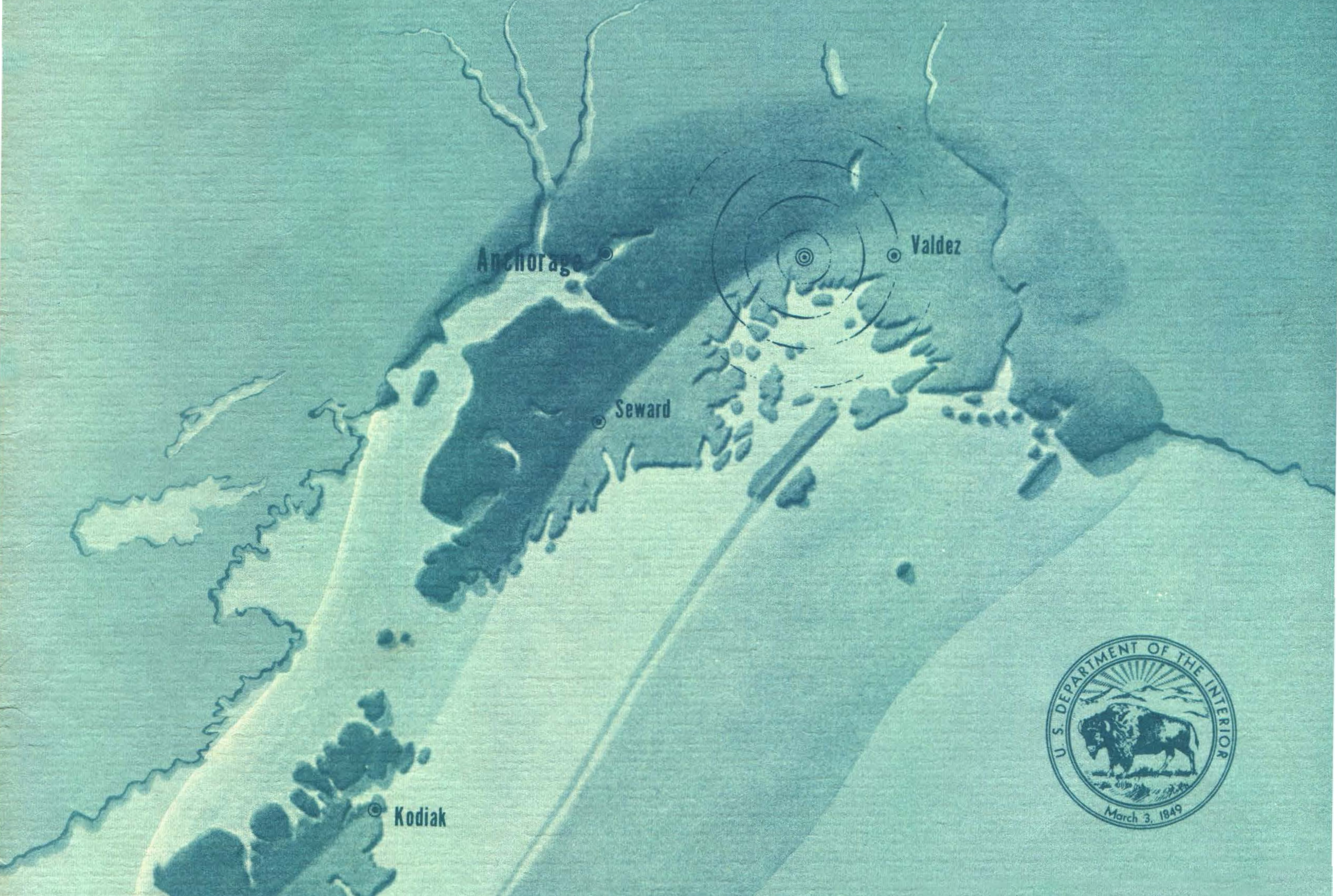
The Alaska Earthquake
March 27, 1964

Effects on Hydrologic Regimen



Anchorage

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

Effects of the March 1964 Alaska Earthquake On the Hydrology Of the Anchorage Area

By ROGER M. WALLER

A description and analysis of temporary and lasting effects of the earthquake on surface and ground water in the Anchorage area

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THE ALASKA EARTHQUAKE SERIES

The U.S. Geological Survey is publishing the results of investigations of the earthquake in a series of six Professional Papers. Professional Paper 544 describes the effects on the hydrology. Other Professional Papers describe the effects of the earthquake on communities; the regional effects of the earthquake; the effects on transportation, communications, and utilities; and the history of the field investigations and the reconstruction effort.

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EFFECTS OF THE MARCH 1964 ALASKA EARTHQUAKE ON THE HYDROLOGY OF THE ANCHORAGE AREA, ALASKA

By Roger M. Waller

ABSTRACT

The Anchorage hydrologic system was greatly affected by the seismic shock. Immediate but temporary effects included increased stream discharge, seiche action on lakes, and fluctuations in ground-water levels. Generally, ground-water levels were residually lowered after the initial period of fluctuation. This lowering is attributed either to changes in the discharge zones offshore or to a change in the permeability of the aquifers by seismically induced strain.

Water supplies were disrupted temporarily by snowslides on streams and by sanding or turbidity in wells. Salt-water encroachment to wells on Fire Island seems to have increased. The approximate 3.7-foot lowering of land level and the diminished artesian head may permit further salt-water encroachment.

Increased pore pressure in the Pleistocene Bootlegger Cove Clay led to liquefaction in silt and sand lenses that contributed to the disastrous bluff landslides. Measurements after the earthquake indicate that most pore pressures are declining, whereas some remain high or are increasing.

Subsidence in the area was caused principally by tectonic readjustment, but differential compaction within the Bootlegger Cove Clay contributed to subsidences estimated to be as much as 0.6 foot beneath Anchorage.

INTRODUCTION

The earthquake occurred at 5:36 p.m. Alaska standard time and lasted about 6 minutes; the epicenter was located in Prince William Sound. The main shock was of Richter magnitude 8.4–8.6. During the main shock, and possibly during some of the earlier aftershocks, about 40,000 square miles of land, including the Anchorage area, was lowered from a fraction of a foot to as much as 8 feet, and about 25,000 square miles of land was raised from a fraction of a foot to as much as 33 feet (Plafker, 1965).

The Geological Survey has been conducting water-resources studies in the Anchorage area for about 15 years. A network of observation wells and stream-gaging stations provided preearthquake control for assessing the effects of the earthquake. The number and frequency of observations were increased for a time after the earthquake.

Information on hydrologic conditions in and near the disastrous landslides along the Anchorage bluffs was obtained during a soils study reported by Shannon and Wilson, Inc. (1964). Measurements of pore pressures in the Bootlegger Cove Clay, of Pleistocene age, were initiated by Shannon and Wilson and were continued by the Geological Survey. The writer is indebted to the District Engineer, U.S. Army Corps of Engineers, for cooperation in making those further studies possible. The well-damage and water-loss data were collected by L. L. Dearborn; his results and interpretations are incorporated in a following section. A description of the general earthquake effects at Anchorage was given by Hansen (1965).

CHANGES IN THE HYDROLOGIC SYSTEM

STREAMS

The Anchorage streams were in their annual period of low flow and were ice covered at the time of the earthquake. The ground waves and the oscillations of water in the shallow streams broke the ice cover. Water and sediment were ejected at some places, particularly along the tidal reach of each stream, as the confined water was subjected to pulsating seismic waves.

Snow and rock avalanches occurred in the headwaters of each stream rising in the Chugach Mountains, but only one slide is known to have affected the streamflow. A snowslide on Ship Creek about 3 miles upstream from the lowland temporarily dammed the stream. In a short time the stream had cut through the slide, but the temporary stoppage of flow had depleted the reservoir at the diversion dam downstream (fig. 6). Within a few hours after the earthquake, all the water behind the dam was diverted to the military and city distribution systems. Because of this complete diversion, no water flowed over the diversion dam until the afternoon of March 29. This 2-day loss of flow had a long-term effect on the downstream part of Ship Creek.

