (pl. 1). Tustumena Lake is 25 miles long and 3 to 6 miles wide; Skilak Lake is 14 miles long and has a maximum width of about 4 miles. Both lakes occupy glacially scoured troughs that have been dammed by moraines.

Ground cracking around these lakes was extensive in the large outwash deltas at the heads of the lakes. Damage elsewhere along the shores of the lakes was minor, although the lakes are surrounded primarily by thick unconsolidated deposits of Quaternary sediments. The several small occurrences of ground cracking which were observed along Tustumena and Skilak Lakes were mostly in unstable slopes of alluvial fan deltas or at the tips of peninsulas or spits projecting into deep water.

TUSTUMENA OUTWASH DELTA

The outwash delta at the head of Tustumena Lake is 4½ miles wide; it partly buries two groups of ice-rounded bedrock hills that divide the outwash plain into two branches with separate delta fronts (pl. 3). During the earthquake, both delta fronts failed by fracturing and slumping into the lake.

Photographs obtained after the earthquake (fig. 16) indicate that a major zone of fissures oriented N. 5°–10° W. formed subparallel to the southern delta front about half a mile from the lake shore. This break defined the inland margin of the part of the delta most disrupted by the earthquake. Much sand was extruded along this fracture zone and flowed out upon the snow-covered surface (fig. 16).

The fracture pattern in the disrupted part of the delta consisted of two sets of diagonal fractures formed on northwest and northeast trends and a less well developed set formed about perpendicular to the main fissured zone. It is believed that this fracture pattern formed during the earthquake when the lakeward unconfined face of the delta extended forward and pulled away from the main mass of the delta. McCulloch has described and explained similar crack patterns in Rocky Creek and Lakeview deltas at Kenai Lake (1966, p. A35).

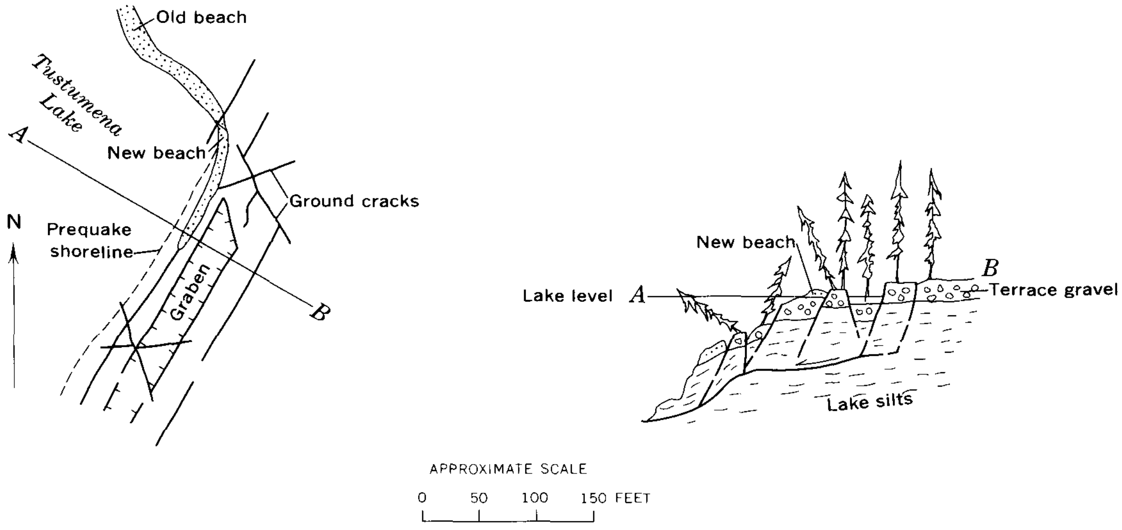
The ground cracks in the outwash delta ranged in width from a fraction of an inch to 4 feet (fig. 17). Most cracks showed no vertical displacement, but a few indicated subsidence of several inches to 1½ feet on the lake side. Little overall evidence of subsidence of the delta front was observed, and it is estimated to have been less than 10 feet.

The southern edge of the outwash delta is bordered by a low forested terrace (pl. 3, fig. 16). Cracks 3 to 4 feet wide and 2 to 3 feet deep spaced at intervals of 10 to 50 feet cut through the forested area in a north-south direction along the lake edge. Many trees were split and offset along cracks, the offset indicating a right-lateral ground displacement of 1 to 3 feet. The walls of the deeper cracks exposed the following terrace stratigraphy from top to bottom: vegetation mat and organic silt about 1 foot thick over stratified pebble-to-boulder gravel containing lenses and beds of sand and silt.

Sand, silt, and some gravel were brought to the surface by forceful ejection of ground water from the cracks. The extruded material spread out to form large sand sheets covering a few acres. Elsewhere sand ridges were deposited

16.—Outwash delta at head of Tustumena Lake a few days after the earthquake. View is south (pl. 3). The ground was snow covered, and water and sand erupted along major cracks (dark-gray areas) partly removing the snow and covering the ground surface with sand. The cracked ice-covered lake surface is to the right. A major fissure system paralleling the delta front is seen to the left of center. Photograph by Avery Thayer, Fish and Wildlife Service, Kenai, Alaska.

17.—Crack between delta front and bedrock at Tustumena Lake (loc. A. pl. 3). A wedge of outwash deposits pulled away from the stable bedrock face during the earthquake shaking.



18.—Diagram showing type of ground disruption on the north shore of Tustumena Lake (loc. 3, pl. 1).

along the margins of the cracks. Locally, boulders as much as 8 inches in long dimension were brought to the surface from the underlying gravel beds by the ejecting ground water.

Such forceful ejection at this single locality may have been caused by conditions which differed slightly from those in the delta to the north. Water moving through the outwash terrace under higher hydrostatic head (probably because the surface gradient of the terrace is steeper than that of the bordering outwash) may have been confined between more firmly frozen sediment layers. The firmer freezing could obtain because of the thicker organic silt layer, continuous vegetation mat, and extensive forest cover. The difference in the pattern of cracking between the terrace and the outwash delta may reflect differences in the underlying bedrock topography. Because of the general configuration of this valley, the bedrock slope under the terrace may be northwestward and that under the outwash delta may be more to the west. Slippage of the lake front sediments over a northwest-sloping bedrock floor would explain the observed displacement.

