The Alaska Earthquake
March 27, 1964

Regional Effects

Slide-induced waves, seiching and ground fracturing at Kenai Lake

GEOLOGICAL SURVEY PROFESSIONAL PAPER 543-A

THE ALASKA EARTHQUAKE, MARCH 27, 1964:
REGIONAL EFFECTS

Slide-Induced Waves, Seiching And Ground Fracturing Caused by the Earthquake Of March 27, 1964 At Kenai Lake, Alaska

By DAVID S. McCULLOCH

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THE ALASKA EARTHQUAKE SERIES

The U.S. Geological Survey is publishing the results of investigations of the Alaska earthquake of March 27, 1964, in a series of six professional papers. Professional Paper 542 describes the effects of the earthquake on Alaskan communities. Professional Paper 543 describes the earthquake's regional effects. Other professional papers will describe the effects on the hydrologic regimen; the effects on transportation, communications, and utilities; and the history of the field investigations and reconstruction effort.

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SLIDE-INDUCED WAVES, SEICHING, AND GROUND FRACTURING CAUSED BY THE EARTHQUAKE OF MARCH 27, 1964, AT KENAI LAKE, ALASKA

By David S. McCulloch

ABSTRACT

The March 27, 1964, earthquake dislodged slides from nine deltas in Kenai Lake, south-central Alaska. Sliding removed protruding parts of deltas—often the youngest parts—and steepened delta fronts, increasing the chances of further sliding. Fathograms show that debris from large slides spread widely over the lake floor, some reaching the toe of the opposite shore; at one place debris traveled 5,000 feet over the horizontal lake floor.

Slides generated two kinds of local waves: a backfill and far-shore wave. Backfill waves were formed by water that rushed toward the delta to fill the void left by the sinking slide mass, overtopped the slide scrap, and came ashore over the delta. Some backfill waves had runup heights of 30 feet and ran inland more than 300 feet, uprooting and breaking off large trees. Far-shore waves hit the shore opposite the slides. They were formed by slide debris that crossed the lake floor and forced water ahead of it, which then ran up the opposite slope, burst above the lake surface, and struck the shore. One far-shore wave had a runup height of 72 feet.

Kenai Lake was tilted and seiched; a power spectrum analysis of a limnogram shows a wave having the period of the calculated uninodal seiche (36 minutes) and several shorter period waves. In constricted and shallow reaches, waves caused by seiching had 20- and 30-foot runup heights.

Deep lateral spreading of sediments toward delta margins displaced deeply driven railroad-bridge piles, and set up stress fields in the surface sediments which resulted in the formation of many shear and some tension fractures on the surface of two deltas.

INTRODUCTION

Most of the loss of life and damage to property during the Alaska earthquake of 1964 was caused by waves that inundated coastal communities. Some of the waves were of the tsunami type, some were seiches, and some were caused by submarine sliding including slides from the margins of deltas.

Along the coastline of Prince William Sound, the deltas provide almost the only flat land for building sites that is far enough from the steep fiord walls to be safe from avalanches yet close enough to sea level to be useful as harbors. Consequently, waves produced by slides along the delta margins assume great importance. Many residents of these coastal communities realized immediately that some of the waves that washed over the deltas were caused by slides from the delta edges (Grantz and others, 1964).

During the months following the earthquake, geologists of the U.S. Geological Survey studying some of these communities (Henry Coulter, Reuben Kachadoorian, Richard Lemke) and geologists studying the shoreline of Prince William Sound (Lawrence Mayo, George Plafker) attempted to distinguish between damage caused by tsunamis, by seiches and by waves produced by local submarine slides. To assist in making these distinctions, bathymetric contour maps were made in some areas of suspected sliding. Areas of erosion and deposition could be clearly outlined by comparing preearthquake and postearthquake bathymetry, and at one place (Kachadoorian, 1965) sliding has been related to a wave that swept over a delta.

In a study of earthquake damage to The Alaska Railroad, the author and M. G. Bonilla examined landslides from deltas in Kenai Lake. At three places, there was clear evidence that the slides had created local damaging waves. As these waves came ashore carrying broken pieces of lake ice as much as 2 feet thick they tore blocks of frozen sediment weighing as much as 50 tons from the delta surface. Some waves were 30 feet high and ran inshore for 320 feet. Waves broke off large spruce trees or tore them out by the roots, and drove them inland like battering rams.

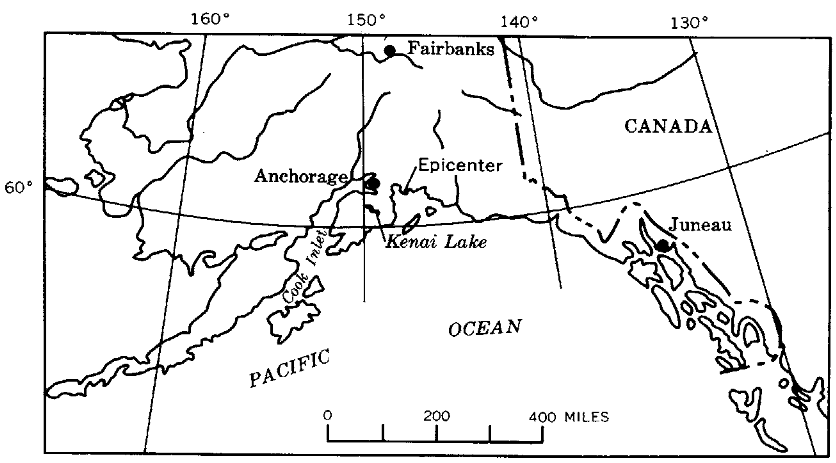
The author, assisted by Lawrence Mayo, made a bathymetric map of the lake and mapped the wave damage along its shoreline. This study showed that underwater areas of erosion and deposition caused by sliding can be mapped, that a characteristic wave pattern is caused by landslides, that some slides may occur without producing waves, and that certain parts of deltas may be more susceptible to sliding than others. A seiche formed in the lake, but in most places the effects of the seiche could be clearly distinguished from those of the slide-induced waves.

Several deltas were laced with a network of ground fractures caused by the earthquake. Some of this fracturing seems to be related to the stress formed in the surface material of the delta by the lateral spreading of the underlying sediments.

The author is grateful to his colleagues in the U.S. Geological Survey both for assistance in the field and for much helpful discussion. M. G. Bonilla collected some of the field data. David Dawdy helped with the analysis of a limnogram lent to the author by R. A. Johnson of the Chugach Electric Association, and Richard Singleton of Stanford Research Institute made the computer program for this analysis available. John Ingram of Cooper Landing, Alaska, provided lake-level data for Kenai Lake; Lee Gotch of The Alaska Railroad and Frank Buskie of the Alaska Department of Highways, assisted the author in surveys to establish the amount of tilting in the Kenai Lake basin.

LOCATION AND PHYSIOGRAPHIC SETTING

Kenai Lake lies in a narrow, glacially scoured trough near the center of the Kenai Peninsula in south-central Alaska (fig. 1). The lake is 60 miles south of Anchorage and 80 miles southwest of the calculated position of the epicenter of the 1964 earthquake. The lake is about 23 miles long and averages $1\frac{1}{3}$ miles wide. Its deepest part is approximately 135 feet below sea level and the steep rock walls on either side reach altitudes of 3,000–4,000 feet; were the lake open to the sea it would be a fiord.



1.—Index map showing location of Kenai Lake.

Deltas have been built by creeks flowing down the steep valley walls, by rivers flowing into the eastern arm of the lake, and by a river that enters the lake at the junction of the two western arms. The lake is drained by Kenai River which flows out of the lake at its western end near the town of Cooper Landing, then westward into Skilak Lake and eventually into Cook Inlet at the town of Kenai.

In plan the lake has four straight segments, three of which join at abrupt angles. Although Martin, Johnson, and Grant (1915) showed no faults in this area, the rectilinear shape of the basin suggests that it is structurally controlled.

BATHYMETRY

The underwater contours of the lake were plotted by making 85 traverses across the lake in a 14-foot skiff powered by an outboard motor. Soundings were made with a portable continuously recording fathometer (Triton, model F-712-A). A transducer having a sounding pulse rate of 50 kc was placed in a few inches of water in the stern of the boat so that it would give the strongest return signal on the fathogram. A speed of approximately 8 miles per hour gave the best signal-to-noise ratio. Sounding traverses were run between points on shore identifiable on aerial photographs. Sidewise drift was kept to a minimum by lining up trees with the point on shore at the end of the traverse. The locations of the sounding traverses, the bathymetric map constructed from them, and some typical cross sections of the lake are shown on plate 1.

The lake basin is a flat-floored trench bounded in places by extremely steep rock walls. The flatness of the floor is interrupted only by deltas and a single bedrock island. The lake is 570 feet deep or 135 feet below sea level at its deepest point, which is about 2½ miles east of Porcupine Island (pl. 1, section *C–C′*). Subbottom reflections recorded on the fathograms show the lake floor to be underlain by horizontal layers of unconsolidated lacustrine sediment that form a smooth bottom surface having a sharp break in slope at the junction with the basin walls.

SLIDES AND SLIDE-GENERATED WAVES

The earthquake triggered slides from nine deltas in Kenai Lake (pl. 2). Some of these slides caused two kinds of destructive local waves. One kind, which will be called a "backfill wave," was formed by water that rushed toward the delta to fill the void left by the sliding mass, overtopped the scarp, and ran inland, inundating the edge of the delta. The other kind of wave, which will be called the "far-shore wave," hit the shore opposite the delta. The fact that the far-shore wave struck the shoreline adjacent to the area on which the debris from the slides was deposited suggests that the movement of the slide debris out across the lake floor was directly related to the movement of the water which caused the far-shore wave.

Waves produced by the sliding of material that was in large part or wholly subaerial are well known and have been described, for example, by Miller (1960), Wiegel (1964, p. 85–87), and Kiersch (1964). However, waves induced by sliding material that was mostly submerged are neither common nor well described. The single example known to the author of a slide-generated wave of the backfill type is the destructive wave that resulted from the earthquake-triggered slide at Port Royal, Jamaica, in 1692 (Heath, 1748; Link, 1960). Similarly the author has found only one example in the literature of a disturbance of water related to the movement of slide debris across the bottom of a body of water which may be similar to the suggested generative process of the far-shore wave (Heim, 1932, p. 42).

Slides from deltas also occurred without producing detectable waves. One such slide carried away 260 feet of railway roadbed on the delta of Rocky Creek.

Being ice-laden, the Kenai Lake waves probably caused more destruction than waves of similar heights in Prince William Sound. Between the time of the earthquake and the time that the wave heights were measured the lake rose 5½ feet. Wave heights corrected to the lake level at the time of the earthquake are shown on plate 2. This rise in lake level obscured the evidence of minor wave action along the eastern arm of the lake and as far west as Cooper Landing that was clearly visible on aerial photographs taken soon after the earthquake.

LAKEVIEW SLIDES

At Lakeview there were two slides from the delta built by Victory Creek (also called Victor and Vicory Creek) into Kenai Lake—a north-facing and a larger west-facing slide. These slides and the waves they generated are described first because the relationship between the slides and their waves is clearer here than elsewhere.

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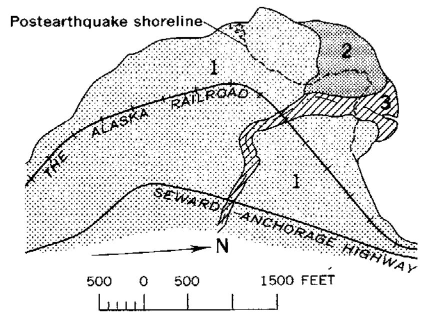
DEPOSITIONAL UNITS ON THE DELTA

At least three depositional units can be recognized on the Lakeview delta surface on an aerial photograph taken in 1951 (fig. 2). The oldest of these, unit 1, is the highest; it has a somewhat irregular surface and is covered with mature spruce trees. The surface has been so modified since deposition that stream channels which must have been present at one time are no longer visible. Unit 2, the next younger unit, is somewhat lower and is covered by low brush; there are many abandoned stream channels. On a photograph probably taken in 1911 (Martin and others, 1915, pl. 27*A*), unit 2 was bare of vegetation and its surface was laced with distributary channels. Unit 3, the youngest unit, was deposited on the northern edge of the delta; its deposition seems to have started just prior to 1911. When photographed in 1951, this unit was still being formed at the mouth of the creek and was still bare of vegetation. The slides removed some of units 1 and 2, and nearly all of unit 3.

All three units, as exposed in the major slide scarps or in scarps of small slumps on the surface of the delta, consist primarily of sandy gravel of subangular to subround platy pebbles and cobbles, and some boulders of metasediment. On the major slide scarps the exposed beds are thick and lensing, and contain only an occasional thin sand lens of short lateral extent.

DESCRIPTION OF SLIDES

The location of the major slide scarps (fig. 2) suggests that the position of the scarps is not governed in any obvious way by the boundaries of the three depositional units. The north-facing scarp cuts across all three units and the west-facing scarp cuts across two units. Sliding seems to have been localized in areas that protrude from the edge of the delta. Such areas are probably more susceptible to sliding than adjacent areas because they are the parts of the delta having the largest amount of material bounded by the shortest possible surface of rupture.



2.—Distribution of depositional units on Lakeview delta.

The curved surface of rupture along which the sliding occurred (fig. 5) suggests that the west-facing slide was a rotational slump (Varnes, 1958, p. 21). It is well known that earthquakes can cause rotational slumps. Terzaghi (1950, p. 89–91) and Taylor (1948, p. 452) have shown that horizontal accelerations in the direction of the free slope increase the shearing stress along the potential sliding surface of rotational slumps. The lateral spreading of the delta sediments suggests that there may have been a considerable loss of strength in the sediments. This would undoubtedly have reduced the resistance to failure along a potential surface of rupture and would have promoted the sliding.

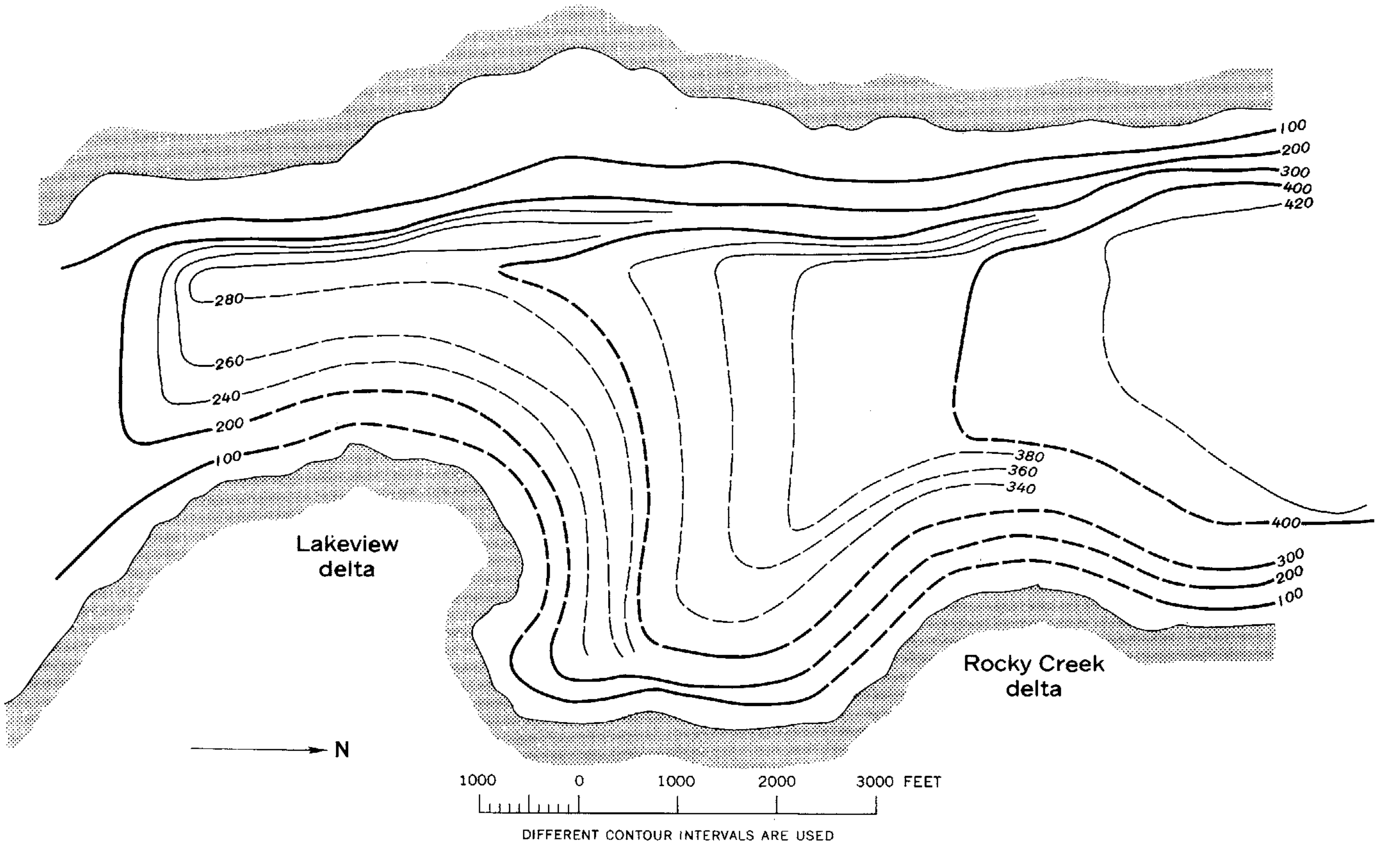
The location of the debris from the Lakeview slides can be approximated by comparing the presliding and postsliding bathymetry (figs. 3 and 4). The presliding bathymetry was reconstructed by extending contours from areas in which there was no evidence for sliding. These contours were drawn by assuming that the delta front was a smooth curve and that the lake floor was as flat here as elsewhere.