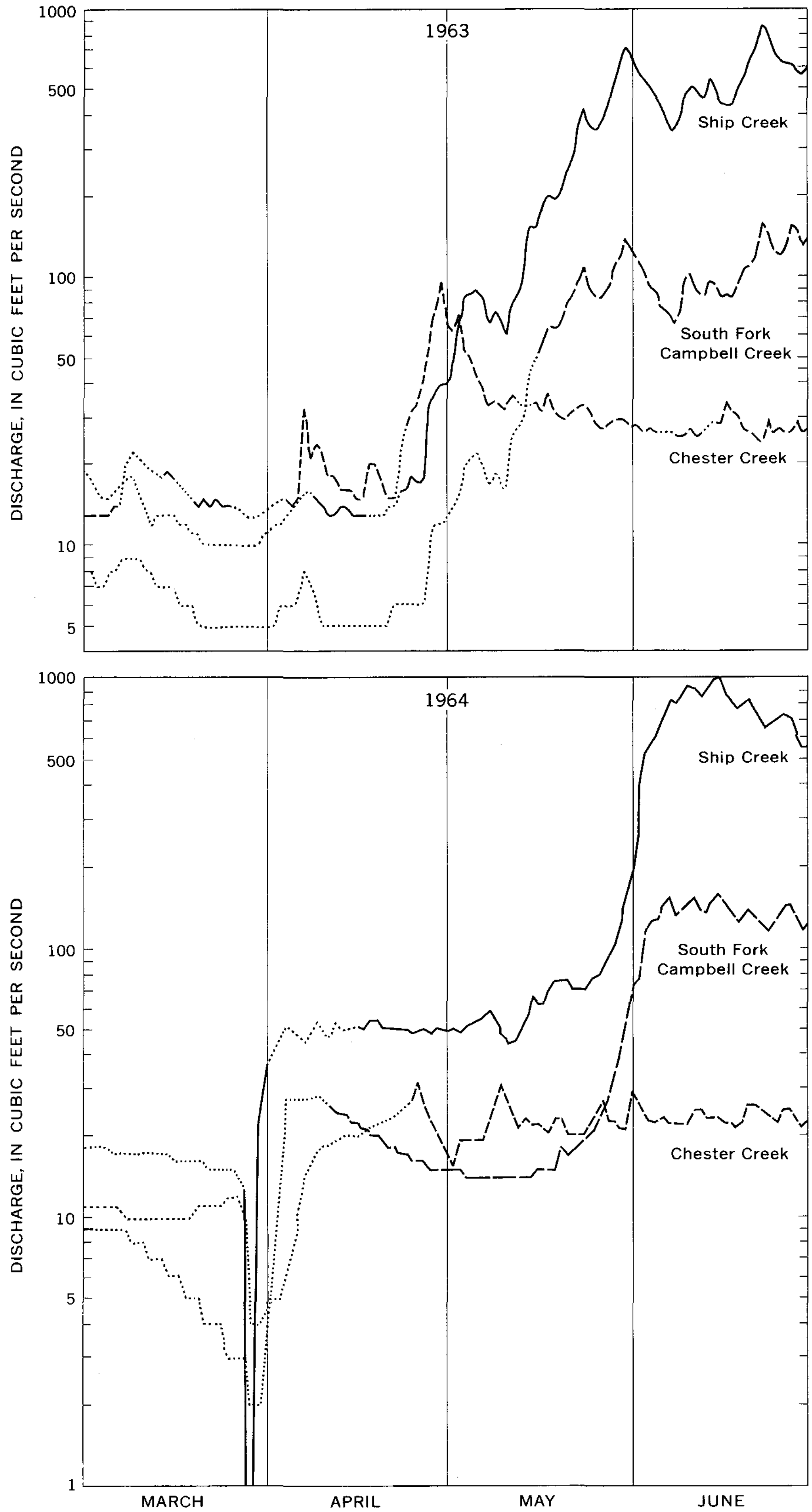
The discharge of Ship Creek, South Fork Campbell Creek, and Chester Creek during the periods March–June in 1963 and 1964, respectively, is shown by hydrographs (fig. 1). The 1964 discharge pattern differs from the discharge pattern for 1963 and indeed for the preceding 10 years. For example, the prequake discharge of Ship Creek was about 15 cfs (cubic feet per second). After recovering from the effect of the snowslide, discharge increased abruptly and reached a plateau at about 50 cfs. This rate of flow was maintained for about 6 weeks, and then discharge increased normally as a result of increasing snowmelt in the mountains. The earthquake therefore temporarily increased the rate of discharge by about 200 percent until the normal discharge pattern was resumed.

Discharge records of the South Fork Campbell Creek show nearly the same pattern (fig. 1) as that for Ship Creek. Preearthquake discharge records for South Fork Campbell Creek are not as dependable as those for Ship Creek, but the increased flow related to the earthquake apparently was between 20 and 25 cfs. The plateau on the discharge hydrograph is similar to that of Ship Creek, and was maintained for about 6 weeks until snowmelt greatly increased the discharge. Differences between the Campbell Creek and Ship Creek hydrographs probably are dependent, at least in part, upon locations of the gaging stations (pl. 1). The South Fork Campbell Creek gage is more than 2 miles from the mountains, and within this distance the stream has cut through glacial till and has deposited an alluvial fan (Miller and Dobrovolny, 1959; Cederstrom and others, 1964), whereas the Ship Creek station fronts the bedrock mountain. Thus, the additional discharge recorded at the South Fork Campbell Creek station during the early part of April probably was derived from ground water.

Discharge records of Ship Creek and South Fork Campbell Creek indicate that base flow from the mountain valleys was increased by the earthquake. Ground water in glacial deposits, as well as in the bedrock, provides the base flow for the streams throughout most of the winter. The intense ground movement probably fractured the frost cover and compacted streambeds, and thereby released ground water to the streams. Similar increases were noted in streams draining areas affected by an underground nuclear detonation in Mississippi (C. P. Humphreys, Jr., and R. E. Taylor, written commun., 1965). The major cause of increased discharge in both places probably is compaction of near-surface sediments which releases water from the unconfined aquifer.

Chester Creek, a stream that rises in the lowland (fig. 6), displayed a postearthquake discharge pattern somewhat different from that of Ship and Campbell Creeks. The preearthquake discharge had been about 12 cfs for more than a month; on March 31, when the first information was obtained after the earthquake, the flow was 4 cfs but apparently was increasing. The stream either lost water from its channel after the earthquake, or recharge from the ground-water reservoir decreased. Channel loss is more likely because the streambed was probably perched above the water table at that time of the year and the frozen streambanks were fractured.

Discharge measurements of Russian Jack Springs were made frequently after the earthquake. No decrease in discharge was found, but the March 1964 discharge was lower than any March discharge except one in the preceding 13-year period of record (Waller, 1964, p. 11). This apparent lack of decrease in discharge of Rus-



1.—Hydrographs of three Anchorage streams, March–June, 1963 and 1964.

sian Jack Springs, which derives water from the confined aquifers, is in contrast to the loss of artesian pressure noted in wells that tap those aquifers (Waller and others, 1965, p. 126).

The postearthquake pattern of discharge from Chester Creek differs from that of previous years (fig. 1). The 1963 hydrograph shows the normal increase in discharge which is greater than that of Ship Creek owing to early meltwater contribution in the lowland; the two sharp peaks on the hydrograph in April illustrate this meltwater contribution. In 1964, discharge from Chester Creek did not exceed that of Ship Creek and it did not produce normal peaks. The reduced artesian pressures and the fractured ground in and adjacent to the stream both probably influenced streamflow during April and May by allowing greater loss of water through percolation to the ground.

The 2-day cessation of flow in Ship Creek below the diversion dam resulted in dewatering the stretch of the creek immediately below the dam. During the first week after flow over the dam resumed, streambed losses below the dam, as shown by the gaging station at Elmendorf Air Force Base (pl. 1), amounted to 60–65 percent of the flow over the dam. Discharge measurements at these two stations are shown in the following table.

