The Alaska Earthquake
March 27, 1964

Effects on Hydrologic Regimen

South-Central Alaska

GEOLOGICAL SURVEY PROFESSIONAL PAPER 544-A

THE ALASKA EARTHQUAKE, MARCH 27, 1964:
EFFECTS ON THE HYDROLOGIC REGIMEN

Effects of the March 1964 Alaska Earthquake On the Hydrology Of South-Central Alaska

By ROGER M. WALLER

Water-level fluctuations, long-term changes, and temporary effects caused by response of the ground water to seismic waves

GEOLOGICAL SURVEY PROFESSIONAL PAPER 544-A

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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, and Professional Paper 544 describes the effects of the earthquake on the hydrologic regimen. Other Professional Papers will describe the history of the field investigations and reconstruction effort and the effects on transportation, communications, and utilities.

CONTENTS

ILLUSTRATIONS

FIGURES

EFFECTS OF THE MARCH 1964 ALASKA EARTHQUAKE ON THE HYDROLOGY OF SOUTH-CENTRAL ALASKA

By Roger M. Waller

ABSTRACT

The earthquake of March 27, 1964, greatly affected the hydrology of Alaska and many other parts of the world. Its far-reaching effects were recorded as water-level fluctuations in gages operated on water wells and streams. The close-in effects were even more striking, however; sediment-laden ground water erupted at the surface, and even ice-covered lakes and streams responded by seiching.

Lake and river ice was broken for distances of 450 miles from the epicenter by seismic shock and seiche action. The surging action temporarily dewatered some lakes. Fissuring of streambeds and lakeshores, in particular, caused a loss of water, and hydrologic recovery took weeks in some places. Landslides and snow avalanches temporarily blocked streams and diverted some permanently. The only stream or lake structures damaged were a tunnel intake and two earthen dams. The winter conditions—low stages of water and the extensive ice cover on lakes and streams—at the time of the earthquake greatly reduced the damaging potential.

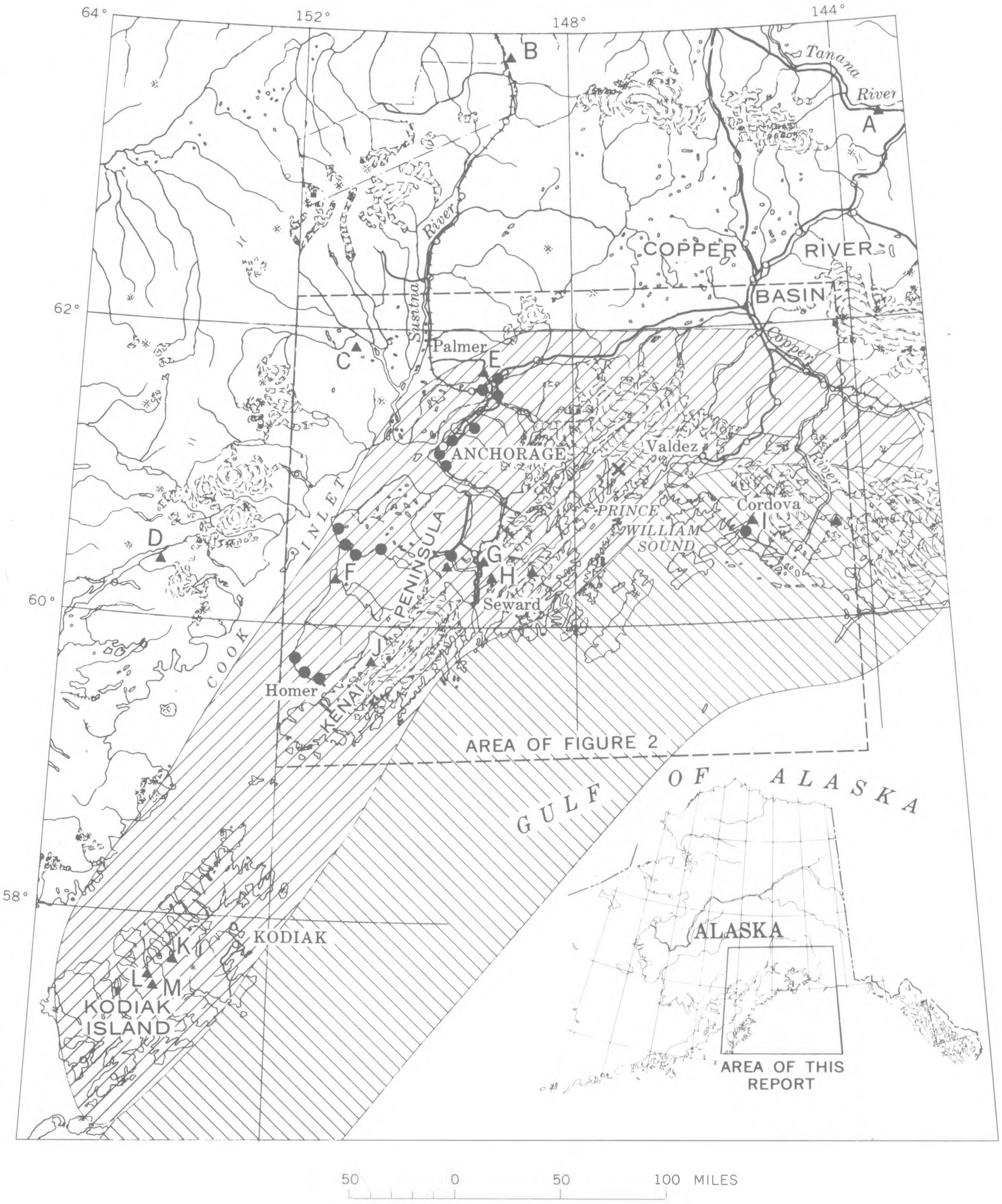
Ground water was drastically affected mostly in unconsolidated aquifers for at least 160 miles from the epicenter. Within 100 miles of the epicenter, vast quantities of sediment-laden water were ejected in most of the flood plains of the glaciofluvial valleys. A shallow water table and confinement by frost seemed to be requirements for the ejections, which were commonly associated with cratering and subsidence of the unconsolidated material. Subsidence was also common near the disastrous submarine landslides, and was probably caused by loss of water pressure and by lateral spreading of sediments. Effects on ground water in bedrock were not determinable because of lack of data and accessibility, particularly within 50 miles of the epicenter.

Deep aquifers in unconsolidated sediments, which in most areas are under high hydrostatic pressure, were also greatly affected. Postearthquake water levels for a year were compared with long-term prequake levels to show permanent changes in an aquifer system. At Anchorage and in parts of the Kenai Peninsula, artesian-pressure levels dropped as much as 15 feet. These lower pressures were probably caused either by grain rearrangement which increased the porosity within the aquifer or by a displacement of material that allowed water to discharge more freely at the submarine terminus of the aquifer.

Seismically induced pressure on ground water was instrumental in causing most of the disastrous slides. Water quality was not changed except for temporary increases in turbidity in wells and streams. The sediment load in streams during the April spring runoff appeared to be greatly increased over previous years.

INTRODUCTION

The earthquake occurred March 27, 1964, at 5:36 p.m. Alaska standard time and was centered in Prince William Sound (fig. 1). The land vibrated for as long as 6 minutes from this main shock which had a Richter magnitude of 8.4–8.6. Numerous aftershocks were distributed for about 500 miles (Press and Jackson, 1965) along a zone of faulting extending from Prince William Sound to Kodiak Island. During the main shock, and possibly during some of the first aftershocks, more than 40,000 square miles of land was lowered as much as 8 feet, and more than 25,000 square miles of land was raised as much as 33 feet (Plafker, 1965). Surface bodies immediately responded to the shaking and tilting of the land. Fortunately, from the standpoint of life and property, reservoir storage and streamflow were at their annual minimums, and a 2- to 6-foot seasonal frost penetrated



EXPLANATION

Zone of subsidence
(After Plafker, 1965)

Zone of uplift
(After Plafker, 1965)

Extent of appreciable effect on ground and surface water

× Epicenter

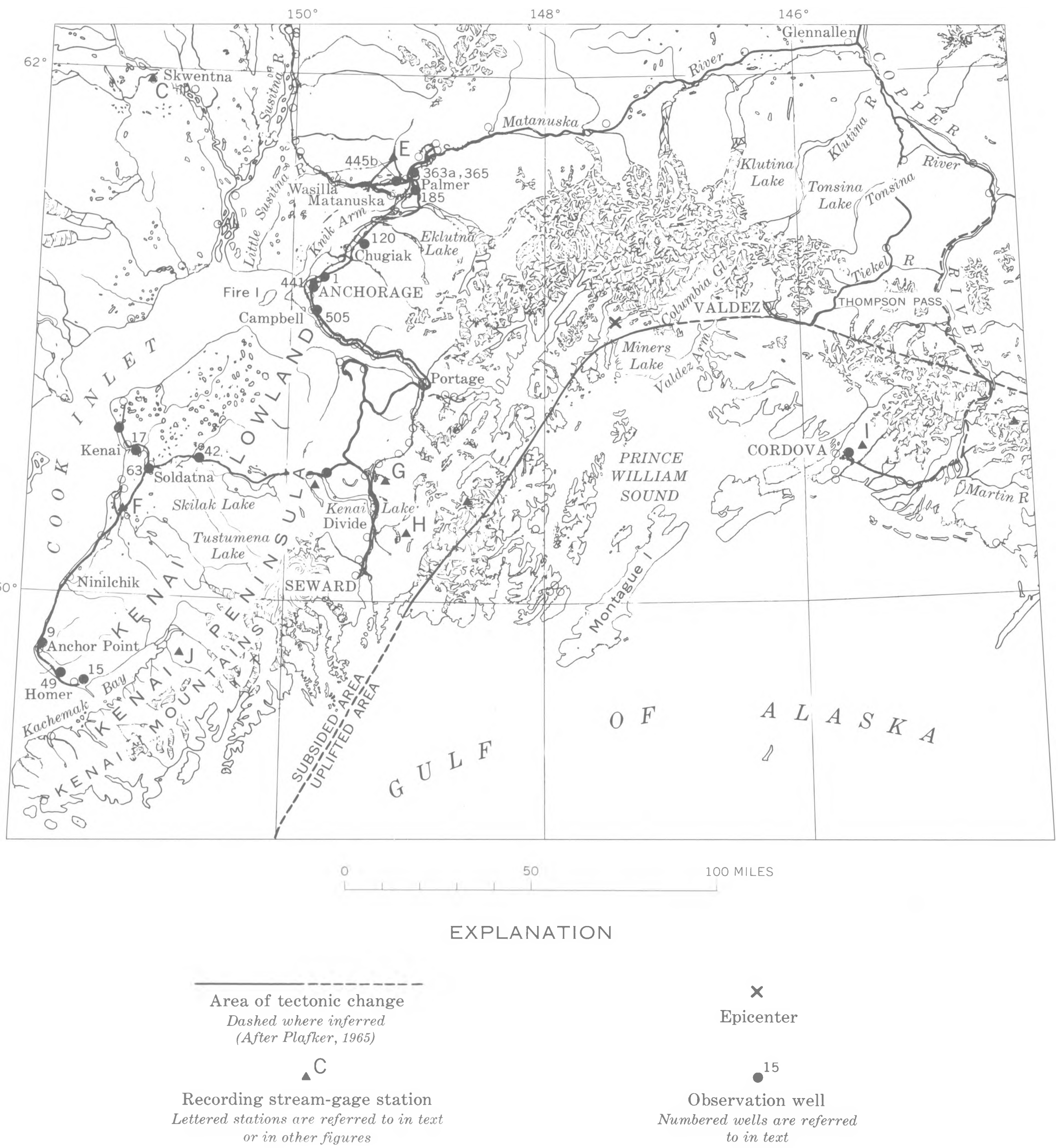
▲ E
Recording stream-gage station
Lettered stations are referred to in text or in other figures

● Observation well

1.—Map of Alaska showing epicenter, areas of uplift and subsidence, and extent of significant hydrologic effects.

most of the land and water surface. The minimum water and maximum ice conditions reduced fluctuations and lessened the flooding from temporarily impounded streams or breached outlets.

The extent of the hydrologic effects was possibly the greatest that has ever occurred on the North American continent and probably the greatest ever recorded. Water levels in streams, lakes, bays, and reservoirs fluctuated throughout most of the continent. Alaska has only a few recording stream-gage stations (figs. 1, 2), hence records of surface-water fluctuations are scarce. Several gages recorded the



2.—Map of south-central Alaska showing locations of surface-water and ground-water observation stations.

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earthquake, and one gage (McCulloch, 1966) recorded most of the postquake seiche action on Kenai Lake. A few visual observations by witnesses supplement the available data. Hydrologic effects outside of Alaska have been described by Donn (1964), Wigen and White (1964), Miller and Reddell (1964), and McGarr (1965).

Subsurface water was also affected at great distances—fluctuations of ground-water levels were recorded as far away as Europe (Vorhis, 1966). Articles published to date on ground-water fluctuations include reports by the U.S. Coast and Geodetic Survey (1964), Miller and Reddell (1964), and Waller and others (1965). Only five water-level recorders were operating in wells in Alaska—all at Anchorage. Hence, this great event occurred not only in an area of sparse population, but also in an area of sparse instrumentation.

