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UNITED STATES
DEPARTMENT OF THE INTERIOR
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A PRELIMINARY EVALUATION OF SELECTED EARTHQUAKE-RELATED GEOLOGIC HAZARDS IN THE KENAI LOWLAND, ALASKA

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Menlo Park, California

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Russell G. Tysdal

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ABSTRACT

Several major faults exist beneath the Kenai Lowland, and others may be inferred. No surface evidence was found to indicate that any of the faults have been active in Holocene time. The sparse shallow seismicity thus far recorded does not correlate with known faults, nor does it define linear trends suggestive of faulting. Tidal flats at the mouths of the Kenai, Kasilof, and Chickaloon Rivers have been uplifted in the Holocene, however, and the uplift may reflect growing anticlines at depth. Some faults associated with folding may be active, but they are probably too limited in size to generate destructive earthquakes. They could, however, constitute a hazard to manmade structures in their immediate vicinity.

Vibrational damage and ground failure during the 1964 earthquake were most extensive north of Tustumena Lake in areas of water-saturated unconsolidated deposits with uneven topography. South of Tustumena Lake, damage resulted mainly from landslides formed along unconfined bluffs and riverbanks, and from submarine sliding and subsidence at Homer Spit. A comparable distribution of surficial effects may be anticipated in future large earthquakes on the Kenai Lowland.

INTRODUCTION

This text outlines the major tectonic elements of the Kenai Lowland, presents a preliminary evaluation of the relations between the tectonic elements, possible geologic hazards, and documented seismic events, and summarizes the effects on the lowland resulting from the 1964 Alaska earthquake. The geologic map (fig. 1) shows the locations of known and inferred faults, known folds, and the major lithologic units in the Kenai Lowland. Although the lowland region is largely wilderness, much of the readily accessible area is undergoing rapid rural and urban development; land-users should be cognizant of the potential geologic hazards related to the tectonic elements. Professional guidance is recommended for evaluation of geologic hazards that may exist in specific site areas.

The text is based largely on interpretation of data published previously by other workers, supplemented by study of aerial photographs, topographic maps, and a few days fieldwork by me in the Homer area and along the Sterling Highway north of Skilak Lake. The surface geology shown in figure 1 is mainly from Barnes and Cobb (1959), Karlstrom (1964), and Foster and Karlstrom (1967); the subsurface tectonic elements are chiefly from publications of the Alaska Geological Society (1970), and Kirschner and Lyon (1973). Additional information on geology and earthquake hazards in the Kenai Lowland has been obtained from discussions with Windsor Adkison, David Barnes, Edward Cobb, Warren Coonrad, David Hopkins, George Plafker, and John Kelley of the U.S. Geological Survey, and Charles Kirschner of Standard Oil Company of California

GEOLOGIC SETTING

The Kenai Lowland is part of the Cook Inlet basin, an intermontane basin containing Tertiary sedimentary deposits that overlie Mesozoic basement rocks. The main structural elements within the basin are elongate,

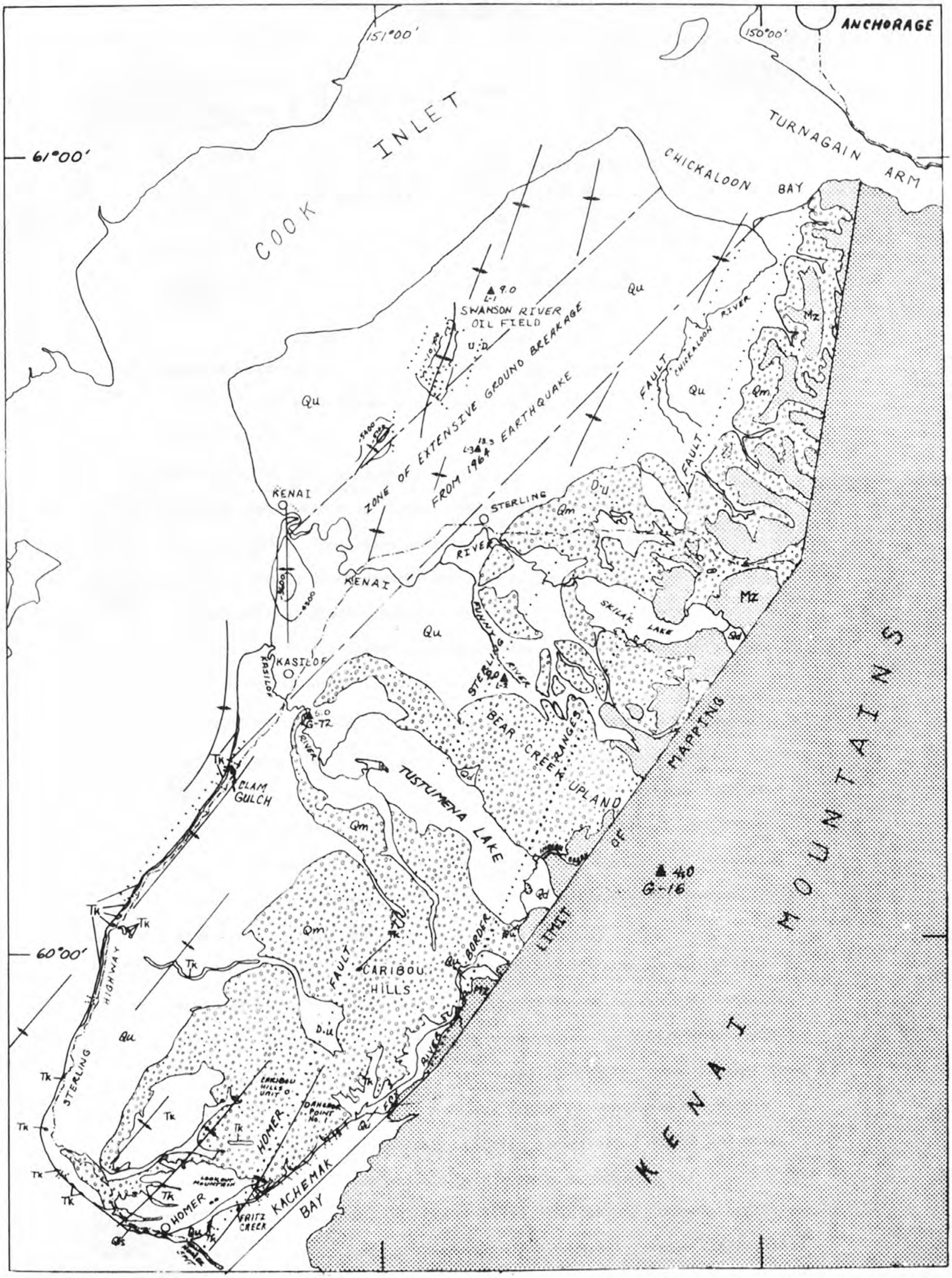
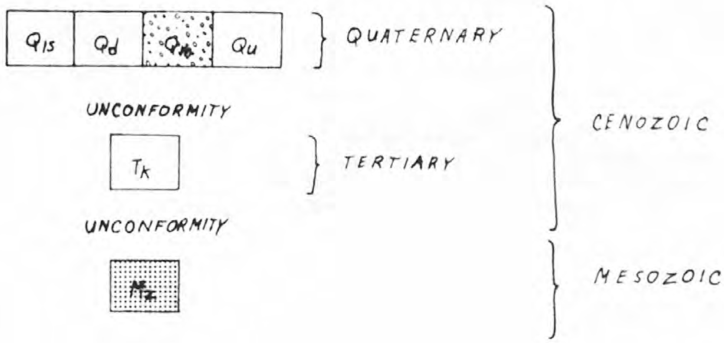