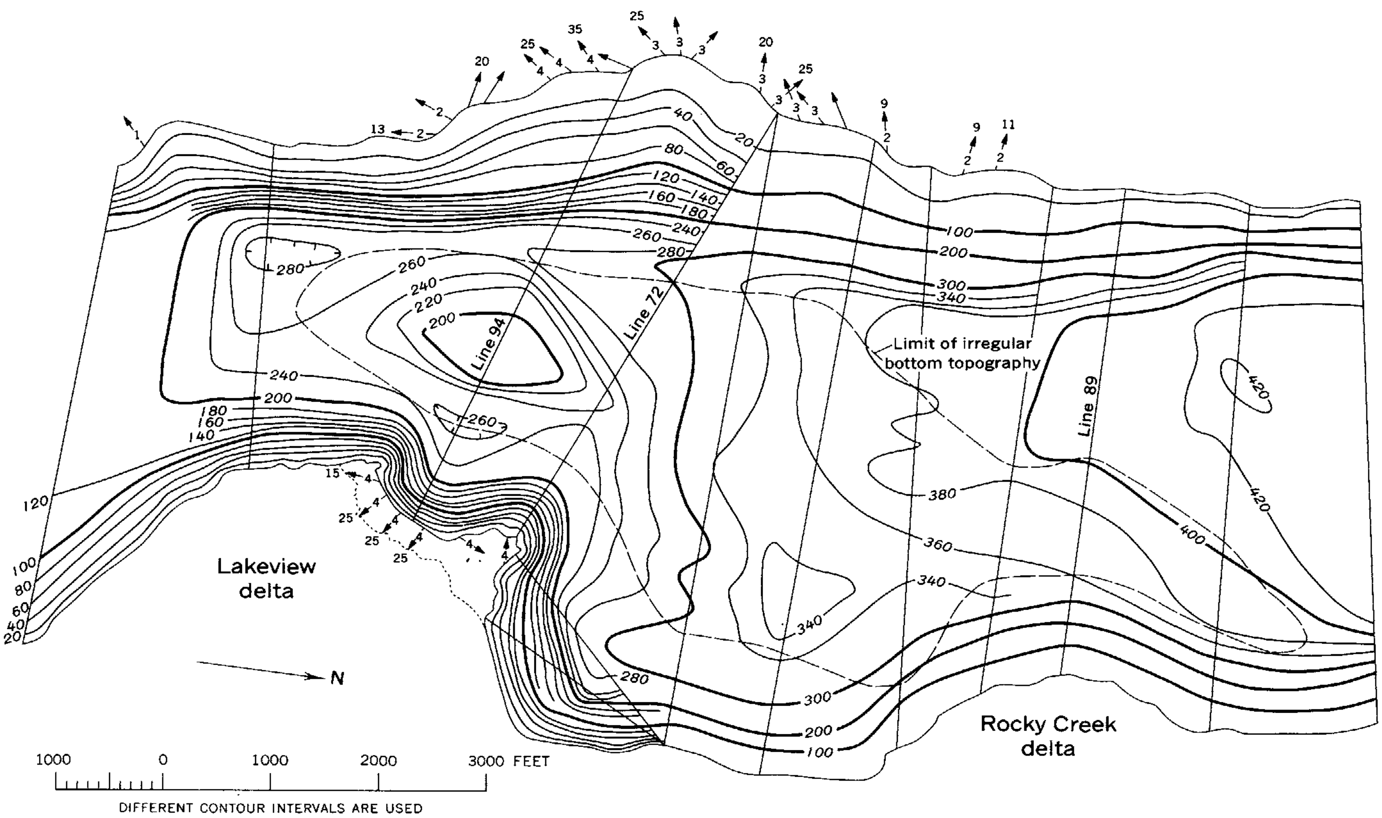
3.—Preslide bathymetry off Lakeview and Rocky Creek deltas. Contours solid in areas in which no sliding is thought to have occurred and dashed where reconstructed in areas of erosion and deposition. ⟶

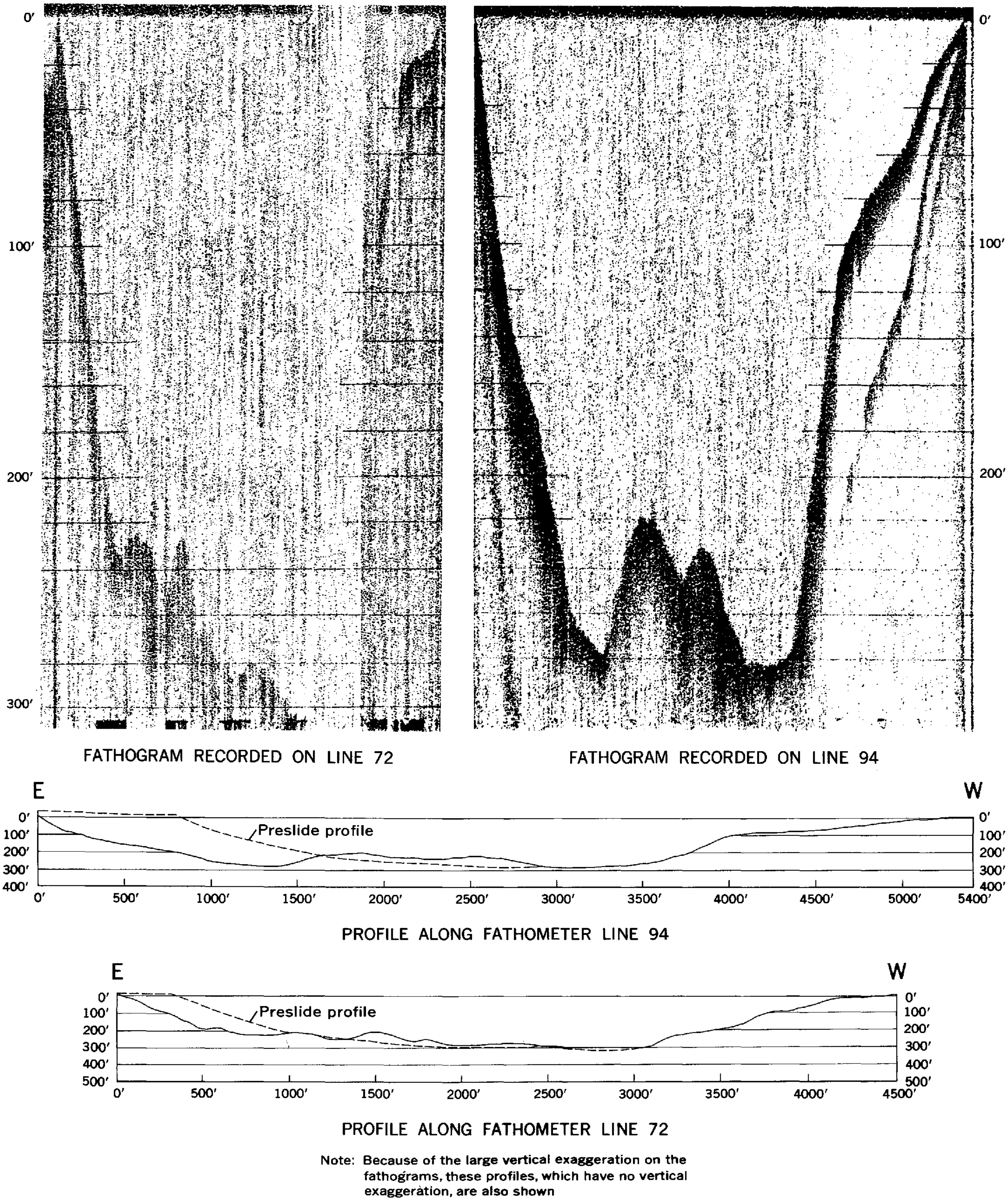
The west-facing slide cut an arcuate scallop from the delta. The sliding took place along an irregular curved surface, its lower part extending below the lake floor. The scarp has a slope of about 44° in the upper 15 feet, 28° to a depth of 75 feet, and finally about 11° to a depth of 285 feet. It then rises in a reverse slope at an angle of about 13°.

During deposition the slide material must have spread laterally because there is a great difference between the volume of material removed from the delta and the material deposited at the base of the

4.—Postslide bathymetry off Lakeview and Rocky Creek deltas showing direction (arrow), magnitude of damage (on arrow shaft), and runup heights (at arrow point, in feet) of slide-induced waves. ⟶


100
200
300
400
420
280
260
240
200
100
380
360
340
400
300
200
100
Lakeview delta
Rocky Creek delta
N
1000 0 1000 2000 3000 FEET
DIFFERENT CONTOUR INTERVALS ARE USED


Line 94
Line 72
Line 89
Limit of irregular bottom topography
100
200
300
340
380
360
340
400
420
280
260
240
220
200
120
Lakeview delta
Rocky Creek delta
N
1000 0 1000 2000 3000 FEET
DIFFERENT CONTOUR INTERVALS ARE USED



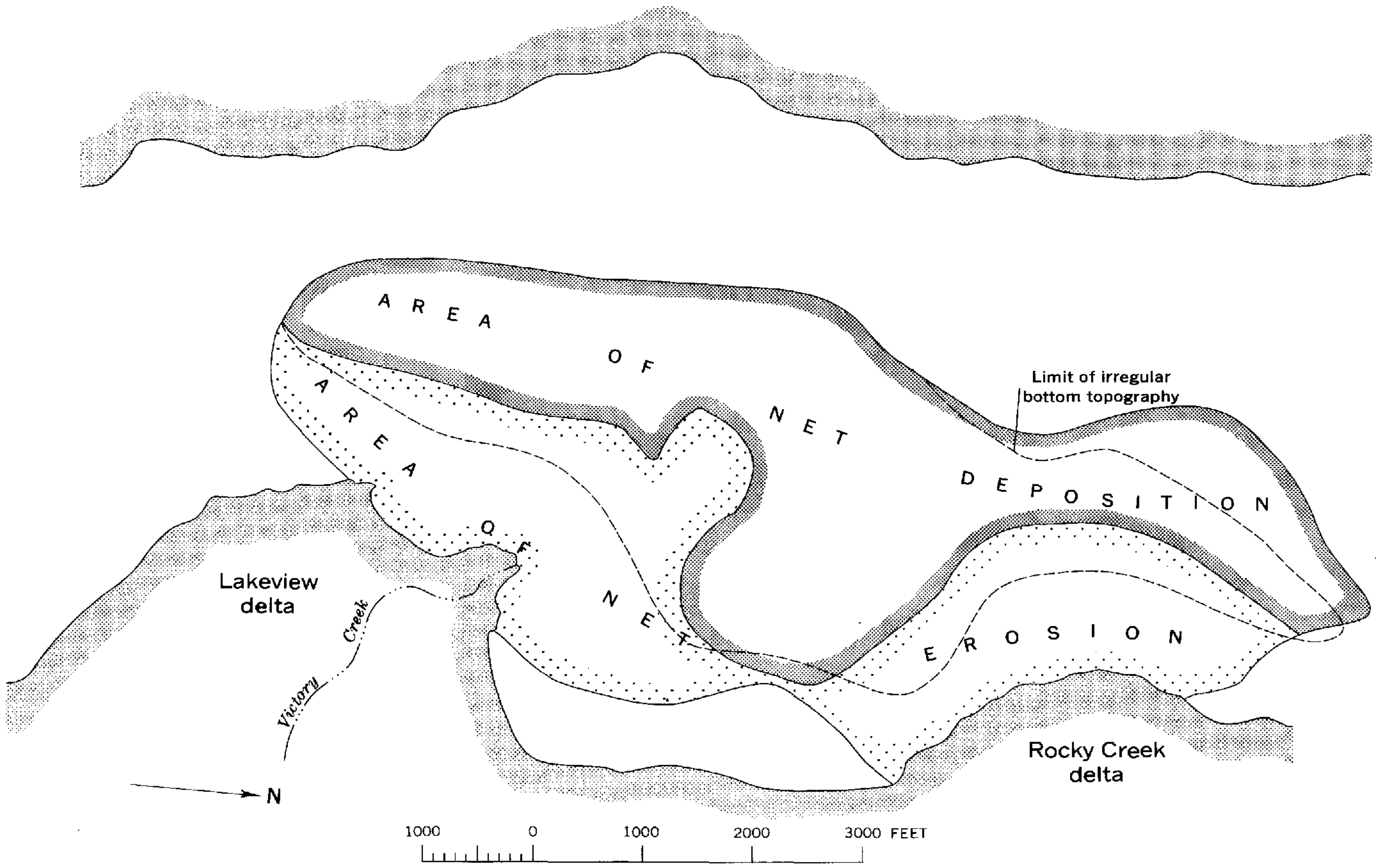
5.—Fathograms and profiles of Lakeview delta slides. Lines of profiles are shown on figure 4.

scarp (fig. 5). The extent of lateral spreading can be estimated two ways: first, by noting the area of deposition indicated by the pre-earthquake and postearthquake bathymetry; and second, by outlining the areas of rough bottom topography shown on the fathometer profiles (fig. 6). The boundary of the irregular topography coincides approximately with the western edge of the depositional area, but the eastern boundary lies within the zone of erosion. This relationship suggests that the lower part of the slide scarps are covered by slide material.

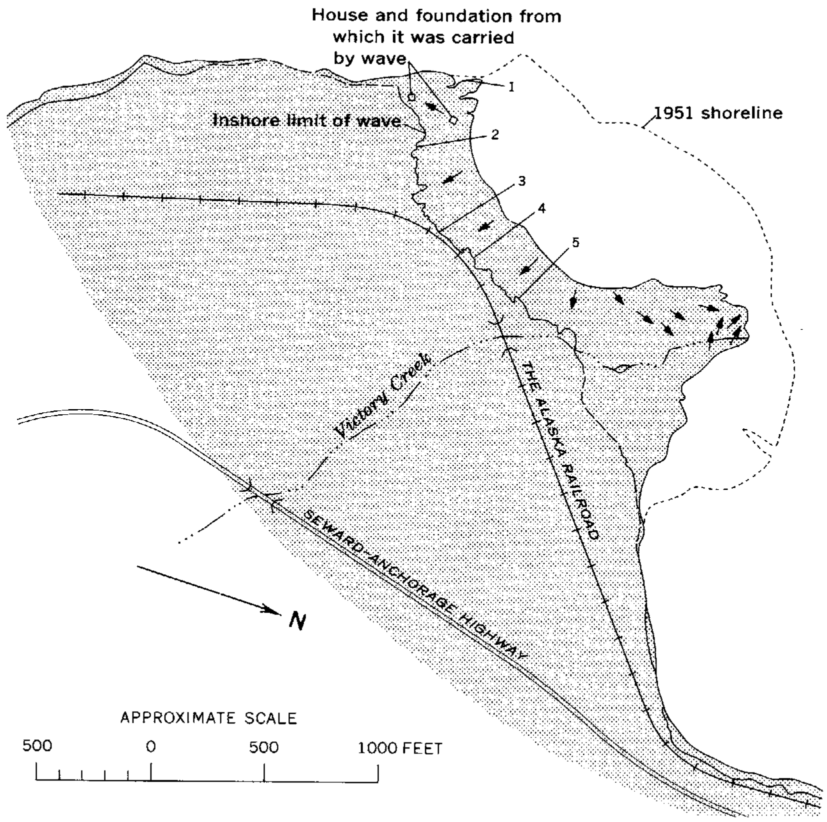
BACKFILL WAVES

Powerful backfill waves rushed back up onto the delta surface after each of the slides at Lakeview. The wave direction was determined by noting which sides of the trees had been debarked, how trees had fallen, how the brush had been combed, and, in one place, by the direction in which a house had been carried from its foundations (fig. 7, next page). The waves broke off some spruce trees near the ground and uprooted others—some as much as 2½ feet in diameter at the base. Trees that had traveled farthest in the waves were shorn of their limbs and stripped of their bark; others that had traveled shorter distances retained most of their limbs and had been only partially stripped of bark.

A roughly rectangular block about 3 by 15 by 20 feet, composed of bedded sandy gravel with clasts up to boulder size, was found 40 feet from the scarp, approximately halfway between lines 2 and 3 on figure 7. Assuming a density of 1.75 (50 percent of the total as saturated void space with a density of 1.0 and 50 percent of the total as sediment with a density of 2.5), this block would have a weight of about 50 tons. This block of sediment, like the extensively battered trees, was probably torn from the surface of the slide block by the incoming waves, for no place was found on the delta surface from which the block could have come. Although the block did not appear to be frozen when examined on the 8th of August, it probably was frozen at the time it was carried in by the waves; without interstitial ice the block would undoubtedly have distintegrated.



6.—Areas of net erosion and net deposition off Lakeview and Rocky Creek deltas as indicated by differences between presliding and postsliding bathymetry.



7.—Map of Lakeview delta showing direction of travel and inshore limit of slide-induced backfill waves. The five traverses on which the height of wave damage was measured are shown in figure 8.

A log house was carried by the backfill wave for more than 200 feet from the concrete foundation to which its sill had been bolted (fig. 7). The walls were demolished but the roof structure having a braced triangular cross section, although distorted, remained intact. The roof and the remains of the walls were deposited by the wave in a tangle of uprooted and broken spruce trees.

The ground was snow covered at the time of the earthquake and the wave washed away the snow, leaving a clear record of its inshore limit. This inshore limit is drawn on figure 7, as shown on aerial photographs taken a few days after the earthquake. The debris transported by the waves decreased in size inshore—the farthest inshore deposit consisting of small pockets of sand and pebbles, twigs, and small turf blocks. Many blocks of ice, some to which sand and pebbles were frozen, were carried to the inshore limit of the wave-washed area.

To determine the altitude of the crest (runup) of the backfill wave as it ran up on shore, the height of the damage to trees was recorded. Four traverses were run from the toe of the scarp in the direction of wave travel on the delta (figs. 7 and 8). Horizontal distances were determined by pace, and altitudes were measured with a stadia rod and hand level. Altitudes were also recorded for the base of the damaged trees and for the heads and toes of small scarps. The lake level was 437.0 feet when the traverses were run, and these altitudes have been adjusted in figure 8 to the altitude of the lake at the time of the earthquake (431.6 ft). The height of the wave above the lake surface may have been somewhat greater or less than indicated by these altitudes, for the lake might have been seiching at the time the wave was formed. The crest of the backfill wave was about 10 feet above the delta surface as the wave crossed the scarp. The height of the wave decreased inshore but the altitude of the highest damage rose and fell somewhat with the changing slope of the delta surface.

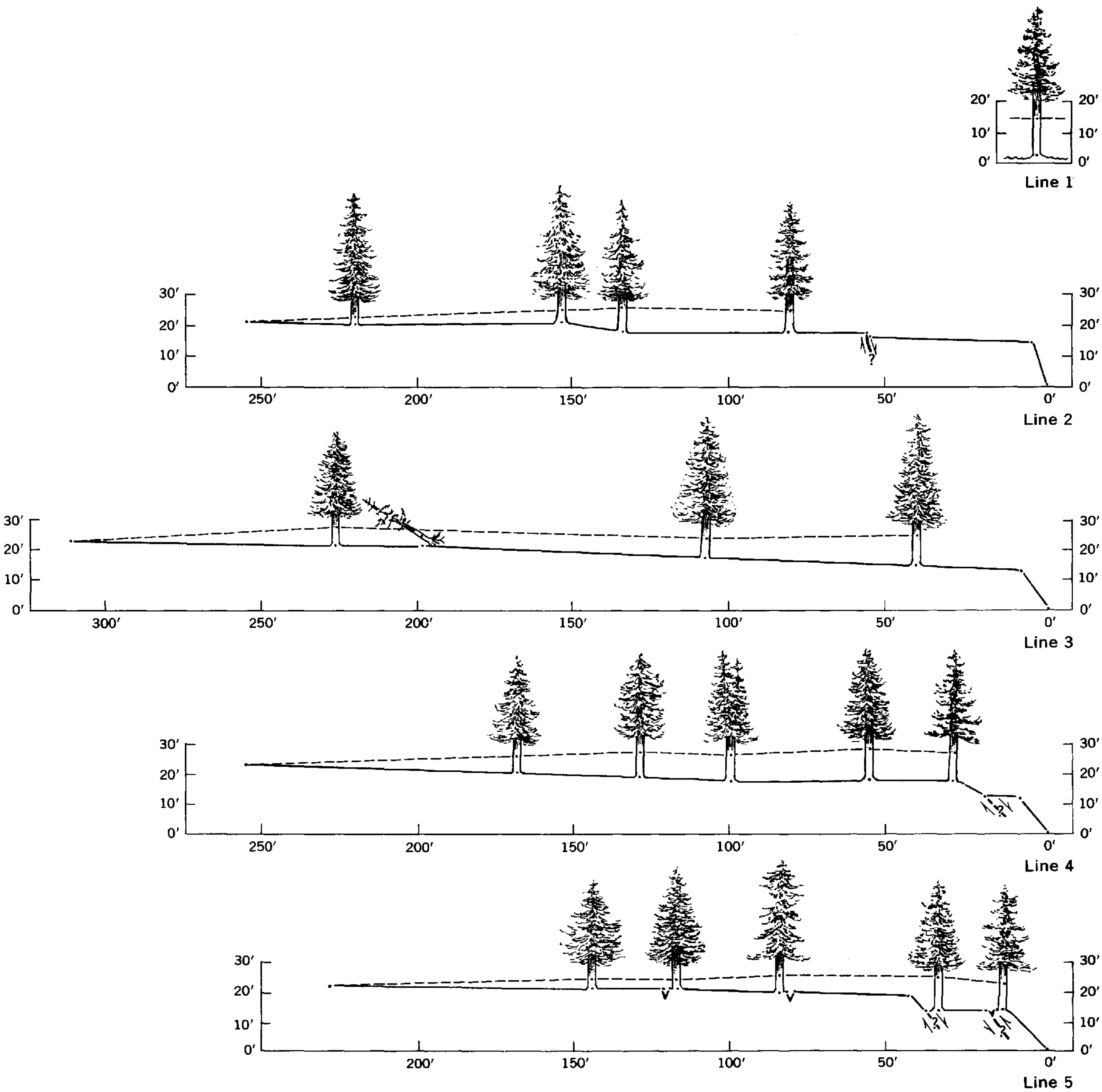
FAR-SHORE WAVES

The far-shore wave hit the shore across the lake from the delta. In the middle of the wave-washed area the runup reached 25–35 feet above lake level and decreased to 11–13 feet to the sides. The orientation of the damage indicates that there was considerable variation in the direction of the wave travel. In the most severely damaged area the waves tore vegetation from the bedrock shoreline, and broke off large spruce trees or stripped off their bark and lower limbs.