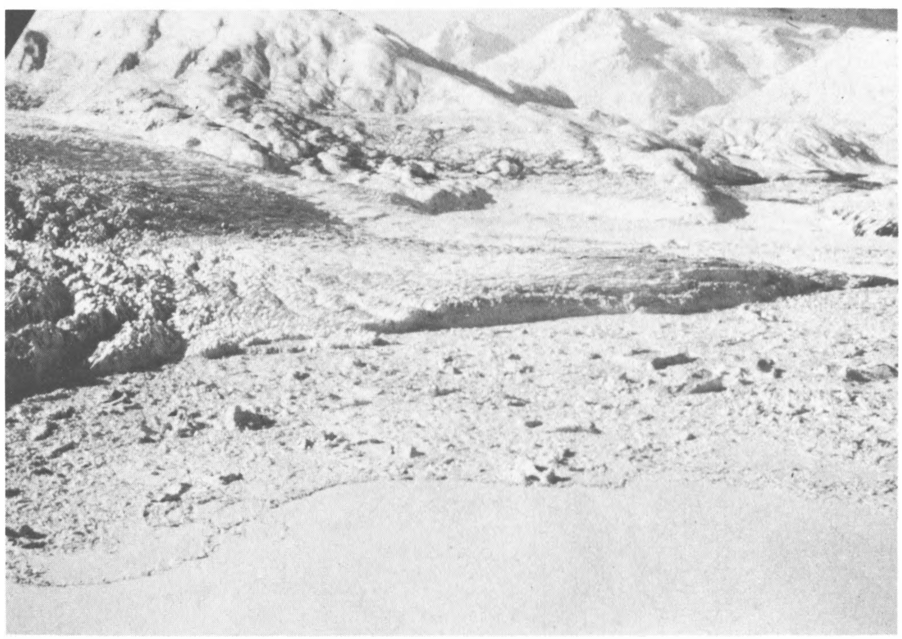
The effects described in this chapter are not at or near the epicenter. Most were observed from 25 to 200 miles away (fig. 2).

The writer has relied on eyewitnesses and colleagues for their field observations and descriptions. In addition, several published articles have supplemented both the data and the interpretations of various aspects of hydrology. The help of the author's colleagues in Alaska during the first few weeks after the earthquake is gratefully acknowledged.

EFFECTS ON LAKES

ICE COVER

One of the most noticeable effects of the earthquake was the breaking of the ice cover—as much as 3.5 feet thick—on most of the lakes in south-central Alaska. The ice cover was randomly broken in most lakes, pressure ridges were produced in the ice along the shoreline of many, and ice chunks were thrown on the beaches of others. Grantz and others (1964, p. 6, 10) noted a generally east-west orientation of the pressure ridges and cracks in the lake ice. The extent of the ice breakage in Alaska is also shown by Grantz and others (1964, fig. 1) and lies far beyond the zone significantly affected by the quake (fig. 1). Kachadoorian (1964) indicated ice breakage in an area of 100,000 square miles, and Péwé stated (1964, p. 9) that "Strong oscillations were noted in lakes on Seward Peninsula and on the south side of Brooks Range, more than 500 miles away from the epicenter."

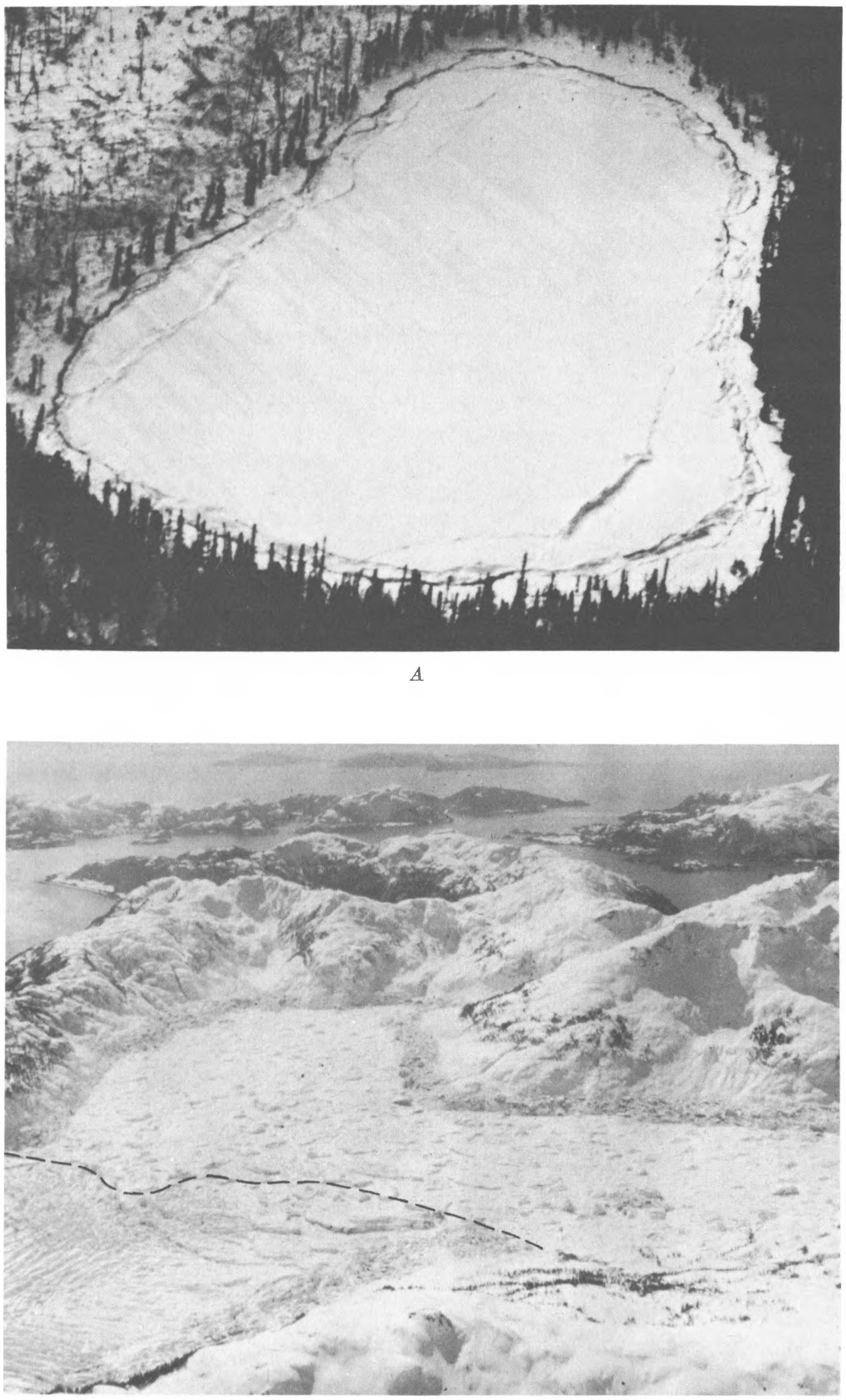


3.—Front of Colony Glacier shattered by earthquake and scattered on Lake George ice; photograph by C. M. Hembree, April 4, 1964.

Where the lakes fronted glaciers (fig. 3), some glacier fronts were shattered and glacial ice was thrown out onto the ice-covered lake. Although Ragle and others (1965, p. 13) reported some shattering, they found no direct proof that the glacier fronts of Colony, Portage, and Miles Glaciers calved extensively as a result of the earthquake. Other observers disagree. For example, Arthur Kennedy, U.S. Forest Service, who was at Portage Glacier at the time of the earthquake, noted in his personal diary for March 28, 1964, that "The glacier no longer has a sheer face—it is sloped upglacier from lake at about a 30° angle."

WAVE ACTION

Although most of the lake ice was doubtless fractured during the earthquake as seismic waves traversed the land, most of the ice was broken by wave action as the lake waters continued to oscillate long



A

B

4.—Earthquake-induced features on lakes. *A*, Pressure ridges on Kenai Lowland lake. *B*, Broken ice on a lake fronting Columbia Glacier; dashed line indicates front of glacier; photograph by C. H. Hembree, April 4, 1964.

after the earthquake. In some lakes, secondary waves were generated by subaerial or subaqueous landslides. The larger lakes showed the most extensive wave action and subsequent breakage of ice, whereas the smaller shallow lakes showed the most conspicuous pressure ridges along the shores (fig. 4*A*). A comprehensive study on fisheries, including effects on lakes, was made by the Alaska Department of Fish and Game (1965). Many of their observations are included below.

The rough texture of the lake ice and the abundance of jumbled ice blocks deposited on the shore of the lake fronting Columbia Glacier (fig. 4*B*) give the impression that the glacier itself had collapsed rather than that ice was stranded on the shore by the drop in lake level. The latter interpretation is that of Ragle and others (1965, p. 20), who then conclude that all the stranded ice disappeared as the level rose during the summer of 1964, because by August the lake had reached the April preearthquake level again. A drop in lake level would have left large sheets of ice on the shore, much like those left on Eklutna Lake each winter as water is withdrawn for hydroelectric power generation. Thus it seems more likely that the stranded ice was deposited by seiche action and that by August it had melted.

SEICHE WAVES

Arthur Kennedy also recorded in his diary for March 27–28, 1964, an eyewitness account of wave action and ice breakage. Kennedy and four others were making depth soundings on Portage Lake, fronting Portage Glacier, when the earthquake occurred. They had just finished measuring the depth (534 ft plus 3 ft of ice) in one hole when, as Kennedy states, "I first recall a distant roar sound then the lake began to violently vibrate. Toward the glacier I heard a very loud roaring." Then the ice "began to heave * * * at the hole we had just drilled—the water was going down and out of sight, then gushing up to the top and slightly over-flowing. The ice was now heaving up and down in big surges and at the same time violently vibrating. We noticed small cracks (couple inches wide) running great distances * * *. I could hear these cracks forming * * *." After the major rumbling stopped and the vibrations and heaving had diminished, they headed for shore. About 400 feet from shore, "The cracked ice began to get more frequent * * *. We edged forward to within 75 feet of shore." As they started to cross this badly fractured zone, noting the time as 6:15 p.m., they noticed that the ice began to move, and they heard water running. Kennedy continues, "Then I noticed the shoreline looked higher than it was before.* * * [The] lake surface ice was going up and down—I think it was oscillation." (Kennedy later wrote that he estimated this oscillation was about 5 ft.) The party then walked around the west shore of the lake looking for an escape route. The ice was still surging about 3 feet at the lake outlet.

Kennedy wrote that the "interval between oscillations in time was about 2 minutes [from the] highest point to low and return—then there was a period of about 5 minutes between each then back to 2 minutes * * *." Finally, at 7:20 p.m., they found a place to get ashore; at that time no noticeable surge was felt. This party apparently experienced the direct seismic motion as an intense vibration, and then felt the secondary effect as an oscillation (seiche) of the water body which continued almost 2 hours. Whether any subaqueous slides occurred in this lake is unknown, but if there were any, they would also create waves.

Seiche action was also noted in other large lakes. Joe Secora, living on the northeast shore of Tustumena Lake on the Kenai Peninsula (fig. 2), stated (oral commun., 1964) that the 5-inch lake ice started "boiling" and that wave action lasted about 2 hours. The ice

A

B

5.—Seiche-induced features on lakes. *A*, Deposits of iron-stained gravel derived from nearshore lake ice washed up on the beach by seiche waves. *B*, Lake-bottom ripples possibly formed by organic material sorted by seiche waves.

cracked badly, especially along the shore, as the water level oscillated about 2 feet. Other lakes which had notable seiche action are Skilak Lake, north of Tustumena Lake; Bradley Lake, at the head of Kachemak Bay, Kenai Peninsula; Campbell Lake, south of Anchorage; and Eklutna Lake, south of Palmer. Tuthill and others (1964) state that "All lakes in the Martin River area [east of Copper River delta, fig. 2] experienced subaqueous landslides, some of which generated seiches." A stream-gage recorder, located on the outlet of Trail Lake (north of Seward, fig. 2), shows a typical oscillation pattern (fig. 8).

At Kenai Lake on the Kenai Peninsula a water-level recorder, operated by a power company, registered for about 18 hours the seiche action caused by the seismic disturbance as well as wave action generated by landslides. McCulloch (1966) gives a complete description of the effects on Kenai Lake.

Some lakes showed no evidence of wave action, even though they were adjacent to others where the ice was highly fractured. Small circular fracture patterns were observed in several large lakes—usually in the center, but sometimes in a bay or near one end. This pattern may reflect seiche action limited to the deeper parts of the lake. One large lake near the epicenter was practically devoid of extensive fracturing; Ralph Migliaccio (written commun., 1964) flew over Miners Lake a few days after the earthquake and noted the absence of fractures, although snow could have covered small cracks. The closeness to the epicenter may not have been conducive to development of damaging long-period seismic waves. Furthermore, the bedrock basin underlying the lake would respond less to long-period seismic shock waves than would unconsolidated material.

Some effects of wave action continued to be visible long after the earthquake. At Tustumena Lake, isolated piles of gravel and cobbles on the beach (fig. 5*A*) were obviously foreign to the beach and were probably derived from the underside of ice blocks that had been washed up on shore by wave action. The nearshore lake ice had frozen into the beach prior to the quake. Other investigators noted similar deposits on other lakeshores. In the Copper River basin the Alaska Department of Fish and Game (1965, p. 35) reported that ridges of sand and gravel, deposited from ice, blocked some lake outlets. Ripples composed of organic material, probably derived from the beach, formed in a shallow embayment of Tustumena Lake at low lake level (fig. 5*B*). The ripples were about 1–2 feet high and about 50 feet between crests. These ripples may have been formed by the extended seiche action after the quake. Local residents did not recall having seen such ripples prior to the quake.

Trees along the shoreline of many lakes have been scarred by ice. Bark was peeled off as high as 20 feet on trees on Kenai Lake (Alaska Dept. Fish and Game, 1965, p. 29, fig. 20) and 30 feet on Tonsina Lake (p. 35).

LANDSLIDES

The glacial landscape, including many lakes, was modified by snow and rock avalanches, earth slumps, and subaqueous slides which were triggered by the earthquake. The prime sources of slides were glacial deposits along steep valley walls and rapidly deposited alluvial or delta deposits encroaching upon the lakes. In general, the snow and rock avalanches had a negligible effect on the lakes, although when they occurred beneath or slid into a lake they generated waves and a few of these were destructive to manmade structures or to vegetation.

The earth slumps were the most destructive slides. The delta fronts along large lakes usually slumped and fractured (fig. 6). Trees growing along such delta fronts and bordering alluvial fans

6.—Fractured outwash delta and sand flows at head of Tustumena Lake. Photograph by U.S. Fish and Wildlife Service.