Figure 1.--Map of Kenai Lowland showing major structures, stratigraphic units, and earthquake epicenters. Explanation is on pages 4 and 5.

EXPLANATION



Qls LANDSLIDE DEPOSITS (Holocene) Deposits formed by mass movement on steep slopes. Landslide deposits are unstable and can be expected to move during earthquakes

Qd LAKE-DELTA DEPOSITS (Holocene) Deposits of sand, silt, and gravel where streams empty into major lakes. Delta deposits are unstable and were areas of ground fracturing and slumping during 1964 earthquake

Qm MORAINAL DEPOSITS (Quaternary) Moraines of Caribou Hills, Eklutna, Knik, and Naptowne (including Naptowne "terraced" moraines) glaciations, as mapped by Karlstrom (1964). Morainal deposits experienced only minor local slumping during 1964 earthquake.

Qu UNCONSOLIDATED DEPOSITS, UNDIVIDED (Quaternary) Loess, wind-deposited sand, and bog material; proglacial lake silt, with interbedded sand and gravel; marine sand, silt, and clay (may be equivalent to Bootlegger Cove Clay in Anchorage area); till, glaciolacustrine, glaciofluvial, and other glacial deposits; deltaic deposits; peat deposits; alluvium. Deposits had variable response to 1964 earthquake, ranging from no deformation to ground failure caused by liquifaction

Tk KENAI GROUP, UNDIVIDED (Tertiary) Moderately indurated nonmarine fine- to medium-grained sandstone, conglomeratic sandstone, siltstone, and claystone; beds range from a few centimeters to several meters thick; subbituminous and lignitic coal is interbedded with above rocks, in beds from a few centimeters to about 2 m thick; lenses of conglomerate present locally. Deposits are generally stable, except along cliffs and steep slopes where landslides and slumps are to be expected

Mz MESOZOIC ROCKS, UNDIVIDED Slate, phyllite, and schist; probably equivalent to Valdez Group to north. These rocks are generally stable except along steep slopes where minor fracturing of weathered rock might occur

Contact

U
D
Fault
Dotted where concealed.
D, downthrown side; U, upthrown side
No surface evidence was found to indicate that any of the faults are active

Anticline
showing trace of axial surface

Syncline (in subsurface)
showing trace of axial surface

Approximate edge of zone of extensive ground breakage from 1964 earthquake

-5400

Structure contour
Contour on top of Hemlock Conglomerate, Oligocene formation of Kenai Group

Anchor River No. 1

Well
Exploration borehole for oil, showing name. Only selected wells are indicated

9.0
G-72
Earthquake Epicenter
Number is depth to hypocenter, in Km; "G-72" indicates data source is Gedney and VanWormer (1974), epicenter no. 72; "L", Lahr and others (1974)

Landslide deposit generated during 1964 earthquake complexly faulted belts of anticlines that trend northeast; the major faults trend parallel to the folds. The basin lies near the east end of a seismically active zone that follows the Aleutian volcanic arc and Aleutain trench for a distance of 2,900 km (1,800 mi) from Kamchatka, U.S.S.R., to south-central Alaska, where the Aleutian arc intersects the North American continent (fig. 2).

The rocks that underlie the Kenai Lowland are a predominantly continental sequence of sandstone, siltstone, coal, and conglomerate. These rocks constitute the Tertiary Kenai Group which is made up of the West Foreland Formation, the Hemlock Conglomerate, and the Tyonek, Beluga, and Sterling Formations, in ascending order (Calderwood and Fackler, 1972). The formations are not distinguished on figure 1. The Kenai Group crops out only locally, although drill records show that thicknesses greater than 5,500 m (18,000 ft) occur beneath the lowland (Kelly, 1968). Most of the Kenai Group is overlain by unconsolidated Quaternary deposits, largely of glacial origin, that range from about a metre to more than 215 m (700 ft) in thickness.

STRUCTURE

Faults

Most destructive earthquakes are caused by movement along exposed or shallow faults; hence, the character and distribution of faults in the Kenai Lowland are of major importance. Faults were observed only in the southern part of the lowland and where rocks of the Tertiary Kenai Group are exposed. Faults are inferred to exist beneath the unconsolidated glacial, glacial fluvial, glacial lacustrine, alluvial, and marine sediments that blanket more of the area.