The northern delta front was fractured in a pattern similar to that of the southern front, but less severely. The diagonal and perpendicular crack sets and the subparallel fissure zone separating the extended block from the inland part of the delta were present, but the patterns were not as strongly developed as in the southern front. A considerable amount of sand was extruded along many of the fractures. The fracturing was apparently caused by lateral spreading of the deltaic sediments toward the lake as a result of the earthquake shaking.

OTHER TUSTUMENA LAKE GROUND CRACKING

Local slumping at the fronts of alluvial-fan deltas occurred at the mouths of Indian Creek, Moose Creek, and Bear Creek (pl. 1). Slumping took place largely by vertical displacement along ground cracks parallel to the lake margin. At Windy Point a block of beach and terrace gravel 50 by 100 feet slumped into the lake largely submerging spruce and birch trees 40 to 60 feet tall. Subparallel fractures 1 to 6 inches wide developed landward of the slump-block scarp. At the western end of Caribou Island the narrow tip of beach gravel cracked but did not slump. Ground cracking occurred over fairly large areas on shoreline terraces on opposite sides of the narrowest part of Tustumena Lake.

Near Tanya Lake (loc. 3, pl. 1), a northeast-trending set of ground cracks spaced 10 to 30 feet apart cut the beach deposits and a low forested gravel terrace. A graben 10 to 30 feet wide, about 100 feet long, and downdropped 4 to 6 feet formed and filled with water (fig. 18). Gravelly terrace deposits underlain by lake silt apparently broke into blocks along northeast fractures and slid lakeward upon a slightly inclined slip plane in the silt (fig. 18). The forward translation and slumping of the lakeward blocks permitted the interior block to drop down. This mechanism is similar to that described for some of the landslides in the Anchorage area (Hansen, 1965). The submerged block with mature spruce trees indicated vertical slump of at least 20 feet at the shore.

On the opposite shore of the lake (loc. 4, pl. 1), a section of a low forested terrace 500 feet long and 100 feet wide slumped toward the lake. The disrupted block is defined by an arcuate set of large fractures that intersect the lake margin at both ends; however, no displacement of the terrace is visible where the fractures meet the lake shore. Tilted trees occur on low ridges that appear to have formed by slight rotation along subordinate cracks in the block (fig. 19). Visible vertical displacements were slight, and modern beach deposits fronting the block were probably lowered only a few inches relative to the unaffected beaches to the north and south of the slumped area.

SKILAK LAKE

The entire outwash plain between the front of Skilak Glacier and Skilak Lake was extensively fractured, and the delta front at the head of Skilak Lake slumped into the lake. The amount of slumping of the delta front below lake level is not known, but examination of aerial photographs and ground observations suggest that a segment of the delta front about half a mile wide may have subsided sufficiently to be partially submerged during the low mean lake-level phase. Aspen and brush 10 to 20 feet high were standing in water 3 to 10 feet deep as much as 1,000 feet offshore from the new shore line. However, the fact that no freshly ice-scoured trees or other evidence of major water-level changes were observed anywhere along the shores in the upper part of the lake suggests that the amount of material that slumped from the delta front at the time of the earthquake was not large enough to generate large waves. Fracturing of the outwash plain drained a beaver-dammed lake along the south side of the valley about 2 miles from the head of the Skilak Lake (Avery Thayer, written commun., 1964).

The beach fronting the Pipe Creek alluvial-fan delta (loc. 5, pl. 1) was cut by a system of intersecting fractures one-half inch to 3 inches wide. The most conspicuous cracks trended north or northeast, that is, transverse to rather than parallel to the shore.

At the lower campground (loc. 6, pl. 1) near the outlet of Skilak Lake, ground cracks, mole tracks, and pressure ridges formed on a low forested terrace. The pressure ridges, 6 inches to 2 feet high, border the muskeg back of the campground and trend northwestward. The mole tracks developed by overthrusting (or underthrusting) of the forest litter layer; they are slightly offset along transecting cracks which trend northeast. This pattern suggests formation under compression, but the mechanism is not clear. In the absence of subsurface data, it cannot be determined whether the surface deformation resulted from stresses set up by slumping confined to the upper layers of the unconsolidated deposits or whether the deformation resulted from accommodation of the unconsolidated section to displacements at depth. The possibility of formation by movement of the lake ice during the earthquake must also be considered.

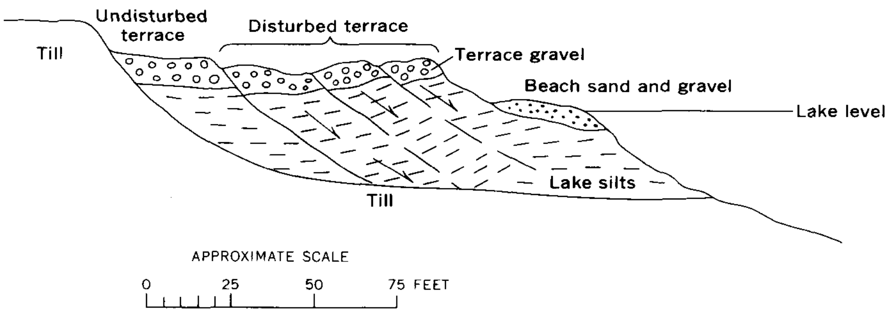
The north- to northeast-trending beaches at the lower end of the lake were fractured in two places. At locality 7 (pl. 1) the cracks are 3 inches to 1 foot wide and are confined to the modern beach gravel deposits. The largest crack was at the base of the scarp defining the inner edge of the beach. It was intersected by a few transverse cracks that extended diagonally across the beach toward the lake.

At locality 8 (pl. 1) a north- to northeast-trending crack 5 to 15 inches wide cut diagonally across the beach and was traceable into higher ground a few hundred feet from the lake before being lost in dense forest.