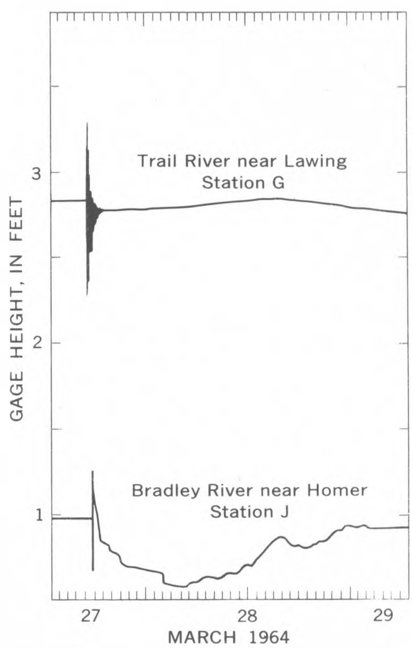
were submerged (fig. 7) as the land subsided. McCulloch (1966) reported that the earthquake-induced slides in Kenai Lake generated waves that washed back into the slide area and also waves that hit the opposite shore. These waves destroyed buildings and scarred the trees several feet above ground level.

Many coastal lakes along Prince William Sound and on Kodiak Island were inundated with salt water and silt by the series of tsunamis that washed inland. For example, Potatopatch Lake at Kodiak is now part of the tidal flats. Some of these lakes had been the source of fresh-water supply for nearby residents or were important for fresh-water sport fishing. Now the lakes will remain saline until the salts have been flushed out.

7.—Trees submerged by minor earth slump along lakeshore.

CHANGES IN WATER STORAGE

Secondary effects of the Alaska earthquake temporarily drained or dewatered many lakes. Lake levels were lowered either by spillage and overflow during seiching or by drainage through fracture systems in the lake basin. Gages on the Bradley Lake and Trail Lake outlets (fig. 2) recorded a temporary loss in stream stage (fig. 8), reflecting lowered lake levels. Discharge from Kenai and Tustumena Lakes also decreased for several hours to several days after the quake. The Finger Lakes in the northern part of the Kenai Lowland (fig. 2) showed the only long-term change in storage capacity. These lake levels were five feet below their prequake levels by October 26, 1964 (Alaska Dept. Fish and Game, 1965, p. 27, fig. 19). A small lake north of Kenai started losing water as late as mid-June.



8.—Hydrographs of two streams draining lakes on the Kenai Peninsula. See figure 2 for locations.

Many lakes were perched above the seasonal areal water table at the time of the earthquake and thus were able to drain through seismic fractures in the frozen unconsolidated material. The lake levels also were lowered from seiche action. The prolonged wave action, as long as 2 hours on Portage and Kenai Lakes, repeatedly washed water over low points of the shoreline or out through the normal outlet of the lake. Hence, some lakes were partially or completely drained. Former levels were restored within a few days by streams or within a few weeks by snowmelt.

Tectonic tilting may have changed the storage capacity in some lakes, particularly those long lakes that lie parallel to the direction of tilting. Kenai Lake was tilted to the east, and Skilak and Tustumena Lakes were possibly tilted eastward 1–2 feet, as inferred from regional tectonic subsidence (Grantz and others, 1964). Field investigations of these lakes and Eklutna and Bradley Lakes were inconclusive because of lack of prequake control. Hence, a program of establishing bench marks to determine future tilting was established on 17 large lakes in south-central Alaska (Hansen, 1966).

DAMAGE TO WATER-SYSTEM STRUCTURES

Two manmade lakes were drained because of the earthquake. The rupturing of the earth-filled dam on Campbell Lake, at the mouth of Campbell Creek south of Anchorage, allowed the water to drain out. The dam on a lake near O'Malley Road south of Anchorage also was breached.

Perhaps the most serious and costly damage was the displacement of a tunnel-intake structure in Eklutna Lake. The structure was partially displaced either by wave action or by differential subsidence of the lake floor; the earth below the log and earth-filled dam had also subsided. A peripheral area of lake bottom about 200 feet wide was exposed because the lake was at a low level from winter withdrawals. This area subsided because of compaction or lateral spreading of the offshore lake-bottom silt. It appears that the submerged intake-structure was disturbed primarily by subsidence, although seiche action may have contributed to the damage.

EFFECTS ON STREAMS

ICE COVER

The ice cover on many streams was broken during the earthquake. However, the ice cover was not broken extensively; seiche waves, therefore, presumably did not develop in the streams and breakage must have resulted from seismic shock. The ice remained unbroken on the Copper River where it flows through Woods Canyon—a bedrock gorge about 70 miles east of the epicenter. Bedrock is known to respond less than unconsolidated material to seismic shock; thus, the lower amplitude of the ground response may explain why the ice was not broken in this bedrock gorge. Other streams were routinely checked for this relationship during air reconnaissance, but no consistent pattern was found—perhaps because the other major streams observed do not flow in such a bedrock gorge.

GROUND FISSURES AND SLIDES

Extensive fissuring and associated earth flowage were the most prevalent effects of the earthquake along the streams in south-central Alaska. Fissuring was fairly random throughout the area but was very noticeable because of the exposed sand and gravel bars of the braided streams. Some fissures extended across stream flood plains, but most were on adjacent terraces parallel to the streambanks (fig. 9). Silt, sand, or gravel were ejected along many of the fissures and formed ridges on one or both sides, or sometimes formed flows or sheets which extended many feet from the fissures.

Landslides or snow avalanches blocked several streams, notably the Klutina River in the Copper River basin, Ship Creek near Anchorage, and the Tiekel River and several other streams along the Richardson Highway north of Thompson Pass. A snow and earth slide on the Klutina River about 9 miles below Klutina Lake (fig. 2) apparently did not block the river immediately, but, as reported by the Alaska Department of Fish and Game (1965, p. 43, fig. 33), "Before the spring breakup

9.—Fissures on terrace parallel to Copper River bank. Photograph by R. M. Migliaccio, September 14, 1964.

the river had begun to cut a new channel around the slide. By midsummer the channel re-routing had been completed * * *."

A minor snow slide on Ship Creek about 4 miles upstream from the lowland caused much concern and anxiety to water-supply officials, because the slide temporarily dammed the creek and therefore cut off the water supply for the city of Anchorage and nearby military bases immediately after the quake. It was almost 48 hours before normal flow resumed at the diversion dam, and about 10 days before downstream flow returned to prequake levels.

There were numerous reports of slides that blocked other streams; one report of a slide on the Copper River received national news coverage. The writer believes that most such reports of dry riverbeds were based on aerial observations of extensive mudflows subsequently frozen on top of river ice in some reaches of the rivers. In other instances, where snowslides appeared to block a channel completely, the slide had not broken the ice cover.

CHANGES IN FLOW

Changes in streamflow were controlled by fissures in and adjacent to streambeds and by landslides and snow avalanches. The slides commonly did not block the flow for long, but some residual effects persisted for longer periods. For example, Ship Creek, which was flowing about 15 cfs (cubic feet per second), was dammed for about 18 hours. During this time the underflow in the streambed below the dam continued to drain, and the upstream supply was entirely diverted for public use at the dam. Thirty-six hours after the earthquake the creek supply at the dam exceeded the diversion and began to recharge the drained-out creekbed. It took about 10 days for the creek to regain its prequake flow, and by then snowmelt began to augment the base flow of the stream.

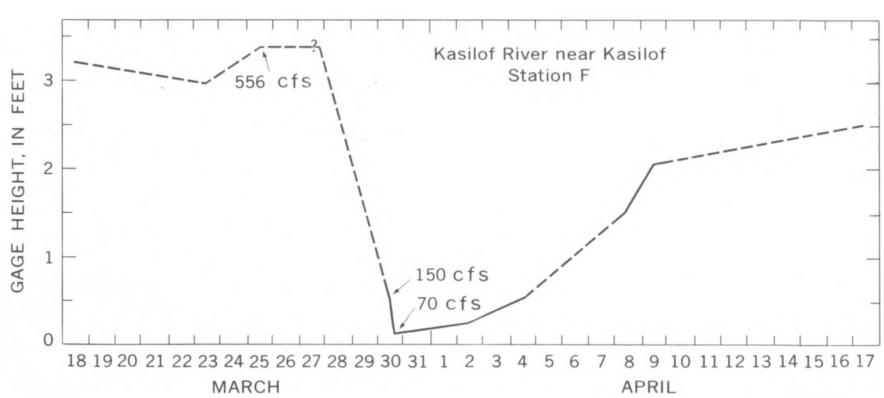
Hydrographic loss in the reach of Ship Creek, a very flat alluvial fan, was increased by ground fissuring in and adjacent to the stream. Flow in a neighboring stream, Chester Creek, which depends entirely upon ground-water discharge in late winter, decreased from 12 to 4 cfs on March 31, and recovered to 13.6 cfs by April 6. The flow decrease is attributed to loss through fractures in the streambed and to decreased outflow of ground water. The latter is believed to be more significant, because artesian levels in the area were drastically reduced immediately after the quake.

Changes in flow, particularly losses, were noted in larger streams also, but ice cover inhibited accurate observations. Extensive areas of fissuring on adjacent banks were noted along many streams. The most conclusive evidence for streamflow loss was noted where a stream drains a lake. The U.S. Geological Survey has installed stream-gage recorders on outlets of several lakes in this region (fig. 2). The hydrographs shown in figure 8 illustrate the drop in height of the water surface which indicates a decrease in streamflow.

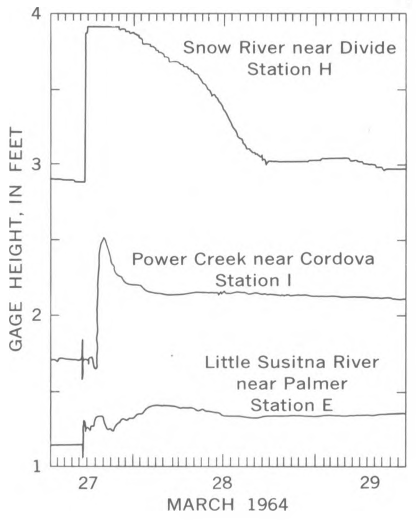
Flow in the Kasilof River, which drains Tustumena Lake (fig. 2), was so reduced that many observers reported that it was dry. The Alaska Department of Fish and Game (1965, p. 29) stated that "Its flow was halted to such an extent that a biologist was able to walk up its channel the following day wearing overshoes." A plot of the river stages at the Geological Survey gaging station on the Kasilof River bridge (fig. 2) is shown on figure 10. The plot shows diminution of flow, from 566 to 70 cfs, by March 30.

The loss of flow in the Kasilof River and in other streams draining lakes is due primarily to decreased outflow from the lakes. Many such streams recovered their flow slowly because, like Ship Creek, the subsurface sediments had to be recharged before the streams could resume their normal flow.

An increased flow was also recorded in some streams, but it was not as common as stream losses. The hydrographs of three streams in south-central Alaska which showed an apparent increase in flow are shown in figure 11. The increased flow of Power Creek is believed (M. J. Slaughter, written commun., 1964) to be "* * * the



10.—Water-level stage of Kasilof River from March 18 to April 17, 1964. See figure 2 for location.



11.—Hydrographs of three streams in south-central Alaska. See figure 2 for locations.

result of released water stored behind an ice dam upstream prior to the quake." The Little Susitna River had an increased flow which perhaps is also attributable to release of water from behind ice constrictions. Here, as in most of the streams, the seasonal warming trend was beginning, and snowmelt began to mask the prolonged earthquake effects in a few days. The flow of Snow River was unusual. The water level, in the stilling well at least, rose more than a foot in a few minutes with no apparent surge. The water then gradually receded to about its former level in 24 hours. A possible mechanical cause of this unusual fluctuation was reported by J. P. Meckel, hydraulic engineer (oral commun., 1965). He believes that the bubble gage did not respond to the rapid upward surge caused by the seismic shock because the gage is "sensitized to normal fluctuations." Probably the water was rapidly forced up into the stilling well, as noted in wells and in sand fountains, and then gradually drained out.

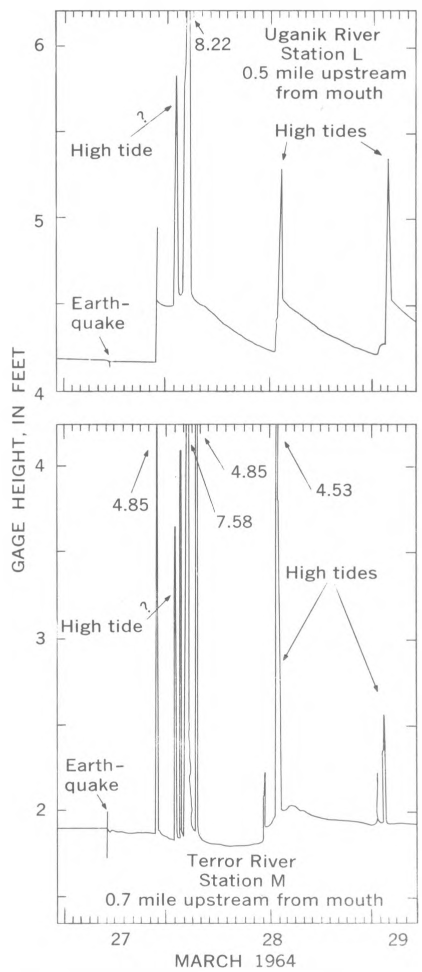
The Tiekel River north of Valdez was dammed by a snowslide and nearby Tonsina River was dammed by ice jams; both had to be opened with explosives to prevent highway flooding.

Gages on three streams on Kodiak Island recorded the tsunamis that were so destructive at Kodiak, Old Harbor, and elsewhere. Figure 12 shows two of these hydrographs that reflect the earthquake shock, tsunamis, and high tides. Tsunamis traveled up these streams at least five times as recorded at the Myrtle Creek gage. The float was hung up by the third wave, but it registered subsequent 7- and 9-foot surges.

Tectonic land subsidence or uplift may eventually steepen or lessen, respectively, the gradients of these streams and thus alter the streamflow pattern. The pattern alteration may not be recognizable in the immediate years ahead except in areas of extreme change, such as the part of Montague Island (fig. 2) which was uplifted 33 feet. The most immediate and noticeable effect in subsided areas is the greater extent of tidal inundation and backwater in coastal streams. This condition was disastrous to fish-spawning areas and has been investigated by the Alaska Department of Fish and Game (1965). U.S. Geological Survey recorders on the three streams on Kodiak Island now register most high tides, whereas before the subsidence they recorded only extreme high tides.