Discharge of Ship Creek, March–April 1964, in cubic feet per second

Date	Below diversion dam	At Elmendorf Air Force Base	Loss (rounded)
Mar. 31	35.9	2.05	33
Apr. 3	50.9	17.1	34
6	45.0	29.6	15
8	52.3	32.2	20
10	47.3	40.0	7
24	44.4	39.3	5

Measurements had been made in each of 3 previous years to determine normal water loss between these stations and thus to estimate the amount of recharge to the ground-water basin from this source (Waller, 1964, p. 12). Those measurements showed losses ranging from 3 to 6 cfs. Analysis of records from the two gaging stations for the year preceding the earthquake showed that the monthly mean loss between the diversion dam and the gage at Elmendorf Air Force Base ranged from a high of 93 cfs in July to a low of 10 cfs in October. During the 3 months just preceding the earthquake the average loss was 10 cfs. Hence, although the loss in flow during the week following the earthquake was large for that time of year, it was not exceptional. The apparent postearthquake losses probably were in part recharging the dewatered permeable materials immediately underlying the bed of Ship Creek below the diversion dam. When flow past the dam resumed, much water sank into the streambed and subjacent permeable material, and utimately restored the streambed to its normal condition of saturation.

Analysis of discharge records of Ship Creek for the year following the earthquake shows that the monthly mean discharge loss in the reach ranged from 148 cfs in June 1964 to 9 cfs in March 1965. A comparison of monthly means for the 2 years does not indicate an increase in loss nor a decrease of flow. The high loss of 148 cfs in June 1964 may reflect increased percolation resulting from low ground-water levels during a period of unusually heavy pumping.

LAKES

The most noticeable hydrologic effect of the earthquake was the random breakage of the ice cover by oscillating waves (seiches) caused by the seismic waves. These waves, in general, were small because the lakes are shallow. The ice was broken up mainly along the shorelines by the seiches, which continued for an undetermined period. People living near Campbell Lake (fig. 6) reportedly saw water and sediment ejected 200 feet or more from the lake. According to Hansen (1965, p. 29), large mud fountains formed at Lake Otis, Lake Spenard, Hood Lake, Connors Lake, and others.

The earth-filled dam creating Campbell Lake and one dam on a lake south of O'Malley Road were breached (Engineering Geology Evaluation Group, 1964, p. 25) either by fracturing or by compaction and lateral spreading of the earth fill.

The lakes in the Anchorage area represent the level of the water table in the surficial deposits. Reports (Engineering Geology Evaluation Group, 1964, p. 25) of 2–3-foot lowering of lake levels were not confirmed by continuation of measurements started in 1958 (Waller, 1964, fig. 2).

GROUND WATER

The earthquake effects on ground water were determined in part from water-level records of wells penetrating the shallow water table and deeper aquifers.

Water-level records of five wells in the Anchorage area show the immediate upward fluctuation of the water in the well casing as seismic waves induced pressure on the aquifer. The other immediate effects on ground water in the Anchorage area included reported failures of well systems and muddied or turbid well or spring water. Generally the ground-water levels were residually lowered after the initial fluctuation.

The failure of some of the well systems resulted mainly from sanding or silting of the pump following agitation of the well water and differential movement between well casings and the surrounding rock. Most of the wells are unscreened and reportedly have as much as 1 foot of uncased hole at the bottom. These conditions facilitate the heaving of material under earthquake stress. Fine-grained material flushed into the well by dilation and compression of the aquifer was pumped into some systems; this material caused turbid water and possibly a malfunction of the pump. Erroneous reports of dry wells were common, probably because some pumps that require a full pipe of water for a prime lost their prime during the violent water fluctuation in the well.

Anchorage lost three wells (The Johnson National Drillers' Journal, 1964). At well 1 (fig. 10) the casing was bent when artificial fill failed, but the well was repaired. Well 7 at the edge of the Turnagain slide was damaged beyond repair. Well 6 was abandoned because of its low yield.

WATER WELLS

Surging of water in wells in regions affected by earthquakes probably has been noted ever since wells have been constructed. The immediate surging effects on aquifers at Anchorage were no different from those near previous large earthquakes, but the magnitude and duration of residual or long-term effects may be greater. Surging of water in artesian wells near an epicenter is due principally to the compressional waves acting on the aquifer and, to a lesser extent, to differential movements of well casing and the water standing in the well. Ferris and others (1962, p. 87) summarize previously published American works on such temporary fluctuations and state that when shock waves from an earthquake pass through 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." This phenomenon has been noted in wells that are hundreds and even thousands of miles from epicenters. At these distances the long-period waves of the earthquake cause the fluctuations, whereas in wells close to the epicenter only the short-period waves can effectively move water rapidly into and out of the well (Thomas, 1940, p. 97).

A water-well survey was made by L. L. Dearborn of the Geological Survey to determine if well depth, type of aquifer, type of well construction, or geologic conditions played a significant role in the observed and reported effects of the earthquake upon wells. In addition to 30 wells used for water-level measurements by the Geological Survey, 70 additional wells were selected, generally one per square mile, to obtain data on earthquake effects. Efforts were made to select wells that included a wide range in depth, penetrated a variety of aquifer lithologies, and had detailed drillers' logs. Most of the information on the 70 wells was obtained from well owners several weeks or months after the earthquake and, therefore, could not be verified by personal observation. The results of the survey are shown on figure 2; Dearborn's interpretations (written commun., 1964) are presented in the following paragraphs.

Seventy percent of the wells were affected in some manner other than the initial water-level fluctuations. The data indicate that wells were affected by the earthquake without regard to their depth. Among the wells less than 100 feet deep, 73 percent were affected; wells between 100 and 200 feet deep, 62 percent; and wells deeper than 200 feet, 75 percent. The wells range in depth from 16 to 540 feet.

Gross aquifer lithologies range from fine sand to coarse gravel (pl. 1). Of the 55 wells affected by the earthquake for which adequate logs are available, 33 percent are in sand, 23 percent in gravel, 28 percent in sand and gravel, and 16 percent in till. Of the 23 unaffected wells for which logs are available, 31 percent are in sand, 17 percent in gravel, 35 percent in sand and gravel, and 17 percent in till. Presumably those wells drilled into till, such as well 44 (Anc 64; see table, pl. 1) obtain water from thin layers of sand and gravel (Cederstrom and others, 1964, p. 50). These data suggest that the lithology of the aquifers was not a significant factor in controlling the overall effects of the earthquake upon wells.

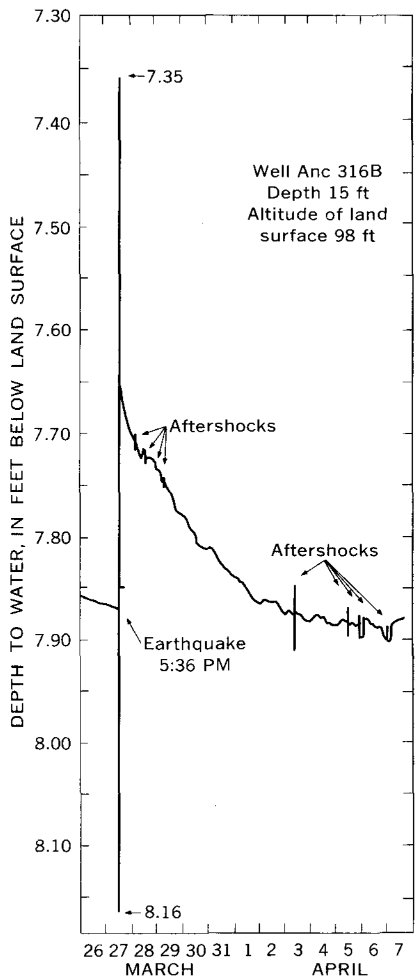
Of the 100 wells inventoried, 6 have screens and 62 have open end or slotted casing. No information is available as to the finish of the 32 remaining wells, but presumably most are open end. The number of wells equipped with screens is too few to provide convincing evidence as to the relationship, if any, between method of well construction and the effect of the earthquake upon the well.

In summary, Dearborn concluded that well depth, type of aquifer, and geographic distribution of wells were not determining factors of the earthquake effect on wells. A factor which may have been significant, but which cannot be evaluated because of the lack of information, is the percentage of silt and clay in the aquifers. Continuing measurements subsequently showed that long-term changes of water levels had occurred and that there is a pattern to the areal distribution of those effects (fig. 6; see p. B11).