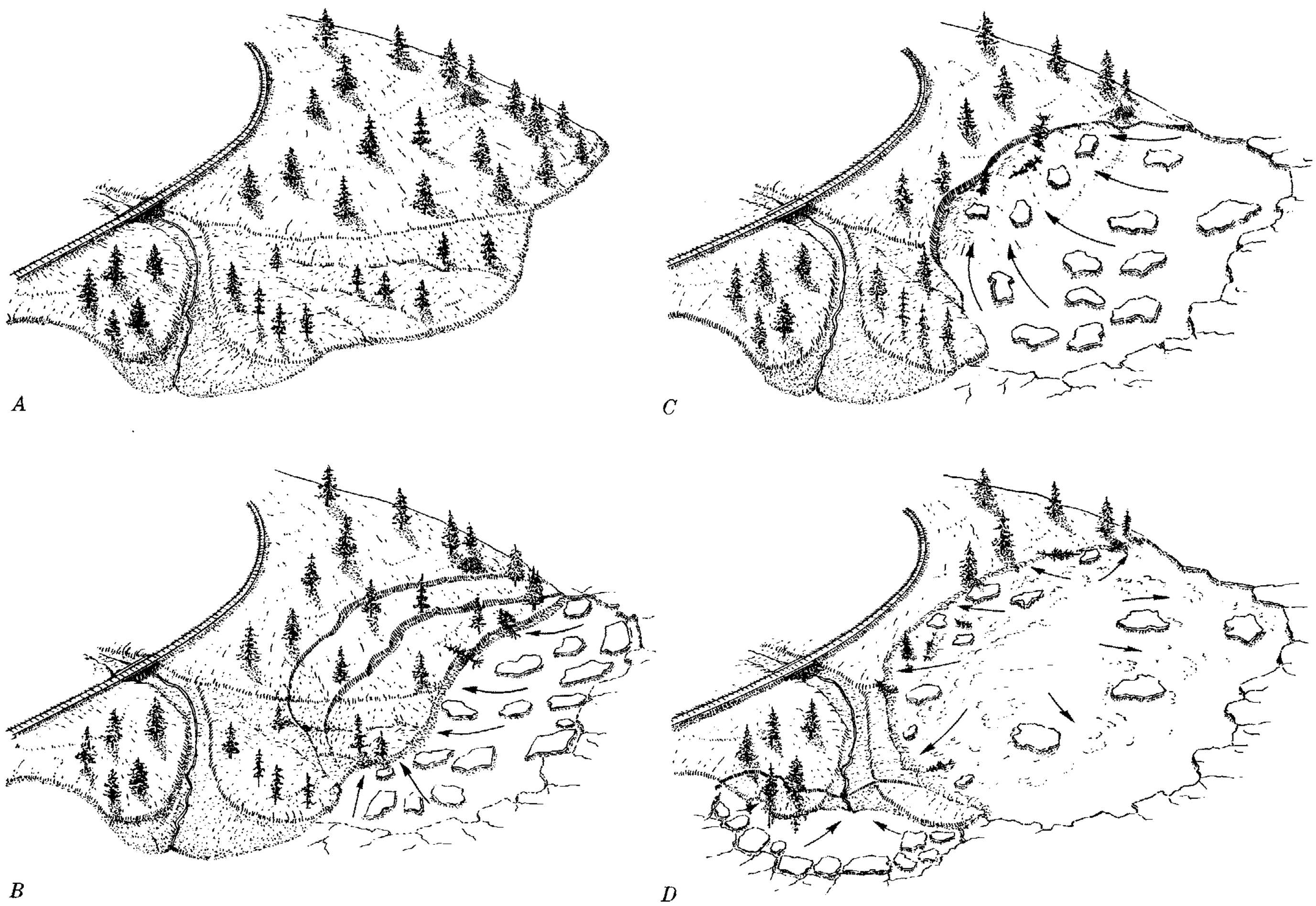
GENERATION OF THE SLIDE-INDUCED WAVES

Because the relationship between slides and waves is clearer at the Lakeview delta than elsewhere, the Lakeview slides will be used as the model for the discussion of slide-generated waves. It is believed that the waves were generated as described below (fig. 9, p. A10).

The west-facing slide seems to have occurred first for on the point of land between the two scarps, where damage to trees indicates that the area was washed over by waves from both slides, the debris



8.—Upper limit of backfill wave damage along traverses run parallel to wave travel direction on Lakeview delta. Location of traverses shown on figure 7.



9.—Sequential sketches of the slide-generated backfill wave that ran back up onto Lakeview delta. *A*, Preslide delta. *B*, Start of slumping and water rushing down into the void left by the sinking slide. *C*, Inward-rushing water formed a welt of high water just off the slide scarp. *D*, High water ran inland over the delta, radiating away from the high-water welt. As shown in *D*, the second slide near the mouth of the creek occurred after the larger slide.

is alined as it would have been by a wave from the north-facing scarp. Thus the north-facing slide occurred after the west-facing slide. As the western slide mass submerged, water rushed into the void behind it. The inrush of water must have taken place almost simultaneously with the downward movement of the block, as shown by the extensively damaged trees and blocks of sediment found above the scarp that had been torn from the slide areas. Being composed of granular material the slide mass was probably broken by progressive slumping as it moved.

As the whole slide mass finally submerged, water rushed in from all but the scarp side. The level of the inrushing water would have been below the general lake level because it must have run down slope to fill the void. This probably was why no evidence was found for damage caused by water rushing into the slide area. The water rushing toward the delta formed a wave that overran the edge of the delta. The direction in which the wave traveled over the delta surface (figs. 7 and 9*D*) shows that the water was spreading radially from an area that lay just off the scarp, suggesting that the inward-rushing water formed a welt of high water in that location (fig. 9*C*). This high-water welt probably resulted from a combination of (1) the convergence of the inward-rushing water and (2) the upward deflection of this water by the slide scarp.

In model studies, in which waves were impulsively generated (Johnson and Bermal, 1949; Wiegel, 1955; Prins, 1957) waves of the backfill type have either not been observed or not described. However, the models were generally designed for the study of gravity waves that traveled away from an initial disturbance.

The far-shore wave may have been formed in the following way: As the landslide block moved downward into the lake, it displaced water ahead of it. Once set in motion by the landsliding, some of the sediment probably became entrained in the water. Entrainment could have been rapid, because the sediment lacked clay-sized material and was therefore noncohesive. Furthermore, being largely below lake level before sliding, it was water saturated. The moving water, part of which contained entrained debris, ran across the lake floor to the toe of the far shore, ran up the sloping far side of the lake basin, and broke above the surface of the lake as a far-shore wave. This relationship between the far-shore wave and the moving water that probably assisted in the transportation of the debris is suggested by the fact that the far-shore wave occurred only along the shore that was adjacent to the area of the lake floor on which debris was deposited (fig. 4). Thus, the far-shore wave may have been produced by water forced ahead of the entrained debris, in much the same way that violent winds were forced ahead of subaerial landslides (Witkind, 1964) and forced ahead of the giant wave produced by the overtopping of Vaiont Dam (Kiersch, 1964). This mechanism was suggested by Heim (1924, p. 22):

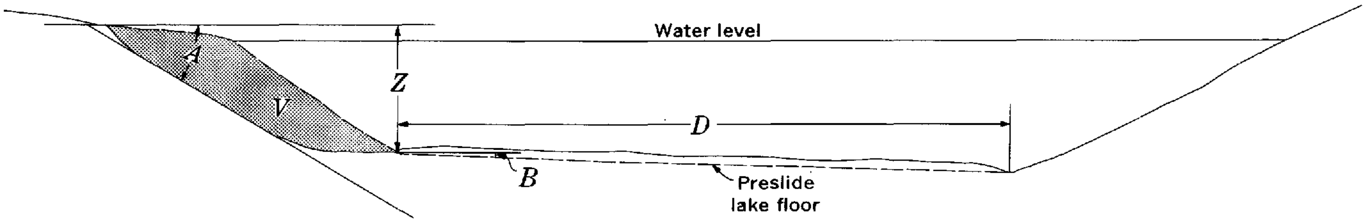
> * * * When a wind from a landslide can sweep down an entire forest and can carry people and cattle several hundred meters through the air, so a subaqueous slide of the larger kind on a steep slope must be accompanied by a tidal wave (Flutwelle) that can be propagated over and beyond the area of deposition, can tear out sediments, form ripple marks and disturb the benthos.

The orientation of damage caused by the far-shore wave shows that there was considerable variation in the direction in which the water was traveling as it came onshore. This variation in direction raises the possibility that the movement of the slide debris was not unidirectional on the lake floor, and that if one had the opportunity to study current-oriented features in the slide debris one might find some variation in their directions.

A possible alternative cause of the far-shore wave is that it was produced near the slide and then traveled across the lake as a wave and hit the opposite shore. Slides have been known to cause such waves (Jones and others, 1961), but, for several reasons, this alternative seems unlikely for the Lakeview slide. The correspondence between the edge of the depositional area on the lake floor and the wave-washed area would have to be a fortuitous rather than a causative relationship. The fact that this same relationship occurs in three other areas suggests that it is causative. Furthermore, if the far-shore wave had been generated near the slide area, one might expect that, allowing for refraction, the directions of wave travel would converge toward the point of origin. However, the directions do not seem to show any such pattern; rather, they show a wide variation in direction of travel.

A disturbance of water possibly analogous to the mechanism proposed for the far-shore wave was caused by a slump described by Heim in 1932 (p. 42). In 1875, in the town of Horgan on Lake Zurich, Switzerland, a part of the shoreline subsided. The floor of the lake, which had been at a depth of 135 meters, was raised 1–2 meters, and on the opposite shore the water became disturbed or turbid (trübte). Kuenen (1950, p. 49), apparently describing observations by Heim, said that the turbulent water suddenly appeared as boiling masses of muddy water. Kuenen concluded that, because the slump could not rise much above the deepest part of the lake and because sounding showed that the main mass of sediment spread out on the deeper part of the lake floor, a watery turbidity current must have been developed that had sufficient momentum to cross the lake floor and be carried up the opposite slope to the surface. Although Kuenen attributes the upwelling at Horgan to a turbidity current, there is no direct evidence that such a current was created by the Lakeview slide. The coarseness of the sediments involved in the Lakeview slide and the fact that the sheet of debris has an abrupt front and a relief of about 60 feet (fig. 5) argue against transportation by a turbidity current. The wide lateral spreading of the slide debris is more likely to be due to some degree of entrainment of the sediment into water partially set in motion by the displacement of the slide mass. Even a small degree of entrainment would have reduced internal friction; this reduced friction would have resulted in a lower angle of repose, which would have allowed the sediments to move down a more gentle slope.

In figure 10 (next page) values are given for the volume, potential energy, angle of slope, and distance traveled for the Lakeview and the three other slides. The volumes and potential energies are calculated for a vertical slice having a thickness of 1 foot as measured from the reconstructed preslide bathymetry.



Slide	Volume (cu ft)	Potential energy (10^6 ft lbs)	Normalized potential energy (potential energy ÷ volume)	Scarp slope (angle *A*, in degrees)	Depth (*Z*, in feet)	Lake-floor slope (angle *B*, in degrees)	Distance of debris travel (*D*, in feet)
Lakeview	226,875	[1] 17,285.97	76,191	10.5	220	3	1,280
Lawing	74,125	9,390.15	126,679	20	400	2	2,100
Ship Creek	198,250	28,079.59	148,372	25	520	0	4,750
Rocky Creek	66,375	6,998.55	105,439	25	380	2.5	600

[1] Because some material was moved upward by rotation at the Lakeview slide, the potential energy of the material raised to the level of the lake floor has been subtracted from the potential energy of the material above the level of the lake floor.

10.—The volume, potential energy, scarp slope, and the distance traveled by the slide debris of the four major slides. The volume and potential energy are calculated for a vertical slice having a thickness of 1 foot as measured from reconstructed preslide bathymetric contours along fathogram line 94 (fig. 5), profiles *A–A′* (figs. 13, 18), and fathogram line 89 (fig. 20).

LAWING SLIDE

DELTA MATERIALS

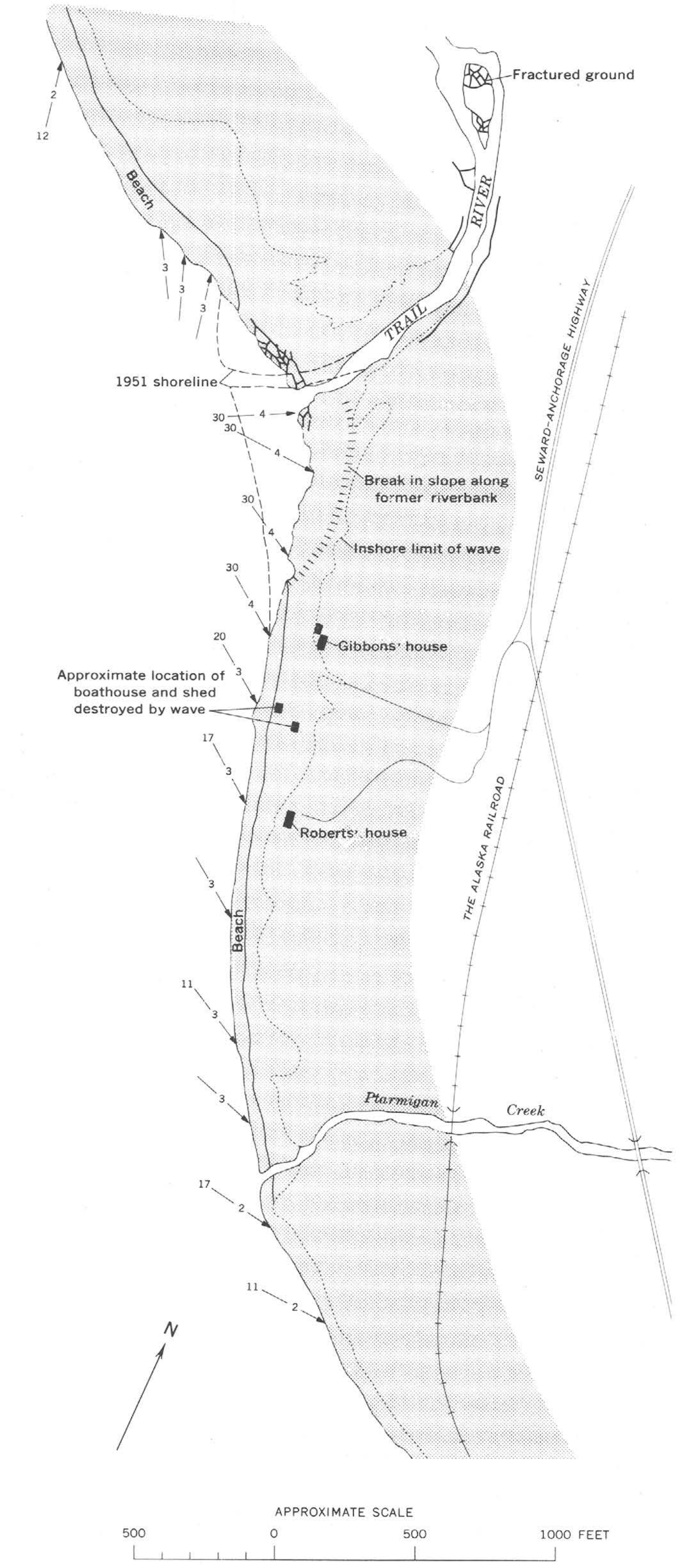
The Lawing delta is at the northeast end of the lake (pl. 2). Trial River and Ptarmigan Creek flow across the delta, but the shape suggests that the delta was built principally by Ptarmigan Creek. The slide removed the most recently deposited material at the mouth of Trail River. The area had a cover of low brush and formed a slight bulge on the shoreline of the delta (fig. 11), according to 1951 aerial photographs. The sediments exposed along the scarp and in blocks carried onto the delta surface by the wave consist of stratified sandy pebble gravel and pebbly sand. The pebbles are tabular and subangular to subround. Although cobbles are present, the sediment is generally finer than in the Lakeview delta.

DESCRIPTION OF THE SLIDE

The amount of erosion caused by the sliding and the distribution of the slide debris can be approximated, as they were at Lakeview, by comparing presliding and postsliding bathymetry. The postslide bathymetry off Lawing (fig. 12, p. A14) shows a reentrant in the contours downslope from the slide scarp probably caused by the sliding. Farther downslope, and extending nearly to the deepest part of the lake, is an area of irregular topography. A cross section on which the postslide and reconstructed preslide bathymetry are compared shows that the slide removed a block of sediment above the scarp as much as 80 feet thick (fig. 13, p. A15). Before the slide, the steepest part of the delta had a slope of about 22°; after the slide it was about 24.5°. Thus here, as at Lakeview, sliding locally steepened the front of the delta. At Lakeview the amount of deposition on the lower part of the lake changed the bottom bathymetry enough that the depositional area could be reasonably well delineated by comparing postslide and preslide contours. At Lawing, however, the amount of material involved in the sliding was considerably less (fig. 10), and only a suggestion of a depositional area is indicated by the slight southward displacement of the 420- and 440-foot contours (fig. 12). If there were no other reason to believe that there had been deposition in the area, this evidence would be inconclusive, but as at Lakeview, the probable depositional area lies within the area of irregular topography. Isolated topographic highs in this area suggest that it is unlike the adjacent smooth lake floor; and, as at Lakeview, there was wave damage on the shore opposite the scarp, in front of the depositional area. A comparison of areas of erosion and deposition and a comparison of cross sections of preslide and postslide bathymetry (figs. 12 and 13) indicate that there was considerable lateral spreading of the slide debris as it moved down and out over the nearly level lake floor. The fact that slide debris traveled about 3,000 feet on a slope of about 1.5° suggests that there may have been some entrainment of the debris in the water that was set in motion by the sliding.

BACKFILL WAVE

The two waves at Lawing were similar in pattern to the waves produced by the sliding at Lakeview.

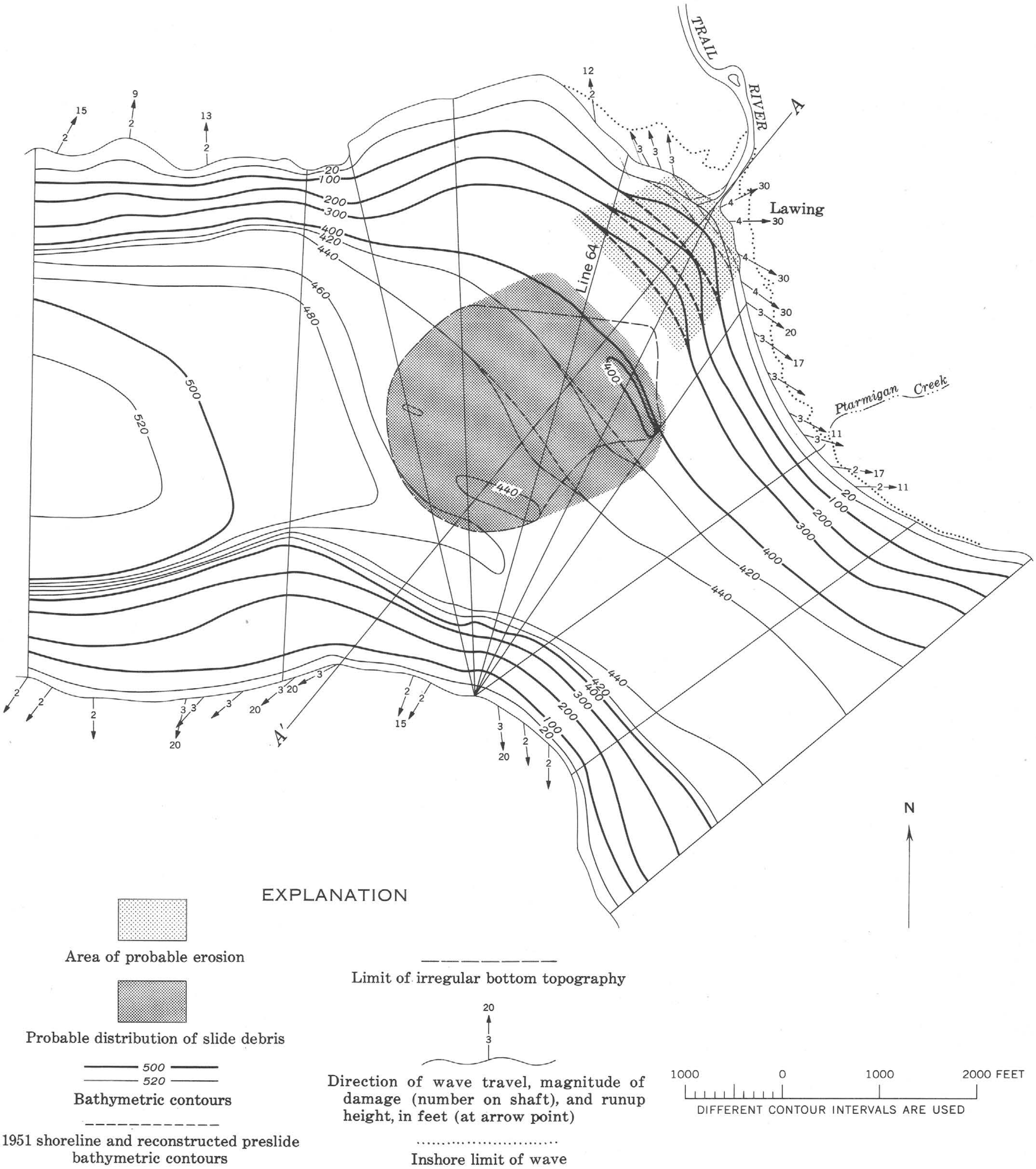


11.—Map of Lawing area showing the slide scarp and former shoreline, and the direction (arrow), magnitude of damage (on arrow shaft), and runup height, in feet (at arrow base), of the backfill wave. The inshore limit of the wave is indicated by the dotted line. Houses of two eyewitnesses are noted.