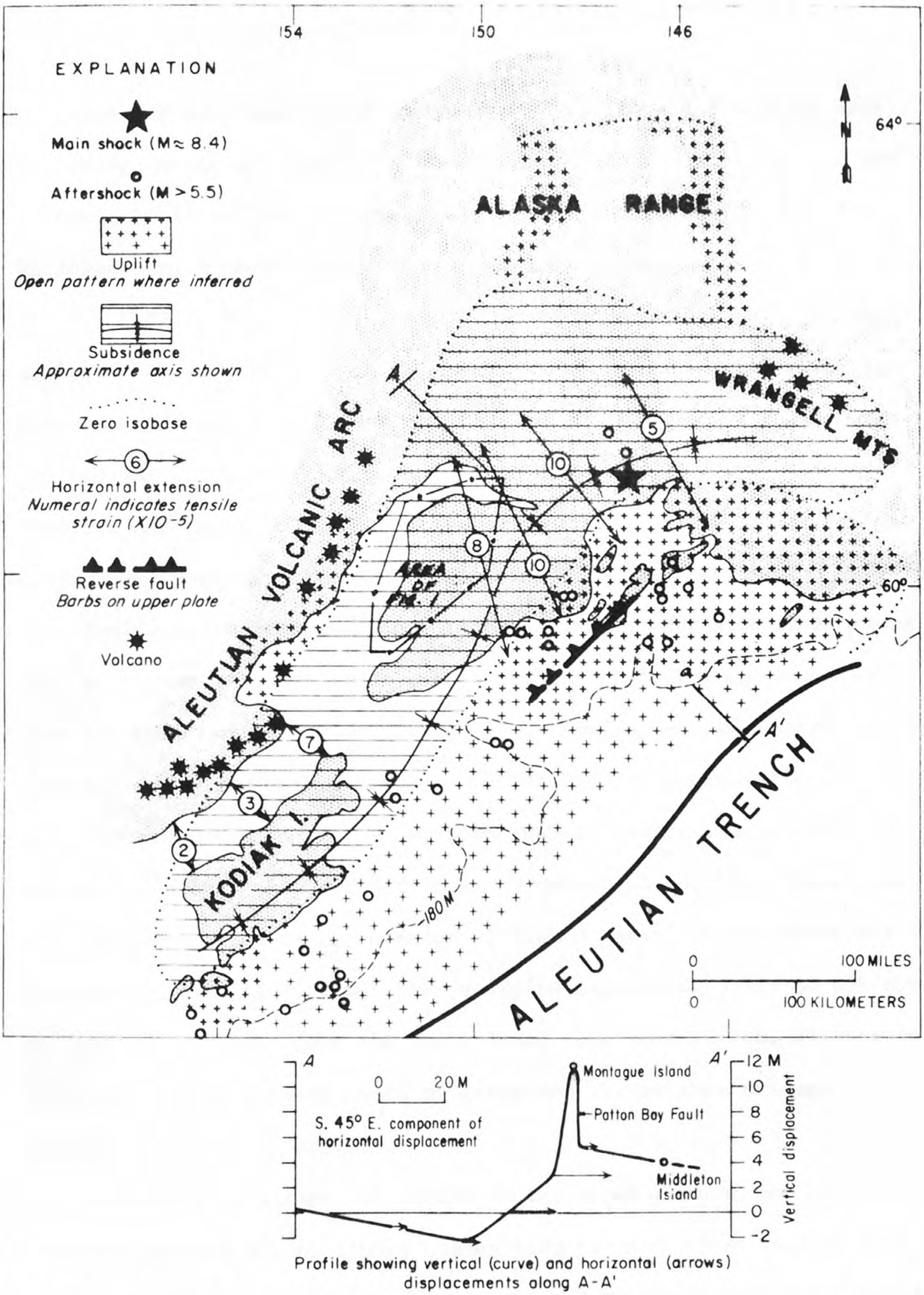


Figure 2.--Location of Kenai Lowland relative to Aleutian trench and volcanic arc (Lowland map area outlined by dot-dash line). Tectonic displacements and seismicity associated with the 1964 Alaska earthquake (after Plafker, 1972, fig. 2, p. 904).

Exposed faults

Bedrock outcrops in the southern part of the Kenai Lowland were mapped by Barnes and Cobb (1959) who noted that faults exposed in sea cliffs exhibit only minor displacements, not exceeding 27 m (88 ft). At least one, however, may have a displacement of as much as 60 m (200 ft) (J. Kelley, oral commun., 1974). The rock units cut by the faults are probably late Miocene or Pliocene in age (Wolfe and others, 1966; Kirschner and Lyon, 1973) and are overlain by unfaulted glacial deposits (Barnes and Cobb, 1959) of Naptowne age (Karlstrom, 1964). These glacial deposits are no older than about 14,000 years according to radiometric dating of correlative strata near Anchorage (Schmoll and others, 1972).

Faults are numerous in the bluffs along the west side of Kachemak Bay, northeast of Homer. The author studied 11 faults in this area, none of which offset the overlying soil. Some have been accentuated by erosion, and a few permit downward percolation of water and are thus conspicuous because of denser vegetation than in nearby areas; other faults are so tight that they are difficult to detect in the bluff face, and they are impervious to percolation of ground water. Talus marks the location of some faults, but the overlying glacial deposits do not appear to have been offset along the fault trace (see sketch, fig. 3), nor do observed lateral-growing roots of trees and shrubs show evidence of disruption in overlying soils.

Landslips or slumps are common in the upper part of the bluff along Kachemak Bay and are much more common than faults. They seem to bear no direct relation to faults but rather reflect movement caused by percolation of surface water into the soil and rock, in combination with a lack of lateral support at the cliff face or drainage channel.

Slumping is evident along the traces of a few faults, particularly where the fault trace coincides with a drainage course. Figure 4 illustrates a locality at which two scarps are caused by slumping. The scarps are quite fresh, cutting the soil and sod, but the fault itself is sealed and shows no sign of recent movement. Neither scarp is directly above the fault nor abuts it, and the height of each scarp exceeds the measured displacement of Tertiary strata on the fault. In a study made after the 1964 earthquake, Waller (1966a) noted a small landslide near a fault in the Homer area but was unable to find evidence for fault movement.

Concealed faults

Much of the Kenai Lowland is covered by glacial deposits that do not appear to have been disrupted by postglacial faulting. In such areas, information on concealed faults has been obtained primarily from geophysical data and from projection of structural elements in areas to the north where the geology is better known.