RESPONSE OF THE SHALLOW WATER TABLE

Water in unconfined aquifers generally is not as much affected by seismic waves at great distances from the epicenter as is water under pressure in artesian aquifers. In south-central Alaska, however, water was violently ejected wherever it was close to the land surface. Housner (1958, p. 161) has concluded that ejection of sand and water during earthquakes does not require "any unusual properties of soils." However, it is believed that the seasonal frost layer prevailing at the time of the Alaska earthquake temporarily confined the water so that the shallow water-table aquifers responded in much the same manner as would deeper confined aquifers (Waller, 1966).

Evidence that a confining layer may determine the degree of response is provided by the record of well Anc 316B (pl. 1; fig. 10), which taps a water-bearing sand extending from 7.8 to 15 feet below the land surface. The depth of frozen ground in the vicinity of this well probably was not more than 5 feet at the time—hence, there was about 3 feet of unsaturated sand between the bottom of the frozen zone and the water table, so the aquifer was not confined. The record (fig. 2) shows that in this well the water level fluctuated less than 1 foot because there was no restrictive confining layer in the aquifer. This well is probably typical of the en-



2.—Hydrograph of water-table well Anc 316B from March 26, 1964, to April 7, 1964. (See fig. 10 for locations.)

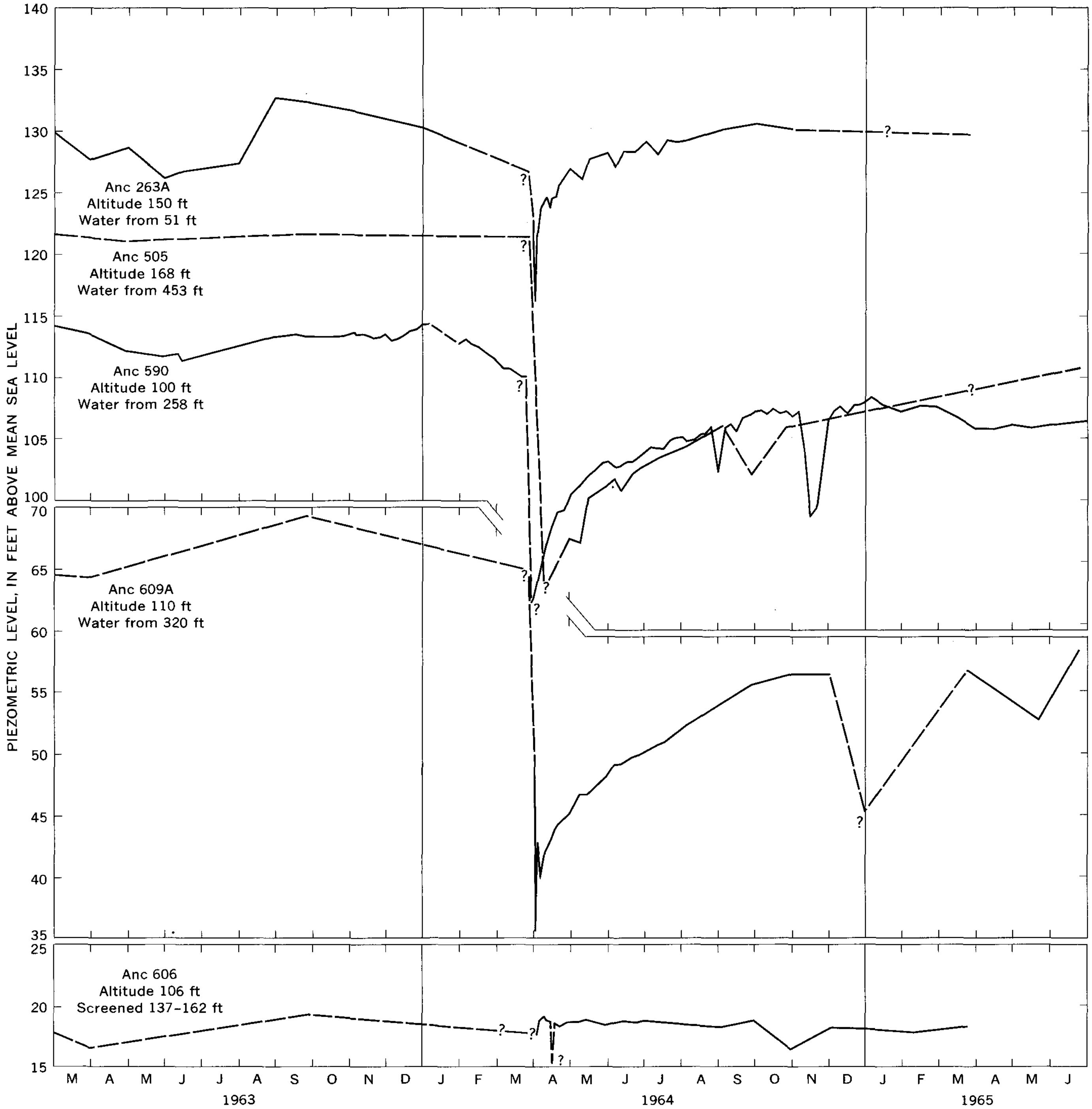
tire Spenard area, as well as the Turnagain area to the west, where no signs or reports of sand or water ejections are known. There the low late-winter water table must have been generally below the depth of frost penetrations. In contrast, water and mud were ejected locally in stream valleys, notably the 3,200-square foot sand boil in the shallow valley of Fish Creek in the Turnagain area (Engineering Geology Evaluation Group, 1964, pl. 8), and on highest tidal marshes at Anchorage (Hansen, 1965, p. 29). In such areas, the water table was probably at or above the base of the frost layer, and the water in the shallow valley-bottom aquifers was thus effectively confined—therefore, under pressure.

ARTESIAN-AQUIFER RESPONSE

The mechanics governing the response of well-aquifer systems to seismic waves was analyzed recently by Cooper and others (1965). Using this analysis, Bredehoeft and others (1965) computed from a recorded water-level fluctuation in a Florida well the oscillation of the pressure head in the aquifer and the vertical land-surface motion due to the Alaska seismic wave. The theory developed by these investigators enhances the usefulness of the water-level recorder as a seismic tool.

At Anchorage the Geological Survey had recorders on four artesian wells. Hydrographs from two instruments were unintelligible. The recorder on a well east of Anchorage showed at least 6 feet of fluctuations before the pen flipped off the chart. The other recorder (Anc 590, fig. 3) that continued operating throughout the earthquake showed virtually continuous activity of the water level for about 8 hours, and the fluctuations are estimated to have exceeded 24 feet. The pre-earthquake water level was about 5 feet below the surface. After the 8-hour period of fluctuation, there was a continuous decline for over 5 hours to about 23 feet where the water level remained steady for several days.

The 8-hour period of continuous fluctuation probably resulted in part from the beginning of continuous pumping in nearby housing-development wells. Power was restored in some areas shortly after the earthquake, and it is reasonable to assume that some pumps were in steady operation for several hours or days either to catch up with the demand or