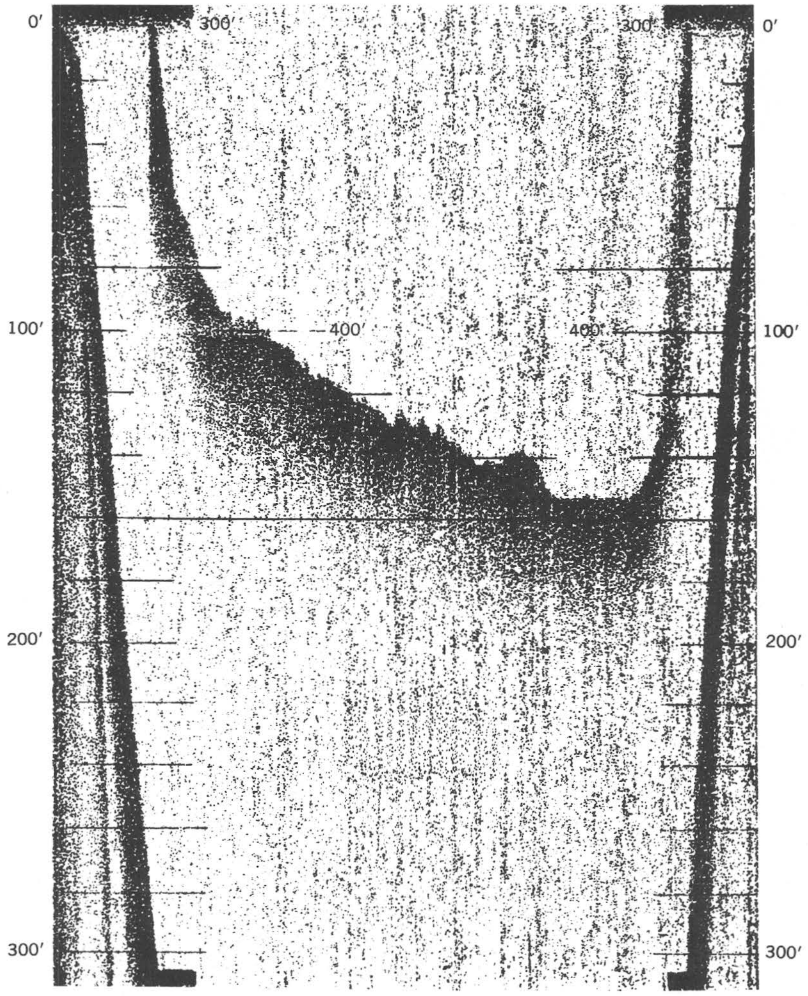
The wave that struck and overran the edge of Lawing delta spread radially as it came on shore as did the backfill wave at Lakeview. The wave directions (fig. 11) indicate that as the wave traveled to the west and south from the scarp it was refracted by the shallow water along the delta. The wave was carrying blocks of ice 16–20 inches thick (as reported by Mr. Gibbons, a resident at Lawing), and as it came on shore it broke off large spruce and cottonwood trees (fig. 14, p. A16). Some of the blocks of ice that had been frozen to the beach carried sediment on their undersides (fig. 15, p. A16). Frozen blocks of sediment were also carried ashore by the wave; the largest of these was a flat-topped, pyramidal-shaped block approximately 14 feet wide at the base and about 4½ feet high (fig. 16, p. A17). This block still had a considerable amount of interstitial ice when seen on the 15th of May. The wave also carried driftwood, cobbles, pebbles, and unfrozen turf. A flower garden that lay just at the edge of the wave-washed area was covered by several inches of sand.

The residents at Lawing were fortunate in that the wave stopped just short of two occupied houses; the only buildings destroyed were a shed and boat house.

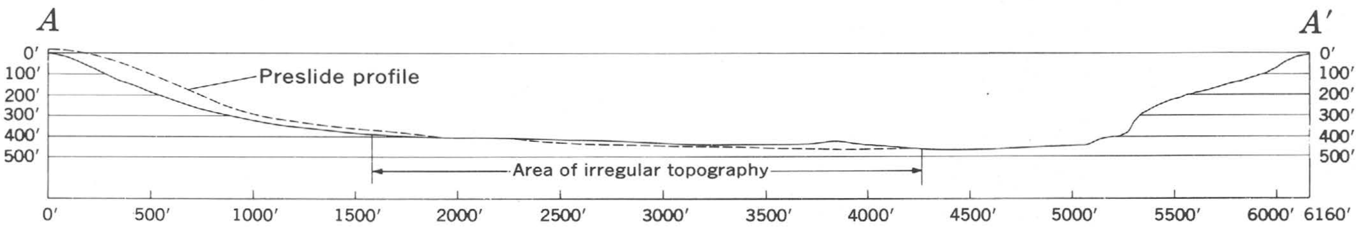
Along the western edge of the wave-washed area the wave stopped at the foot of a break in slope. In the central part of the area, where wave heights were greatest, the wave ran back up the valley of Trail River for a distance of about 800 feet and overflowed the low west riverbank. Aerial photographs taken by the U.S. Army the day of the earthquake show a pile of broken ice, higher than the level of the river, filling the channel from bank to bank at the inshore limit of the wave.



12.—Probable distribution of erosion and deposition that resulted from the slide and the direction, magnitude, runup heights, and inshore limit of waves. Profiles along *A–A'* in figure 13.



FATHOGRAM RECORDED ON LINE 64

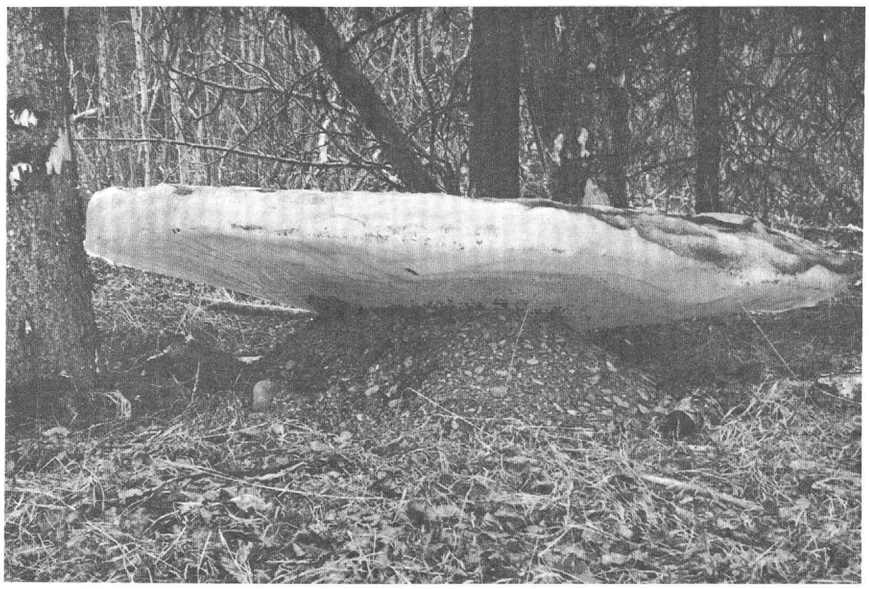


PROFILES ALONG LINE *A–A'*

Note: Because of the large vertical exaggeration on the fathogram, this profile, which has no vertical exaggeration, is also shown

13.—Fathogram and profiles of Lawing slide. Line of profiles is shown on figure 12. Note that when the depth on the fathogram exceeds 300 feet, the recording is shifted upward and the 300-foot-depth is placed at the original zero depth.

14.—Area washed over by the backfill wave at Lawing. The wave traveled from left to right, breaking down and debarking the trees. Brush in the background was bent to the right. The only branches left on the spruce tree beside the man are on the lee side. The pile of gravel in the left foreground was probably frozen at the time it was carried ashore by the wave.



15.—A large block of lake ice to which sediment was frozen when carried ashore by the wave.

The estimated runup heights along the shore are shown in figure 11. A maximum of about 30 feet occurred in the area behind the scarp, and heights decreased irregularly away from the scarp. An abrupt break in slope bounding a former course of Trail River (fig. 10) may have locally increased runup heights, because runup heights increase with the steepness of the bank hit by the wave (U.S. Army Corps Engineers, 1961, p. 89).

16.—Large block of bedded sandy pebble gravel carried ashore by the wave at Lawing. The slide scarp forms the boundary of the beach to the right; debarked trees in the background.

ACCOUNTS BY LOCAL RESIDENTS

To the author's knowledge the first person to study the Lawing slide and its associated wave was Hadley Roberts, of the U.S. Forest Service, whose house is just beyond the inshore limit of the wave on the Lawing delta (fig. 11). Mr. Roberts deduced from the radiating pattern of damage to trees that the slide had caused the wave. He drew a sketch map showing the preslide and postslide shorelines, the direction of wave travel, and the inshore limit of the wave. The map of this same area prepared by the present writer includes additional observations and is constructed from preearthquake and postearthquake aerial photographs, but it differs only slightly from the map made by Mr. Roberts.

Fortunately, there were two eyewitnesses to some of the wave action at Lawing—Mr. Frank Gibbons and Mrs. Hadley Roberts. Both live on Lawing delta and both were at home at the time of the earthquake (houses shown on fig. 11).

Mr. Gibbons was in his living room at the time of the earthquake. The first tremor, a strong north-south motion, knocked him to his knees in front of a large window facing west over the lake. There was a pause in the shaking and then the motion shifted to east-west. During the east-west shaking he saw a wave about one-fourth mile from shore. It is not clear if he saw the wave form or if it had already formed when he first saw it. As the wave came toward him the ice broke across its rising front "like a patchwork quilt." The wave hit the shore and ran up around his house. As the water receded, Mr. and Mrs. Gibbons tried to leave their house, but the ground was shaking so violently that they couldn't get out. A second smaller wave ran up on shore about a minute after the large wave. Then they left the house.

The following is a part of a letter written by Mrs. Roberts.

On March 27, 1964, at 5:36 p.m. I was standing at the stove getting ready to put a lid on a pan of potatoes. The kids (Carol and Bruce) were near me and as the earthquake started their eyes popped open wider and they came to me. As it got worse we huddled together. I think at this time I remember hearing cupboard doors banging and dishes crashing to the floor. I could hear the house squeaking and groaning and we were swaying so very hard that I decided to get out. I noticed that the propane was still burning under the potatoes so I turned it off. The crashing dishes were between me and the back door so we stepped out the garage door. The kids were both crying and screaming at this time and I really can't remember too many details. In the garage Carol screamed that she had lost her shoe as we were going out the door and I kept thinking I had to get back in there and get her shoe before we could go out in the snow. All this time the car was swaying tremendously and also sliding back and forth on the concrete floor. I was afraid of being crushed between it and the wall so was really watching it closely. Carol has reminded me that while we were in the garage we saw a gallon bottle of milk tip over and we were standing among the broken pieces of glass and in the milk part of the time. This bothered Carol since she was missing a shoe, and is no doubt why she remembered it and I didn't. After a while in the garage—and I haven't the slightest idea how long we were there—it started letting up a little so I stepped back into the kitchen just in time to see some big wave action on the lake * * *.

That ice on the lake was breaking up so fast, and oscillating so and then all of a sudden I could see lots of black muddy water and it was at a much higher level than normal; in fact, it was almost up level with the bank. At this time I thought I saw a life jacket floating by but quickly decided that it couldn't be (but it was, as the boat house had just been ripped to shreds). Right behind the jacket was a huge wall of water and I noticed that the splashes were going ever so high. Then remembering what had happened at the Madison Canyon Earthquake (near Yellowstone), in 1959, that we had just visited this past summer, I decided to get away from the waters edge. I also saw a snowslide across the lake and from the looks of the flying snow it looked like a real big one. The wave was going parallel to the beach and our house, and was going south.

We walked past the fireplace (the kitchen way was too littered to walk through) over to the basement door, and we must have walked through debris but I really can't remember doing it. The kids' boots were in the basement so I had them stand at the head of the stairs while I ran down for them. I remember them screaming and crying for having been left alone and I think Carol even started down the steps after me. But I hurried and ran back up the steps two at a time. The house was still rocking some and that was scaring them. When I first saw the wave action I think I said something like "we'd better get out of here before that water gets us". This scared Carol, too, I think, as she kept saying that we were going to die. I got their boots and coats on and went to the front room closet for my coat and when I passed the window I looked out and didn't see any sign of a wave but did notice the water level was much higher and flowing quite close to the house. We went out the back door and I carried Bruce and Carol and ran and we beat it for the bunkhouse where we found Freddy. The bunkhouse isn't any higher, but is certainly a lot further away from the waters edge.

Both observers noted a pause after the initial shaking, and Mr. Gibbons indicated that the direction of shaking changed after the pause. Also after the pause Mrs. Roberts saw "wave action" and oscillation in the lake and rising water. During the second period of shaking both saw a large wave; it is not certain, however, that both saw the same wave. The wave came ashore around Mr. Gibbon's house from an estimated distance of a quarter of a mile to the west. Mrs. Roberts saw what may have been the same wave as a "high wall of muddy water" running south along the edge of the delta from the direction of Mr. Gibbon's house. If this "wall" was the slide-induced wave, it suggests that the slide occurred during the latter part of the shaking after a seiche had been initiated in the lake.

SHIP CREEK SLIDE

DELTA MATERIALS

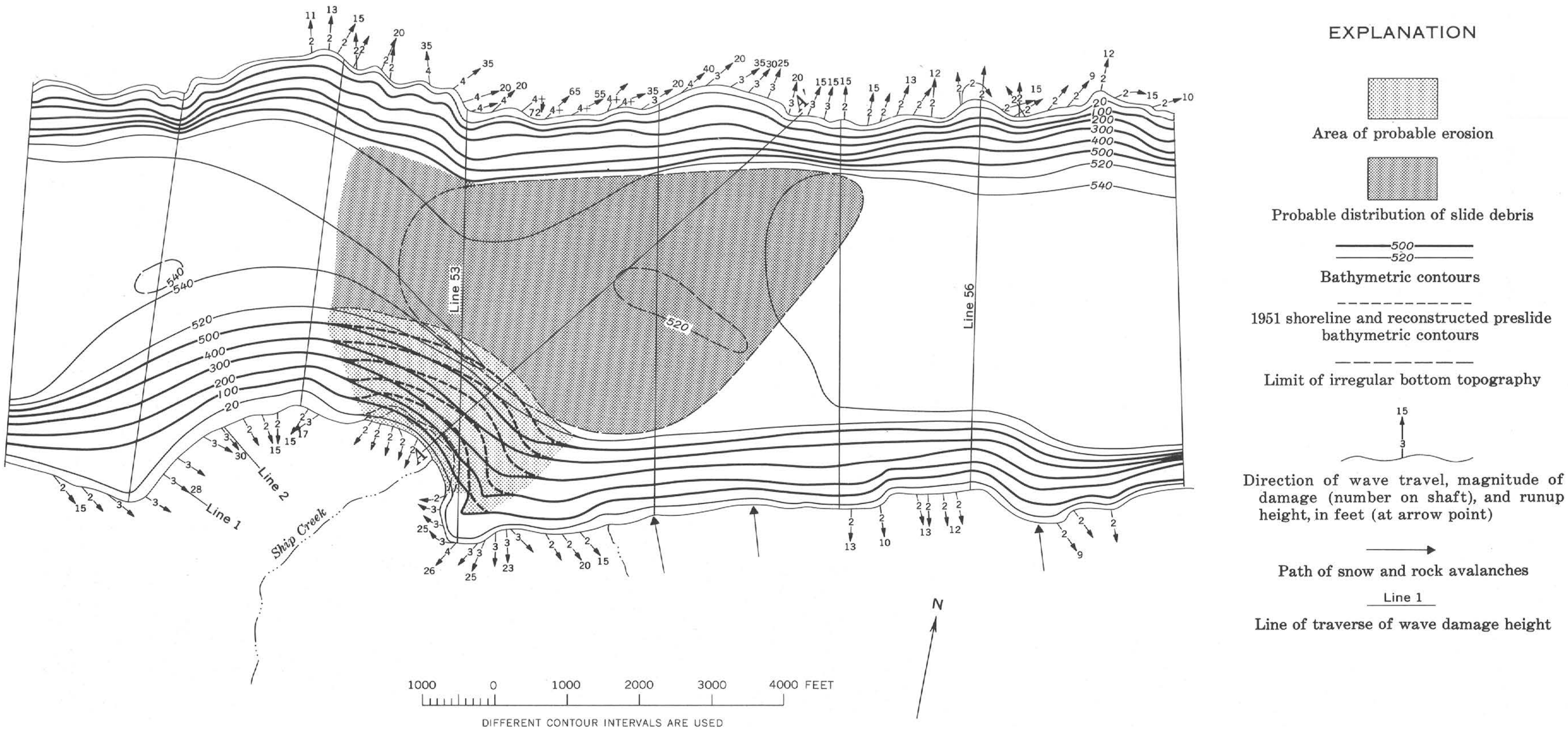
A slide at Ship Creek delta removed a low protruding strip of sediment about 1,400 feet long and 250 feet wide from the delta edge. On 1951 aerial photographs the slide area was seen to be bare of trees and was probably composed of the youngest delta sediments (fig. 17). Sliding also is suggested at the eastern edge of the delta by the radiating pattern formed by incoming waves immediately inshore of a reentrant in the bathymetric contours. No scarp was found here, however, and if sliding did occur, it involved material that was entirely submerged. The sediment in the delta was not examined, but because Ship Creek has a high gradient having a fall of 3,000 feet per mile, the sediment is probably relatively coarse.

In front of and somewhat to the east of the delta the topography of the lake floor is slightly irregular. Comparison of fathometer profiles across this area and across the flat lake floor about 5,000 feet to the east shows that the slide debris can be readily recognized (fig. 18, p. A20–A21). In the slide area the normal horizontal bedding shown by subbottom reflections has been destroyed, and if the lake floor was as flat here before the slide as it is now to the east and west, then the sliding can be assumed to have formed 50 feet of relief. How much of the relief is due to deposition and how much to erosion is difficult to determine from a comparison of reconstructed presliding and postsliding bathymetry because there is good reason to suspect that erosion did occur. The fact that subbottom reflections were recorded in the undisturbed areas by the high-frequency, low-power signal from the fathometer suggests that the bottom sediment is very soft. Soft sediments are typical of fiords where there is quiet-water sedimentation of fine sediment (Bennett and Savin, 1963). Richard Malloy of the U.S. Coast and Geodetic Survey examined the records and said that he had seen similar records made with a comparable fathometer where the sediment was so soft that a sounding lead easily penetrated it and recorded depths several feet deeper than the fathometer. Such soft sediment should have been easily eroded.