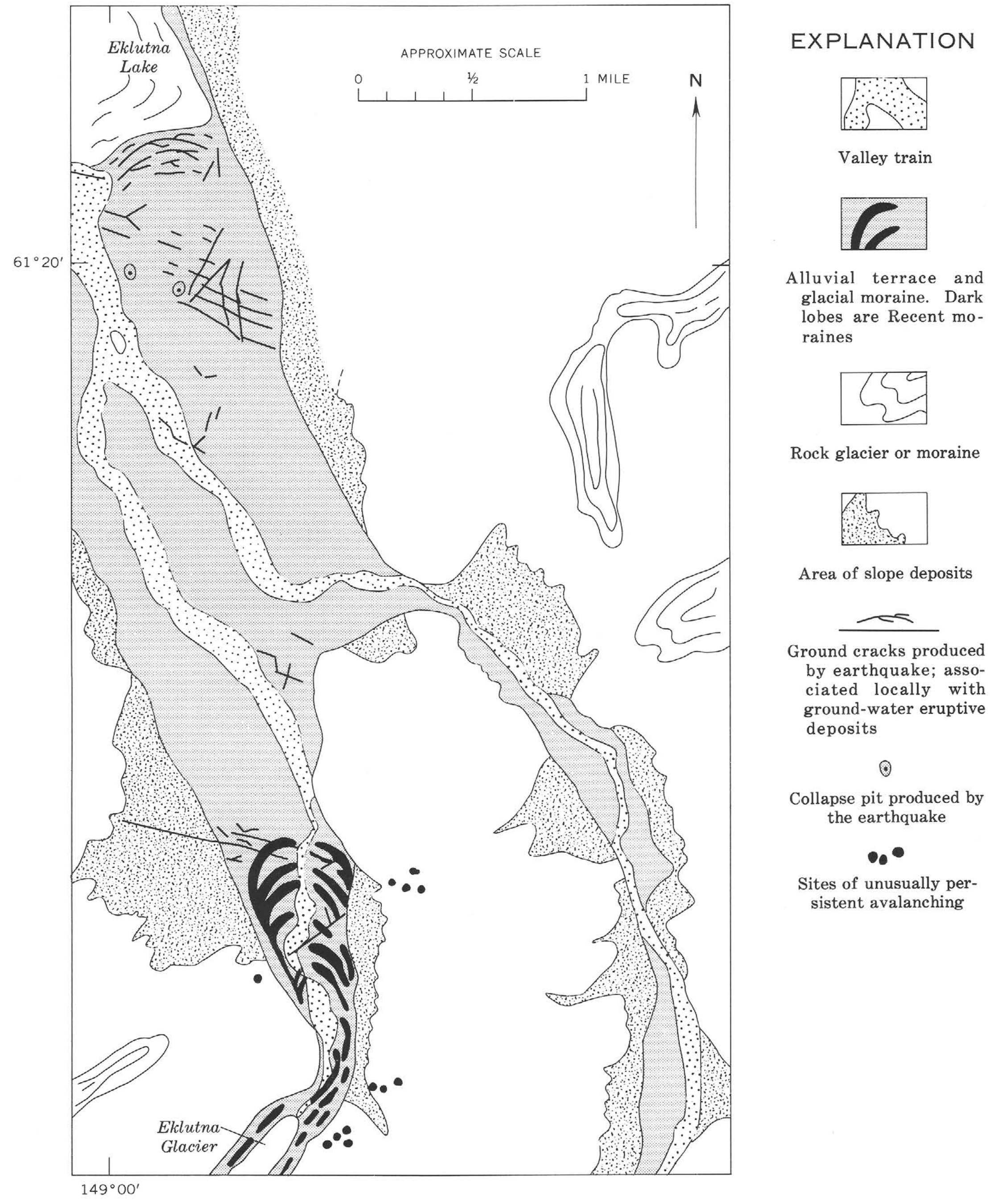
SOUTHERN INTERIOR

Ground breakage in the interior of the Kenai Lowland outside of the northeast zone was limited to a few scattered localities (pl. 1) where the following types of disruption were observed:

1. Landslides in unconsolidated deposits on moderate to steep slopes. Northeast of Homer.
2. Large avalanches. Anchor River.
3. Slumps in unconsolidated deposits on or toward unconfined faces such as river banks, lake shores, and delta fronts. Chakok River, Fox River, Tustumena Lake, Skilak Lake, and Stariski Creek.
4. Ground cracks in lowlands covered by silty lake deposits, alluvium, or fluvioglacial de-



19.—Diagram showing a type of slumping on the south shore of Tustumena Lake (loc. 4, pl. 1).



20.—Sketch map of Eklutna valley showing sites of persistent avalanching and location of ground breakage.

posits. Upland in headwaters of Bear Creek.

5. Ground cracks and pressure ridges in muskeg areas. Half a mile south of Clam Creek, Slikok Creek.
6. Cracks in flood plains and valley trains underlain by sand and gravel. Skilak River, Fox River.

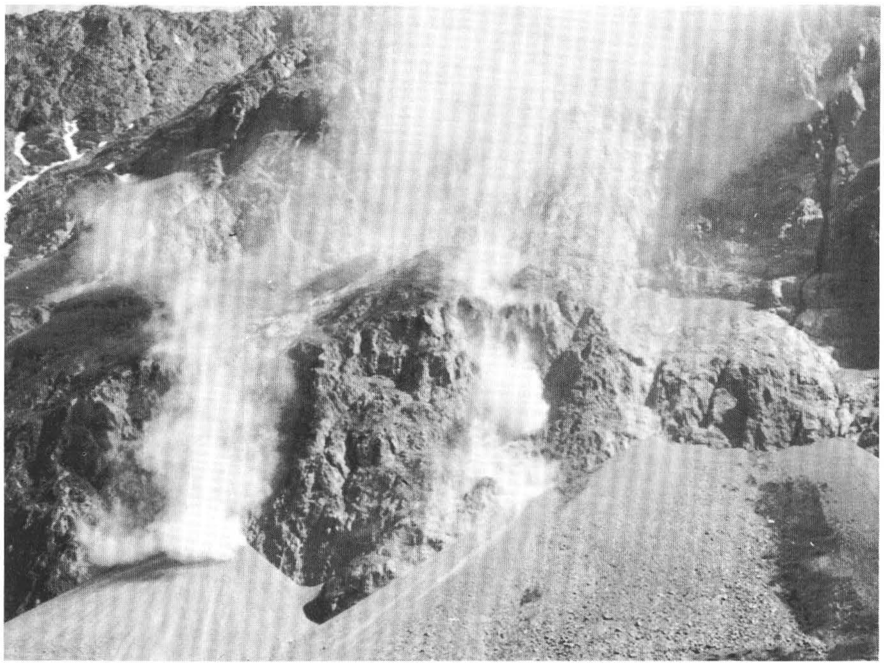
The cracking in the Fox River flood plain was particularly spectacular on the alluvial fan formed at the confluence between Sheep Creek and the Fox River. Copious amounts of sand erupted along an extensive mosaic of cracks. Along the channels of the Fox River, numerous alluvial deposits on slip-off slopes were broken along longitudinal and transverse cracks. The alluvial flats on the inside of meanders were cracked and channel banks slumped at numerous places. The cracking appeared to be concentrated along the axis of the Fox River valley. No flood-plain failures were apparent in tributaries heading in the Kenai Mountains.