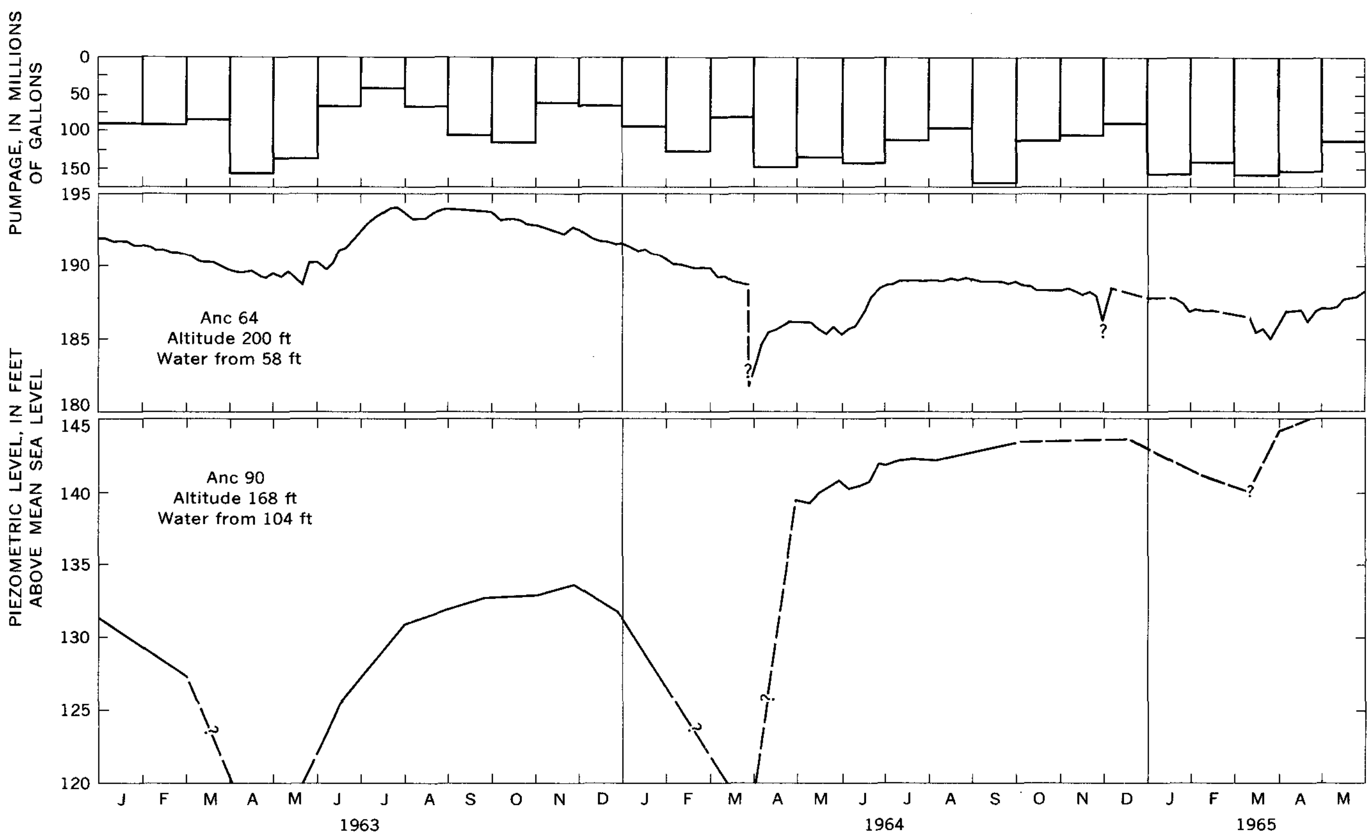
3.—Hydrographs, 1963–65, of five wells in the Anchorage area but probably outside the area influenced by pumping of city and military wells. The graphs show, by yearly comparison, the residual changes in artesian water levels after the earthquake. (See figs. 6 and 10 for locations.)

perhaps to compensate for leaks in distribution systems. After several days the water level began to recover. Recovery, however, was not complete, and by fall the level was still about 5 feet below that prevailing before the quake. This lowering may be permanent.

Because of the small number of recorders and the incomplete hydrographs obtained, neither a detailed evaluation of the immediate effects on the artesian system nor a calculation of aquifer piezometric levels using the method of Bredehoeft and others (1965) can be made. Resumption of pumping from wells before recorders were restored to operation also complicated evaluation of the immediate earthquake effects. However, it is reasonable to assume that the artesian system was materially affected by the intense oscillating pressures which lasted for 3–5 minutes. The surging in and out of well intakes caused fluctuations of as much as 24 feet and caused sanding of wells. Beyond these immediate and transient effects, however, there were seemingly residual or permanent changes in piezometric levels. Water-level measurements, begun a few days after the earthquake, indicated lowered water levels, which in turn implied changes in the aquifers. These changes have persisted for a year after the quake. Such permanent changes at Anchorage are important with respect to changes in aquifer yield, interference between pumping wells, rates of recharge, and sea-water encroachment.

PIEZOMETRIC LEVELS

About 50 observation wells (see locations on pl. 1) were measured periodically starting a few days after the earthquake. Most of the wells had records of previous measurements—some of several years duration—so the postearthquake changes could be evaluated. Nearly all the pertinent data show that the artesian-pressure surface was lowered, locally as much as 24 feet, but that recovery started immediately and that within 6 months the water levels either had recovered to their former level or stabilized at a different level. The new piezometric level is as much as 15 feet lower than preearthquake levels in about one-third of the wells. Almost all the observations indicate changes in the artesian-aquifer system in the glaciofluvial deposits. The record from one well (Anc 1, on Fort Richardson; see pl. 1) shows that similar changes may have occurred in the Tertiary bedrock beneath about 400 feet of the glacial drift.



4.—Hydrographs of wells Anc 64 and Anc 90, and graph of Anchorage pumpage for 1963–65. (See fig. 6 for locations.)

Because pumping was resumed at greatly increased rates when electric power had been restored after the earthquake, the artesian-pressure levels were also greatly affected by pumping. Postearthquake pumpage and comparable preearthquake (1963) pumpage is shown on figure 4. The postearthquake increase of about 2 mgd (million gallons per day), together with increased military pumpage during April, undoubtedly extended the area of reduced artesian pressure not only far beyond the limits of effect noted during the previous year, but also beyond that determined in an earlier study when total pumpage was about 8 mgd (Waller, 1964, pl. 3).

Hydrographs of water levels in five representative wells are shown on figure 3. These wells (pl. 1) are west or south of Anchorage and are believed to be outside the area influenced by pumping of city and military wells. The hydrographs show the extensive lowering of artesian pressures after the earthquake and the gradual recovery to a new level somewhat lower than 1963. On the other hand, the hydrograph for Anc 606 (fig. 3) shows little change in level; evidently some aquifers or parts of aquifers had no lasting changes.

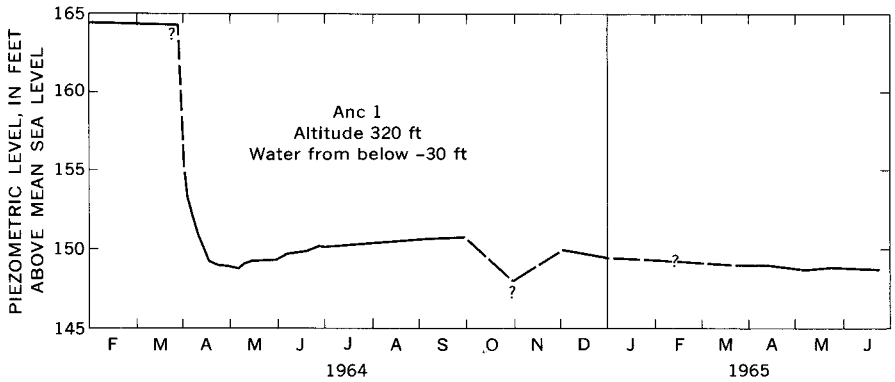
Although the hydrographs (fig. 3) are thought to represent effects on wells that are outside the area of influence of the city well field, earlier studies (Waller, 1964, p. 30) showed that the area of influence may extend 3–4 miles from the city well field. Well Anc 590 lies within this distance. Furthermore, pumping wells in a nearby housing development probably caused some of the drawdown observed in Anc 590 after the earthquake. Nearby pumping may also be responsible for as much as 8 feet of drawdown in Anc 609A and about 5 feet in Anc 263A. Water levels in Anc 505 are not known to be influenced by pumping of other wells. The 10-foot lowering of levels in that well, therefore, probably resulted entirely from changes in the aquifer brought about by the earthquake. Well Anc 503A, nearby, shows a similar change in level of about 13 feet.

Well Anc 606 does not show appreciable change in water level after the earthquake. This well, which penetrates a coarse aquifer and is one of the most efficient wells in the Anchorage area, produces 320 gpm (gallons per minute) with only 1.9 feet of drawdown (Cederstrom and others, 1964, p. 91). The coarseness of the aquifer in that vicinity, the construction and good development of the well, and its location far west of the city well field may be factors that help to explain the lack of residual lowering of water level following the earthquake.