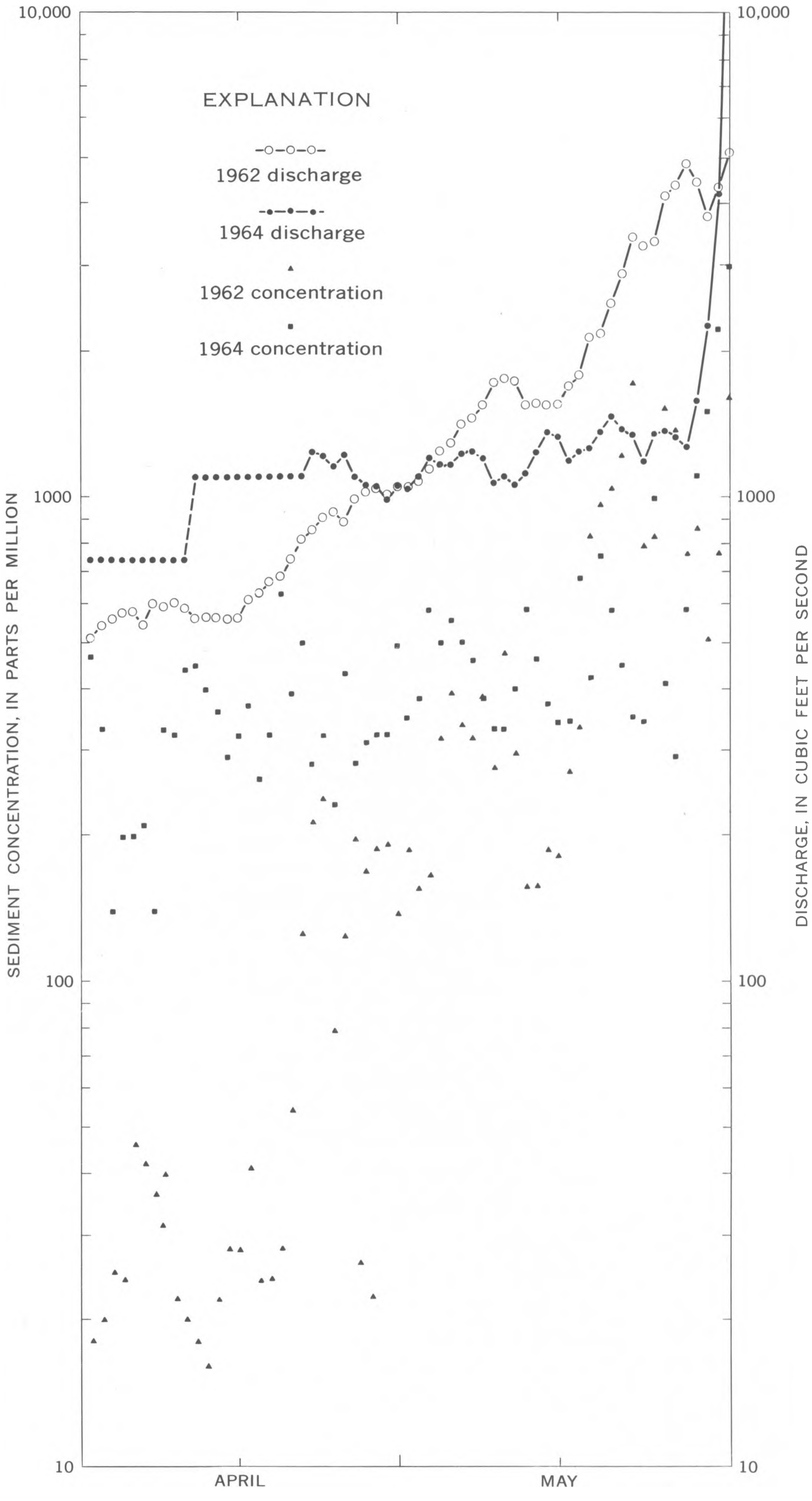
Other gages in south-central Alaska (fig. 2) responded to the earthquake shock, but either the records were disrupted or the float was too solidly frozen into the stilling well to show postquake effects clearly.

The U.S. Geological Survey operated recorders in other parts of Alaska. The northernmost station that registered the shock was on



12.—Hydrographs of two Kodiak Island streams showing effects of tsunamis and of land subsidence. See figure 1 for locations.

the Tanana River at Tanacross (fig. 1, location A). Three other stations west and north of Cook Inlet (fig. 1, locations B, C, and D) did not record the seismic shock even though they were within 200 miles of the epicenter. One other instrument, north of Bristol Bay and about 400 miles WSW from the epicenter, also was not visibly affected. In contrast, 19 of the 30 hydrograph stations in southeastern Alaska, some as much as 700 miles distant, recorded effects of the shock wave. Six stations near tidewater recorded the tsunamis. One station on a lake recorded seiche action for several hours.



13.—Suspended-sediment concentration and discharge in the Matanuska River near Palmer, 1962 and 1964.

Several hydrographs indicate an increase of streamflow immediately after the trace of the shock. However, V. K. Berwick, hydraulic engineer, reported (written commun., 1965) that an analysis of precipitation data indicates that rainfall occurring on March 27 and subsequent days probably caused the increases. The writer concurs with this analysis because data from 12 stations showed a beginning rise in stream stage before the quake, whereas only 5 stations show a rise coincident with the arrival of the shock wave. Probably the shaking motion, although not generally felt in bedrock areas of southeast Alaska, disturbed the ice-choked parts of some of the streams and thus caused a temporary rise in streamflow. Two hydrographs, which showed an appreciable drop after the disturbance, probably reflect temporary damming of the streams by ice.

SEDIMENT LOAD

As a result of the intensive fissuring and the ejection of sediments into the streambeds, the deposition of landslide material onto the ice-covered streams, and the erosion of loosened material on the mountain slopes, the spring runoff transported unusual amounts of sediment. The sediment load of the streams was greatly increased, but the increase was apparently of short duration. Three stations for measuring daily sediment load were in operation in south-central Alaska. The station at the highway bridge on Twentymile River at Portage (fig. 2) was destroyed, however, and was discontinued after the observer was evacuated. The station on the Ninilchik River bridge north of Homer (fig. 2) continued in operation, but recorded no significant change, probably because the stream flows through a lowland having no steep valley slopes and because the site is about 150 miles from the epicenter.

The long-established station on the Matanuska River bridge (fig. 2) showed a large increase in sediment load during the month of April (fig. 13). A plot of the suspended-sediment concentration shows that in April 1964 the stream carried five times the amount of sediment it carried in 1962 during a comparable period and flow. L. S. Leveen (written commun., 1965) stated that suspended-sediment loads during the summer were normal.

EFFECTS ON GROUND WATER

IMMEDIATE EFFECTS

The initial seismic shock and the associated seismic waves immediately altered the hydrologic regimen. Short-term effects included (a) surging of water in wells, (b) extrusion of water, mud, and sand, (c) failure of well system, and (d) turbidity of water in wells and springs. The long-term effects, resulting from physical changes in the aquifers, are discussed in a later section (p. A17).

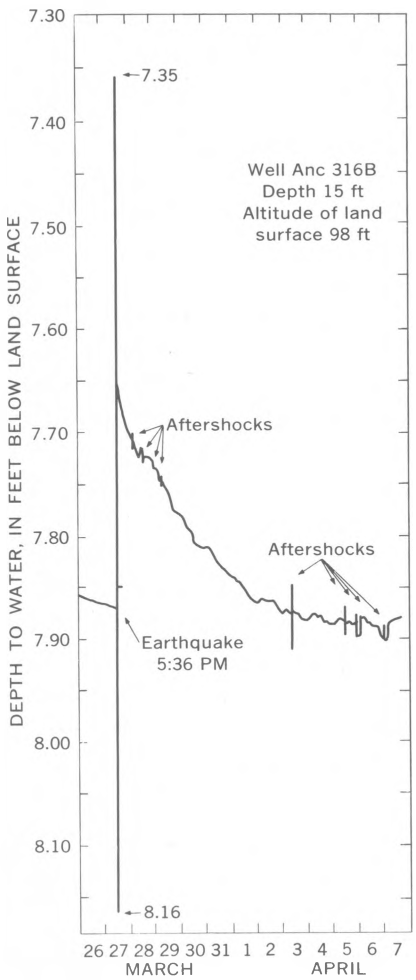
ARTESIAN WELLS

The immediate reaction of water in artesian wells near an epicenter is due principally to the stresses imparted to the aquifer. Ferris and others (1962, p. 87) summarize previously published American works on such fluctuations and state that when shock waves from an earthquake reach an aquifer "* * * there will first be an abrupt increase in water pressure as the water assumes part of the imposed compressive stress, followed by an abrupt decrease in water pressure as the imposed stress is removed. In attempting to adjust to the pressure changes, the water level in an artesian well first rises and then falls."

Of the five recorders operating at Anchorage, four were on artesian wells. However, the instrumentation was not sufficiently damped to register accurately the sudden and intense fluctuations in water level caused by the seismic impulses on the aquifers. Two records were unintelligble. One well recorded 6 feet of fluctuation before the pen was flipped off the chart. The fourth instrument operated during the quake and for 8 hours recorded continuous fluctuations of the water level. The total fluctuation, estimated to exceed 24 feet, is some indication of the fluctuations of this and other artesian systems of south-central Alaska.

SHALLOW WELLS

Shallow wells, as considered here, are wells that tap near-surface aquifers that are not overlain by a confining layer. Water in these water-table wells does not respond to seismic waves as does water in artesian wells because it is free to move vertically as the pressure wave passes through the aquifer. However, within the region of intense ground motion, the inertia of the water body and the oscillations set up in the ground water produce movements that oppose the ground movement. Hence, unconfined ground water,



14.—Hydrograph of water-table well Anc 316B, south of Anchorage, from March 26, 1964, to April 7, 1964.

as well as bodies of surface water, probably tends to oscillate but the the ground-water motion is damped by friction within the aquifer.

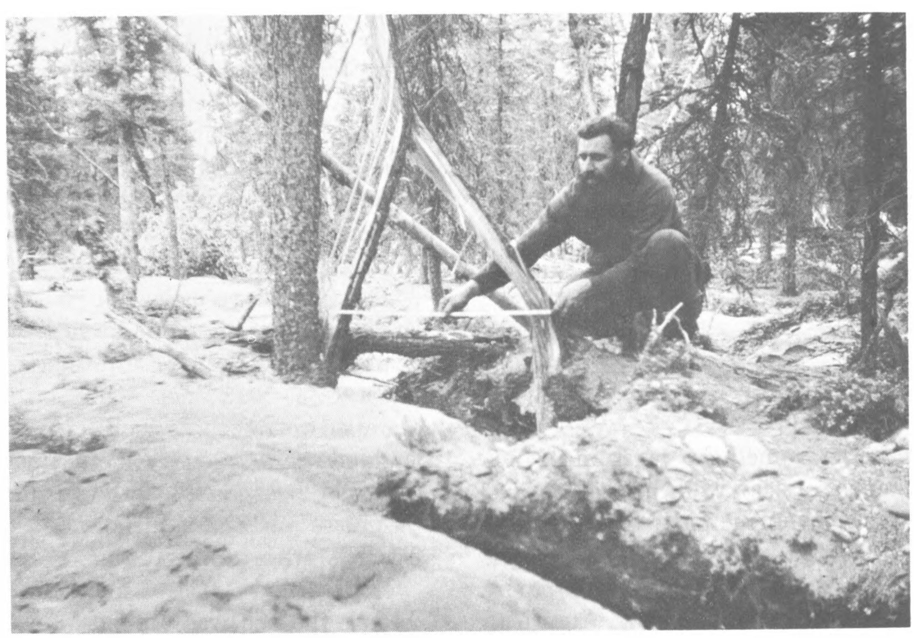
The widespread water fountains and flows of sand and mud were erupted from the water-table zone. These extrusions indicate that high pressures must have existed in the water-table aquifer, and thus a temporary confining layer must have been present.

The behavior of unconfined water levels during an earthquake is illustrated by an excellent record obtained at Spenard, south of Anchorage, in a well tapping a zone of water-saturated sand 7.8–15 feet below land surface. The depth of frozen ground probably was about 5 feet at the time—hence the water was not confined, because there was about 3 feet of unsaturated sand between the frozen layer and the water table at 7.8 feet. The record (fig. 14) shows that in this well the water table fluctuated less than a foot. The area near this well, and the well-known Turnagain area, where similar conditions prevailed, yielded no signs or reports of sand or water ejections. In contrast, stream valleys and high tidal marshes at Anchorage did have areas of ejected water and mud, because there the water table was confined by the seasonal frost.