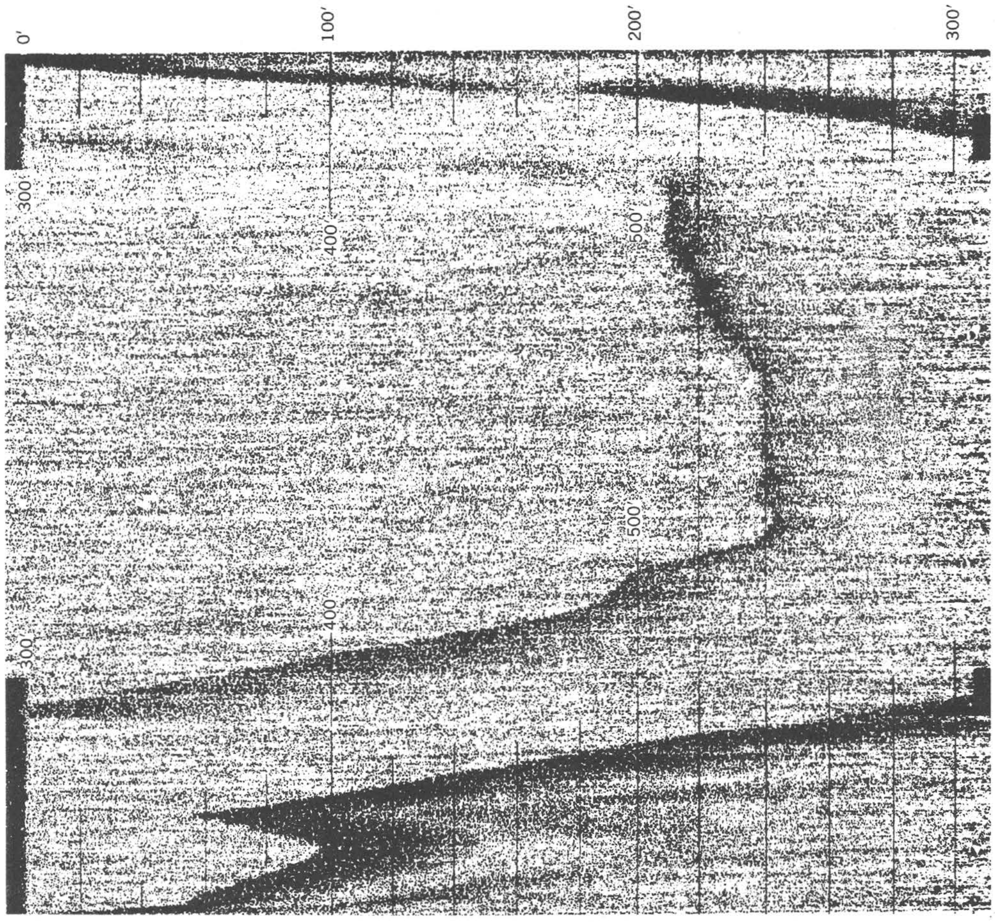
Some of the slide debris may have traveled as much as 7,000 feet, or more than twice the distance traveled by the material in the Lawing slide. This distance is not surprising, however, for not only was more material involved in the slide at Ship Creek, but the lake here is nearly 100 feet deeper. Thus the available energy and the resulting momentum of the slide debris would have been much greater at Ship Creek (fig. 10).

WAVES

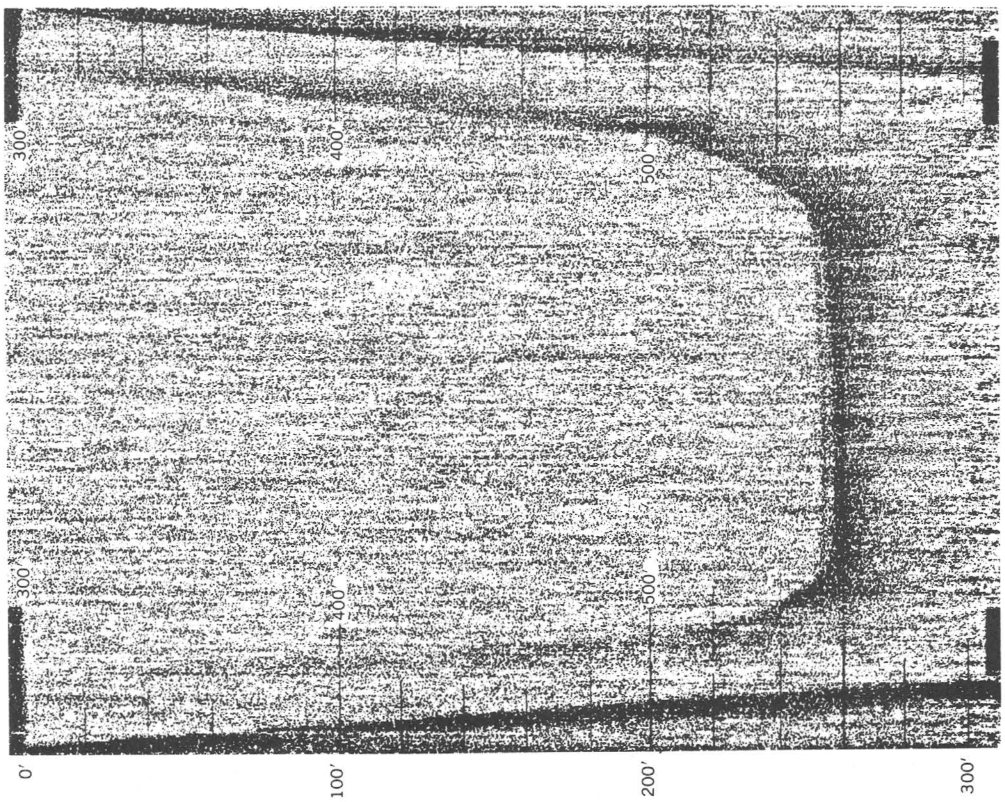
There was a considerable amount of wave damage in the Ship Creek delta reach of the lake (pl. 2). On the western margin of the delta, damage was clearly due to a wave produced by seicheing (see p. A30), but the damage on the rest of the delta and on the far shore was



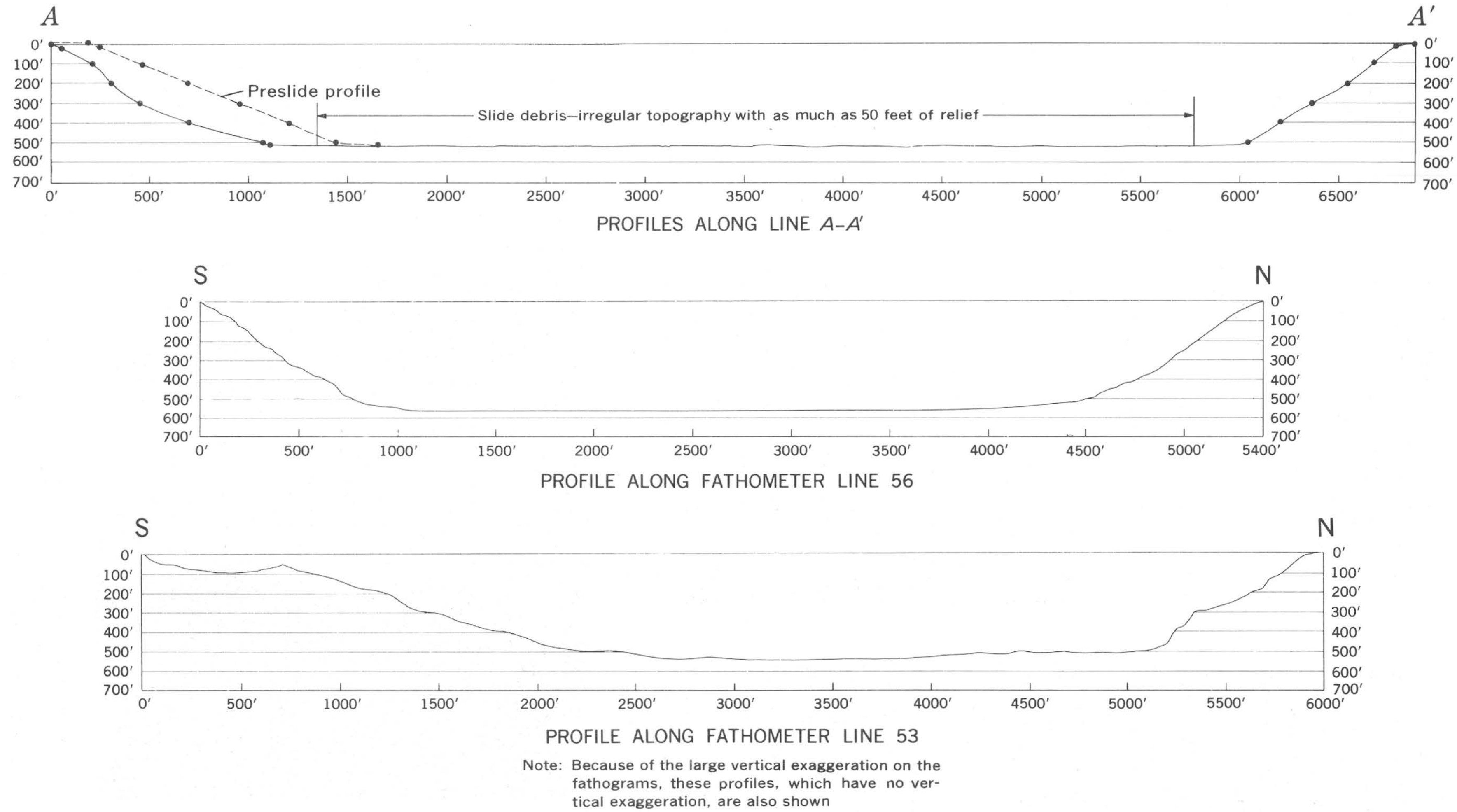
17.—Slide from Ship Creek delta showing areas of erosion and deposition, and the direction, magnitude, and runup heights of waves. Lines of traverse of wave-damage height are shown in figure 23 and the line of profile *A–A′* is shown on figure 18.



FATHOGRAM RECORDED ON LINE 53



FATHOGRAM RECORDED ON LINE 56



18.—Fathograms and profiles off Ship Creek delta. Lines of profiles are shown on figure 17.

probably caused by slide-generated waves. If these waves are analogous to those caused by the Lakeview slides, the wave that overtopped the scarp was a backfill wave and the wave that caused the severe damage opposite the delta and extending to the east was a far-shore wave. Where the far-shore wave hit a steep bank, it had a maximum runup height of 72 feet—the highest along the entire lake. The wave damage caused by the far-shore wave was similar to that at Lakeview in that generally the intensity of the damage decreased toward the margins of the wave-washed area, and the wave directions were not uniform.

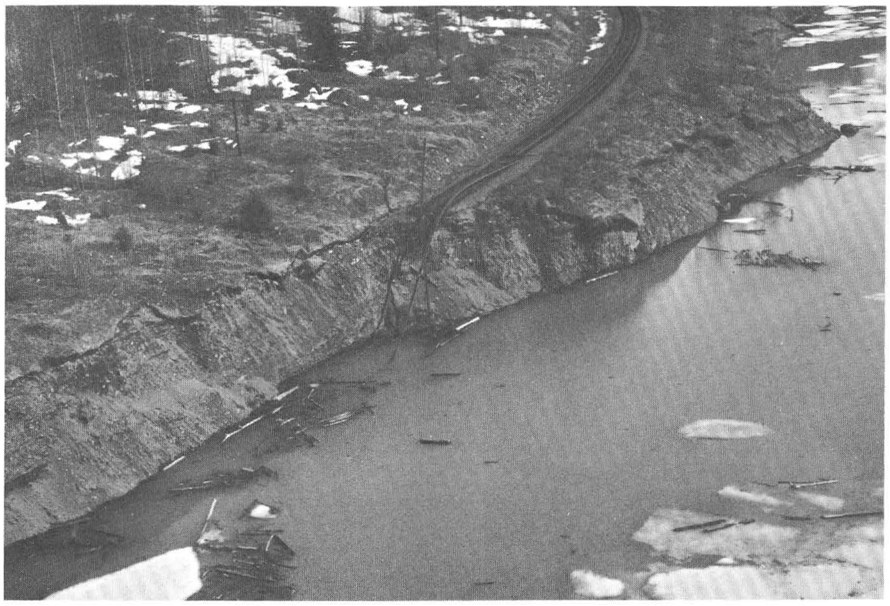
The shoreline hit by the far-shore wave extends to the east and west of the area of deposition, as shown on figure 17. The depositional area is drawn conservatively however, and debris might occur farther west—nearly to the fathogram that shows no irregular topography. The position of the western edge of the area of probable erosion also suggests this possibility. Control is somewhat better on the eastern side of the depositional area, and debris probably does not extend much farther east. Despite these small discrepancies, the general relationship between debris and the far-shore wave established at the Lakeview slide seems also to exist here.

ROCKY CREEK SLIDES

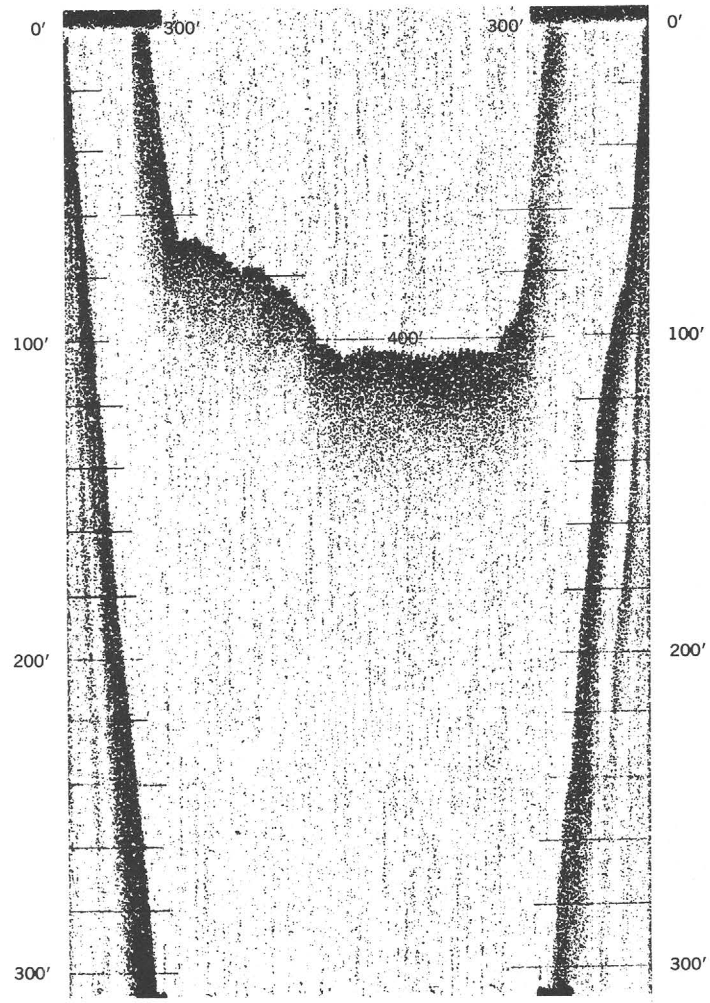
The slides that occurred at the delta of Rocky Creek (also called Boulder Creek) just north of Lakeview (pl. 2) differed from those previously described. Many small slumps trimmed back the shore of the delta by as much as 180 feet (fig. 29). One slump carried away 260 feet of track and roadbed of The Alaska Railroad. At one location where the centerline of the track formerly lay about 30 feet above the lake, sounding shows that there is now 9 feet of water (fig. 19). This sliding also differed from the Lawing and Lakeview slides in that there was no evidence of waves, either on the delta or on the opposite shore.

DELTA MATERIALS

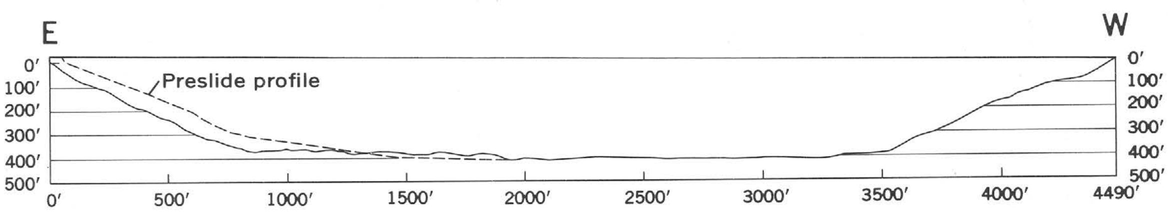
Rocky Creek has a steep gradient, falling about 4,500 feet in 2 miles. The sediments exposed along the scarps are therefore coarse, poorly sorted sand and sandy gravel. Most of the apparent dips visible on the scarps were estimated to be less than 10°. In mid-May and early August the face of the scarp was dry, except for a few wet lenticular sandy silt beds of short lateral extent and about 6 inches thick (fig. 19). The gravel is composed primarily of angular and subangular tabular pebbles and some cobbles of slaty shale. About 150 feet upslope from the scarp of the slide that carried away the rail line, 8 feet of very sandy gravel is exposed in a shallow borrow pit. The coarse sediment seen in these outcrops is probably representative of the delta as a whole.



19.—Scarps along the front of Rocky Creek delta produced by many small slump-type slides. The gently dipping coarse sediment is clearly visible. With the exception of the sandy lens at left, most of the sediment is dry.



FATHOGRAM RECORDED ON LINE 89



PROFILE ALONG FATHOMETER LINE 89

Note: Because of the large vertical exaggeration on the fathogram, this profile, which has no vertical exaggeration, is also shown

20.—Fathogram and profile at Rocky Creek delta. Line of profiles shown on figure 4.

DESCRIPTION OF SLIDES

A comparison of the areas of net erosion and net deposition (fig. 6) and a comparison of the profiles shown in figure 20 (p. A23) suggest that there was some lateral spreading of the slide debris on the lake floor during deposition. Just how much spreading occurred is difficult to say, for, unlike the edges of the Lawing and Lakeview slides, the edge of the depositional areas farthest from the scarp at Rocky Creek does not coincide with the limit of irregular bottom topography. However, the reconstructed preearthquake bathymetry off the Rocky Creek delta may be in error. At any rate, because the discrepancy occurs at the edge of the area where the sheet of slide debris was probably thin, it is not important in terms of the amount of material involved.

Although it is difficult to locate the position of the outer margin of the depositional area, an outer limit defined either by the edge of the area of irregular bottom topography or by the difference between the preslide and postslide bathymetry suggests that the slide debris traveled a shorter distance than that of the Lakeview slides. The contrast with the Lawing slide is even greater. At Lawing the slide debris moved down a slope of about 20°, traveled for about 2,100 feet over the bottom, and reached a final depth of about 450 feet. At Rocky Creek the sediment moved down a somewhat steeper slope (25°), reached approximately the same final depth (400 ft), yet traveled only about 600 feet over the lake floor. Another important difference between the slides is that at Lawing there were both backfill and farshore waves, but at Rocky Creek there was no evidence that the sliding generated waves. A probable explanation is that at Lawing the slide acted as a single mass and that the volume of the material and the speed of the sliding were sufficient to deliver enough energy to the water to carry the debris a long way from the scarp and to create a wave on the far shore. At Rocky Creek, although a given amount of slide debris had about the same potential energy as at Lawing (fig. 10) and although the total amount of slide material and hence the total potential energy was considerably greater, the sliding took place as a series of small slumps. Furthermore, the slumping occurred over a longer period of time, and at any given moment the total amount of material moving downslope was not large enough to deliver sufficient energy to the water to carry the slide debris any great distance across the lake floor or to create a wave on the far shore.

Sliding steepened the delta front, especially in the upper part (fig. 20); in the upper 100 feet the angle of the slope has been changed from about 22° to about 30°. Unless the slope is regraded, chances for subsequent sliding have been increased.

OTHER SLIDES

Several other slides occurred in the lake. One small slide removed a point of land on the edge of a delta on the south shore of the lake 2 miles east of Cooper Landing (pl. 2). The slide half submerged a boathouse and carried away a stone-filled wooden crib 60 feet long, 5 feet wide, and 8 feet high that served as a pier. Another slide probably occurred on the southeast side of Quartz Creek delta, as suggested by an area of irregular bottom topography. No scarp was formed but the outermost 200 feet of the point was submerged during the earthquake. Soundings showed that the point had dropped approximately 12–14 feet. The fact that the trees in the submerged area were not tilted indicates that there was no appreciable rotation of the delta sediments during submergence. Two small scarps were found 3 miles southeast of Quartz Creek; both were slumps in delta deposits. None of these slides caused detected waves.