Two hydrographs of wells representative of the eastern part of the Anchorage area are shown in figure 4 along with a graph of city pumpage. Well Anc 64 has been measured periodically since 1954, so there is a fairly long record of its annual fluctuation and its response to city and military pumping (Waller, 1964, fig. 4). The data indicate a residual lowering of 4 feet at the end of 1964.

The apparent response of Anc 90 (fig. 4) to the earthquake is exceptional. Prior to the earthquake, water levels in Anc 90 fluctuated quickly and greatly in response to pumping at the city well field. Water-level contours in the vicinity of Anc 90, prior to the earthquake (Waller, 1964, pl. 3), showed a conspicuous valley of low permeability. The response since the earthquake has been much different. Water levels in Anc 90 rose to elevations not reached in the well between 1960 and the time of the earthquake, and the hydrograph obtained thereafter shows virtually no response to pumping of city wells even though withdrawals from that well field have been larger than they were prior to the earthquake. This rise during a period of increased discharge must reflect more effective recharge, perhaps from overlying aquifers.

The thick sequence of glaciofluvial sediments in the Anchorage area is underlain by sandstone and shale of Tertiary age (Cederstrom and others, 1964). Aquifers in the sandstone have not been developed because of their low yield, but one well (Anc 1, which was 540 feet deep when drilled and which taps those aquifers) has been used as an observation well by the Geological Survey for 7 years. The water level fluctuated seasonally less than 3 feet during this period. Measurements made shortly after the earthquake showed (fig. 5, next page) that the water level declined nearly 15 feet; subsequent measurements through June 1965 show no return to preearthquake levels. Because the well is uncased below 350 feet, its total depth was checked in 1965 and found to be only 285 feet. The well had either filled with material prior to or during the earthquake. The Tertiary formations are weakly indurated and could be expected to cave into an uncased well. However, filling probably occurred gradually during several years, because if filling was earthquake induced, the water level should have risen rapidly and then slowly declined to the normal static level. The lowered water level correlates with the general lowering of artesian pressure elsewhere in the Anchorage area. Thus, Anc 1 is probably hydraulically connected with the overlying glaciofluvial aquifers.



5.—Hydrograph of a well in Tertiary bedrock at Anchorage, 1964–65. (See pl. 1 for location.)

Measurements for a full year after the earthquake showed that the general lowering of the artesian-pressure level in the Anchorage area persisted. The pattern of seasonal fluctuation remains as it was before the quake. Thus, recharge to the system occurs at the same time of the year, and discharge from the aquifers continues as before. The areal distribution of water-level changes is plotted on figure 6.

The contours on figure 6 show the residual lowering of piezometric levels in the Anchorage area as inferred by the writer from the data available. Location of the line representing zero change near the Anchorage well field is tentative inasmuch as postearthquake measurements reflect not only the drilling and pumping of wells that were added to the system after most of the preearthquake reference measurements had been made, but also possible earthquake-induced changes. A. J. Feulner (oral commun., 1964) believes that there is a residual lowering of water levels in the city well field of 5–10 feet. The writer admits to both the new-well influence and earthquake-caused change possibilities, but believes that earthquake-caused changes in the city well field are not required to explain piezometric levels observed there since the earthquake. Evidence for greater residual lowering of water levels in aquifers south of Anchorage near Turnagain Arm of Cook Inlet is reasonably conclusive. Neither the known geology nor the known characteristics of aquifers from place to place in the area explains the inferred pattern of residual change illustrated in figure 6.

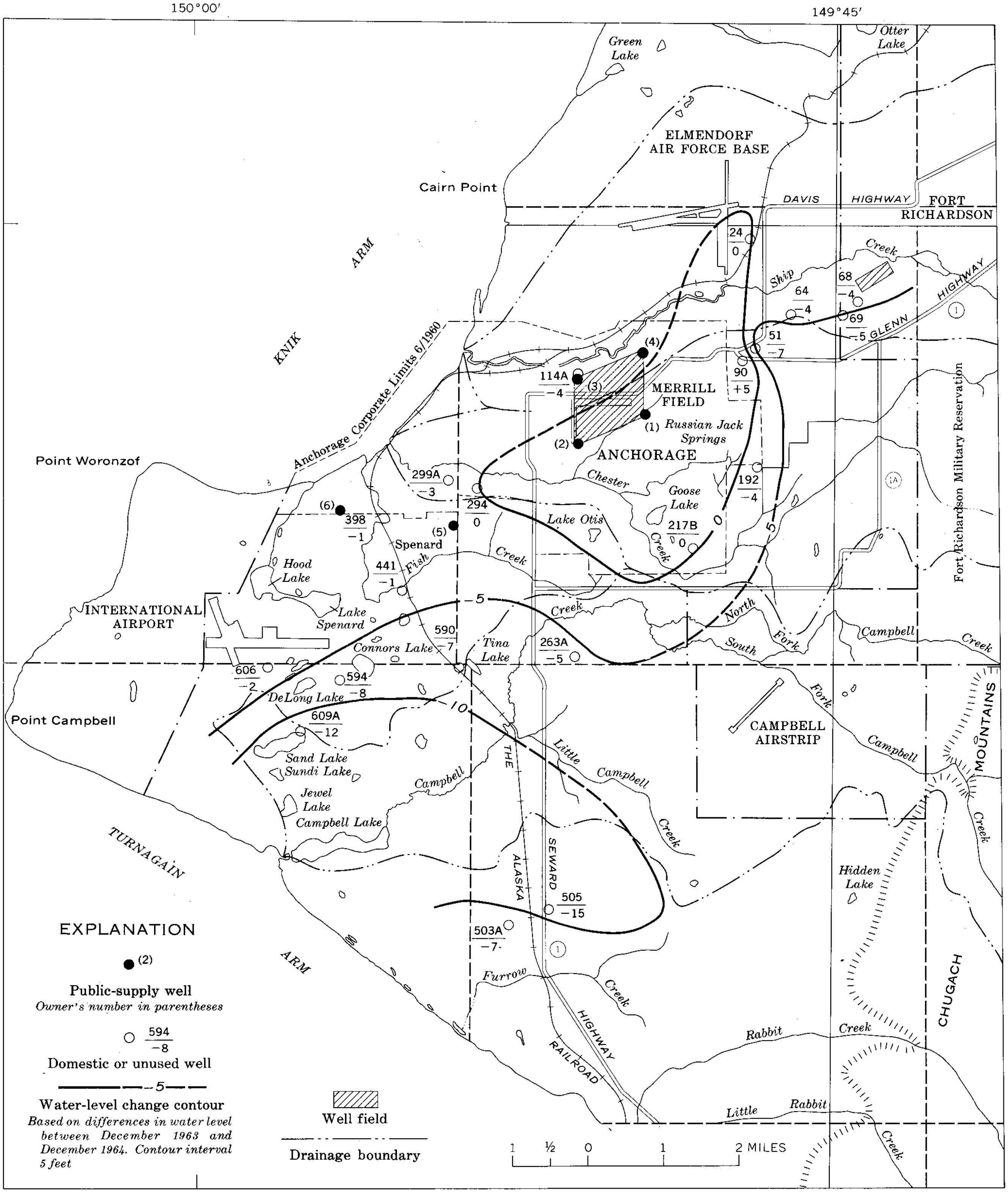
CAUSES OF RESIDUAL CHANGES

The causes of residual changes in water levels in aquifers of the Anchorage area could not be determined from field evidence, but several possibilities exist. Among these are tectonic lowering of the land in relation to sea level, a change in the recharge to the aquifers, a change in the porosity of the aquifers as a result of strain from seismic stresses—stresses which may take time to dissipate, the opening or closing of passages in till or clay, or a change in the subsurface discharge zone. Some of these causes have been previously suggested for residual changes noted from other earthquakes and for this earthquake in other parts of Alaska (see Waller, 1966).

The Anchorage piezometric levels show residual lowering ranging from near zero to more than 10 feet. Only one well showed a residual rise. The tectonic lowering of the land should have resulted in a general rise of water levels from 3.7 feet at the shoreline to progressively lesser rises inland. This raised water level may have been cancelled by the generally lowered water levels resulting from other causes.