Border Ranges fault.--The Kenai Mountains adjoin the Kenai Lowland along a rather abrupt linear front, and the very linearity of the junction suggests that it might be a fault trace. The linear front is here inferred to be a segment of the Border Ranges fault (MacKevett and Plafker, 1974) that extends for more than 1,000 km (625 mi) from the Canadian border on the east through the northern Chugach, Kenai, and Kodiak Mountains. It is a major throughgoing structure that juxtaposes Paleozoic

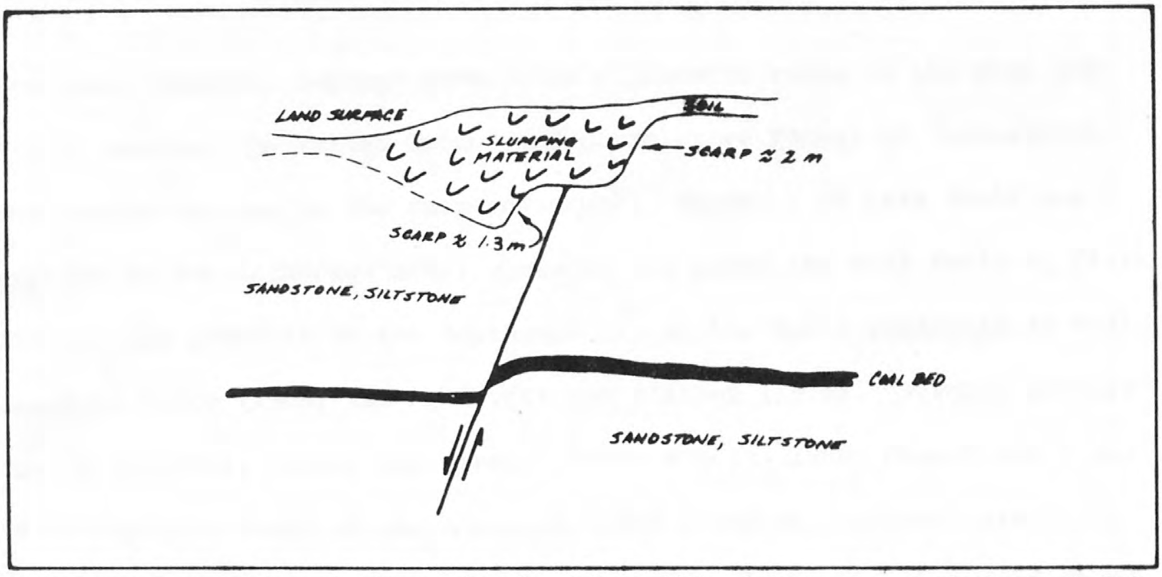


Figure 3.--Inactive fault emphasized by slide debris located about 1.5 km (1 mi) north of mouth of Corea Creek, south of Clam Gulch on west side of Kenai Lowland (after sketch by E. H. Cobb, written commun., 1950).

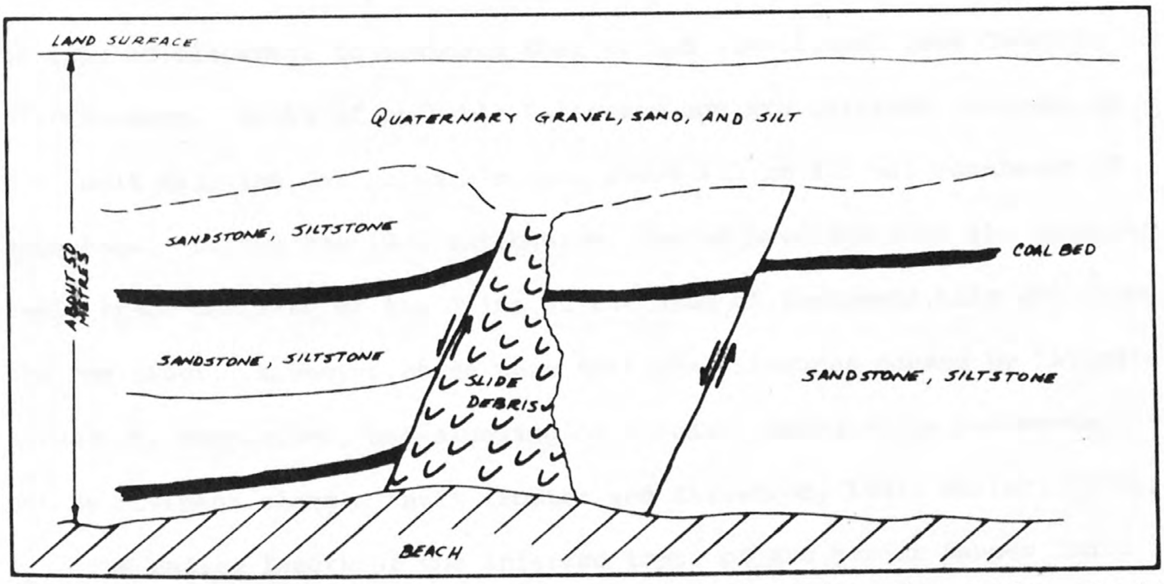


Figure 4.--Slumping of near-surface material above inactive fault. Fault is 3 km (2 mi) northeast of mouth of Fritz Creek, along Kachemak Bay, near Homer.

and lower Mesozoic terrane containing ultramafic rocks to the west and north, against the Valdez Group (and correlative rocks) of Jurassic(?) and Cretaceous age to the east and south. Segments of this fault are exposed in the Anchorage area, where it was named the Knik fault by Clark (1972), and possibly in the southwest tip of the Kenai Peninsula as indicated by Kelly (1968) and MacKevett and Plafker (1974). Several authors (cf. Hill, 1963; Osment and others, 1967; Woncik, 1968; Church and Lian, 1970) depict a fault at the mountain front trending southwestward along the axis of Kachemak Bay. However, geologic relations interpreted from early reconnaissance in this area (Martin and others, 1915) suggest that the Border Ranges fault probably cuts from the head of Kachemak Bay southwestward across the Kenai Mountains.

The Border Ranges fault is interpreted by MacKevett and Plafker (1974) to mark a plate boundary that developed near the close of the Mesozoic or in the early Tertiary. There is no evidence where the fault is exposed elsewhere to indicate that it had significant late Cenozoic displacement. Rocks of probable Paleocene age are deformed adjacent to the fault near the Matanuska Glacier, about 125 km (75 mi) northeast of Anchorage. During the 1964 earthquake, ground breakage near the inferred fault trace occurred on the delta at the head of Tustumena Lake and along the Fox River. However, these were surficial fissures caused by lateral spreading, compaction, and slumping of unconsolidated delta sediments, not by movement along a fault (Foster and Karlstrom, 1967; Waller, 1968).