Small slides occurred along the front of Meadow Creek delta about 2 miles west of Lawing. Two fathograms off the delta show minor topographic irregularities having local relief of about 3 feet, but show no horizontal bedding as in immediately adjacent fathograms. The fact that the area of irregular topography lies in a lakeward bow of the 500- and 520-foot contours suggests that deposition has taken place. Sliding may have caused the waves that struck the delta and the far shore.

Sliding also occurred from the small delta of Porcupine Creek, west of the mouth of Snow River. A scarp was visible along the mouth of the creek, but to the north the delta edge had been submerged during the earthquake and no scarp could be seen. Two cottages on the northwest side of the delta were partially submerged. An area of irregular bottom topography lies just offshore. Wave damage occurred in the area, the wave probably having been induced by the sliding. Fracturing of the delta surface that accompanied the sliding severely damaged an asphalt-paved parking lot belonging to the U.S. Forest Service.

SEICHING

Seiches are periodic oscillations in lakes, bays, or rivers that are commonly produced by changes in wind stress or atmospheric pressure, and less commonly by earthquakes. The oscillations take the form of standing waves. The periods of the standing waves may be the natural period of the basin, harmonics of the natural period, or, in a complicated basin, they may be controlled by some segment of the basin. The earthquake produced complex seiching in Kenai Lake. In areas of abrupt shallowing and where the water was constricted, some of the waves damaged the shoreline.

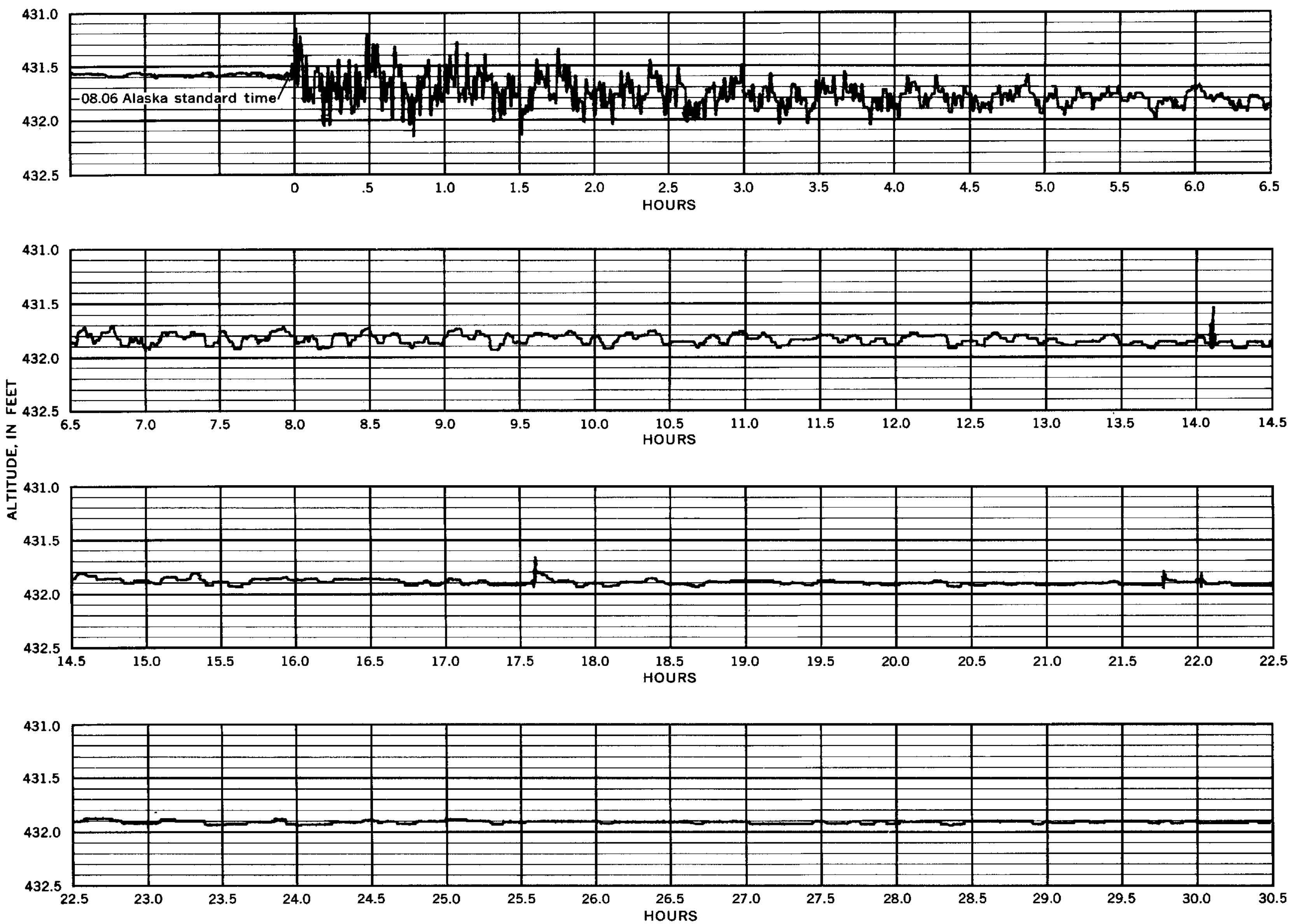
SEICHE PERIODS

A record of most of the seiching was made by a continuously recording water-level gauge at the Chugach Electric Association power station near Porcupine Island (pl. 2), the record (limnogram) of the seiching is reproduced photographically at natural scale in figure 21 (next page).

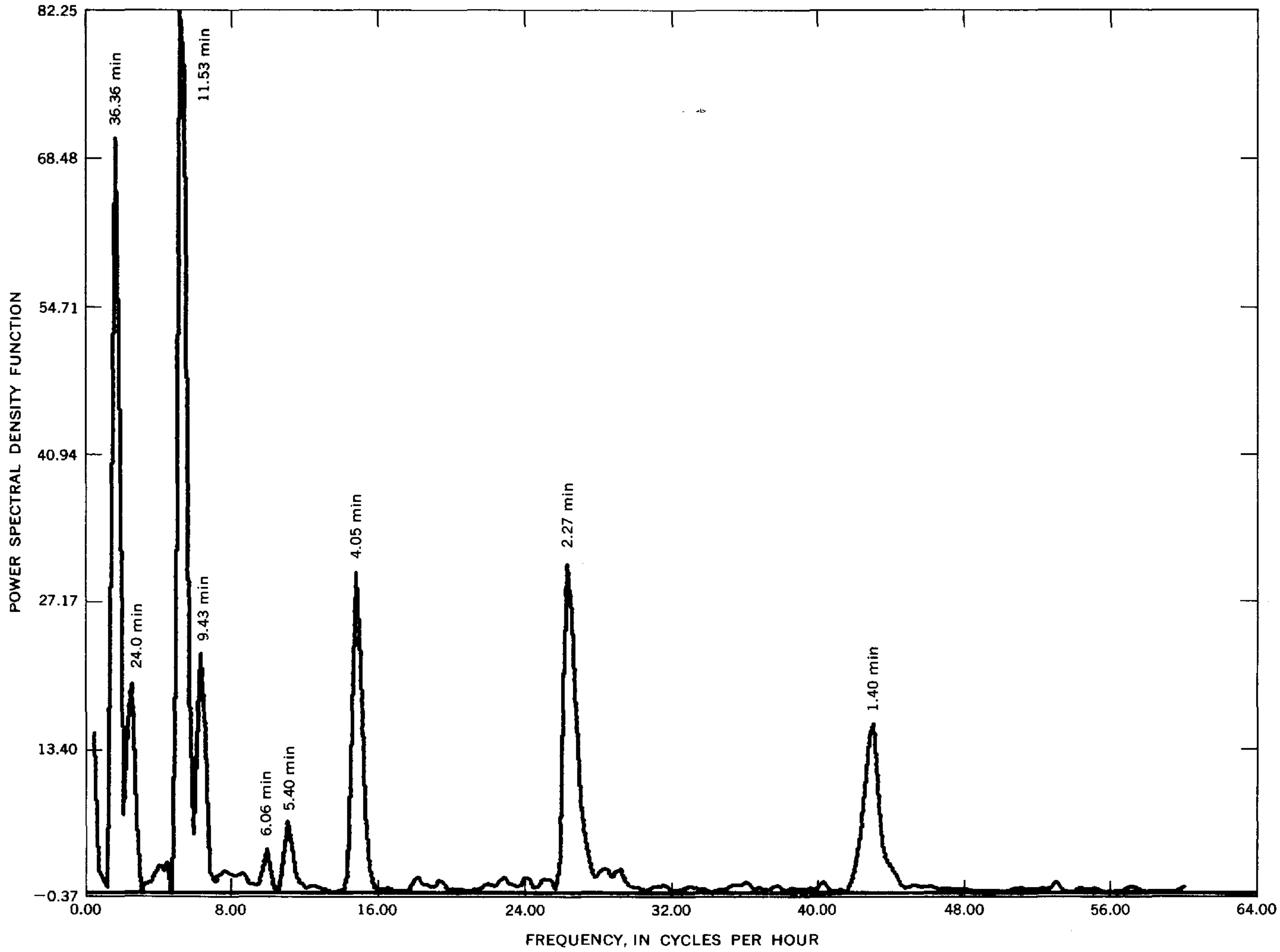
The recording device is a 12-inch (inside diameter) vertical pipe which is located inside the powerplant at the edge of the lake. The bottom of the pipe is in the lake, the top is at an altitude of 443.5 feet, and at 426 feet there is a 1½-inch opening into the pipe. A float rides in the water within the pipe, and the movement of a wire attached to the float is converted to an electric signal by a Leeds and Northrup 7948 transmitter. The signal is recorded by a General Electric-type H.L. pen recorder on paper driven at a rate of 1 inch per hour. (Specifications courtesy of R. A. Johnson, Chugach Electric Association.)

The lake-level recorder stopped about 5:30 p.m., the time of the main shock when the power was cut at the plant, and did not start recording until 8:06 p.m.; thus about 2½ hours of the initial seiching was not recorded. The limnogram shows a long-period oscillation and superimposed higher frequency waves having periods of only a few minutes. It is extremely difficult to tell the number and frequency of the waves that occurred by looking at this record. However, it is possible to determine the frequency and the relative amounts of energy of the waves at the water-level gauge by a power spectrum analysis of the limnogram. [The power spectrum analysis used (Blackman and Tukey, 1959) is a type of Fourier analysis that considers the recorded events to be aperiodic and treats data points as statistical samples based on the premise that even if an event is periodic, data points selected from the record do not accurately represent the event. The data points were taken at one-half-minute intervals for the first 8.5 hours of record using a $X4$ photographic enlargement of the limnogram.] The analysis was done by a computer that plotted the relative amounts of energy against the frequency of all waves from 0 to 64 cycles per hour (fig. 22). [Amounts of energy are shown as the "power spectral density function" defined by Blackman and Tukey (1959, p. 176) as "a value of a function (or the entire function) whose intergral over any frequency interval represents the contribution to the variance from that frequency interval".] Because the total amount of energy dissipated at any frequency as given by this analysis depends in part upon a comparison of the amplitude of the wave at this frequency with the amplitudes of all other waves measured by the lake-level recorder and because seiching produces standing waves with maximum amplitudes between nodes and minimum amplitudes at nodes, the amount of energy dissipated at any given frequency depends in part on the location of the lake-level recorder. Thus, the closer the lake-level recorder is to a node, the lower the value of the power-spectral density function for a wave oscillating around that node. The power spectrum analysis showed that the complex record of seiching was produced by at least nine distinct waves having periods between 1.40 and 36.36 minutes.

The periods of the standing waves formed by seiching are determined by the size and shape of the basin (for a thorough discussion of seiching, see Hutchinson, 1957, p. 299–333). The natural period of a basin can be approximated by using the Merian formula (Hutchinson, 1957, p. 301) for an elongate rectangular tank having vertical sides: $T=\frac{2l}{(g\bar{z})^{1/2}}$ where T is the period, l is lake length, g is the gravitational force, and the average depth. For the total lake, $\bar{z}$ (402.5 ft) was determined by averaging the depths at 187 points spaced one-eighth mile



21.—Limnogram of seiching recorded at the hydrolectric powerplant at Kenai Lake.



22.—Computed power spectral density function versus the frequency of the seiching recorded on the limnogram at the hydroelectric powerplant. Each peak represents a wave of that frequency, and the periods of these waves (in minutes) are indicated for the larger waves.

apart along a line 23.375 miles long drawn halfway between the lake shores. The calculated period of the lake is 36.35 minutes; thus, the observed wave having a period of 36.36 minutes was a uninodal seiche at the natural period of the basin. The near agreement of the calculated and observed periods reflects the fact that despite its two sharp bends, the steep-walled generally flat-floored lake behaved like a rectangular tank.

The relationship of the shape of the lake basin to the periods of the other waves is not as easily established. In the ideal rectangular tank, seiches can form as harmonics of the natural basin. They may oscillate around 2, 3, 4 . . . n nodes, their periods being related to that of the uninodal seiche by $Tn = \frac{1}{n}\frac{2l}{(g\bar{z})^{1/2}}$ where n is the number of nodes. Assuming that Kenai Lake acted as a rectangular tank, the calculated periods (in minutes) of the harmonic waves would be $n_2=18.14$, $n_3=12.11$, $n_4=9.08$, $n_5=7.27$, $n_6=6.05$, and $n_7=5.12$. Although the observed periods (fig. 22) are longer than these predicted values, departures in the shape of a lake basin from a rectangular tank generally lengthen the periods of the harmonic waves (Hutchinson, 1957, p. 307); thus, these waves may have been harmonics. However, the seiches could have formed as oscillations in the straight segments of the rectilinear basin or for the short-period waves, as transverse seiches (the calculated period for a transverse seiche west of the power station is 2.25 minutes, and a wave having a 2.27-minute period was recorded on the limnogram). It is, therefore, unjustifiable to assume, without further study, that the observed waves were harmonics of the whole lake basin.

EYEWITNESS ACCOUNTS OF SEICHING

The seiching was seen by people at Cooper Landing on the Kenai River, at the west end of the lake, at Lawing, and near Snow River. As might be expected by looking at the limnogram (fig. 21) these people saw only the short-period waves. If the amplitude of the long-period wave had been considerably greater than that of the shorter period waves, the long-period wave might have been recognized by the observers. Perhaps it would have been possible to detect the long-period seiche by noting changes in the runup height of successive waves, but without the limnogram all waves having periods of more than 4 minutes would have been undetected.

Mr. I. P. Cooke, chief engineer of The Alaska Railroad, was alongside the Kenai River near Cooper Landing at the time of the earthquake. He said that he saw the Kenai River reverse its direction and flow back toward Kenai Lake.

Mr. John Ingram of Cooper Landing was on the Snug Harbor Road (along the south side of the lake) near its junction with the main highway west of the mouth of Kenai River. When the earthquake started, he checked his parents' house near the lakeshore to be sure that they were all right. He went to his car to drive to his home at Cooper Landing but had trouble driving back because the slope of the moving ground kept changing and stalling the car, and he had to wait until cracks that were opening and closing were closed to permit his passing. He said that as some of the cracks closed they spouted sand into the air. When he reached the highway junction, he looked to the right toward Kenai River and saw the highway bridge and then noticed a ball of asphalt (he later explained he meant a ground wave) moving toward the bridge. He turned toward the bridge and saw that it had been knocked from its pilings and was lying in the water. He estimates that it took him about 4 minutes to reach this spot after the start of the shaking.

While looking at the bridge, Mr. Ingram saw the lake water begin to recede from the highway embankment. He estimates that the lake was lowered about 40 feet (soundings suggest closer to 15 feet), and he could see dead logs on the lake bottom. During withdrawal, he saw Kenai River flow back into the lake as a stretch of rapids. He said that the reverse flow extended as far downstream as Cooper Landing. When he saw the depth to which the water withdrew, he became alarmed for his children's safety because his is the first house west of the highway, beside Kenai River. He immediately went home and got his children out of the house and into the car. He returned to the house to shut off his propane tank, came out, and then went back to shut off his oil tank. He met a highly agitated neighbor and told her "to get hold of herself because the shaking might not stop." Then he drove his children away from the house westward on the highway but was stopped by a slump that had dropped the roadbed along a 3-foot high scarp. When they stopped and got out of the car the ground was still shaking so violently that the trees were swinging sharply. Mr. Ingram estimated that the time between waves, from high water to the following high water, was about 4 minutes. He noted that on the following day the ice in the lake at the bridge site moved back and forth as this wave continued to affect the lake water.

The seiching at the west end of the lake was also seen about 25 minutes after the earthquake by Mr. J. W. Moorcroft of Moose Pass. He estimated that the time from high water to high water was 3–4 minutes, and that the total change in water level was about 20 feet. He said that the rising water "looked like a wave, but not a wall of water." He also estimated that for 150 yards water ran backward from the Kenai River into the lake.

Because wave damage was very slight at the western end of the lake, field evidence for the height of the waves was difficult to find. Hand leveling from the lake surface to the upper limit of driftwood and silt on the south shore near the highway crossing indicated that some waves had runup heights of at least 7 feet.

Seiching was seen at Lawing by Mrs. Hadley Roberts and Mr. Frank Gibbons. Their full descriptions were given in the discussion of the slide-generated waves at Lawing. The highest probable wave formed by seiching is described by Mrs. Roberts as having been "almost up level with the bank." This level would indicate a height of about 10 feet. Neither observer estimated the time between successive waves.

Seiching at the eastern end of the lake was seen by Mr. Thrall from his home just west of the Snow River delta. He did not see the lake during the earthquake but watched it for about an hour after the shaking stopped. Mr. Thrall said that the water went in and out like a wave and he guessed, but said he was not sure, that it was about a minute between successive highs. The water carried ice up onto the edge of Snow River delta and piled it into the river mouth. From the high-water mark indicated on the bank by Mr. Thrall, the wave had a height of 8½ feet.

TILTING OF THE LAKE—THE PROBABLE CAUSE OF SEICHING

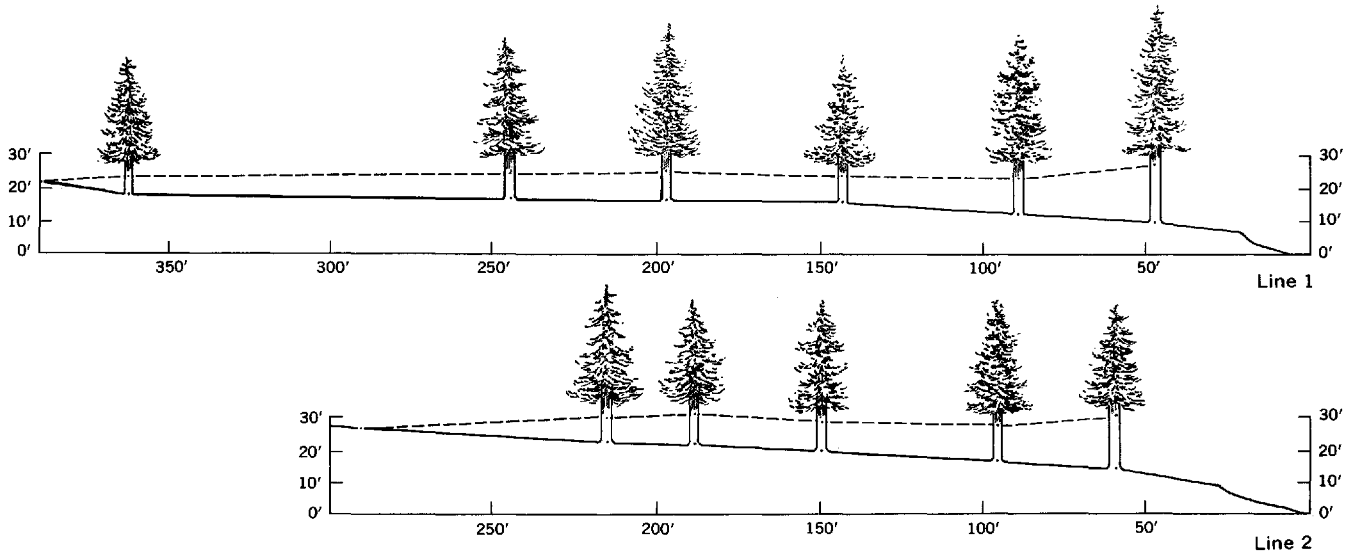
Seiches caused by earthquakes have been known for a long time; the 1755 Lisbon earthquake produced seiches in lakes in Scotland, England, Germany, and the Low Countries (Hutchinson, 1957, p. 300). Similarly the 1964 Alaska earthquake caused seiches as far away as Michigan (Waller and others, 1965). However, as quoted by Hutchinson (1957, p. 328), G. Chrystal pointed out that generally the vibrations caused by earthquakes have too short a period to cause a resonant response by a lake; even as a result of the Lisbon earthquake, Loch Lomond responded with a trinodal or quadrinodal rather than a uninodal seiche. Hebgen Lake, Mont., experienced seiching that resulted from the 1957 earthquake. The seiching was attributed to tilting of the lake basin (Myers and Hamilton, 1964). Wiegel and Camotim (1962) succeeded in producing seiches by suddenly lowering one end of a model of Hebgen Lake basin. Their analysis showed that the observed wave was the first harmonic of a seiche that formed in one arm of the lake. As shown below, Kenai Lake basin was so tilted that its western end was lowered about 3 feet more than its eastern end. Although the earthquake might have produced short-period seiches within the lake, the uninodal seiche may have resulted from the tilting of the lake.