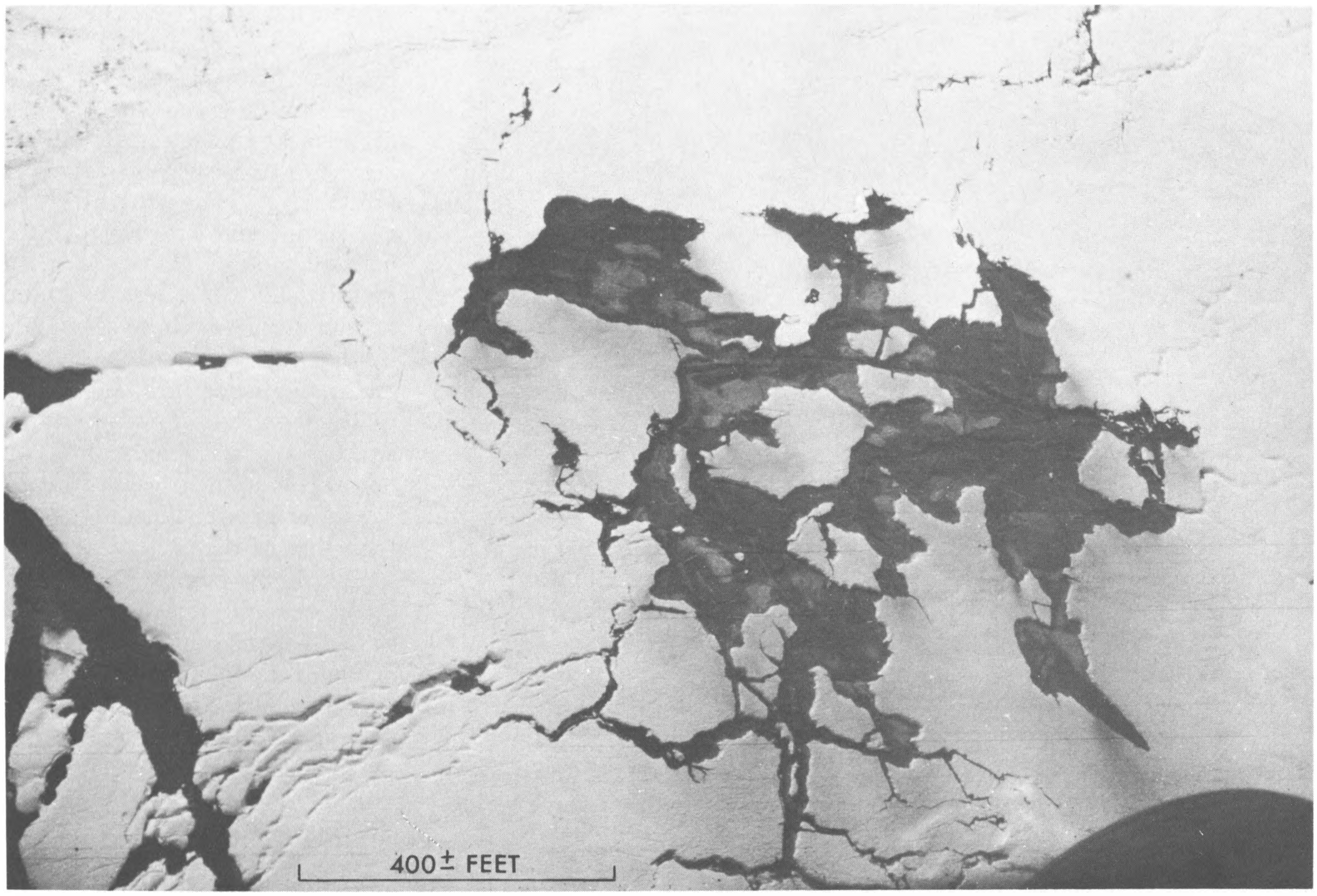
FLOWS OF SAND AND MUD

"Sand-spout,'' and "mud-spout," or "mud fountain," "mud volcano," "sand blow," "sand boil," "mudvent," crater, and several other terms have been used to describe certain features which appear during most great earthquakes and are associated with water-saturated sediments. Water-borne material is ejected from fissures during the earth movements and, in some places, the flows continued long after the shocks had passed. In areas where the ground water is confined, as in river beds, the increased hydrostatic pressure is also relieved. The pressure head raises or otherwise disturbs the streambed, and the sediments are saturated to the quicksand condition. Probably every major valley in south-central Alaska showed evidence of fissures and flows.

Lemke (1965, p. 121) reported that the lower part of the Jap Creek fan at Seward fissured when "loose gravels were compacted by vibratory action during strong ground motion. Where the water table was high the frozen ground surface was ruptured." Ground water was released under hydrostatic pressure to heights of 6 feet and sand boils developed. The ejected sediment came principally from well-sorted sand lenses, one of them 12.5 feet deep. Lemke also suggests that differential com-



15.—Large fissure and sand flow in the Skilak River valley near Tustumena Lake. Split tree indicates about 3-foot displacement. Note 6- and 8-inch rocks ejected upslope.



16.—Aerial view of extensive mud flows and fissures in the Placer River valley near Portage.

paction, controlled by the irregular buried bedrock surface, limited the areas of fracturing to the outer parts of the fan. In contrast to the Jap Creek alluvial fan, the Lowell Creek fan at Seward did not fissure extensively. The Lowell Creek fan has been largely dewatered, and only near sea level, where the water table is near the surface, were fissures formed.

Fissures on deltas also occurred only on the lower slopes. In those areas, however, the fissures are undoubtedly tensional features formed behind the free face of the delta front (fig. 6). Furthermore, the hydrostatic pressures in the acquifers are less confined because the water table is very near the surface on the lower slopes. A typical fissure parallel to the shore of the delta in the Skilak River Valley is shown in figure 15. The extruded material—silt, sand, and gravel—was deposited principally downslope.

Fissures and flows in stream valleys and on flood plains were locally controlled by the configuration of the water table. Constrictions in the valley floor and the points of change in slope of the stream are places where the ground-water movement is restrained; hence, the water level is nearer the surface than elsewhere in the valley. At such places fissuring and outflows seemed to be more extensive than elsewhere. One extensive area of fissuring and flowage is in a poorly drained part of Placer River Valley, near Portage (fig. 16).

In some places (fig. 17, p. A16), the outflows removed so much material from the ground that local collapse and probably general subsidence occurred. Although collapse craters generally had outflow channels, some craters formed where there was no evidence of discharge. Some of these were on river terraces, but most were on flood plains. This restricted occurrence indicates either that the underlying material was compacted or that the fine material was removed by ground water and ejected some distance from the crater. Davis (1960, p. 499) noted extensive separation between craters and flows at Huslia in 1958, and found that the distance between one crater and the nearest flow was 600 feet. It is also possible that these craters formed long after the earthquake. R. M. Migliaccio (oral commun., 1965) stated that

17.—Sand flow from 2-foot fissure more than 200 feet long, parallel to Tustumena Lake shore. Sand flowed mainly to left toward the lake.

some craters were first noted after the early-summer stream runoff.

Another effect of the seismic waves on shallow water confined by seasonal frost was formation of pressure ridges along the margin of a long, large swamp representing an abandoned glacial-meltwater channel south of Tustumena Lake (fig. 18). The ridges were observed from the air and were seen to be overthrust layers of the surface vegetal material about 3 feet thick and jutting upward as much as 10 feet in the air (on the basis of comparison with the height of a fleeing moose). The linearity of the pressure ridges suggests tectonic movement, but a more logical explanation is that the compression was caused by the oscillation of the frozen surface layers over a water-saturated substratum.

An example of the pressures that can be created by compression of the shallow water table was noted at Anchorage 2 weeks after the earthquake. The floor of a small swale in southwest Anchorage bulged, and many residents thought that a volcano was about to erupt. At that season, however, the shallow ground-water table characteristically begins to reflect annual spring recharge. The seasonal frost cover, and possibly an abnormal constriction down gradient at a road crossing confined the increasing head of water, and the ground rose about 2 feet in a 20-foot area.

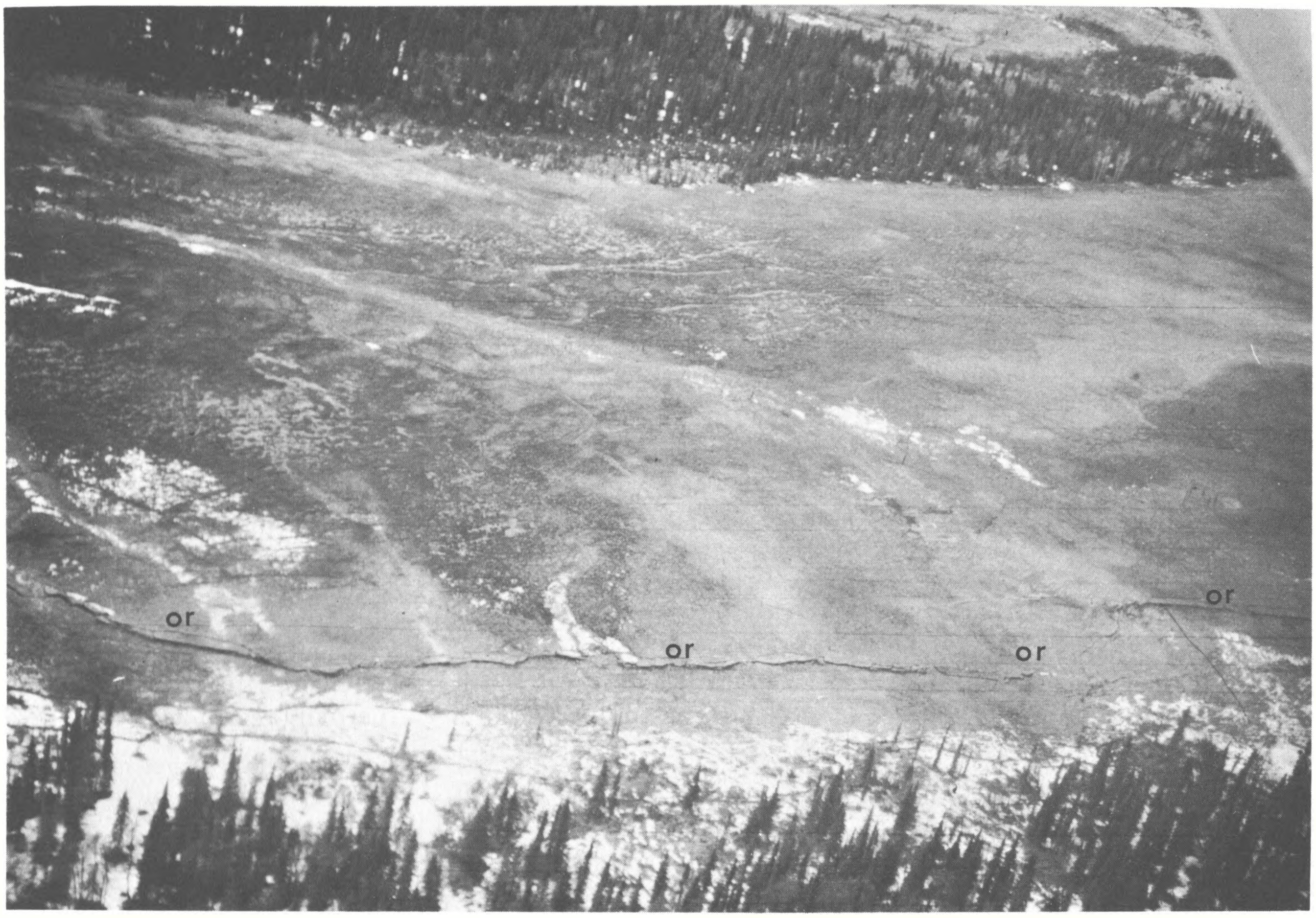
A shallow water table apparently contributed to the extensive effects noted in unconsolidated material in south-central Alaska. Where the water table was somewhat lower than the seasonal frost or a semiconfining zone at the land surface, there was little surface evidence of earthquake effects.

DAMAGE TO WELL STRUCTURES

The failure of some well systems was mainly due to sanding or silting of the pump column or to the differential movement of well casings and the surrounding rock. Most of the wells are unscreened and have a foot or several feet of uncased hole. These conditions readily lend themselves to cave-ins or slumping of the walls under earthquake stress. Fine-grained material washed into the well by dilation and compression of the aquifer may also contribute, but normal pumping of wells probably causes a greater flushing action than that of the earthquake. Resumption of pumping after the quake brought fine material into the system and caused turbid water or malfunction of the pump. Other wells that have pumps requiring a full pipe of water for a prime probably lost their prime during the violent water fluctuation in the well. Thus, erroneous reports of dry wells were as common as they usually are after most quakes.

At Anchorage three city wells were damaged. The most significant damage was caused by the failure of artificial fill at the city's main well. The resulting movement destroyed the pumphouse and bent the well casing. The casing was straightened and a new pumphouse was built. A well near the large Turnagain slide was destroyed by lateral movement. The third well, also in the Turnagain area, was abandoned because of damage, apparently from lateral movement.

At Seward the three city wells (4–6; see fig. 24, p. A25), all believed to be about 100 feet deep, were ruined by ground movement and fissuring. Wells Sew 4 and 5 (old City 1 and 2, respectively) would not pump water after the earthquake. When an attempt was made to pull the pump



18.—Pressure ridges in a long, large swamp (Kenai Lowland). Ridge of overthrust material (or) in foreground is about 500 feet long.

columns, the binding of the column and casing was so great that the casing pulled apart in Sew 4 and the column would not budge at Sew 5—probably because of the horizontal shift of part of the alluvial fan. Well Sew 6, about 10 feet higher than Sew 4 and 5, survived the earthquake, but near the end of April 1964, the pump turbine jammed because the ground moved or settled and caused a gradual increase of friction. The pump column could not be pulled because of a casing offset. In the meantime, the U.S. Army Corps of Engineers drilled replacement wells adjacent to Sew 5 and 6. These two new wells had water from a depth of 34 feet intermittently to a total depth of 200 feet. The wells were developed in the best part of the aquifer, at about 160–170 feet, and had water levels of about 21 feet below the surface—a confined aquifer is thus indicated.

At Valdez a 24-foot well was bent seaward by land movement, and its casing was sheared at a threaded joint 15.5 feet below the surface. One of the city wells was damaged, possibly by an electric failure during the quake, but the other was operable and was being used to pump water into temporary surface pipe for distribution.

LONG-TERM CHANGES

The long-term effects on the hydrology of south-central Alaska include temperature changes, changes in the chemical quality of the water supply, and the residual lowering of water-level or artesian pressures. The lower water levels or lower artesian pressures were the most noticeable effect and presumably stem from changes in discharge rates or transmissibility of aquifers.

Locally, notable subsidence of land, not related to tectonic subsidence, marks another residual effect. This subsidence is generally associated with areas of extrusion of water and mud. Some subsided areas, such as at Portage and at Anchorage (Waller, 1966b), showed no surface evidence of loss of water or sediment; subsidence probably reflects compaction of the aquifer after loss of hydrostatic pressure in the higher reaches of the aquifer.