The entire length of the inferred trace of the Border Ranges fault in the map area was flown at low altitude in a fixed-wing aircraft, but no evidence of recent faulting was recognized. Northeast of Tustumena Lake a broad piedmontlike surface known as the Bear Creek upland, which ranges from about 450 to 900 m (1,500 to 3,000 ft) in elevation, slopes gently from within the Kenai Mountains across the linear mountain front out into the Kenai Lowland for a distance of 25 km (15½ mi). The upland is covered with a veneer of muskeg and glacial drift and does not support trees except sparsely near its northwest end. A range-front fault would have to intersect the upland, and surface effects of recent movement should be visible if present.

At the south corner of the upland, Indian Creek has incised a canyon as much as 175 m (600 ft) deep, exposing the contact of bedrock in the Kenai Mountains with glacial sediments flanking the upland. Observation from a reconnaissance flight into the canyon suggests that the contact is depositional, and evidence for recent faulting was not seen. Some of the rock near the junction of the two units is discolored and apparently altered, however, suggesting the possible presence of a fault in bedrock at this locality.

The last movement on the inferred range-front fault of the Bear Creek upland apparently predates deposits (mapped by Karlstrom, 1960, 1964) of the Caribou Hills, Knik, Eklutna, and Naptowne Glaciations that overlie or flank the upland; it is not known if the fault cuts the Kenai Group. Near Anchorage, the Naptowne deposits are overlain by marine sediments formed about 14,000 years ago, and the Knik deposits immediately underlie the same sediments (Schmoll and others, 1972). The Eklutna Glaciation spans the time interval of about 42,000 to 60,000 years ago, according to Hopkins (1974, table I), and the Caribou Hills Glaciation may date from as much as 130,000 to 150,000 years ago (D. M. Hopkins, oral commun., 1974). Although none of these deposits in the Bear Creek upland appears to be offset, it seems possible that periglacial processes associated with the last major glaciation (Naptowne) could have acted to modify beyond recognition any prior scarp that may have been present along the fault. Thus, caution must be used in assigning the period of quiescence along the inferred fault, although it seems likely that the fault has not had significant vertical displacement during the Holocene.

Sterling fault.--A fault is inferred by Kirschner and Lyon (1973, fig. 15) beneath the Kenai Lowland, about 10 km (6 mi) west of and about parallel to the front of the mountains. This inferred fault, which is called the Sterling fault, coincides with the steepest part of a gravity gradient evident on the map of Barnes (1967, oral commun., 1974), the gradient being a conspicuous feature from Turnagain Arm southwestward to the vicinity of Tustumena Lake. The depression occupied by Tustumena Lake marks a topographic and lithologic contrast of areas to the north and south and may be the location of a large syncline oriented normal to the regional structural grain (Kelly, 1968). Geophysical evidence for the continuation of the fault southwest of the Tustumena Lake area is lacking. Evidence of ground breakage was not recognized on aerial photographs along this trend north of the lake, and the cross section in

Kirschner and Lyon (1973) shows that the fault does not offset the ground surface.

Homer fault.--Another northeast-trending concealed fault is present near Homer and is called the Homer fault. This subsurface fault, delineated by Kirschner and Lyon (1973), separates Mesozoic crystalline rocks on the east from Cretaceous sedimentary rocks on the west.

Kirschner and Lyon probably determined the location of the Homer fault from well data and geophysical data. There are only three exploration wells in the area, and the two that must provide control for the fault are present about 25 km (15½ mi) northeast of Homer. In the eastern one, the Anchor River No. 1 (Standard Oil Co. of California), Jurassic(?) rocks were penetrated at 2,051 m (6,725 ft), and the West Foreland Formation of Oligocene age is absent. In the other well, the Caribou Hills unit (Gulf Oil Co.), drilling was terminated in the West Foreland Formation at 3,078 m (10,091 ft) (American Stratigraphic Co. well logs). The two wells are only 3 km (2 mi) apart and provide narrow guideposts between which the fault must trend. In order for the fault to pass between these two wells and to strike northeast, its location must be about 5 km (3 mi) east of where Kirschner and Lyon (1973) show it.

There is no evidence for offset of the ground surface along the Homer fault from Homer north to the Caribou Hills. The fault trends beneath undisturbed deposits of the Naptowne Glaciation near Homer and of the Caribou Hills Glaciation at its locality in the Caribou Hills.

Near Homer, the fault trends between Kachemak Bay and Lookout Mountain, an area mostly devoid of outcrops. It seems that most of the movement along the fault must have occurred in the early Tertiary because the flat-lying Kenai Group exposed in outcrops east and west of the trace can be correlated across the fault without apparent offset (Barnes and Cobb, 1959). The portion of the Kenai Group in this area has been dated as Miocene or Pliocene by Wolfe and others (1966) and Kirschner and Lyon (1973).

Zone of ground breakage.--After the 1964 Alaska earthquake, a northeast-trending zone of concentrated ground breakage in unconsolidated deposits was delimited in the northern part of the Kenai Lowland by Foster and Karlstrom (1967). They suggest that this zone of ground breakage might be related to movement on a subsurface fault. The zone, described more fully in a later section, is about 9 km (6 mi) wide and 90 km (60 mi) long, extending from Kasilof on the east shore of Cook Inlet to Chickaloon Bay on the south shore of Turnagain Arm (fig. 1). The broken ground exhibits a mosaic of ground cracks and displacements resulting from slumping, differential compaction, or removal of underlying materials by ground-water eruption.

Foster and Karlstrom (1967) suggest that this zone of ground breakage might be related to movement on a subsurface fault. However, no discernible aftershock activity occurred along the postulated fault in the months after the earthquake, as would be expected for an active fault, and no evidence was found for vertical displacements where the extension of this inferred fault zone crosses postearthquake level lines of the U.S. Coast and Geodetic Survey south of Anchorage (Plafker, 1969, p. 26). Neither a fault nor a gravity high (buried ridge) is shown beneath the zone of ground breakage in cross sections of Church and Lian (1970), Kelly (1961, 1963, 1968), or Kirschner and Lyon (1973), which are based on extensive subsurface geophysical and well data. Similarly, aeromagnetic profiles (Grantz and others, 1963) and gravity data (Barnes, 1967) are not suggestive of faulting along this zone.

Folds

Tertiary sediments beneath the Kenai Lowland have been deformed into a series of en echelon folds with axes that trend north to northeast (Kelly, 1961, 1963, 1968; Kirschner and Lyon, 1973). According to Kirschner and Lyon (1973), virtually all of the anticlines are asymmetric with a steeper western flank that is commonly faulted on the topographicaly high part of major folds (fig. 5). The faults do not crop out, but because they are related to apparently growing anticlines, their locations are deemed significant. Anticlinal trends are shown on the map, along with accompanying faults for which data have been published. Faults probably flank the western sides of other anticlines, but available data are insufficient for verification.