Kenai Lake basin was tilted. The tilt was measured to establish the deformation of the land surface in the area affected by the earthquake. Because Kenai Lake was the only long lake that had bench marks near its ends prior to the earthquake, it was the only lake on which tilting could be readily established.

Eighteen days after the earthquake, temporary bench marks were placed at the ends of the lake—one on bedrock on the north shore 2½ miles east of Cooper Landing, the other on the rail of The Alaska Railroad line on the east shore one-third mile south of Rocky Creek. The bench marks were installed on a calm day while the lake was frozen; thus distortion of the water surface due to wind stress was probably minimal. The U.S. Army supplied helicopter transportation, and both bench marks were placed within 1½ hours.

Temporary bench marks were used because the ground was snow covered and the preearthquake bench marks could not be found. In a later survey, run to relate the preearthquake and postearthquake bench marks, only the horizontal hole drilled in a vertical rock cut could be found for the preearthquake bench mark south of Rocky Creek (U.S. Coast and Geodetic first order bench mark Z11); the center of the hole was taken as the position of the bench mark. At the west end of the lake the original bench mark (U.S. Army Engineers third order bench mark MR4) had been replaced by the Alaska Department of Highways; the postearthquake bench mark was related to this replacement. The postearthquake survey indicated that the western preearthquake bench mark had been lowered 3.0 feet with respect to the bench mark on the eastern end of the lake. These measurements combined with the postearthquake releveling survey by the U.S. Coast and Geodetic Survey along the eastern shore of the lake which shows that Lawing was lowered 0.430 feet more than Primrose (pl. 2) indicate that the true dip of the tilted surface is N. 72° W. at 1 foot in 5.4 miles.

Both the amount and the direction of tilt as given by this calculation are somewhat questionable. The accuracy is not known for the altitude of either the original third order bench mark or its replacement. Furthermore, bends in the isobases of land-level changes (Plafker, 1965) suggest that tilting was accompanied by local warping; thus, Kenai Lake basin may not have been tilted as a plane. The 3-foot westward tilt indicated by this survey is, however, so great that probably some tilting did occur. A comparable tilt in approximately the same direction is suggested by the isobases drawn by Plafker (1965, p. 1677, fig. 2). According to these isobases the eastern end of the lake (on the basis of the U.S. Coast and Geodetic Survey releveling) was lowered 4.6 feet, and the western end of the lake lies in the trough of maximum land depression, which was lowered as much as 8 feet to the northeast and southwest of the lake. A westward tilt of the lake basin also is suggested by an eyewitness (Mr. Hadley Roberts), who said that the water at Lawing on the eastern end of the lake was 2 feet lower after the earthquake.



23.—Upper limit of wave damage caused by seiching along two traverses run parallel to wave travel direction on the west side of Ship Creek delta. Locations of traverses are shown on figure 17.

SEICHE WAVE DAMAGE

Slide-generated waves did not cause all the wave damage shown in plate 2, and as noted earlier there was additional minor wave action visible along the entire shoreline after the earthquake. Much of this minor wave action resulted from seiching. Although seiching produces standing waves, these waves become translationary where the water shallows or the lake is constricted.

One constricted area is the narrow shallow gut between Porcupine Island and the north shore of the lake. High water rushed through the gut from the arm to the northwest and from the arm to the east. Ice scars on spruce trees indicate that the water reached a maximum height of 20 feet on the low point on the north side of Porcupine Island. On the north shore of the lake by Porcupine Island, some aspens and bushes were bent by the water, and the ground was covered with a thin layer of sand and silt. On the south shore of the lake opposite Porcupine Island, where the lake is not constricted and the water is deep, Mr. Stanley Weller, an employee of the Chugach Electric Association, said that the water removed snow within 2 feet below a catwalk on the north side of the powerhouse that stands at the lakeshore. This level would indicate a maximum runup height of about 11 feet, or only about half the height of the crest of the wave that washed through the constricted gut north of Porcupine Island.

Waves formed by the seiching were the probable cause of two areas of wave damage on the south shore of the lake, about 2 miles southeast of Quartz Creek, where waves came ashore over an abrupt shallowing (pls. 1 and 2). All the trees at the water's edge were knocked down by the waves though most were still attached to their roots. The largest tree was about 1½ feet in diameter. Some turf was stripped from the bedrock, and cobbles, pebbles, and sand were thrown up on the washed area. The upper limit of wave damage at the shoreline was about 30 feet above the lake, yet despite the relatively gentle slope of the ground, the wave damage extended only about 100 feet inshore.

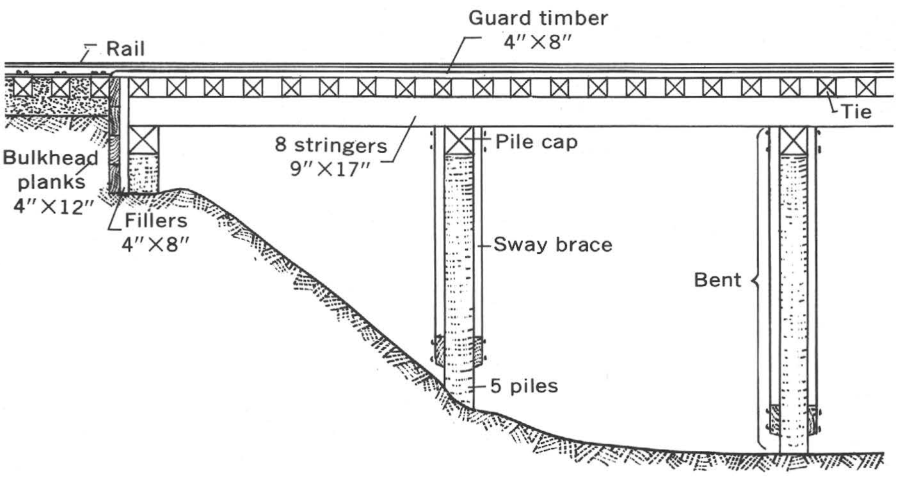
In several other areas of wave damage where there is no evidence that the waves were generated by slides, the waves are assumed to have been caused by seiching. On the west shore of Ship Creek delta, water ran inland for at least 366 feet and had initial runup heights as much as 30 feet (fig. 23). The travel directions indicate that the wave came from the west and was refracted along the curved delta face. This powerful wave seems rather large for a seiche, but there is no evidence that it was generated by a slide. No slide scarp was visible along the shoreline, and although the small topographic high at the toe of the delta might suggest that sliding had occurred, fathograms showed undisturbed horizontal bedding beyond and to either side of the high.

SPREADING OF DELTA SEDIMENTS

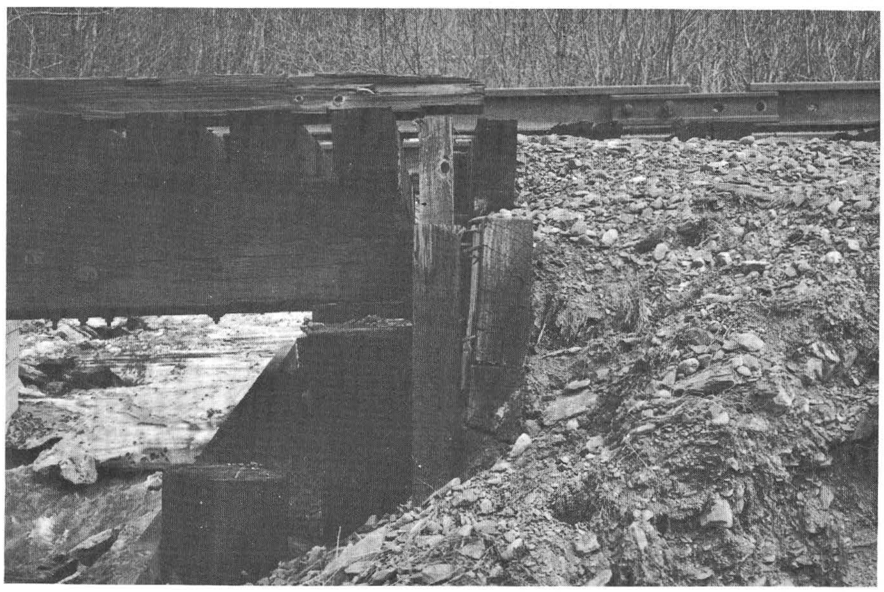
The long period of shaking that accompanied the earthquake mobilized wet unconsolidated sediments ranging in composition from silt to coarse gravel. On some deltas the sediment spread radially downslope and toward delta margins.

At Kenai Lake radial spreading is well shown on Lakeview and Rocky Creek deltas by damage inflicted upon the railroad bridges. (Construction of these bridges is shown on fig. 24.) The bridges were placed under tension when the spreading of the sediments beneath the bridges increased the distance between bents. Some tension was released as stringers skidded over the tops of the bents. Spreading also moved the bulkheads apart; bulkheads were moved 4 and 8 inches away from the ends of the stringers at Lakeview and 3½ and 4 inches at Rocky Creek (fig. 25).

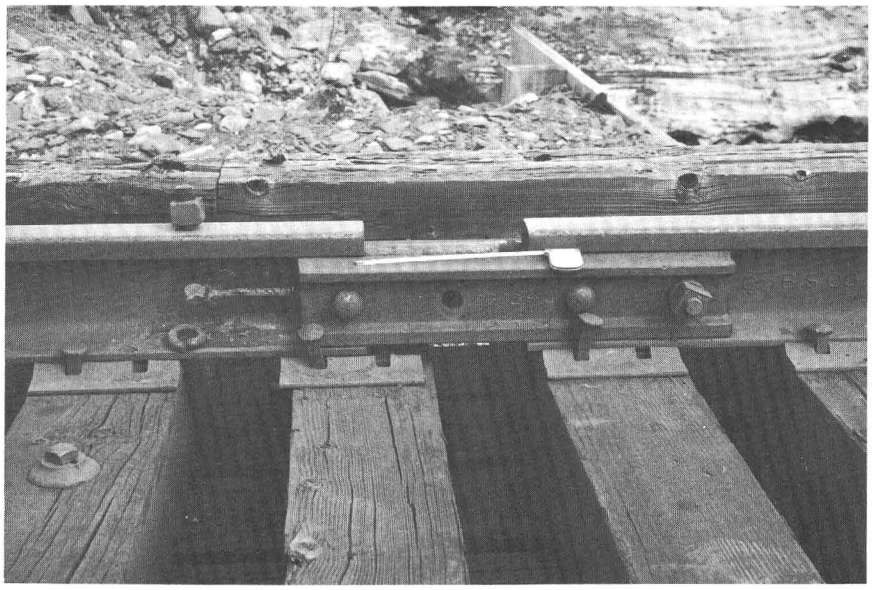
The track was also put in tension, and the rails were pulled apart endwise on the bridges and adjacent embankments. Expansion joints were opened to their



24 (left).—Parts of a typical wooden railroad bridge. The ties lie across heavy wooden "stringers," which in turn rest upon horizontal timbers called "pile caps" that are fastened by iron drift pins to the tops of five supporting "piles." Each group of five piles and its pile cap is called a "bent." A retaining wall at each end of the bridge is called a "bulkhead" and is made by nailing horizontal 4- by 12-inch planks to vertical 4- by 8-inch wooden "fillers." The fillers in turn are bolted to the pile cap of the end bents. "Guard timbers" (4- by 8-inch planks) are lag bolted to the ends of the ties on the top of the bridge.



25 (right).—Northeast corner of the railroad bridge on Rocky Creek delta. The stringers rammed the bulkhead and drove the bulkhead timbers away from the fillers during the early part of the shaking. As shaking continued, the underlying sediments of the delta spread laterally and put the bridge and rail line in tension; this tension pulled the stringers part way off the pile cap and sheared the bolts in the track connectors (angle bars).



26.—Tension on Rocky Creek railroad bridge relieved by shearing the bolts in an angle bar and pulling the track apart.

27.—Tension on Lakeview delta railroad bridge pulled guard timbers apart and split a tie.

maximum width, and in several places the tensional force was great enough to shear the bolts in the track connectors (angle bars) (fig. 26). The largest pull-apart was 17 inches at the south end of the Lakeview bridge, and two pull-aparts of 9 inches each were measured on the Rocky Creek bridge. Tension also pulled a guard timber endwise on the Lakeview bridge and split the tie to which it was lag bolted (fig. 27).

The most deeply driven piles in the end bents of the Lakeview bridge had penetration depths of 15 and 20 feet, and of the Rocky Creek bridge 19 and 27 feet. There was no indication that these piles had been tilted while being carried horizontally by the spreading sediment. This lack of tilting suggests that sediment as deep or deeper than the piles was involved in the lateral spreading.

There is some evidence that the end of Rocky Creek bridge was given compressive blows during the earthquake. This evidence consists of multiple dents made by a pebble as it was caught between the bridge and the bulkhead and then fell free, only to be caught again by the successive compression. Four, and possibly five, dents made by the pebble suggest that there were at least this many blows. These compressive blows were so strong that the stringers rammed the bulkhead timbers away from the fillers (fig. 25).

Although pulsating compressive blows were given to the Rocky Creek bridge, the bridge was ultimately put in tension. Thus there is evidence for transient compression on the bridge only during the initial period of the shaking. However, there is no reason to believe that compressive pulses did not continue throughout the duration of the shaking—while the ground was spreading laterally.

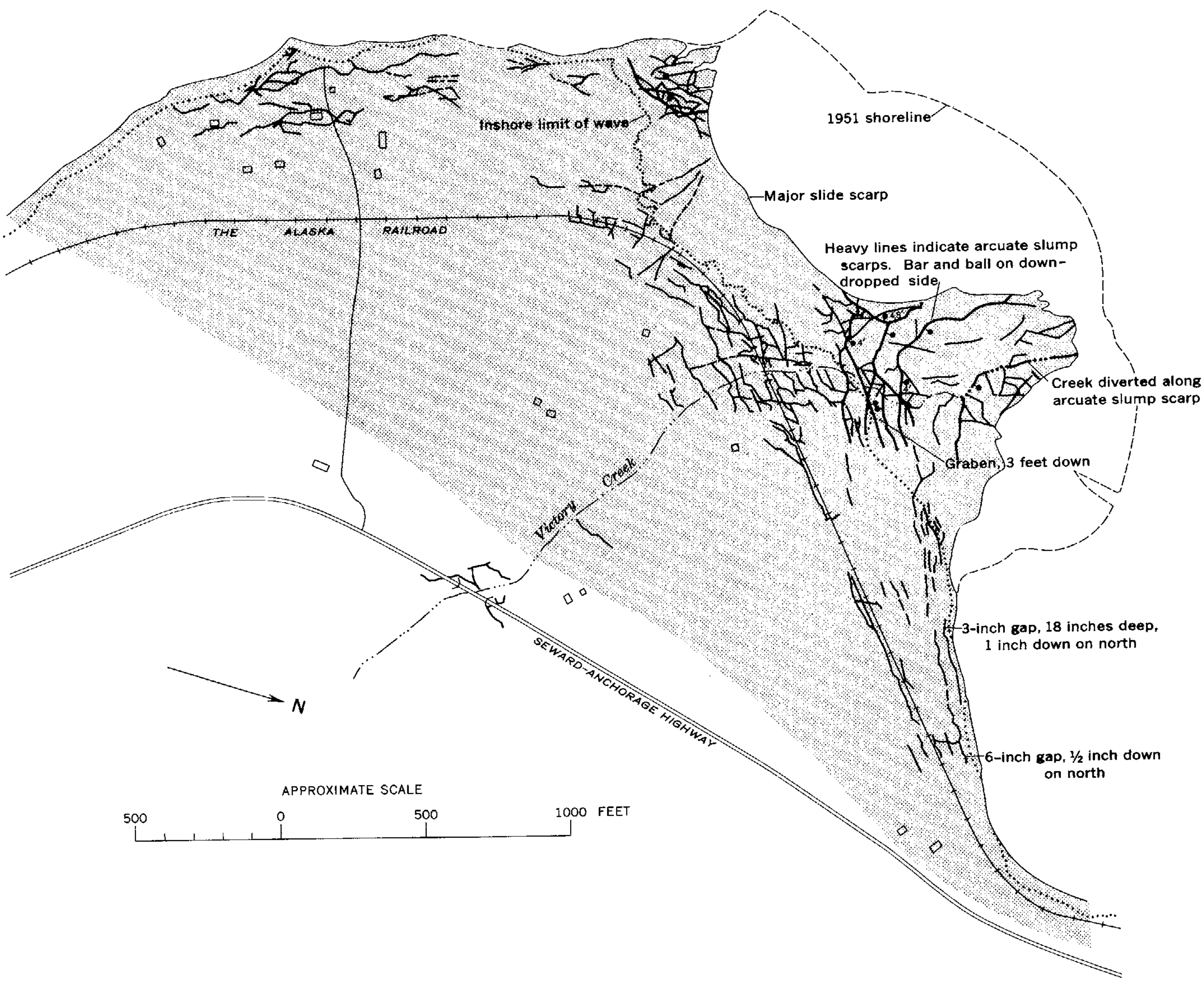
Deep horizontal movement of unconsolidated sediment during the earthquake was not restricted to deltas. Evidence of such movement was observed at many places by the author and M. G. Bonilla during a 2-month study of earthquake damage to the rail belt. Unconsolidated sediment suffered a general loss of strength that reduced its capacity to maintain the local, normally stable topographic relief. As a result, in areas underlain by unconsolidated sediment, almost invariably, deep ground movement occurred toward free faces—stream valleys and breaks in slope. This movement was especially well shown by the damage to railway bridges at stream valleys. As the ground moved toward the streams, it carried piles driven to as much as 30 feet below the ground surface. The streamward movement of the ground decreased bank-to-bank widths by as much as 6 feet, and as a result bridges were arched upward or deflected horizontally by the compression. Multiple pebble dents on the ends of some of the bridges show that compressive blows were also given to bridges ultimately put in compression by converging stream banks. The strength of the unconsolidated sediment of the valley bottoms was so reduced by the earthquake that the horizontally deflected bridges dragged deeply driven piling several feet sidewise through the sediment.