NORTHERN COOK INLET AREA

The major ground breakage in the northern Cook Inlet area was in and around Anchorage and Portage. Ground cracks and landslides were abundant and destructive and have been described in detail by Hansen (1965), McCulloch (1966), Kachadoorian (1965) and others. Ground breakage in this area also occurred in the Eklutna valley, around Lake George, in valleys in the western Chugach Mountains, and west of Anchorage including the delta of the Susitna River.

At the head of Eklutna valley, unusual avalanche activity followed the earthquake. It began after the earthquake and continued throughout the summer of 1964. Periodic observations made in the valley by U.S. Geological Survey personnel stationed in Anchorage indicate that it commenced again after the spring thaw in 1965 and continued throughout that summer. As late as August 2, 1966, minor avalanche activity was reported (Ruth Schmidt, written commun., 1966). However, the total activity in the summer of 1966 was apparently considerably less than that in 1964, but more than before the earthquake.

In the early part of the summer of 1964, rock debris cascaded nearly continually from three principal places on the steep high cliffs above Eklutna valley (fig. 20). Talus cones at the base of the cliffs were much enlarged (fig. 21). Dense dust clouds emanated from the avalanches and resulted in erroneous reports of volcanic eruptions when spotted by airplane pilots (figs. 21, 22). Later in the summer, several of the avalanches became inactive, and by August 1965 activity was largely



21.—Sites of avalanche activity in Eklutna valley. These talus cones were present before the earthquake but have been enlarged by avalanche activity since the earthquake. The dust clouds are created by the avalanching.

22.—Dust cloud in Eklutna valley caused by avalanche activity. The avalanching has been persistent during the summers since the earthquake.

23.—Crack in gravel outwash in Eklutna valley. Crack was about 10 inches wide and split a tree stump. The two halves of the stump were offset about 14 inches.

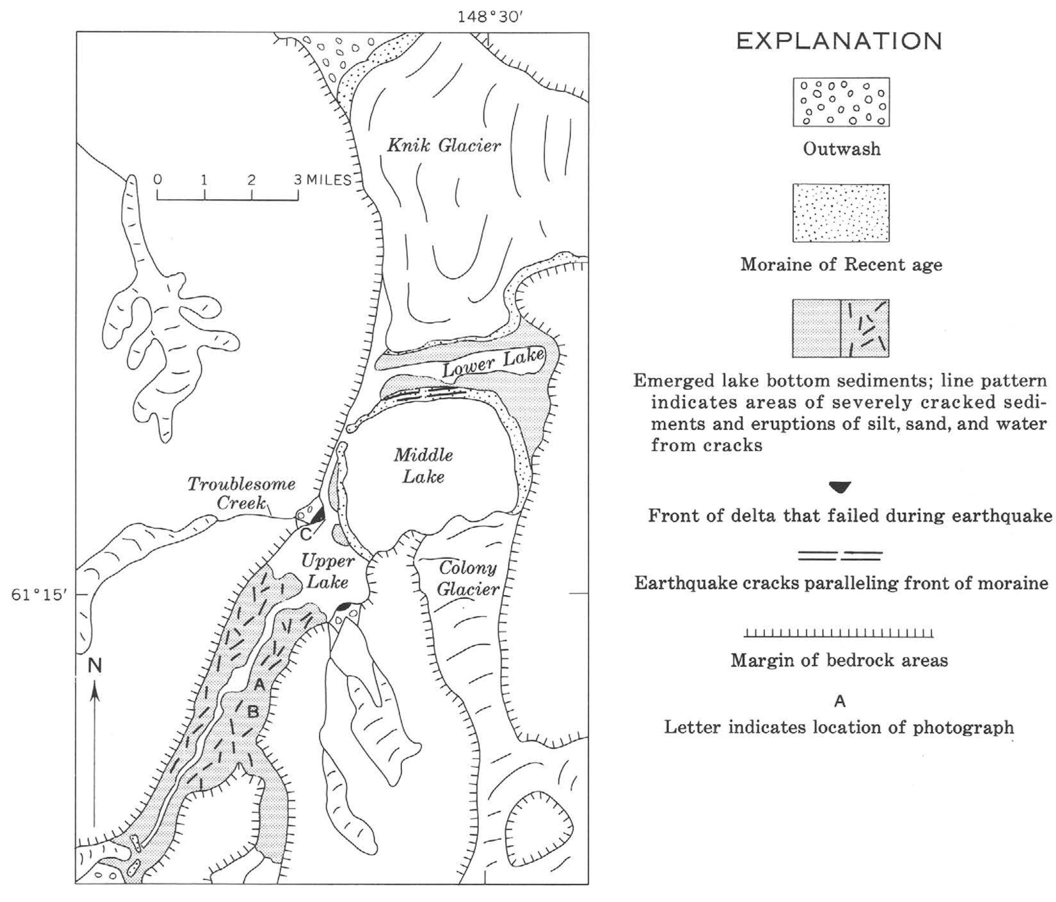
restricted to one avalanche chute at the head of the valley. Karl Gladys (oral commun., 1964) estimated that the normal avalanche activity, which usually lasts 2 to 3 weeks after spring thaw, constituted less than 2 percent of the avalanche activity during the summer of 1964. The remainder is attributed to disruption caused by the earthquake along shear zones. Ground breakage was noted on the high terraces in the valley bottom below the northernmost avalanche source. One conspicuous set of cracks had a southeastward trend and crossed moraines, outwash, and colluvial deposits. An intersecting set trends northeast.