Faults of lesser magnitude and a different character are also related to the anticlines. A structure contour map of the Swanson River anticline (figs. 5 and 6) shows several normal faults that trend approximately perpendicular to the anticlinal axis and thus perpendicular to the major

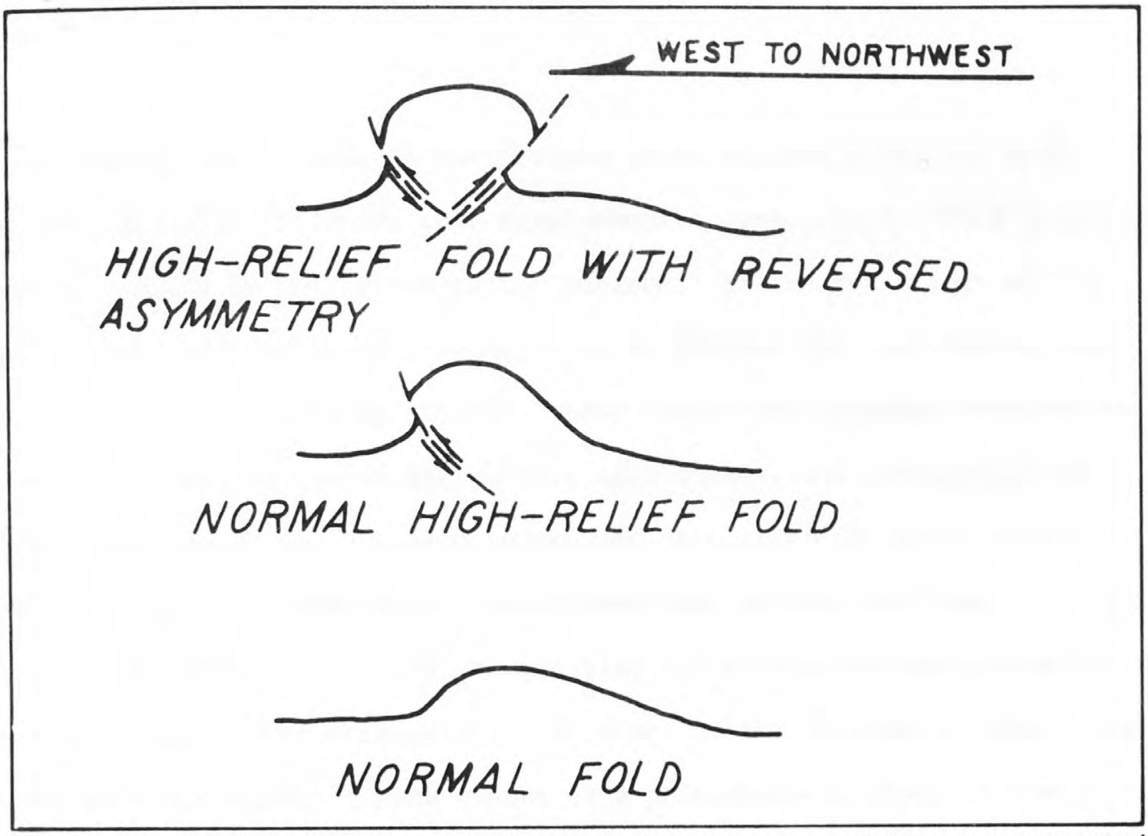


Figure 5.--Fold development in the Cook Inlet basin. Folds are asymmetric (steep to northwest), concentric in habit, and most involve pre-Tertiary rocks in their cores (after Kirschner and Lyon, 1973, fig. 17, p. 406).

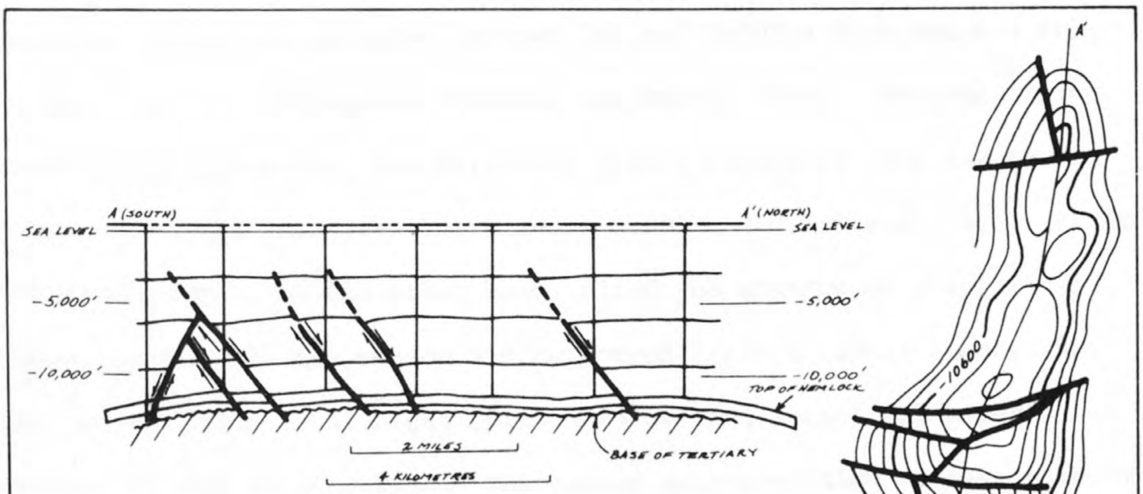


Figure 6.--Structure contour map and longitudinal section of the Swanson River anticline showing tensional normal faults developed as a result of stretching along the longitudinal axis of the fold. The faults appear to involve the pre-Tertiary and to diminish in throw and die out upward in the section (after Kirschner and Lyon, 1973, fig. 18, p. 406).

fault on its west flank. A north-south cross section along the anticlinal axis (fig. 6) shows that displacements gradually decrease upsection but the faults do not extend to the surface. If the anticlines of the Cook Inlet area are still growing, then it follows that the faults associated with them would be active. These faults are probably too limited in size to generate large destructive earthquakes, but movement along them could constitute a hazard to manmade structures in their immediate vicinity by both direct fault displacement and seismic shaking.