GROUND FRACTURES ON DELTAS

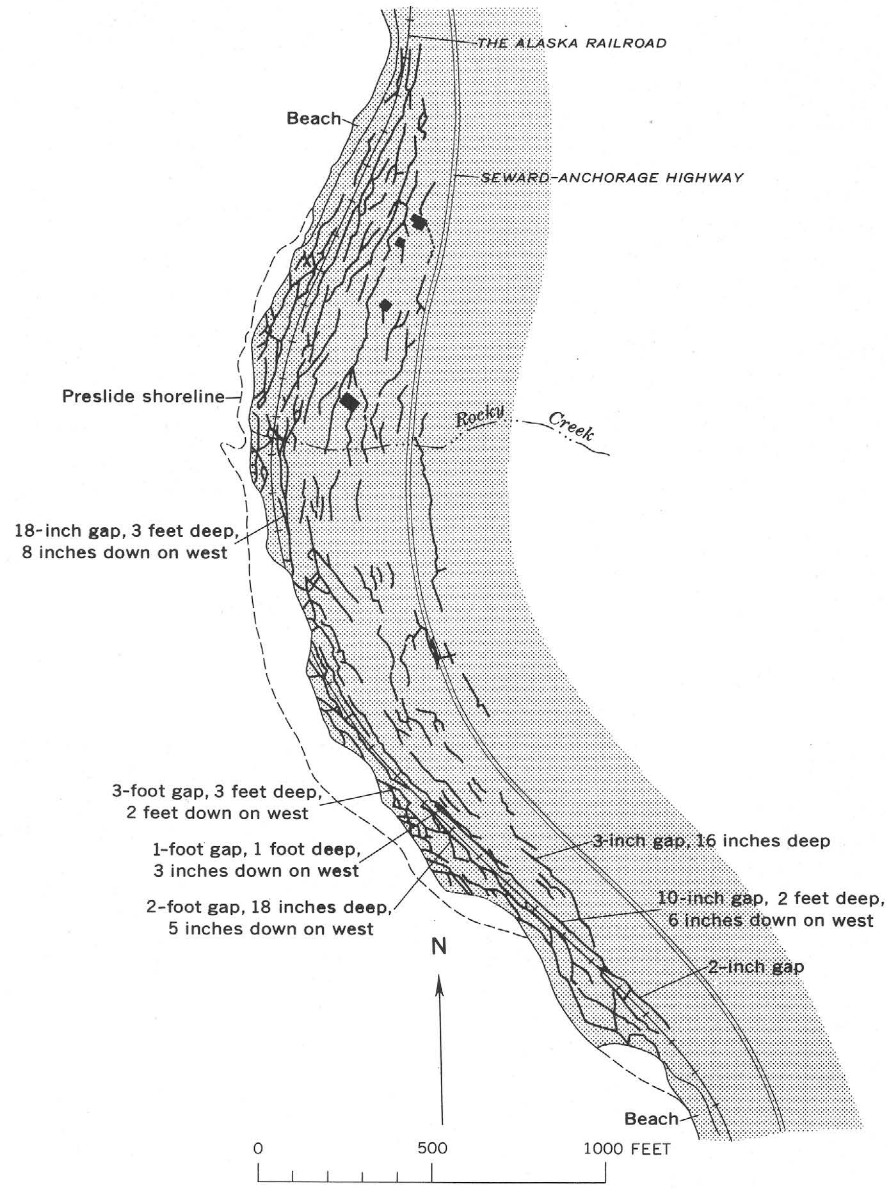
Ground fractures produced by the earthquake on Lakeview and Rocky Creek deltas are of two principal types: (1) arcuate fractures bounding rotational slump blocks and (2) interconnected fractures forming networks of parallelograms produced by lateral spreading of the sediment. The parallelogram-shaped network is the predominant fracture pattern; arcuate fractures also occurred on both deltas, but were larger and more extensive on Lakeview delta. Figures 28 and 29 (p. A34, A35) show these fractures as mapped on the ground and on low-level aerial photographs. Because the upper few feet of the ground was frozen at the time of the earthquake, the fractures were clearly defined (in some places fractures cut twigs and leaves frozen to the surface) and relative movement between adjacent blocks was readily established.

The arcuate fractures on Lakeview delta occur on the points of land north and south of the west-facing scarp. The fractures form irregular scarps bounding blocks that have been downdropped and moved lakeward. Downdropping was as much as 5 feet along some scarps, and some blocks have undergone slight backward rotation (figs. 30 and 31, p. A36). The lower end of Victory Creek was diverted into one of these arcuate fractures.

Although movement of the slump blocks was minor, continued shaking might well have triggered additional landslides. Landslides bounded by the arcuate scarps



28.—Slide scarps and surface fracturing on Lakeview delta.



29.—Preslide shoreline, slump scarps, and ground fracturing on Rocky Creek delta.

30.—Five-foot high scarp along the back of a rotational slump on Lakeview delta. Kenai Lake lies to the left. The slide-induced wave deposited the small pile of sediment on the dirt road displaced by the scarp and debarked the trees.

31.—High scarp (4½ ft) of a rotational slump on the south side of Victory Creek on Lakeview delta.

would have removed the remaining protruding areas from the delta margin. The location of the arcuate slump scarps corroborates the proposition that protruding areas are less stable than adjacent parts of the delta because they contain the greatest amount of mass bounded by the shortest potential surface of rupture.

The second principal type of fracturing occurred over most of the surface of Rocky Creek delta and in two areas on Lakeview delta. On the upper parts of Rocky Creek delta the fractures are 1–1½ feet deep. The blocks appear to have been separated horizontally by downslope movement, and there is no evidence of rotation. Downslope the fractures become longer and more interconnected. Further downslope the horizontal and vertical displacements between blocks increase progressively. The blocks fringing the delta's edge (fig. 32) were downdropped as much as several feet. In plan view, most of the interconnected fractures form parallelograms having acute angles of about 60°. The long axis of the parallelogram lies normal to the slope and approximately parallel to the adjacent face of the delta. There are also occasional short fractures that lie parallel to the shoreline.

A similar network of fractures bounding parallelogram-shaped blocks occurs on the lower slopes of Lakeview delta near Victory Creek and on the south shore (fig. 28). As at Rocky Creek delta, the long axes lie normal to the slope and, on the south shore, parallel to the delta face. The movement between blocks was primarily horizontal, and in some places it was large. Mr. Bruce Cannon, engineer of structures for The Alaska Railroad, measured gaps as great as 4 feet near Victory Creek while the ground was frozen.

32.—Slump block having some rotation and horizontal separation at the edge of Rocky Creek delta.

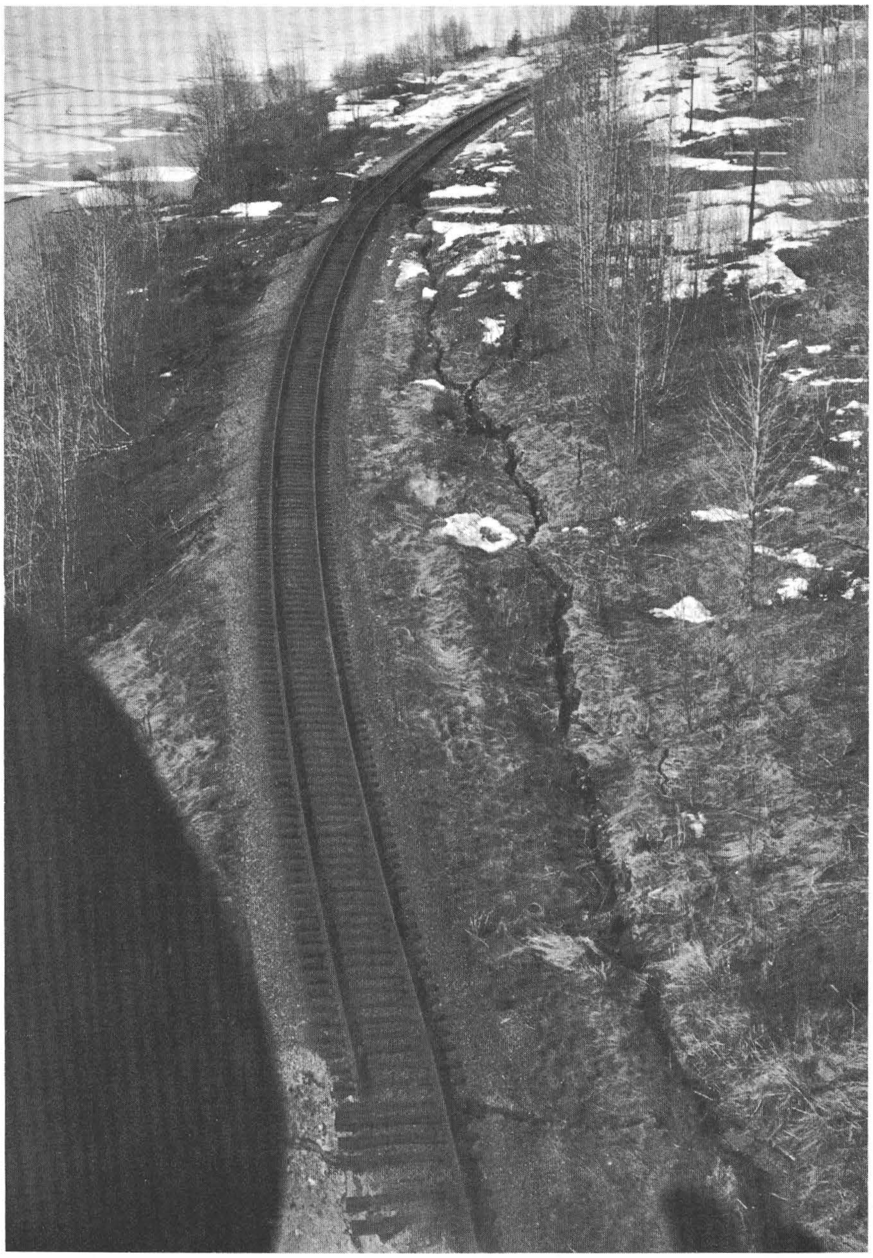
CAUSES OF FRACTURING

The parallelogram pattern of fracturing probably involved only a shallow surface layer, for downdropping was significant only on blocks adjacent to the faces of the deltas. Considering the deep ground movement on both of these deltas and the shallow fracturing, it seems likely that this fracturing was produced by stress developed in the somewhat more brittle surface layer by the spreading of the underlying sediment. Furthermore, the surface fracture patterns are consistent with the stress distribution that would be set up by deep ground movement.

The relationship between the probable stress field and the resulting fracture pattern is apparent on both the Rocky Creek and Lakeview deltas. Spreading of the underlying sediment should form a stress field in the overlying layer with components acting at right angles—one parallel and one normal to the delta face. Such a stress field should produce shear fractures that lie at some intermediate position between the axes of maximum and minimum strain. These are probably the fractures that intersect at 60° and form the parallelogram-shaped blocks. This stress distribution should also form tension fractures normal to the axis of maximum strain; indeed, the occasional fractures on Rocky Creek delta that were formed parallel to the shoreline are probably tension fractures.

On Rocky Creek delta the fracture pattern suggests that deep ground movement was generally radial (fig. 29). On Lakeview delta it appears that the principal movement of the unconsolidated sediment, and hence the direction of maximum strain in the surface material lies toward the west-facing scarp that bounded the major slide (fig. 28). This fracture pattern also occurs on the south side of the Lakeview delta, and again it has the same orientation to the probable radial spreading that would have occurred downslope and toward the face of the delta.

A third type of fracturing is found on both deltas; it occurs along the railway line, sometimes in the marginal drainage ditch and sometimes in the adjacent bank



33.—Ground fracture bounding the railroad line on Rocky Creek delta just north of the slide that carried away part of the rail line.

(fig. 33). There is usually horizontal separation along the fracture. At Rocky Creek delta, where the rail line lies near the delta face, there was also some minor downdropping along the fracture. The linear irregularity in the surface may have oriented the stress locally to produce the fracturing or may simply have made the surface layer weaker here than in adjacent areas.

CONCLUSIONS

The earthquake triggered many subaqueous slides from the deltas in Kenai Lake. The slides generally removed protruding areas of the delta margins. Most of the projecting areas were composed of the youngest delta sediments, but one included older delta sediments. Projecting areas are probably the least stable parts of deltas, for they contain the largest amount of mass bounded by the shortest potential surface of rupture. Therefore, slides on projections may be predictable hazards in other areas.

Two kinds of destructive local waves were caused by the slides from deltas:

1. A backfill wave, formed by water that rushed toward the delta to fill the void left by the sinking slide mass, overtopped the slide scarp, and inundated the margin of the delta. Some backfill waves had crests as high as 30 feet above the lake level and ran inshore several hundred feet, uprooting and breaking off large spruce trees.
2. A far-shore wave struck the shore opposite the slides. The wave was formed when water displaced by the slide mass, and possibly carrying some slide debris, flowed across the lake floor to the toe of the far shore and forced water to run up the far side of the like basin and burst above the surface of the lake. Where one of these bursts of water struck a steep bank, it ran up as much as 72 feet above lake level. These waves were also highly destructive to the forest, and in places they broke off large trees and stripped the vegetation from the bedrock shore.

Slide debris ranging in composition from pebbly sand to sandy cobble gravel became entrained in water set in motion by the sliding and was carried radially downslope away from the landslide scarp and out over the nearly horizontal lake floor. Fathograms show that the debris from one slide was transported 5,000 feet or more from the delta. Generally, the larger the slide mass and the deeper the water into which the slide mass moved, the greater was the momentum of the mass; thus the slide debris was carried farther, and the far-shore wave was stronger. Fathograms suggest that the soft lake-floor sediment in the path of the slide debris was eroded. Variations of wave-travel directions in areas struck by the far-shore waves exceed those which might have been produced by refraction, and suggest that the movement of the water-entrained slide debris was not unidirectional.

Not all slides into the lake generated waves. At Rocky Creek, where sliding took place as a series of small slumps along the whole margin of the delta, no evidence was found for wave action on either the delta or the opposite shore. As might be expected, the slide debris from these small slumps was not carried far from the delta.

In several areas, sliding has steepened the slopes on the delta fronts and thus has increased the future hazard of slides. In subaerial slides, although the surface of rupture may be steeper than the original slope, slide debris usually comes to rest at the base of the rupture surface and thus reduces the chances for major sliding. In the subaqueous slides, however, the debris has largely been carried away from the surface of rupture; in the places where sliding has steepened the slope of the delta front, the chances for future sliding may have been increased.

Waves formed by seiching in Kenai Lake during the earthquake oscillated at the calculated uninodal natural period of the basin and at eight or more shorter periods. It was not determined if the shorter period waves were harmonics of the whole basin or if they were seiches controlled by segments of the rectilinear basin. The waves were in general only about 5–6 feet high, but in several places where the lake shallows abruptly or is constricted the waves were considerably higher. In one place on the shallow edge of a delta the waves had initial runup heights of 30 feet and ran inshore as much as 360 feet. Releveling of preearthquake bench marks along the lake suggests that the western end of the lake was lowered about 3 feet below the eastern end. The tilting was probably responsible for the uninodal and multinodal seiches.

During the earthquake the unconsolidated sediments in the deltas spread laterally toward the margins of the deltas. Horizontal displacement of piling on two railroad bridges shows that the spreading involved material as deep or deeper than 30 feet. Multiple dents made by a pebble caught between timbers at the end of one bridge are evidence for transient compression during the shaking. The spreading of the unconsolidated sediments produced stress in the upper few feet of material on the delta surface. The pattern of the surface fractures formed in response to the spreading was controlled by the distribution of stress.

The damage wrought by the earthquake at Kenai Lake was locally severe, but was relatively minor compared to the potential earthquake hazards of this area. Fortunately, the lake was extremely low at the time of the earthquake. Had the lake level been 10 feet higher as it was 6 months later, the effects of seiches and slide-generated waves would have been greatly magnified. Instead of coming only 360 feet inshore at Lawing the waves would have traveled at least 600 feet inland. Houses which this time were just as the inshore limit of the slide-generated waves would have been under 10 feet of water that was driving blocks of sediment and trunks of large trees inland. Undoubtedly such waves would have demolished the houses and would probably have taken the lives of several people. In the future development of this area, and in similar physiographic situations in other earthquake-prone areas, it would be judicious to keep in mind what happened at Kenai Lake during the 1964 earthquake. Building sites on deltas that are not carried away by landslides may be subjected to extremely destructive waves, to severe ground cracking, or to submergence. Areas across the lake from a delta may be struck by a wave produced by a landslide from the delta. Building sites at constrictions in the lake or inshore from abruptly shallowing areas may be subjected to destructive waves caused by seiching.

REFERENCES CITED

Bennett, L. C., and Savin, S. M., 1963, The natural history of Hardangerfjord. Studies of the sediments of parts of the Ytre Samlafjord with the continuous seismic profiles: Sarsia, v. 14, p. 79–94.

Blackman, R. B., and Tukey, J. W., 1959, The measurement of power spectra: New York, Dover Publications, Inc., 190 p.

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

Heath, Rev. E., 1748, A full account of the late dreadfull earthquake at Port Royal in Jamaica, *in* A true and particular relation of the dreadful earthquake which happen'd at Lima * * * 1746: London, printed for T. Osborne in Gray's Inn, p. 327–341.

Heim, Albert, 1932, Bergsturz und Menschenleben: Vierteljahrsschrift Naturf. Gesell. Zürich, v. 77, no. 20, p. 1–218.

Heim, Arnold, 1924, Über submarine denudation und chemische sedimente: Geol. Rundschau, v. 15, no. 1, p. 1–47.

Hutchinson, G. E., 1957, A treatise on limnology: New York, John Wiley & Sons, v. 1, 1,015 p.

Johnson, J. W., and Bermel, K. J., 1949, Impulsive waves in shallow water as generated by falling weights: Am. Geophys. Union Trans., v. 30, no. 2, p. 223–230.

Jones, F. O., Embody, D. R., and Peterson, W. L., 1961, Landslides along the Columbia River valley, northeastern Washington: U.S. Geol. Survey Prof. Paper 367, 98 p. [1962]

Kachadoorian, Reuben, 1965, Effects of the March 27, 1964, earthquake on Whittier, Alaska: U.S. Geol. Survey Prof. Paper 542–B, p. B1–B21.

Kiersch, G. A., 1964, Vaiont reservoir disaster: Civil Eng., v. 34, no. 3, p. 32–39.

Kuenen, Ph. H., 1950, Turbidity currents of high density: Internat. Geol. Cong., 18th, London, 1948, Rept., pt. 8, p. 44–52.

Link, M. C., 1960, Exploring the drowned city of Port Royal: Natl. Geog. Mag., no. 117, p. 151–183.

Martin, G. C., Johnson, B. L., and Grant, U. S., 1915, Geology and mineral resources of Kenai Peninsula, Alaska: U.S. Geol. Survey Bull. 587, 243 p.

Meyers, W. B., and Hamilton, Warren, 1964, Deformation accompanying the Hebgen Lake earthquake of August 17, 1959, *in* The Hebgen Lake, Montana, earthquake of August 17, 1959: U.S. Geol. Survey Prof. Paper 435, p. 55–98.

Miller, D. J., 1960, Giant waves in Lituya Bay, Alaska: U.S. Geol. Survey Prof. Paper 354–C, p. 51–86.

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

Prins, J. E., 1957, Water waves due to a local disturbance: Coastal Eng. Conf., 6th, Proc., p. 147–162.

Richter, C. F., 1958, Elementary seismology: San Francisco, Calif., W. H. Freeman and Co., 768 p.

Taylor, D. W., 1948, Fundamentals of soil mechanics: New York, John Wiley & Sons, 700 p.

Terzaghi, Karl, 1950, Mechanism of landslides, *in* Application of geology to engineering practice, Berkey Volume: New York, Geol. Soc. America, p. 83–123.

U.S. Army Corps Engineers, Beach Erosion Board, 1961, Shore protection and design: U.S. Army Corps Engineers, Beach Erosion Board, Tech. Rept. 4, 242 p.

Varnes, D. J., 1958, Landslide types and processes, *in* Eckel, E. B., ed., Landslides and engineering practice: National Research Council Highway Research Board Spec. Rept. 29, NAS–NRC Pub. 544, p. 20–47.

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

Wiegel, R. L., 1955, Laboratory studies of gravity waves generated by the movement of a submerged body: Am. Geophys. Union Trans., v. 36, no. 5, p. 759–774.

——— 1964, Oceanographical engineering: Englewood Cliffs, N.J., Prentice-Hall, Inc., 532 p.

Wiegel, R. L., and Camotim, Data, 1962, Model study of oscillations of Hebgen Lake: Seismol. Soc. America Bull., v. 52, no. 2, p. 273–277.

Witkind, I. J., 1964, Events of the night of August 17, 1959, The human story, *in* The Hebgen Lake, Montana, earthquake of August 17, 1959; U.S. Geol. Survey Prof. Paper 435, p. 1–4.

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