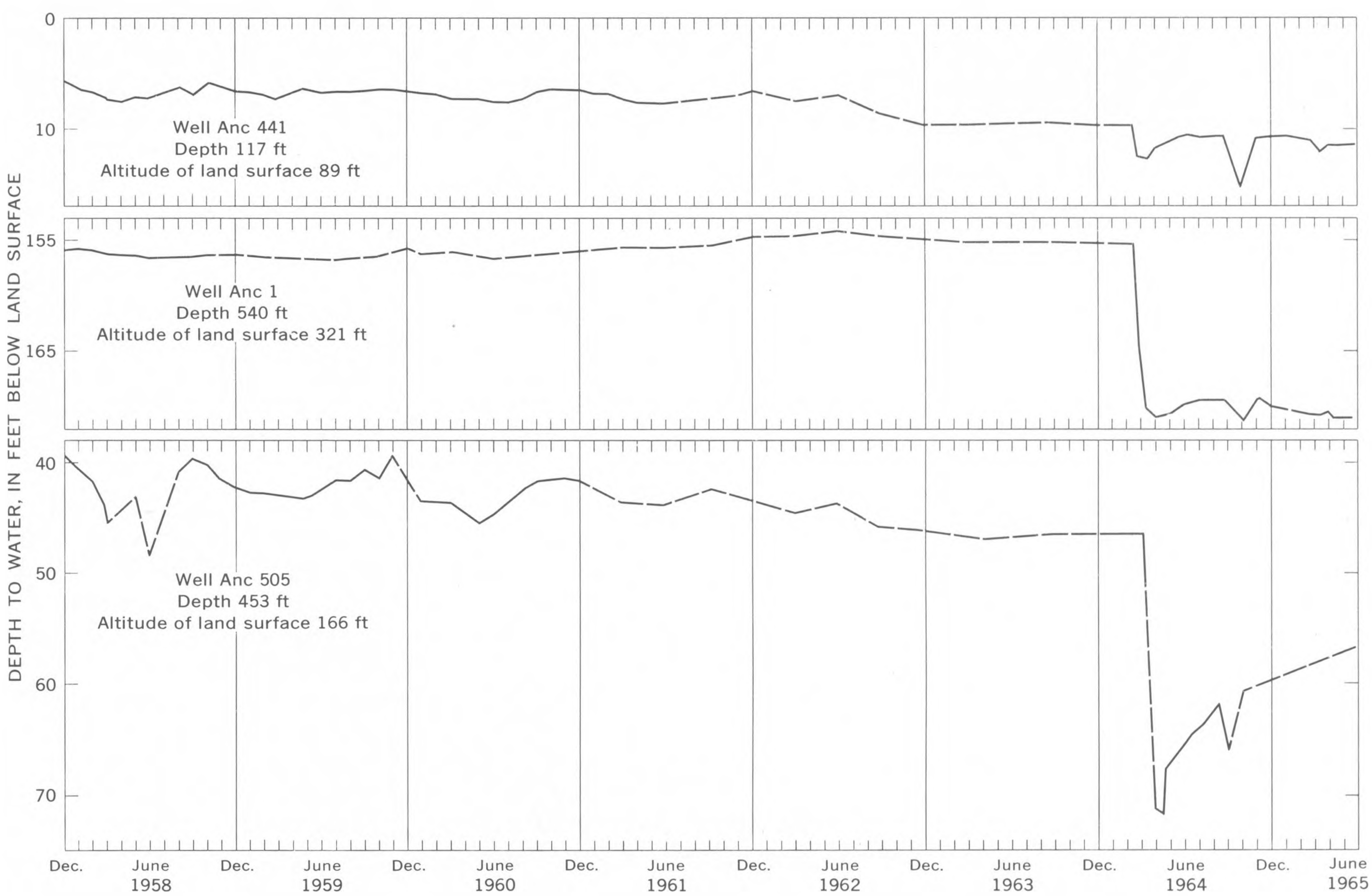
ANCHORAGE

The artesian aquifers at Anchorage are composed of sand and gravel interbedded with clay and glacial till (Cederstrom and others, 1964). The deposits are as much as 500 feet thick and extend under the adjacent Knik and Turnagain Arms of Cook Inlet (fig. 2). Periodic water-level measurements have been made in 50 water wells in the Anchorage area—some dating back to 1951. Hence, preearthquake water-level records, frequent measurements made after the earthquake, and previous studies (Waller, 1964) have all contributed to a thorough evaluation of the long-term effects of this earthquake. A report on the earthquake effects at Anchorage is presented in detail elsewhere (Waller, 1966b). A summary of the preliminary findings is presented here.

The 50 observation wells were measured periodically, starting a few days after the earthquake. All but one of the Anchorage observation wells indicate changes to the water-table and artesian-aquifer system. One well taps the Tertiary bedrock about 400 feet beneath the glacial drift.

Almost all the well measurements show that the pressure level was lowered as much as 24 feet but that recovery started immediately. Within about 6 months the pressure had recovered completely or had risen to a new level of stability. The new pressure level in about one-third of the wells is as much as 15 feet lower than prequake levels. In about two-thirds of the wells the level is within 5 feet of, or at the same level as, the preearthquake level. Representative hydrographs of three wells tapping glaciofluvial aquifers (fig. 19) show the range of residual changes. The areal distribution of the measured changes of water level in the wells is not entirely consistent, but it implies that most of the changes occurred in areas underlain by thick estuarine or lake deposits of fine sand and silt.

In several wells, the postquake water levels are higher than they were before the earthquake. These wells are located within the area of influence of the city and military well fields. Because all wells drawing water from the Anchorage artesian system were suddenly without power for pumping, the artesian system had a chance to partially regain its natural prede-



19.—Hydrographs of three Anchorage wells, 1958–65, showing residual changes in artesian pressure after the earthquake.

velopment pressure. However, power was restored sporadically, and most wells were back in operation within 2 or 3 days. They generally were pumped for greater lengths of time than was customary before the earthquake because of leakage in the distribution systems. As a result of this disruption of the normal pumping pattern, some water levels rose above prequake levels. Many more water levels were extremely low during the first few weeks owing to overdraft of public-supply pumping and the general lowering due directly to the earthquake.

After the summer recharge period (note annual fluctuations in the hydrographs, fig. 19), the residual changes in the water levels could be ascertained. A full year's record now confirms the net lowering of water levels. The residual change to a lower pressure level implies that recharge has decreased, or water has found new outlets and is moving through the aquifer at a faster rate. Because of the lowered pressures and the inference that the water movement in the aquifer has increased, the assumption is made that either the permeability of the aquifer has been increased by an increase in pore size, or a change has taken place in the outlet of the aquifer so that water can leave the aquifer more readily. Fracturing of the subsurface confining beds of clay or glacial till is not considered probable, nor would it cause the variable drop in pressure. The aquifers at Anchorage are interconnected (Cederstrom and others, 1964; Waller, 1964), hence, additional interconnections would have little area-wide effect. Fracturing at depth in the water-saturated deposits also seems unlikely. The natural discharge may have been increased locally by removal or rearrangement of the estuarine silt cover overlying sub-inlet discharge zones of the aquifer. The porosity of the sand and gravel aquifers may have been increased locally by flushing of fine material into wells or areally by aquifer expansion owing to an imposed stress from seismic waves or the tectonic subsidence (about 3.7 ft) and horizontal movements.

Observation of the water level in the one well that taps a Tertiary aquifer (Anc 1, fig. 19) indicates that that aquifer also underwent some changes. The lower water level seems to be permanent.

Water in the Pleistocene Bootlegger Cove Clay was a significant factor in the extensive sliding that occurred at Anchorage. Water pressure in sand lenses within the clay presumably was increased by seismic motion until failure occurred and the land moved laterally toward the sea. Pore pressure measured in the clay since the quake shows that some areas are gradually losing the pressure existing after the quake, whereas a few others show pressure buildup.

Sea water may be encroaching beneath Fire Island in Cook Inlet off Anchorage, inasmuch as the chloride content has steadily increased since the earthquake. One of the wells on the island had been drilled into a salt-water-bearing formation several years previously but was reportedly cemented or sealed off. Possibly the earthquake disrupted this seal, rather than the confining layer over the salt-water formation, and now salt water is leaking into the upper fresh-water aquifer that supplies the other wells. Observation of these wells is continuing.

CHUGIAK

The ground-water conditions in the Chugiak area, adjacent to and northeast of Anchorage (fig. 2), are similar to those at Anchorage except for a greater percentage of till and a lesser thickness of glacial drift. The effects of the earthquake in this area were similar to those at Anchorage. Dale Pierson, Chugiak well driller, reported (The Johnson Drillers Jour., 1964, p. 5) that "Locally * * * numerous wells went dry. Others have become muddy and silty." A well Pierson was drilling at 102 feet reportedly was offset between the 50- and 60-foot level. The statement regarding numerous dry wells has not been verified, but because there are many shallow dug wells in this area and they were at their seasonal low-water level, the statement does appear reasonable. The water levels of six observation wells in this area were periodically measured before and after the earthquake. Two of the four water-table wells showed possible effects of the earthquake—a temporary rise in water level of a few feet, probably owing to recharge from the surface through ground fractures. Of the two wells which tap artesian aquifers, one was little affected and the other (well 120) showed a decline in water level of about 10 feet (fig. 20, next page). Preearthquake water-level data are presented in Waller (1960).

COPPER RIVER BASIN

Effects on the aquifers in the Copper River basin were reflected in water levels in wells (Ferrians, 1966). The following description is drawn largely from Ferrians' findings.

The Copper River region is within the permafrost zone of Alaska and is characterized by a lack of fresh-water aquifers. Moreover, the sparse development of water wells on the aquifers has restricted the interpretation of effects. Water levels in several wells reportedly lowered appreciably, but generally the levels were restored in a few days. Three wells in the Glennallen area were reported to have gone dry. These were probably shallow wells which had low water levels at this time of the year.

The apparent negligible effect of the aquifers in this region, as close to the epicenter as Anchorage or the Matanuska Valley, is probably due to the presence of deep permafrost. Stream flood plains had fissuring and mudflows as did those in the nonpermafrost zone.

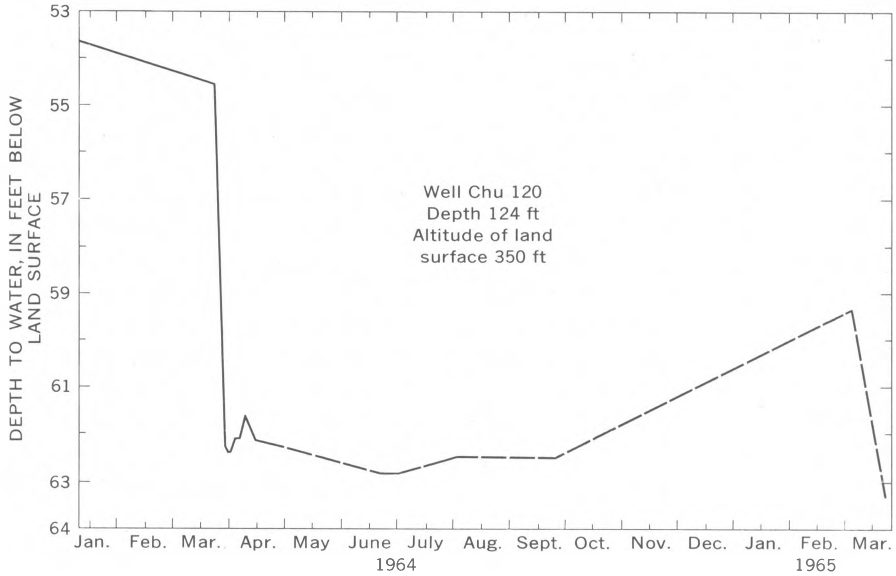
CORDOVA

Cordova is the only community in the uplifted area (fig. 1) that has a drilled-well water supply. The community is largely built on bedrock, but a standby well-water supply is located on a thick deposit of glacial drift (Walters, 1963, p. 4). This small area of unconsolidated material is at least 140 feet thick and separates Eyak Lake from the ocean (fig. 21).

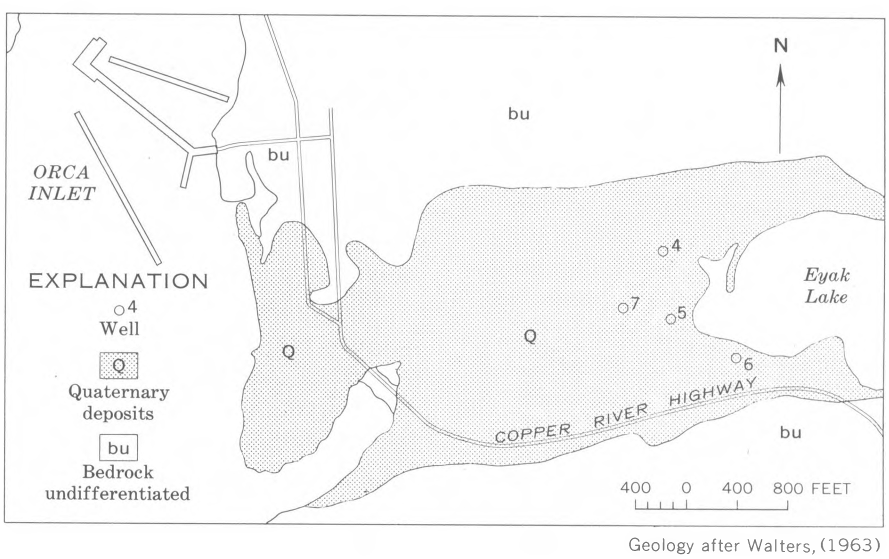
There was little visible effect of the intense earth shocks at this location only 50 miles from the epicenter, probably because most structures are built upon bedrock. The ice on Eyak Lake broke and some pressure ridges developed along the shore. East of Cordova on the outwash deltas of the glacial streams and the Copper River, there was extensive fissuring and flows (Reimnitz and Marshall, 1965) and much damage to the Copper River highway and bridges (Kachadoorian, written commun. 1966). The greatest effect at Cordova was the tectonic uplift of about 6 feet, which left the city with a useless boat harbor (fig. 21) but made some new land of an appreciably flatter slope than much of the city.

The Cordova Public Utilities manager, Reg Bodington, reported that the earthquake had no visible effect on their ground-water supply and facilities. However, possible changes to the unconsolidated material and its relation to sea-water encroachment are of major concern because the town is only about 20 feet above mean sea level (Walters, 1963, p. 8). A water sample, collected on July 27, 1964, from the standby well (Cor 5, fig. 21), had a chloride content of 50 ppm which is an increase of 10 ppm over the content in samples taken in 1962 of wells Cor 4 and 5. Only subsequent analyses can determine if the increase is significant. In general, the chances of sea-water encroachment are slight because Eyak Lake, the probable recharge source for the aquifer, was raised 6 feet relative to sea level and the lake depth was unchanged.