Ground breakage was also present on the floor of the valley at the head of Eklutna Lake. An extensive mosaic of cracks was present in the gravel outwash, and much sand and gravel erupted with the ground water during the earthquake. Fissures were as wide as 1½ feet. Horizontal offsets as much as 2 feet and vertical offsets of 1 foot were observed. Trees were split and offset along some cracks (fig. 23). Circular pits 4½ feet in diameter and as much as 12 feet deep squirted sand and water (Karl Gladys, written commun., 1964). The main zone of cracking at the head of the lake covered an area of about 1 square mile. Additional damage in the Eklutna area, particularly to the power-plant installations at the lower end of Eklutna Lake, is described by Logan (1967).

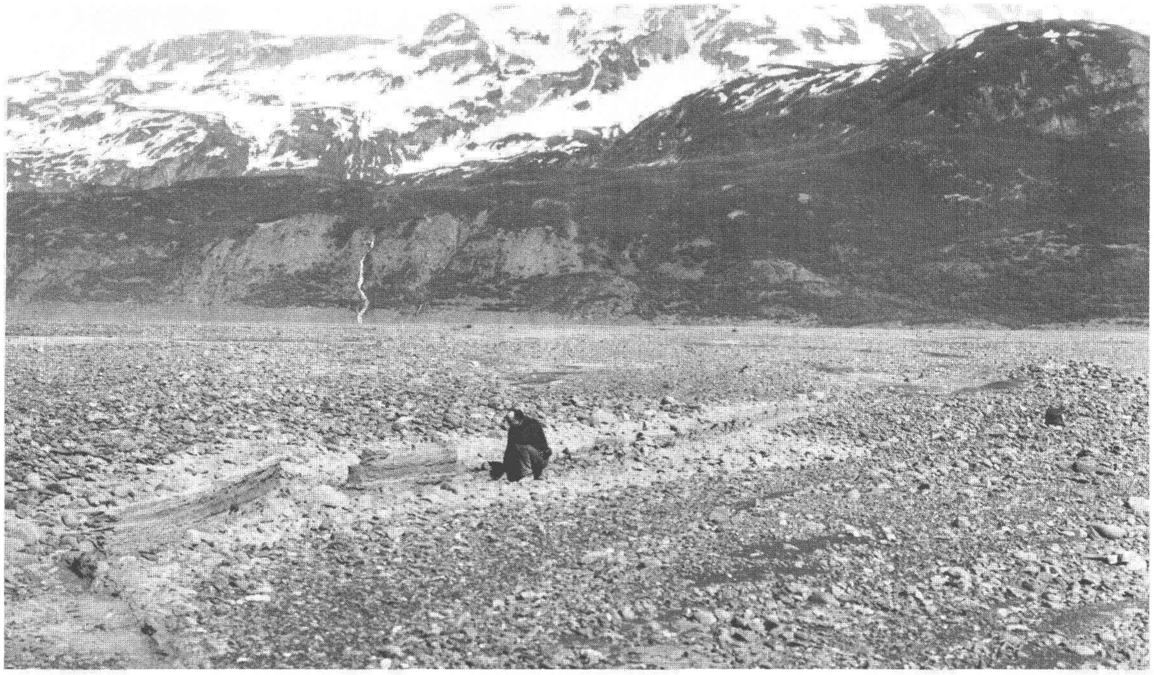
Within the Lake George basin of the Chugach Mountains 28 miles southeast of Palmer, damage resulting from the earthquake included failure along the fronts of deltas built at the mouths of two tributary valleys, and extensive cracking associated with eruptive deposits of emerged bottom sediments at the head of the lake. The most extensive disruption occurred along the front of the Troublesome Creek delta where slumping caused lakeward rotational displacements of frozen gravel blocks as much as 20 feet wide and 100 feet long. Chaotic topography resulted (figs. 24, 25). The delta at the mouth of a creek entering the south end of upper Lake George failed by cracking along the margin of the delta front. Lateral extension, however, was slight, minor vertical or lateral displacements being evident along the cracks.

A mosaic pattern of cracks developed in the exposed lake-bottom sediments near the head of the lake (lake-bottom sediments were exposed at the time of the observations because lake levels were low).

24.—Failure of the delta front at Troublesome Creek, Lake George (loc. C, fig. 25). Man is standing on a large slumped and rotated block that is bounded front and back by large fissures.



25.—Lake George area showing location of ground breakage.



26.—Wall of silt punched up on the emerged bottom of Lake George. The wall was 8 to 24 inches high, 30 feet long, and 6 inches wide (loc. B, fig. 25).

27.—Ridges of silt squeezed up along cracks in the emerged bottom sediments of Lake George (loc. A. fig. 25).

Lake silt was squeezed out of the underlying water-saturated sediments and erupted through cracks in the seasonally frozen surface layer. At one locality a wall of frozen silt, 6 inches wide and about 30 feet long, was punched up 8 to 24 inches by pressures in the underlying unfrozen materials during the earthquake (fig. 26). The undisturbed structure of the fine laminated silts exposed in the wall indicated that the silt must have been rigid and frozen at the time of displacement. Disruption and minor dislocation of the wall along northeast-trending cracks indicate subsequent development of and minor displacements along cracks that cut transversely the northwest set of parallel fractures that defined the wall structure itself. At several locations, mounds of silt 1 to 2 feet high and 2 to 3 feet in diameter and showing internal flow structure formed at the intersection of the cracks. Unfrozen silt was squeezed up as ridges along some of the cracks (fig. 27). On the north side of the moraine along the south side of lower Lake George, some sand eruption occurred at the contact of the moraine with the lake sediments through cracks transecting the moraine.

Reconnaissance observations within the Chugach Mountains between Knik Valley and Turnagain Arm revealed only two other localities of ground breakage: cracks cutting forest turf on thin alluvium over bedrock near the mouth of south fork valley of Campbell Creek and cracks in thick muskeg and alluvial deposits in the middle part of Eagle River valley (pl. 2). The major crack set in Eagle River valley was roughly parallel to the axis of the valley, and the most conspicuous transverse set of cracks trended at right angles to the valley axis. No ground damage was observed upvalley or downvalley from these cracked zones. Ground observations were not made in the other valleys of the mountain range.

West of Anchorage, tidal flats were cracked and slumping occurred at the mouth of Knik Arm on the west side. The delta of the Susitna River was severely cracked; parts of its front subsided into Cook Inlet. In some small lakes in the Susitna River lowland, the sediments in the bottoms of the lakes were cracked. At the base of Mount Susitna along the projected trace of the Lake Clark-Castle Mountain fault, sand eruptions occurred along the margins of lake terraces cut in till. To the northeast about 18 miles, also along the trace of the Lake Clark-Castle Mountain fault, there was disruption and slumping along a bluff face.