Raised tidal flats with accompanying radial drainage and an eastward-deflected major stream channel at the mouth of the Chickaloon River were noted by Kelly (1961) in the course of a photogeologic study of the Kenai Lowland. Similarly, uplifted tidal flats were noted by Karlstrom (1964) at the mouths of the Kenai, Kasilof, and Chickaloon Rivers. They indicate emergence of 1-1/2 to 3 m (5 to 10 ft) relative to present sea level datum in areas that subsided between 1/2 and 1-1/3 m (1.5 and 4.5 ft) during the 1964 earthquake (Plafker and Rubin, 1967). The age of the tidal flats is unknown, but Karlstrom (1964) suggested they may record a maximum marine transgression between 5,000 and 6,000 years ago. Plafker and Rubin (1967), on the other hand, cited the absence of similar features elsewhere in the region and supported Kelly's (1963) theory that they are probably local highs related to growing anticlinal structures within the Cook Inlet region. The latter interpretation is supported by the existence of young anticlinal structures elsewhere in the Cook Inlet area (Kelly, 1961, 1963, 1968).

Drainage anomalies like those of the uplifted tidal flats are common in the Kenai Lowland, particularly in the northern part, and several of them are known to occur above subsurface anticlines. Assuming that the anomalies inland also reflect growing anticlines, they may also be areas of potential faulting, as discussed above. However, the faults are short and shallow so that they are not likely to produce damaging earthquakes even if they are active.

COOK INLET BATHYMETRY

Nautical charts (nos. 8531, 8553, 8554) of Cook Inlet and Kachemak Bay were contoured at 9-m (5-fathom) intervals in an attempt to delineate active structural features. The bathymetry data proved inconclusive because the detectable linear trends are parallel to tidal flow, and increases in water depth along linear trends are apparently due to scour where basin geometry serves to constrict water flow. Submerged wave-cut platforms were not detected. The area was largely covered by ice during the last glaciation, as well as during several earlier ones (Karlstrom, 1964), and irregularities in bottom topography that may have existed are probably modified by ice scour and unconsolidated glacial deposits.

SEISMICITY

One of the goals of the present study was to determine if a correlation exists between epicenters of shallow earthquakes and geologic structures; the sparse, shallow seismicity thus far recorded does not correlate with known faults nor does it define near linear trends suggestive of faulting. The epicenters of most earthquakes recorded for the Kenai

Lowland prior to the 1970's are probably not located with sufficient accuracy to make a reliable correlation because there were few seismographs in or near the map area. In 1971, a network of eleven seismograph stations, three of which are in the Kenai Lowland, was installed in south-central Alaska by the U.S. Geological Survey. One of the main purposes for the network is to evaluate seismic hazards in the Cook Inlet region. The first catalog of earthquakes compiled from the network data, for the period April through June 1972 (Lahr and others, 1974), lists 25 earthquakes with hypocenters beneath the Kenai Lowland. Of these, only three earthquakes have a focal depth of 16 km (10 mi) or less and might correlate with geologic structures in the uppermost part of the earth's crust. They are plotted on figure 1 and listed below:

Sta.	Date	Latitude North		Longitude West			
no.	1972	Deg.	Min.	Deg.	Min.	Depth (km)	Magnitude
L-1	April 13	60	50.2	150	43.7	9.0	2.1
L-2	April 18	60	20.9	150	42.5	9.0	2.4
L-3	June 26	60	37.9	150	46.0	13.3	1.9

The epicenters for the earthquakes of April 13 and June 26 cannot be associated with any recognized geologic structure. The epicenter of the April 18 earthquake is about 1.5 km (1 mi) east of the Sterling fault near the Funny River and could conceivably lie along this fault. In a section across the fault about 40 km (25 mi) to the north, Kirschner and Lyon (1973) show the fault plane dipping steeply to the east. If the dip is similar near the Funny River, the earthquake would be several kilometres west of the fault plane at the hypocentral depth of 9 km (5.6 mi).

Gedney and VanWormer (1974) employed imagery from NASA's ERTS-1 satellite in an effort to identify zones of seismic risk in central and southern Alaska. They used the imagery to draw linears having the appearance of faults and as a base on which to superimpose epicenters of earthquakes recorded in 1972 by the University of Alaska seismology program and a few epicenters determined by NOAA. The resulting mosaic was used to determine areas that might be active seismically.

Two of the epicenters occur within the Kenai Lowland. No. 72 (G-72 at 60.3 N. lat., 151.2 W. long.) is for an earthquake that had a magnitude of 5.0; it does not correlate with any recognized geologic structure. The other epicenter, no. 16 (G-16 at 60.1 N. lat., 150.3 W. long.), is for an earthquake with a magnitude of 4.0 and is shown by Gedney and VanWormer (1974) to coincide with a linear along the front of the Kenai Mountains (Border Ranges fault, shown in figure 1). However, a check of the coordinates of no. 16 shows it to be within the Kenai Mountains about 19 km (12 mi) east of the linear. In any case, evidence of recent faulting has not been found along the linear shown by Gedney and VanWormer, either near the location of epicenter numbers 72 or 16 as plotted by them, nor along any other linear trend in the Kenai Lowland.

GEOLOGIC CONTROL OF DAMAGE FROM THE 1964 ALASKA EARTHQUAKE

The seismic events discussed in the previous section are of low to moderate magnitude (1.9 to 5.0). The 1964 Alaska earthquake was a major seismic event, with a magnitude estimated to have been about 8.4, and caused widespread damage throughout an area of about 130,000 km^2 (50,000 mi^2) (Plafker, 1969). The epicenter was located about 200 km (120 mi) northeast of the center of the Kenai Lowland (fig. 2), and the reaction of the ground in the lowland during the earthquake is considered a good indication of what ground response will be during future large earthquakes.

It has long been recognized that different types of ground react differently during an earthquake (Barosh, 1969). The intensity of seismic shock from the 1964 earthquake, and the resulting damage to manmade structures, was greatest in the area of unconsolidated deposits, particularly where the ground was saturated with water (Foster and Karlstrom, 1967; Plafker and others, 1969). Unconsolidated deposits of the Kenai Lowland are thickest and most widespread in the area north of Tustumena Lake. They consist mainly of Quaternary glacial till, glaciolacustrine and glaciofluvial deposits, pro-glacial lake sediments, marine sediments, alluvium, loess, and clay. These deposits are more than 215 m (700 ft) thick beneath the city of Kenai, about 100 m (300 ft) thick near Boulder Point 25 km (15 mi) to the north, but only a few metres thick where the Tertiary Kenai Group crops out along the beach 25 km (15 mi) to the south of the latitude of Tustumena Lake (Anderson, 1971; Anderson and Jones, 1972).