A few water-level measurements had been taken in wells Cor 2, 3, and 4 in 1961 and 1962, and additional measurements were made in



20.—Hydrograph of water-level changes in a well in the Chugiak area.



21.—Sketch map of Cordova showing well locations.

July 1964. These measurements show that 4 months after the quake the water levels were about 1 foot higher than in July 1962. Eventually, the water level in the aquifer will probably drop in response to the 6-foot uplift of the land.

The artesian-pressure levels in wells 4 and 6, measured July 30–31, 1962, fluctuated with tidal loading of the presumed extension of the aquifers into Orca Inlet. These tide-induced pressures were compared to postearthquake pressure measured in the same wells during a comparable tidal cycle on July 27–28, 1964. The 1964 measurements showed the artesian-pressure cycle was 6 hours out of phase with the tidal cycle—when the tide was high the ground-water level was low, and vice versa. The 1962 measurements were not as complete, but they indicate that the artesian-pressure cycle lagged only about 1 hour behind the tidal cycle. The change in the time lag may relate to changes in aquifer characteristics, to changes in points of tidal loading of the aquifer, or to some combination of these and other causes unknown.

Because of the uplift in this area, the Eyak River may eventually steepen its gradient back to the outlet of Eyak Lake and thus lower the lake level, possibly as much as 6 feet.

HOMER

The effects of the earthquake on the aquifers at Homer have been described in detail (Waller, 1966a); a summary is presented here. To determine the effects of the earthquake on the aquifers, 15 of the wells previously used for an observation-well network were remeasured periodically for a year after the earthquake. The measurements indicated that both the water-table and confined-water aquifers in glaciofluvial and Tertiary formations were greatly disturbed, even though Homer is about 160 miles from the epicenter. However, water levels in all but two wells recovered in a few months. One well tapping Tertiary rocks (Hom 15, fig. 2) had a lowered pressure level of more than 8 feet but had recovered 4 feet in a year's time. The sandstone aquifer probably was dilated by strain induced by seismic stress. If the residual change is permanent, it may be comparable to the change in the Anchorage well (Anc 1, fig. 19) that also taps Tertiary sandstone. The other well (Hom 49, fig. 2) was a shallow water-table well which drained completely dry in the first few months after the earthquake. The water level then recovered to its former level, but its seasonal fluctuation is now greatly amplified over its previous cycle. The aquifer may have been fractured in nearby bluffs so that the rate of natural discharge is increased while seasonal recharge from precipitation is unchanged.

KENAI LOWLAND

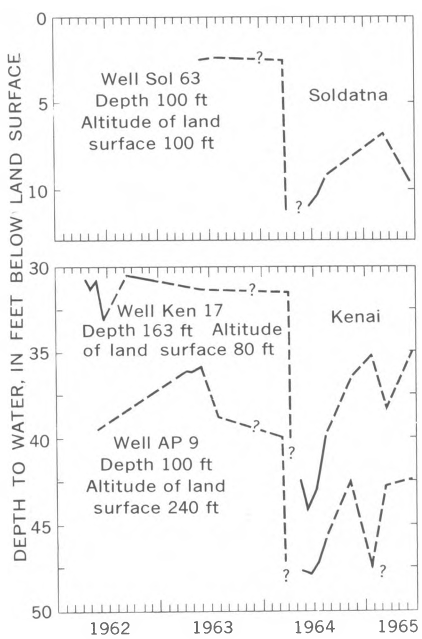
The Kenai Lowland occupies the western part of the Kenai Peninsula (fig. 2) and consists of a thick sequence of glaciofluvial deposits overlying Tertiary rocks. Ground water occurs in both water-table and confined aquifers, and their response to the earthquake is comparable to that at Anchorage. For discussion purposes, the Homer area on the southern tip of the peninsula is excluded.

Eight observation wells had been measured sporadically in the 2 years preceding the earthquake but none had been measured in the preceding 8 months. Although occasional measurements were subsequently resumed in these wells, it is difficult to evaluate the long-term effects on the aquifers. Nevertheless, the record correlations and hydrogeologic similarities to the Anchorage area suggest that the hydrologic effects are also comparable.

Of the eight wells in the Kenai Lowland area (fig. 2), the three wells tapping artesian aquifers had adequate records from which to evaluate seismic effects. Each well represents an area which is discussed separately in the following sections. The water-table wells are discussed also, but their records show that generally they were only slightly affected by the quake.

KENAI AREA

For the Kenai area, measurements from one well (Ken 17, figs. 2, 22) indicate that pressure in the confined aquifer dropped more than 10 feet. The maximum recovery has been only about 9 feet, hence the aquifer sustained a long-lasting change. Although the mineralized water in the aquifer suggests that it is a separate aquifer system, the effects probably are representative for the Kenai area. Measurements in a shallow



22.—Hydrographs of three wells in the Kenai Lowland showing residual changes.

water-table well adjacent to Ken 17 indicated only that the water level might be lower than in other years. The greater Kenai area evidently had more well trouble than any of the other areas except Valdez. Many wells sanded up, probably because the wells are commonly finished with preperforated casing in fine to medium sand.

A verified change in chemical quality and an increase of temperature of ground water was investigated at the Bernice Lake powerplant north of Kenai (fig. 2). The powerplant has two 174-foot drilled wells which pump water used for cooling. The standby well did not operate after the earthquake because it was sanded up to about 168 feet from the surface. The pump column was pulled in mid-April 1964 and reduced in length 5 feet in order to pump water from above the sanded-up part. The water was yellow and was warmer than it had been earlier; one workman reported later that he remarked to his coworker at the time that the pump column felt warm at about the 70-foot level. The well was pumped for a few hours and the water temperature remained about 68°F, whereas water from the other well 200 feet away was 41°F. The temperature of the water from both wells was 39° F at the time of drilling in 1962—normal for this area. The chemical concentrations in the water from the warmer well are shown in the following table:

Constituent	*Parts per million* 1962	1964
Calcium (Ca)	11	48
Magnesium (Mg)	1.3	12
Sodium (Na)	50	80
Bicarbonate (HCO_3)	236	151
Carbonate (CO_3)	0	12
Sulfate (SO_4)	1	41
Chloride (Cl)	9.2	99
Hardness as $CaCO_3$	33	170
Alkalinity as $CaCO_3$	194	124
Total alkalinity as HCO_3	236	151

The geology and hydrology of the site indicate that at about 60–70 feet a water-table aquifer having a high iron content overlies a clay-silt sequence, which acts as a confining layer over the 154- to 174-foot aquifer. The pressure surface for the deeper aquifer is about 130 feet below the surface. The water-table aquifer discharges on the sea bluffs about half a mile west, and presumably the confined aquifer discharges beneath the sea. The water-table aquifer was reported "irony" by the driller, and discharge points along the Kenai bluffs show a distinctive iron-stained precipitate.

A possible source of the increased temperature of the well water is hot water derived from the steam discharge of the plant blow-down pit, a little more than 100 feet upgradient from the assumed ground-water flow. The plant had been in operation for about 6 months, and hot water presumably filtered down to the shallow water and heated it as it slowly migrated seaward. The intense shaking and water-pressure increases at the time of the earthquake probably disrupted the confining layer between the two aquifers, and allowed hot water from the shallow aquifer to flow down to the deeper aquifer, probably along the outside of the casing or possibly through disturbed parts of the confining layer. To test this theory, a dye was put into the blow-down pit, but the test was inconclusive because the well discharge was observed only 1 day, whereas the ground-water flow is most likely much less than 100 feet a day. An alternative explanation would be that the shallow-aquifer water seeped through the well casing, but the plant officials are confident that there is no break in the casing.

Water from the shallow aquifer may have been leaking to the lower aquifer for a considerable time. If so, changes in quality and temperature might never have been known if the well had not been sanded up by the earthquake. A chemical analysis of the shallow water is needed to evaluate better the quality changes. The well upgradient from the blow-down pit is still used. Its water temperature in May 1964 was 41°F, 2°F warmer than it was in 1962.

SOLDATNA-STERLING AREA

The Soldatna-Sterling area is east of Kenai and is very similar to Kenai in geology and hydrology. Soldatna, located in the Kenai River valley, has some flowing artesian wells. Well effects were similar to those in other areas but, because of the flowing conditions at Soldatna, the pressure drop was more noticeable to residents. Many wells in the Sterling area were sanded because the wells penetrating the fine sand aquifers had preperforated casing.

Sporadic observations in two wells near Sterling indicate that the water level in the shallow-water-table gravel aquifer may have been gradually lowered locally owing to increased discharge from springs or outflow along the Kenai River banks. One well (Sol 42, fig. 2), that had had 3 feet of water, was dry by mid-June and was still dry in November.

The plotted hydrograph of the only observation well at Soldatna (Sol 63, figs. 2, 22) shows a drop in pressure level of at least 8 feet. The drop was possibly several feet more, but an ice cap in the well prevented measurements during April and May. The fact that the peak recovery a year later was only 4 feet implies a change in the aquifer. Analogy with geologic conditions at Anchorage and Kenai suggests that permeability of the aquifer may have been increased by removal of fine material, or by dilation of the aquifer by the earthquake-imposed stresses. An alternative explanation, a change in the discharge zone, is difficult to evaluate for the following reasons: (1) The elevation of the well is only about 100 feet above sea level, but the depth of the well is also 100 feet. (2) Moreover, the water level in the well is above the level of the adjacent river, so the aquifer is presumably unrelated to this segment of the river. It is reasoned that the aquifer extends seaward at a gentle gradient and discharges into Cook Inlet, 8 miles away. If so, a lowering of water level caused by a disturbance in the discharge zone should progress inland, as the record of the Kenai well (Ken 17) suggests, and then the water levels should resume a normal seasonal cycle. This progression cannot be substantiated because no measurements were made in the well (Sol 63) during the first 3 months following the quake.

ANCHOR POINT-KASILOF AREA

The geologic and hydrologic conditions in the area between the Kasilof and Anchor Rivers are similar to those in the Kenai Lowland, but the land is generally higher toward the south at Anchor Point. The shallow-water-table wells in sand aquifers south of Ninilchik were remeasured periodically and no change in water levels was detected.

The one observation well at Anchor Point (AP 9, figs. 2, 22), which taps a sand and gravel artesian aquifer, was greatly affected by the seismic shocks. The water level dropped at least 12 feet, and recovered only 5 feet in a year's time. A new seasonal cycle appears to be established for this permanent change in pressure level. The lower water level probably results from a change in the discharge zone. However, water loss owing to earthquake damage to the well casing may be the cause; an obstruction in the well at about 50 feet was noted while sounding the depth of the well.

MATANUSKA VALLEY

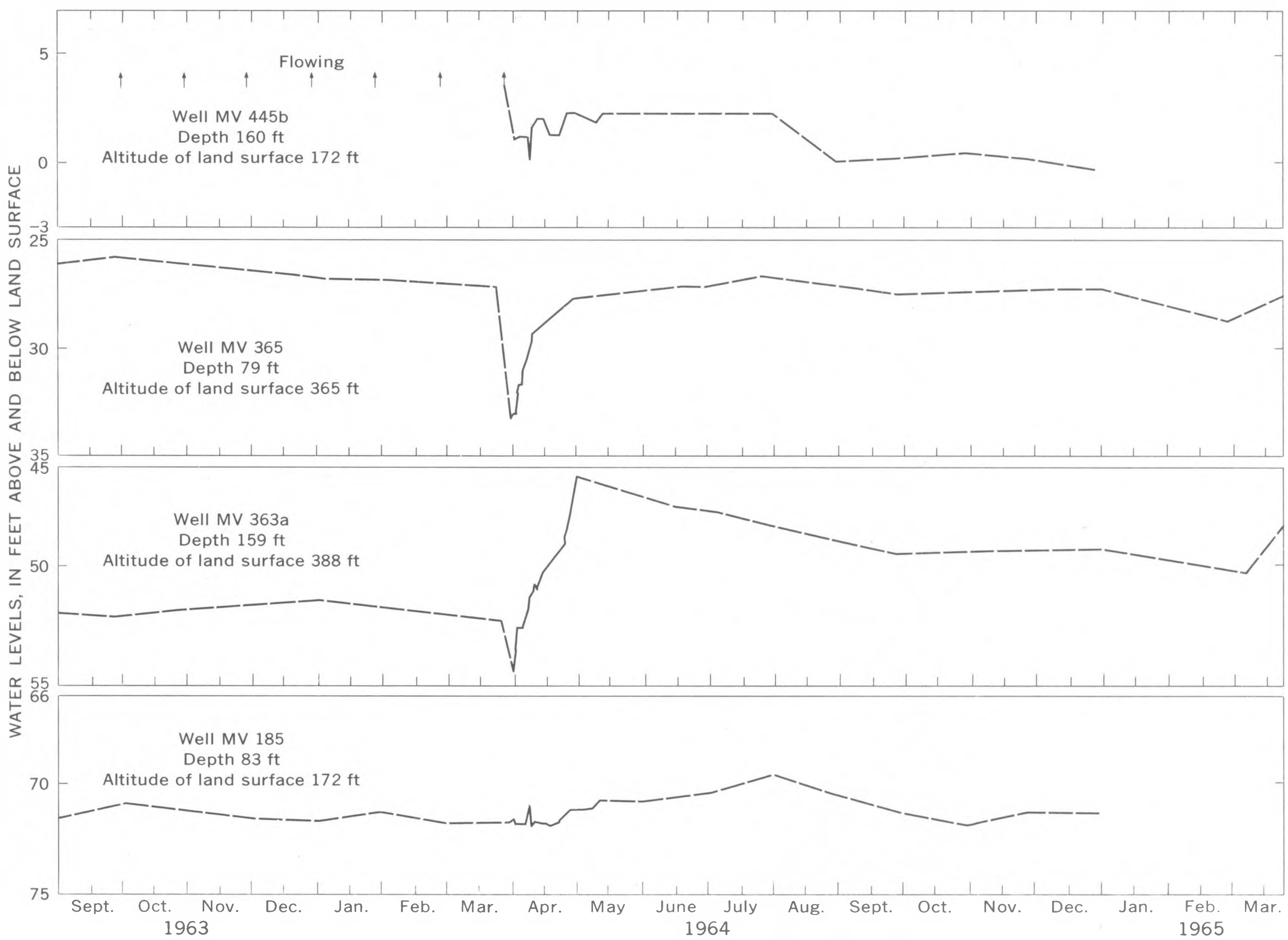
The Matanuska Valley in the area around Palmer and Wasilla (fig. 2) has a geologic and hydrologic environment similar to that of Anchorage, but it does not have as great a thickness of estuarine clay and silt (Trainer, 1960). Trainer established a network of observation wells, and 10 of the wells have been periodically measured since 1952. All the observation wells were measured a few hours or a few days before the quake. These measurements, together with knowledge of the areal hydrology, made possible a thorough evaluation of the effects of the earthquake in this area, some 10 miles closer to the epicenter than Anchorage.