NORTHWEST SIDE OF COOK INLET

Limited observations on the northwest side of Cook Inlet indicate that ground breakage was relatively minor and confined mostly to deltas, tidal flats, and alluvial flats, and occurred in widely scattered localities. Ground breakage was noted in the following places (pl. 2):

1. Beluga Lake. Beluga Lake is divided into upper and lower parts by deltaic outwash sediments deposited by drainage from Capps Glacier. This outwash delta was considerably fractured. At the head of upper Beluga Lake, terraces along outwash channels cut below the main surface level of the large outwash delta were locally fractured. At the head of lower Beluga Lake a large block slumped into the lake submerging trees. Minor fracturing occurred at the outlet of lower Beluga Lake.
2. Inland from Trading Bay, 15 miles to the northeast. Extensive fracturing occurred in a zone extending northeast more or less parallel to the shore of Trading Bay and along the approximate postulated trace of the Lake Clark-Castle Mountain fault. The zone is about 12 miles long. The dominant trend of the fractures is also northeast. Much sand was extruded along many of the fractures.
3. Northeast shore of Chakatchama Lake. Cracks occurred in beach deposits along the shore of the lake (Gordon Giles, written commun., 1964).
4. Tyonek. Lake ice and muskeg were cracked. About 5 miles north of Tyonek, old slumps along the coast were reactivated, but displacement was less than 1 foot.
5. Trading Bay. On the coast 1½ miles east of Kustatan, small slumps occurred in bluffs of glacial till (George Plafker, oral commun., 1966).
6. Redoubt Bay. Cracks were common along the Drift River from the mouth inland 2 miles or more. All breakage was in alluvium. North from the mouth of Drift River, cracks associated with extruded sand occurred along the coast for a distance of about 2 miles (George Plafker, oral commun., 1966).
7. Near the mouth of Tuxedni Channel. On the south side, cracks formed on steep slopes. Two months later, following spring thaw, landslides occurred in the cracked terrain (George Plafker, oral commun., 1966).
8. North shore of Tuxedni Bay. Along the east side of

Squarehead Cove, the bluff face sloughed off along the shore for about 1 mile (George Plafker, oral commun., 1966).

9. Kalgin Island. Slumps developed in unconsolidated deposits on the south end.
10. Augustine Island. Cracks more or less parallel to the coast were noted from the air on the north end and on the northeast side. All appeared to be in recent unconsolidated deposits of volcanic sand, gravel, and bouldery gravel. Some of the cracks were close to the shore, others were higher on the slope and subparallel to it. Slumps and small slides occurred in places along the cracks, and the surface was "stepped" downward toward the coast along some cracks (Bruce Reed and George Plafker, oral commun., 1966).

SOUTHEAST SIDE OF KACHEMAK BAY

Ground breakage at two places along the southeast side of Kachemak Bay was noted by Plafker in a reconnaissance flight in 1964 (George Plafker, oral commun., 1966; pl. 2). Extensive fracturing resembling that of Skilak Lake occurred in the outwash delta at the head of Bradley Lake. Fine closely spaced cracks were noted in the tidal flats along the south shore of China Poot Bay. A rockfall took place on a steep cliff nearby. The outwash flats along the glacial drainage which enters China Poot Bay from the south were considerably fissured. Ground breakage extended from the bay margin inland along the drainage for about 2 miles.

CAUSES OF GROUND BREAKAGE

The northeast-trending zone of ground breakage in the Kenai Lowland may not be caused entirely by simple lateral movements or compaction in unconsolidated sediments. Several features indicate that additional factors were involved. For example, in many places there is no consistent relationship between the cracks and either the local topography or stratigraphy; the cracks are unusually deep and are very persistent and have a marked linear trend.

The following explanations for these features are suggested: (1) The disrupted zone may have resulted from movement triggered by the earthquake along a buried fault. (2) There may have been differential compaction of Quaternary sediments along a buried ridge of Tertiary rock. (3) Gravity sliding may have taken place along the interface between the unconsolidated Quaternary deposits and the Tertiary bedrock. (4) A combination of these processes could have been involved.

The subsurface data available to the authors are insufficient to define clearly the bedrock structures beneath the Kenai Lowland, but some of the data suggest a buried fault; none preclude the possibility of such a fault. Field mapping in the Kenai Lowlands (Karlstrom, 1964) shows that the top of the Tertiary bedrock along the coast generally is above sea level south of, and below sea level north of, Kasilof. Thus there could be either an erosional break or a structural dislocation of the bedrock floor where the inferred fault zone crosses the coast.

In the Swanson River oil field, oil and gas have been produced from the Tertiary sedimentary rocks northwest of the zone of disrupted ground. To date, all wells drilled south of the zone have been dry. This change in subsurface conditions may be due to a fault, or it may indicate a facies change.

By report, seismic profiles obtained from the northern part of the Kenai Lowland are difficult to interpret because of poor signal returns. They do suggest, however, an important subsurface discontinuity, either lithologic or structural, that approximately coincides in position with the zone of broken ground developed during the 1964 earthquake. At one place along the trace of this discontinuity the seismic data can be interpreted as recording a basement fault of northeast strike, a steep southeast dip, and a downdropped south block (C. E. Kirschner, oral commun., 1964).

The unusual avalanche activity at the head of Eklutna valley following the earthquake and continuing into the summer of 1966 might also be related to movement along faults. The rocks in this area are highly sheared and crushed. If these rocks were made unstable by small movements along faults, the avalanche activity could have been set in motion. Furthermore, the continued avalanche activity might be due to minor readjustments in the disturbed blocks following the main displacement. Although the bedrock of this locality has not been mapped in detail, the fractured rock suggests that faults are present. If simple displacement of sheared blocks took place as a result of the shaking of the earthquake without faulting, it seems unlikely that the avalanching would have continued so long. The disruption in the valley floor at the head of Eklutna Lake and the damage to the powerplant facilities (Logan, 1967) also suggest that more than just the usual seismic effects from a distant earthquake were in operation here.