South of Tustumena Lake unconsolidated deposits form a veneer only a few metres thick above the Kenai Group, except at Homer Spit, which consists of a thick accumulation of marine gravel and sand. The Kenai Group crops out along much of the coast and in a few large areas inland.

Fracturing and slumping

The main types of ground breakage in the Kenai Lowland that resulted from the 1964 earthquake were (1) fracturing and the extrusion of sand

and gravel with water along fractures in various types of land forms, and (2) slumping and lateral extension of unconfined faces, particularly along delta fronts (Foster and Karlstrom, 1967). Most of the breakage was confined to a zone about 90 km (60 mi) long and 9 km (6 mi) wide extending from Kasilof on the east shore of Cook Inlet to Chickaloon Bay on the south shore of Turnagain Arm. Within the zone, the localities of ground cracking occur (1) on terraced morainal slopes and crests underlain by thick sections of compact till, (2) on channeled plains flanking moraines and underlain by thick sections of mainly sand, (3) in inter-moraine depressions underlain by sand and silt, and (4) on elevated tidal flats underlain by silt and sand. No consistent relation was found between the cracks and the topography or the underlying unconsolidated deposits (Foster and Karlstrom, 1967).

The cracks were as much as 30 cm (1 ft) across and were sharp, vertical, and straight with abrupt angular changes in trend. Vertical and horizontal displacements of as much as 60 cm (2 ft) occurred along some cracks. Most displacements appeared to be primarily the result of adjustment in the surficial materials by slumping and differential compaction or of removal of underlying materials by ground water eruption. Eruption of ground water was common throughout the zone as evidenced by sand dikes, collapse pits, and outpourings of sand.

Ground cracks and similar associated evidence of eruption of ground water were noted in the uplifted tidal flats near Kasilof and Chickaloon Bays, although ground cracking was not observed on several other tidal flats. Ground cracking was observed in outwash deltas at the heads of several lakes, including Tustumena and Skilak Lakes. The delta front in Skilak Lake failed by fracturing and slumping, partially submerging the delta front over an area about 0.8 km (1/2 mi) wide. Most cracks in the Tustumena delta showed no vertical displacement, but minor subsidence was noted on the lake side (Foster and Karlstrom, 1967; Waller, 1966a).

No evidence was found for the cause of localization of the northeast-trending zone of intense ground fracturing of Foster and Karlstrom (1967), shown in figure 1. The types of unconsolidated deposits present within the zone are also common in the area to the northwest between the zone and Cook Inlet, and the lack of similar ground fracturing there is unexplained. Perhaps the difference is only apparent owing to a lower density of observations in this sector because of limited accessibility and dense timber coverage. On the basis of deposits shown by Karlstrom (1964) in the area and on the similar topography, one would expect vibration damage and ground fracturing resulting from an earthquake to be about the same in the two areas.

North of Tustumena Lake, between the zone of intense ground fracturing and the moraines at the mountain front, the topography has less relief and less potential for ground slumpage. The area is not dotted with lakes as is the zone of intense ground fracturing and the area northeast of it, indicating that the drainage of ground water is better and that the potential for vibratory damage may be lessened somewhat.

Slumping and lateral flowage were noted in several other areas after the 1964 earthquake, and similar effects would be expected from future earthquakes. Adjacent to the front of the Kenai Mountains are unconsolidated deposits of morainal material that showed only minor slumping during the 1964 earthquake. Similar slumping was noted along the margins of Tustumena Lake in unconsolidated deposits with unconfined faces. Slumping of similarly situated deposits was noted locally elsewhere south of Tustumena Lake, particularly along river banks and beach bluffs (Foster and Karlstrom, 1967; Waller, 1966a).

Several landslides were noted northeast of Homer on moderate to steep slopes. Waller (1966a) described one landslide as 183 m (600 ft) long and 30 m (100 ft) wide along a bluff in the Kenai Group. Waller noted that several other localities in the Homer area have the potential for landsliding. He described fissuring of the ground near the edges of bluffs and pointed out that areas near bluffs should be avoided as building sites. An earthflow near Homer, which Waller also noted, measured about 300 m (1,000 ft) long and 120 m (400 ft) wide.

Subsidence

The Kenai Lowland lies within the zone of tectonic subsidence that resulted from the 1964 earthquake. The south shore of Kachemak Bay subsided about 1.2 m (4 ft), and subsidence of the lowland elsewhere is estimated to range from 1.2 m (4 ft) along the east margin to less than 0.6 m (2 ft) along the Cook Inlet side (Plafker, 1969, fig. 3); local exceptions were noted at the mouths of some rivers.

The submergence resulting from the 1964 earthquake is believed to be a regional phenomena that can be expected to recur during future earthquakes; hence, this should be taken into consideration in rural and urban development of low-lying areas along the shores of the Kenai Lowland.

Homer Spit subsided as much as 1.8 m (5.9 ft) during the 1964 earthquake as a result of compaction, lateral spreading, and tectonic subsidence. Fissures were common on the spit, and submarine slides occurred at the end of it. The effect on manmade structures was considerable as the area is the locus of several businesses. Waller (1966a, p. 14) speculated that part of the subsidence was caused by liquefaction of water-bearing silt layers at depth in the spit. Liquefaction was caused by the earthquake shocks, and future large earthquakes could be expected to have a similar effect.

Seiches and tsunamis

Low-lying areas are susceptible to runup of waves caused by seiching and tsunamis. No tsunami resulting from the 1964 earthquake affected the Kenai Lowland, but an earthquake with an epicenter located in the Cook Inlet area could conceivably generate a tsunami that might damage shoreline structures. Dall (1884), for example, reported than an estimated 9-m (30-ft) wave struck the south shore of Kachemak Bay after the 1883 eruption (and (?)earthquake) of a volcano on Augustine Island which is located about 110 km (70 mi) southwest of Homer. Seiches, however, can form with any major earthquake in the region. Seiching occurred on Tustumena and Skilak Lakes during the 1964 earthquake (Waller, 1966b).

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