In the Matanuska Valley, as at Anchorage, all power was cut off by the earthquake so that wells were not pumped for about 20 hours. Initial reports indicated many well failures, but most were mechanical failures, chiefly the parting of plastic pipe joints. The artesian system is not as extensive as at Anchorage, so pumping effects do not greatly influence other wells. Water-level measurements were started on all wells by March 31, and a lower artesian pressure was noted in most. However, when the surge of heavy pumping stopped, most water levels recovered to normal. Residual effects were observed in some wells where water levels either rose higher than normal or did not recover a pressure loss.

The hydrographs of four wells (fig. 23, next page) illustrate significant changes or residual effects. One well (MV 365) illustrates the effects of pumping a little-used standby well (MV 363b) for the city of Palmer for a few days after power was restored. Upon cessation of the pumping, the water level recovered to its prepumping level. However, an abandoned city well (MV 363a) closer to the standby well than MV 365 showed a continued rise and as of March 1965 appears to have had a permanent rise of water level. This rise may not have been due to a widespread aquifer change caused by the earthquake. It is more likely that some local change occurred to improve the recharge area of the well. The standby well and MV 363 have long had peculiar differences of water level that are related to the variations in aquifer characteristics, although they both tap the same aquifer and are only 208 feet apart (Trainer, 1960).

Well MV 445b, adjacent to a well that was extensively pumped after the earthquake, showed progressive lowering of artesian pressure that may be permanent. Because this well taps a higher confined aquifer than the pumped well, and was formerly little affected by its pumping (Trainer, 1960, p. 51), the postquake lowering of the water level apparently is the result of a structure change in the aquifer. Trainer (1960, p. 51) believes that the upper aquifer recharges the lower one through thinner or more permeable parts of generally impermeable till. If so, the pressure head of the lower aquifer should eventually rise.

Well MV 185 (fig. 23) shows the water-level changes in a deep water-table aquifer. The graph shows that there was no change until normal recharge from snowmelt and late summer rains raised the water level to 69.58 feet below the land surface—a new high in



23.—Hydrographs of water-level changes in four wells in the Matanuska Valley.

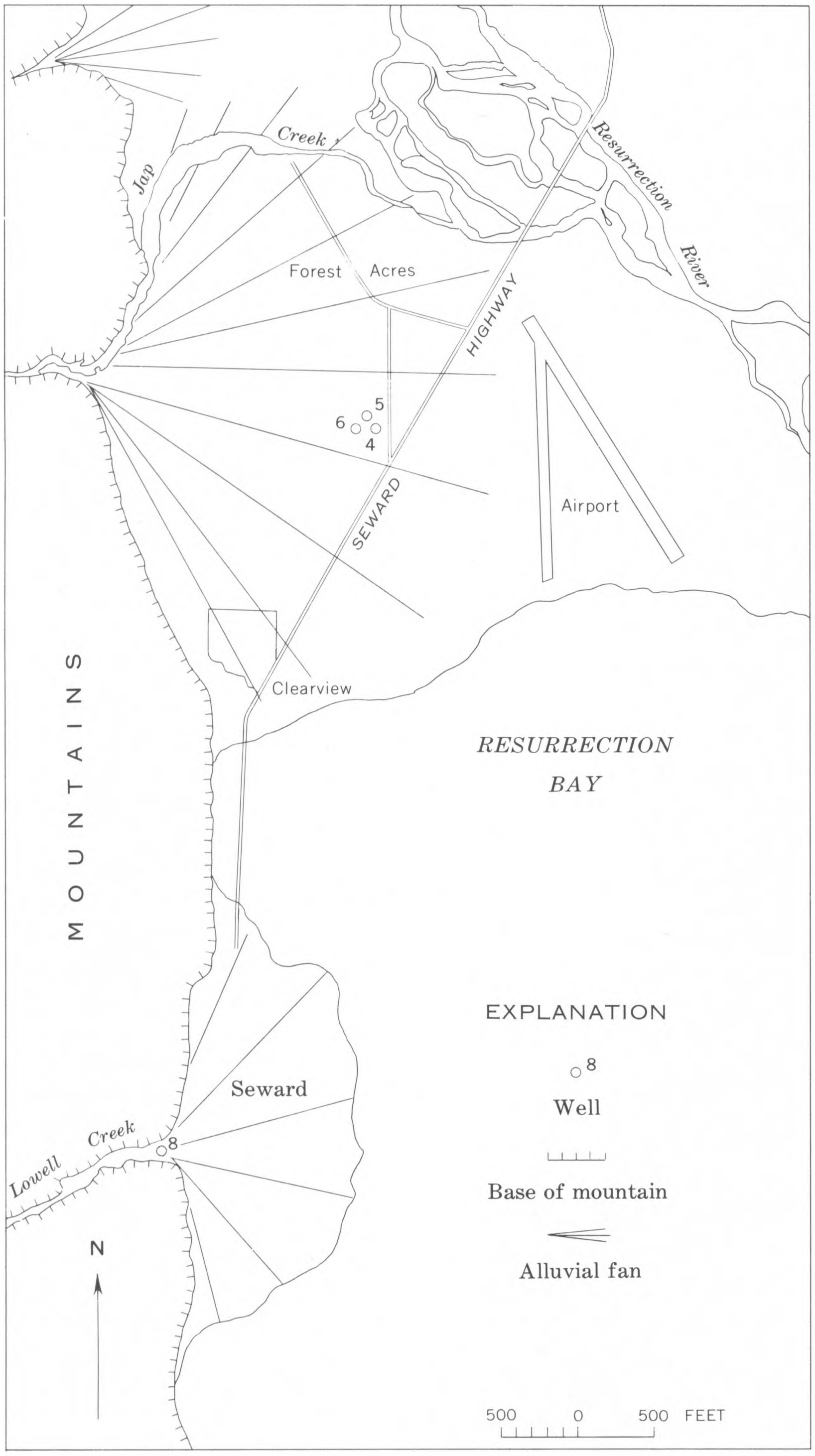
the 15 years of record. Records through 1960 have been published for this well and well MV 365 (Waller, 1963, p. 8–9). The increased rise in water level presumably resulted from above-normal precipitation over a period of several months, or possibly from changes in the aquifer in the recharge area.

SEWARD

Seward is at the head of a steep, mountain-walled fiord (fig. 24). Most of the town and dock facilities lie on an alluvial fan built into the fiord by Lowell Creek. The creek has been diverted into the city water system at the apex of the fan; thus the alluvial fan is probably virtually dewatered. North of the business district, residential areas are located on the Jap Creek alluvial fan which extends onto the Resurrection River valley deposits.

Along the waterfront, near the toe of the alluvial fan, fissures were formed behind submarine slides, and water and sediment were ejected. On the Jap Creek alluvial fan, at the Forest Acres residential area, extensive fissuring and flows also developed.

Lemke (1966) noted the immediate effects on two wells north of Seward. One flowing well was so damaged that no water is now obtainable, but a nearby nonflowing artesian flowed for at neast a week immediately after the earthquake. Only one well (Sew 8) was located on the Lowell Creek alluvial fan. The prequake water level is unknown except for the reported original level of 66 feet when the well was drilled to 78 feet. This low water level at the apex of the fan and the mouth of the canyon, about 123 feet above sea level, may have been due to lack of surface-water recharge because of the upstream diversion. According to Max Lohman, city utilities man (oral commun., 1964), the well could not be used after the quake because water levels were too low. Several measurements made between May 10 and August 23, 1964, showed that the water level rose from 75.12 to 74.07 feet below the land surface. From these measurements it appears that the 78-foot well lost enough head that pumping was not feasible with only 3 feet of water in the well. Whether the water level would have recovered eventually will never be known because the well was deepened to 123 feet in January 1965. A new water-bearing zone, or continuation of the upper zone, was developed near bedrock and the static water level on February 5 was reported to be 96.5 feet.



24.—Sketch map of Seward, at the base of Kenai Mountains, showing geomorphology and well locations.

Water-level measurements were made in wells Sew 5 and 6 on the Jap Creek alluvial fan in June 1961 (Tryck-Nyman and Assoc., written commun., 1961) and were reported to be a little more than 18 feet below land surface in each. One measurement made in each well on May 10, 1964, showed that the water level was still about 18 feet in Sew 5 and about 21 feet in Sew 6. Subsequent measurements could not be made to show any trends or to confirm the measurements. However, measurements made from July 9 to August 23, 1964, in the new well adjacent to Sew 6 showed that the water level lowered from 21.50 to 22.45 feet during this time. Hence, the water level of this new deep well seems to correlate with those of the old wells of unknown depth and implies that they all tap the same aquifer.

The available evidence suggests that aquifers on the Jap Creek fan are a complex of alluvial-fan deposits and an underlying alluvial aquifer deposited by the Resurrection River. The wells tap the deeper part of the aquifer complex. Comparison of water levels in the old wells with those so far determined in the new wells suggests that the earthquake had no permanent effects on the aquifers.

Postearthquake drilling of test holes on the shore at the head of Resurrection Bay (fig. 24) penetrated artesian aquifers having sufficient head to flow 10 gallons per minute at 6 feet above the surface. A water sample taken August 14, 1964, was analyzed by the U.S. Geological Survey. The

61° F water had 25 parts per million chloride, a hardness of 98, a pH of 8.0, and a specific conductance of 250 micromhos at 25° C. This water is probably from an aquifer correlative with the deep aquifer on the Jap Creek alluvial fan. Lemke (1966) believes this artesian system helped to reduce the stability of the submarine slopes that failed nearby during the quake.

VALDEZ

Valdez was perhaps the most extensively devastated of the larger towns affected by the earthquake. The overall effects to the community are described by Coulter and Migliaccio (1966).

Valdez is near the head of Port Valdez (fig. 2) on a glaciofluvial outwash delta that drops off steeply underwater into the fiord. The silt, sand, and gravel deposits of the delta are saturated with water to within 10 feet of the relatively flat land surface. As best as can be determined from the few subsurface data, the water-bearing formations are not confined. Numerous home owners had driven wells to reach the shallow water table. The city had two wells about 60 feet deep. Water levels stood about 4 feet below land surface when these wells were drilled in 1954.

Many first-hand reports of residents indicate the tremendous effects of the earth motion on the ground and on the shallow aquifer. Basements were filled with silty water gushing in through floor drains or cracks. Water and sediment were ejected from cracks that opened in the streets. Elsewhere some 5 feet of snow masked many of the cracks. Water and sewer lines were broken in numerous places, and streets were flooded in places by the outflow of water. Sea water, in successive waves, was mixed with the ejected ground water and with the eruptions from sewerage and water mains in the streets and from the channels formed by the fissuring.

A water-level measurement made on one well in town on May 3, 1964, showed that the water table was 6 feet below the surface. This figure probably represents the approximate low level for the year. The unused city well had a water level of 10.39 feet on May 3, 1964, but the water level was undoubtedly lowered somewhat by an adjacent pumping well. Lack of pre- and post-quake water-level data makes it impossible to determine the long-term effects on the aquifer.

SUMMARY

Alaska's water resources were visibly and invisibly subjected to tremendous forces during the earthquake. The greatest hydrologic effects were confined to areas of thick unconsolidated deposits within a radius of about 200 miles from the epicenter. Effects probably were lessened because the event occurred in late winter, before spring thaws began, when water levels were at their annual low and depth of frozen ground at its seasonal maximum.

Immediate effects were generated by the seismic waves. The ground or surface waves caused noticeable oscillations and turbidity of water in lakes, rivers, and shallow ground water 450 miles from the epicenter. The compressional waves, acting on confined water, caused eruptions of sediment-laden water in most of the alluvial areas within 100 miles of the epicenter and increased the turbidity of artesian wells. Artesian water levels fluctuated as much as 24 feet in one area.

The seismic shock or stresses imposed by the earthquake caused changes in many aquifers that may be permanent. As a result of these aquifer changes, water levels were lowered and some are apparently not recovering to their former height.

Long-term changes in the hydrologic regimen are being brought about by rearrangement of granular material, subsidence or elevation of landmasses, land slides, and the formation of rock fractures and fissures. As a result, ground water is establishing new flow patterns, lakes are establishing new levels, and streams are establishing new gradients and are either aggrading in subsided areas or eroding in uplifted areas. The long-term effects on ground water are the most important because these changes may affect the yield of aquifers and may eventually cause deterioration of the quality of the water.

A quotation of an early, perhaps the first, scientific earthquake writer (Oldham, 1883, p. 60) is an appropriate epilogue:

> Vast, however, as these effects appear, they are in reality insignificant, mere scratches in the paint of the earth in whose history they will leave no permanent record. Hundreds of acres of land may be broken up, thousands of tons of earth may be precipitated into the river, and for days and weeks, or even months, the stream may boil and foam through the wreck, carrying ton after ton of earth away in its turbid stream, but only to be deposited

once more lower down, or even in its ultimate destination, the sea. Time however, will put an end to all this disturbance; soon the river course will be cleared and once more the river will flow as placidly as ever; wind and rain will break down the sharp edges of the overturned masses, will fill up the cracks and holes, and in a few years at most the surface will be smooth and as luxuriantly clad with vegetation as ever it was before the catastrophe.

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