The lowered piezometric surface could be related to a decrease in recharge which takes place in the eastern part of the area. However, there was no apparent, change in stream recharge (see p. B4). A rearrangement of aquifer grains as a result of seismic stresses has been generally accepted as a change which increases compaction and reduces permeability. The lowered water levels can be explained only by visualizing a strain produced by seismic stresses that would rearrange the grains so as to increase the permeability. Such strain seems difficult to visualize at first, but the long period of time during which successive waves of compression and dilation were active at Anchorage and the fact that the seismic wave fronts are refracted by different geologic conditions seem to indicate that some grain rearrangement may have occurred that resulted in increased permeability.

The tectonic subsidence of more than 3 feet and horizontal movement of as much as 10 feet (about 0.5 feet per mile), in the upper Cook Inlet area (U.S. Coast and Geodetic Survey, 1964, 1965, p. 17), could also produce a strain in the aquifers that would change the porosity and permeability. Fracturing in the confining beds of clay or glacial till was also possible, especially in the till, but such fracturing would not have significantly affected water levels inasmuch as the various aquifers were already hydraulically interconnected. The change in the bottom



6.—Areal distribution of artesian-pressure changes in the Anchorage aquifer system. Numbers above line are well numbers; numbers below line are changes in water level, in feet.

topography of Knik Arm (discussed below) and evidence of compaction (discussed under "subsidence") are the only other observations pertinent to evaluation of the causes of the residual changes in water levels.

DISCHARGE ZONES

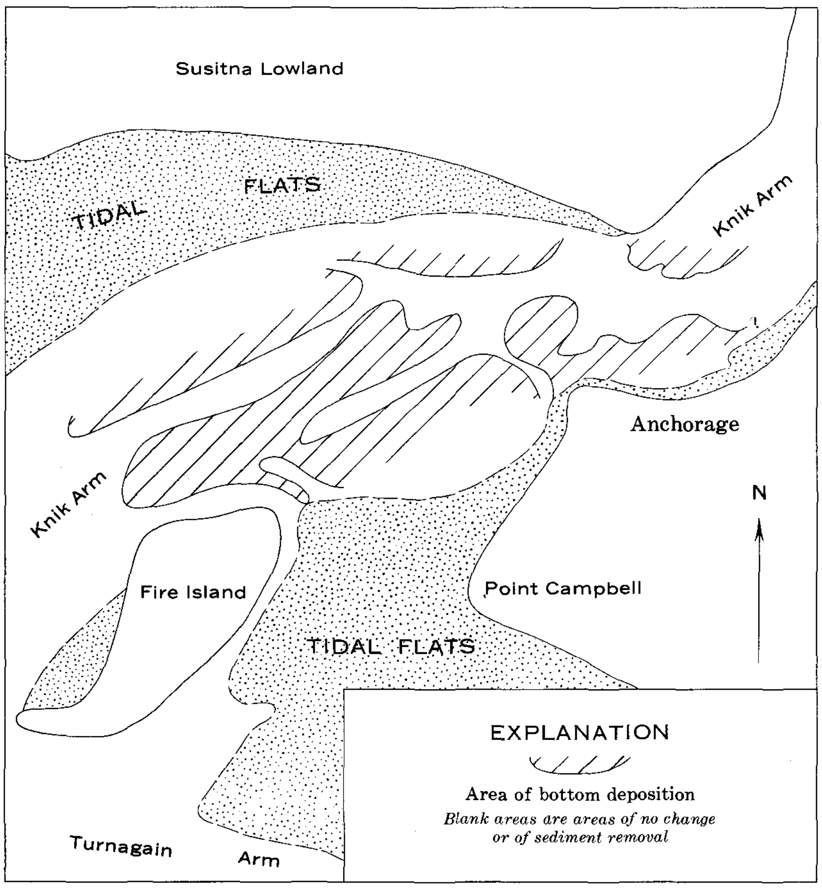
The U.S. Coast and Geodetic Survey makes routine bathymetric surveys of the Knik Arm of Cook Inlet because it is a ship channel. The Turnagain Arm is not routinely surveyed. Surveys of the Knik Arm before and after the quake, plotted by T. N. V. Karlstrom, show (fig. 7) that there were extensive changes in the distribution of bottom sediments between 1963 and the period immediately after the earthquake in 1964. If similar changes occurred in Turnagain Arm, they might have had a significant effect upon the ground-water hydrology of the Anchorage area. Aquifers of the area apparently discharge to the sea through bottom sediments in both Knik and Turnagain Arms (Cederstrom and others, 1964, p. 48; Waller, 1964, p. 33). The discharge is probably by upward movement of water directly from truncated aquifers or less directly by movement from the aquifers upward through semipermeable sediments that floor parts of the estuaries. Thinning or removal of such semiconfining sediments might readily cause increased discharge from the aquifers and resultant lowering of piezometric levels in upgradient parts of the aquifers.

There is no direct evidence that the earthquake caused the redistribution of bottom sediments in Knik Arm as indicated in figure 7. The well-known effects of seismic waves upon unconsolidated water-saturated materials, especially those resting on unstable slopes, suggest, however, that the redistribution was indeed caused by the quake.

CHEMICAL QUALITY

The earthquake probably increased the turbidity of all well water, although the increase in many wells was so slight that it was not visible. L. L. Dearborn (oral commun., 1964) reported one well in which the water remained visibly turbid for 2 weeks following the earthquake. Trouble from this cause in Anchorage, however, was minor. Bothersome turbidity generally disappeared within a few hours or a few days.

The rate of sea-water encroachment at one well on Fire Island, near Anchorage, may have been increased by the earthquake. Analyses of water samples from that well had shown a slow, continuing increase in chloride concentration for some years. The rate of increase of chloride concentration accelerated after the quake; the concentration increased, for example, in the period January–July 1965 from about 600 ppm (parts per million) to 850 ppm chloride. One of three other wells on the island penetrated a saline-water aquifer when drilled. The saline aquifer was reportedly cemented off. Inasmuch as samples of water taken from the cemented well after the earthquake show only 266 ppm chloride, saline water evidently is not leaking into freshwater aquifers along the bore of that well. The sources of increase



7.—Changes in distribution of bottom sediments in the Knik Arm of Cook Inlet, 1963–64. Plotted by T. N. V. Karlstrom from U.S. Coast and Geodetic Survey data.

in the well having 850 ppm chloride in July 1965 have not been discovered.

Observations of water quality on Fire Island are continuing as part of the watch for potential salt-water encroachment upon aquifers underlying Anchorage. It seems likely that tectonic lowering of the land surface of about 3.5 feet at Anchorage has increased the load on the seaward margins of the aquifers underlying Cook Inlet. This load, equivalent to an additional 3.5 feet of water, must favor landward movement of the interface between salt and fresh water in the aquifers.