On the northwest side of Cook Inlet northwest of Trading Bay, a concentration of cracks and sand extrusions in flood-plain deposits was noted near the projected trace of the Lake Clark-Castle Mountain fault. To the northeast of this locality along the trend of the fault, two other localities of disruption were noted within the Cook Inlet area. This ground breakage may be indicative of movement along the Lake Clark-Castle Mountain fault, but other evidence of fault movement, particularly in bedrock, has not been detected.

The remainder of the ground breakage in the Cook Inlet area can be explained by the presence of thick sections of silt and waterlogged sediments which are particularly susceptible to disruption by seismic activity when in topographically unfavorable situations. Despite many such unfavorable situations in the Kenai Lowland and the mountains bordering it, the overall ground breakage in this area was relatively minor. This stability may be explained, at least in part, by the fact that the ground was still firmly frozen at the time of the earthquake.

CRUSTAL CHANGES IN THE COOK INLET AREA

Crustal deformation that accompanied the 1964 earthquake affected an area of 65,600 to 77,200 square miles in south-central Alaska. The deformation consisted of two major northeast-trending zones of uplift and subsidence between the Aleutian Trench and the Aleutian volcanic arc (Plafker, 1965, p. 1686). Most of the Cook Inlet area is in the depressed area, but the region also includes areas ranging from those with no detectable change to some on the northwest side of Cook Inlet that are slightly upwarped. However, maximum change in the Cook Inlet area was small, probably not more than 6 feet, as compared with 50 feet to the southeast.

OBSERVED COASTAL CHANGES

Coastal observations in the Cook Inlet area indicate the following approximate changes in land-sea levels:

1. Along the south shore of Turnagain Arm near Hope, there was 4 to 6 feet of subsidence. Vegetated areas previously above storm beach levels were inundated during high tides following the earthquake. Houses in the low-lying parts of Hope were flooded. Inundation during high spring tides extended to just below the entrance of the General Store. High-water marks on forested slopes of a thick section of coarse alluvial fan east of Hope indicate inundations approximately 5 feet above the preearthquake high-tide mark (fig. 28). The coarse gravel substratum in the area and the absence of cracking or slumping along the coast suggest that most, if not all, of the recorded subsidence resulted from crustal subsidence and not from compaction or slumping of the surficial deposits.
2. Along the south shore of Turnagain Arm in Chickaloon Bay, there was 3 to 4 feet of subsidence. Vegetated elevated tidal flats previously above the reach of high tide were inundated following the earthquake. The estimate of 3 to 4 feet of subsidence is based on observed changes in tidal levels in relation to the floor of a hunter's cabin in

28.—Postearthquake high-tide mark along Turnagain Arm sea bluffs near Hope. Arrows indicate the pre- and postearthquake high-tide positions. The vertical distance of about 5 feet between these two positions approximates the amount of crustal subsidence that accompanied the 1964 earthquake.

the area that was for the first time partly inundated during the high tides (Avery Thayer, oral commun., 1965). However, a thick section of fine-grained deposits underlies the tidal flats, so there is a possibility that part of the observed subsidence may have resulted from compaction.

3. Along the east coast of Cook Inlet from Point Possession to Anchor Point, observed subsidence ranged from a little less than a foot to none it all. Undercutting of the stabilized and vegetated colluvial slopes along the sea bluffs was approximately the same as had been observed by Karlstrom during spring traverses in previous years. Vertical relations between storm beaches, elevated tidal-flat surfaces, and postearthquake high-tide levels appeared comparable to those observed in previous years near Point Possession, Moose Point, Kenai, Kasilof, Ninilchik, and Anchor Point. Local fishermen estimated a subsidence of about half a foot near Ninilchik on the basis of apparent changes in low tides. Careful observations on a pier gage at the cannery on the south side of the mouth of the Kenai River indicated that water levels during the spring high tides following the earthquake did not quite attain the levels reached during the high tides of the preceding fall (Clarence Platt, oral commun., 1964). Because high tides in this area are normally higher in fall than in spring, this observation is consistent with the geologic evidence of very little or no change in datum along the coast. A postearthquake resurvey of the highway from Kenai southwest to Ninilchik indicated no measurable change that could be attributed to regional warping during the earthquake (Alaska Highway Dept. personnel, oral commun., 1964). Short-term postearthquake tidal-gage records suggest a subsidence of 0.9 foot near Nikishka (Small, 1966, p. 20).
4. Along the south coast of the Kenai Lowland between Anchor Point and Homer Spit, regional tilting ranged from none to less than 1 foot of subsidence at Anchor Point, 2 feet at Homer, and 4 to 6 feet at the tip of Homer Spit. These figures are based on a rapid resurvey of the highway after the earthquake by the Alaska Highway Department. Of the 4 to 6 feet of subsidence at the end of Homer Spit—a low sand and gravel bar that extends 5 miles southeastward into Kachemak Bay from Homer—a minimum of 2 feet has been attributed to crustal subsidence and the remainder to differential compaction of the underlying unconsolidated materials (Grantz, Plafker, and Kachadoorian, 1964, p. 9, 24).
5. Along the west shore of Cook Inlet from Point McKenzie to Kamishak Bay, there was 1 to 2 feet of subsidence along the slumped front of the Susitna Delta area; no change to slightly down near Tyonek; 1 to 2 feet of uplift along the coast of Kamishak Bay. The estimate of subsidence in the Susitna Delta area is based on observations of postearthquake tidal changes at a hunter's cabin by personnel of the Fish and Wildlife Service (Theron Smith, oral commun., 1964). Probably most of this subsidence can be attributed to slumping and compaction of the delta front and adjoining elevated tidal flats between the Susitna River and McKenzie Point. This conclusion seems reasonable because (1) the coastal margin was extensively cracked during the earthquake and (2) changes in bathymetry of the bordering seaway (determined by U.S. Coast and Geodetic Surveys in the summers of 1963 and 1964) record a major slump of material along the coast, presumably resulting from the earthquake. No changes were observed along the coast near Tyonek except in one area where subsidence of storm beaches suggested a downdrop of about 1 foot. This area of obvious subsidence occurs at the foot of a section of coastal bluff where large preearthquake slump blocks moved locally during the quake. The anomalously low tide levels following the earthquake that were reported by residents Iliamna and Tuxedni Bays suggest an uplift along the Kamishak Bay coast of 1 to 2 feet.

The estimates of land-sea changes along the south shore of Turnagain Arm are of the same order of magnitude as the changes determined by releveling bench marks in bedrock along the north shore of the arm. This agreement suggests that the estimates elsewhere in the area based on shoreline relations may also be approximately correct.

TILTING OF LAKE BASINS

The large lake basins in the Cook Inlet area serve as natural tiltometers because their long directions are more or less parallel to the known direction of regional tilt. Regional tilting should be detectable in changes of water-plane levels. The positions of preearthquake water levels were checked in a few of the lake basins by referring to established bench marks. A preliminary resurvey of bench marks in relation to lake levels after the earthquake indicated southeastward tilting of Eklutna Lake; the head of the lake was possibly down 1 to 2 feet relative to its mouth (Russell Wayland, written commun., 1964). There was little or no tilting of Lake Chakatchama (Gordon Giles, written commun., 1964); and little or no tilting of Bradley Lake near Homer (Marvin Slaughter, written commun., 1964).

Air reconnaissance observations made of Tustumena Lake immediately after the earthquake suggested southeastward tilting of the lake basin. Outlet drainage through the Kasilof River was reported to have decreased to such an extent that the day following the earthquake a galosh-shod biologist was able to walk up its channel (Alaska Dept. Fish and Game, 1965, p. 29). Forested areas at the lake head were reported to have been submerged. At the time of a 2-day boat traverse around the margins of the lake in June 1964, lake level was below the normal seasonal level (Joe Magargl, oral commun., 1964). It was about 5 feet below the average late autumn high-lake level, as marked by the inner edge of generally barren gravel beaches and by conspicuous high-water marks on rocky cliffs along the margin of the lake. Submerged trees were found to be associated only with locally disturbed and slumped shoreline deposits; in no area could the submerged vegetation be related to regional tilting. Hand-leveling by Brunton compass at numerous localities about the margin of the lake revealed no systematic differences in the vertical interval between lake level and high-water beaches and watermarks. Thus, if the lake basin had been tilted, the amount of tilting was apparently less than the accuracy of measurement by Brunton compass, which is estimated to be ±1 foot.

Observations made at the head of Tustumena Lake during the earthquake (Joe Secora, oral commun., 1964) indicate that the frozen surface of the lake cracked into a mosaic fracture pattern as the lake level rapidly rose and fell. Lake level receded about 2 feet and then rose; sloshing of the lake waters continued for about 2 hours. General lake level was judged to have been somewhat lower during the following day or two and then to have risen to about half a foot higher than the preearthquake level. Whether this rise resulted from belated tilting of the lake basin or from the normal inflow during increased spring thaw is not clear. Mr. Secora's account, however, is consistent with the later crude measurements on shoreline features which suggest that tilting was probably less than 2 feet and conceivably less than 1 foot over a distance of 25 miles between the mouth and head of the lake.

Similar geologic observations and Brunton compass measurements made in June 1964 along the margins of Skilak Lake suggest the same general amount of regional tilting during the earthquake as on Tustumena Lake. Extensive flooding of forests around the margins of Skilak Lake was observed by local pilots in September 1964. A subsequent boat traverse around the lake margin by Avery Thayer (written commun., 1964) revealed unusually high lake levels but no changes that could be attributed to differential tilting. However, Kenai Lake, about 25 miles east of Skilak Lake in the Kenai Mountains, was in a zone of greater deformation and showed about 3 feet of tilt (McCulloch, 1966, p. A29).

PATTERN OF SUBSIDENCE

The combined geologic observations and instrumental releveling data in the Cook Inlet area, together with data from adjoining areas, indicates differential subsidence, maximum crustal depression occurring along a linear zone between Portage and Aialik Bay or approximately coincident with the axis of the Kenai Mountains (Plafker, 1965). U.S. Coast and Geodetic Survey releveling indicates that maximum subsidence (nearly 6 feet) occurred near Portage and that the amount of subsidence diminishes progressively to about 2 feet northwestward towards Anchorage (U.S. Coast and Geodetic Survey, 1966, p. 122). These data indicate regional tilting to the southeast, approximately at right angles to the axis of the Kenai Mountains. The gradient of regional tilt is about 0.1 foot per mile between Anchor Point and the Homer area, and increases to 0.2 foot per mile between Homer and Aialik Bay where the greatest subsidence (7½ feet) measured in the region occurred (George Plafker, written commun., 1966). The releveling and geologic data are insufficient to exclude the possibility of some local vertical fault displacements, but, in general, subsidence appears to have resulted largely from downwarping or folding of the crustal rocks.

The line of zero change separating the depressed area of Cook Inlet from the more stable area to the north can be only approximately located by the available data. Apparently the line of zero change passes southwestward across the Susitna Lowlands, a few miles west of Tyonek and into Cook Inlet along its western side (Thor Karlstrom, unpub. data, 1964; George Plafker, unpub. data, 1965).

CONCLUSIONS

Ground breakage in the Cook Inlet area occurred largely in unconsolidated deposits. It consisted of slumps toward unconfined faces such as river banks, delta fronts, and lake shores; ground cracks in lowland and valley bottom surfaces; transverse and marginal cracks in modern and elevated tidal flats; and cracks in muskeg areas. Most of these breaks can be attributed to various processes and combinations of them such as differential compaction and downslope movements of underlying water-saturated fine-grained sediments. However, distribution of this type of damage was irregular, and localities with seemingly similar conditions were not necessarily similarly affected. Many areas, such as steep bluffs of unconsolidated materials along sea coast, were notable for their lack of visible earthquake effects. Regional structural elements may have had some control over the location and type of damage incurred in the Cook Inlet area, particularly in the northeast-trending zone of ground breakage in the Kenai Lowland. Here, disruption in a thick sequence of unconsolidated deposits may have been due to movement along a fault in the underlying Tertiary rocks. Faulting or adjustments along previous faults also may have contributed to the avalanche activity in the Eklutna area and to the distribution of ground cracks along the west shore of Cook Inlet in line with the Lake Clark-Castle Mountain fault.

The distribution of ground breakage in the 1964 earthquake indicates that in the lowlands of the Cook Inlet area the most damage from future seismic activity can be expected on outwash deltas, lowland areas underlain by thick marine or lake silt, and in alluvium and outwash along the larger streams.

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U.S. GOVERNMENT PRINTING OFFICE: 1967 O—262-870