GROUND WATER IN THE BOOTLEGGER COVE CLAY

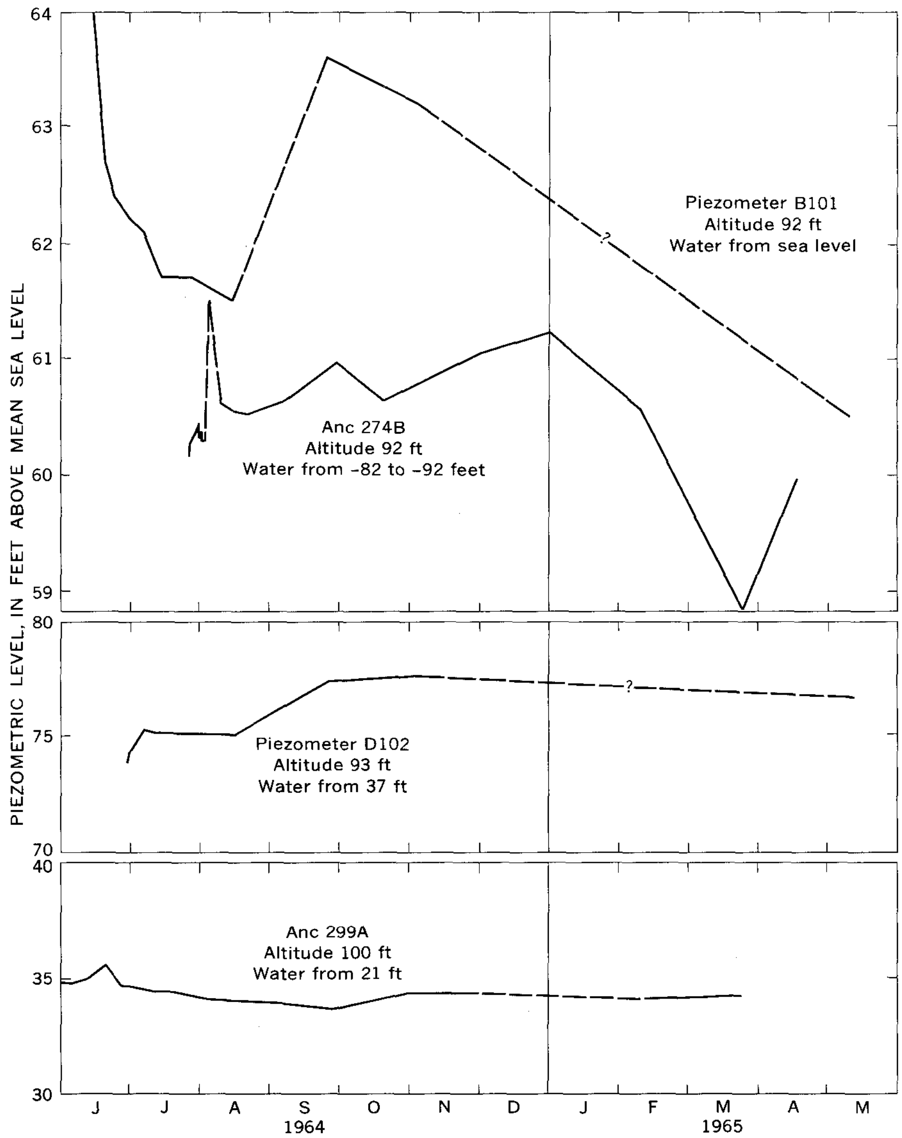
Ground water in sand and silt lenses within the Bootlegger Cove Clay, of Pleistocene age, has been considered a major factor in causing the devastating landslides that occurred at Anchorage (Shannon and Wilson, Inc., 1964). The water-saturated lenses probably became fluid in response to the repeated earthquake shocks, and thus became glide planes along which blocks of ground moved laterally toward the sea. Consideration has been given to dewatering parts of the formation in order to enhance its stability. The relation of the ground water in the Bootlegger Cove Clay to the aquifer system in the Anchorage area is therefore significant, both as to the feasibility of dewatering the formation and as to the effect of dewatering on the Anchorage ground-water supply.

Cederstrom, Trainer, and Waller (1964, p. 56) and Waller (1964, p. 9) reported that ground water in sand and silt lenses in the Bootlegger Cove Clay is derived from the continguous sand and gravel aquifers by lateral movement and slow vertical leakage through the rather impermeable clay confining layers. This conclusion was based on the increase in piezometric levels with depth in wells and on the fact that some of these piezometric levels were above the water table in the area underlain by the Bootlegger Cove Clay. Furthermore, interconnection is suggested by the observation that some shallow artesian aquifers appeared to be influenced by pumping from the deeper artesian aquifers. Pore pressures in the sand and silt lenses in the slide and in areas immediately adjacent were unknown except from a few wells tapping sand lenses in the eastern part of the formation. Further evidence of the hydraulic interconnection of the water-saturated Bootlegger Cove Clay and the artesian aquifer system, and to the overlying water-table aquifer was indicated by the lack of salinity in the water-bearing lenses in the clay. The formation, marine in part, has been partly elevated above sea level in relatively recent times, and the entrapped connate water has been flushed out by the dynamic hydrologic system (Cederstrom and others, 1964, p. 73).

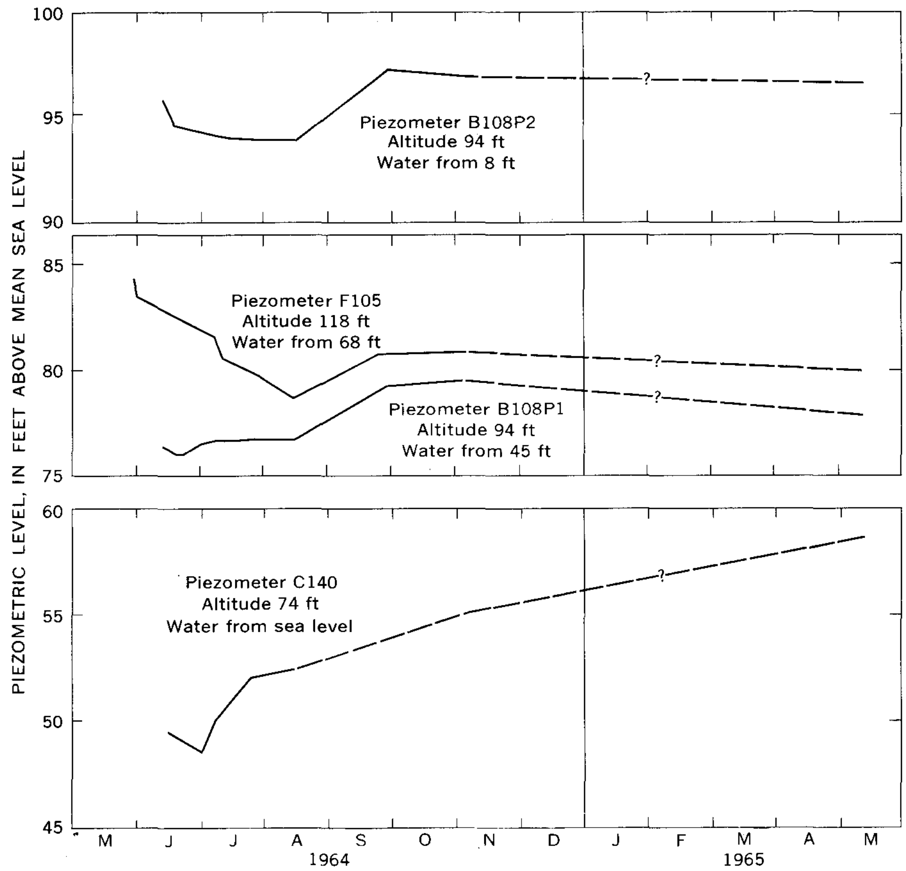
Measurements of the peizometric level in the artesian aquifers indicate that the level in the Turnagain slide area was about 20 feet and in the downtown area about 15 feet above sea level at the time of the earthquake. Measurements in the surface sands indicate a water-table level of about 80 feet above sea level in the Anchorage downtown area and 60 feet in the Turnagain area. Pore-pressures in the various sand and silt lenses and layers within the clay were unknown.

After the earthquake, nearly 50 piezometers were installed in the clay, and pore pressures were monitored (Shannon and Wilson, Inc., 1964) until August 1964. Since then, the Geological Survey has measured the pore pressures in most of the piezometers at irregular intervals. Pore pressures generally decreased in the months following the earthquake, but there was little uniformity. The pressures varied from stratum to stratum within the formation and from place to place at equivalent depths. However, according to M. M. Marcher (oral commun., Oct. 6, 1965), pore pressures in many of the peizometers had declined to levels that were equivalent to or less than piezometric levels measured at the same time in wells tapping the main artesian aquifers of the area. This decline implies that the seismically induced pore pressures may have gradually returned to a natural state. In a few piezometers, however, pore pressures remained significantly higher than the artesian-aquifier piezometric level. The possibility exists that those high readings reflect piezometer tubes that are plugged. Figure 8 shows a possible correlation of pore pressures and piezometric levels of artesian aquifers at two sites. The patterns of representative pore-pressure fluctuations from June 1964 to May 1965 are shown in figure 9.

Reduction of pore pressures in the Bootlegger Cove Clay is being attempted by partial dewatering of the formation in areas where pressures are relatively high and the danger of future land-



8.—Hyrodgraphs of pore pressures (piezometers B101 and D102) versus artesian-aquifer pressures (wells Anc 274B and 299A) at sites near the West High School and L Street slides. (See fig. 10 for locations.)



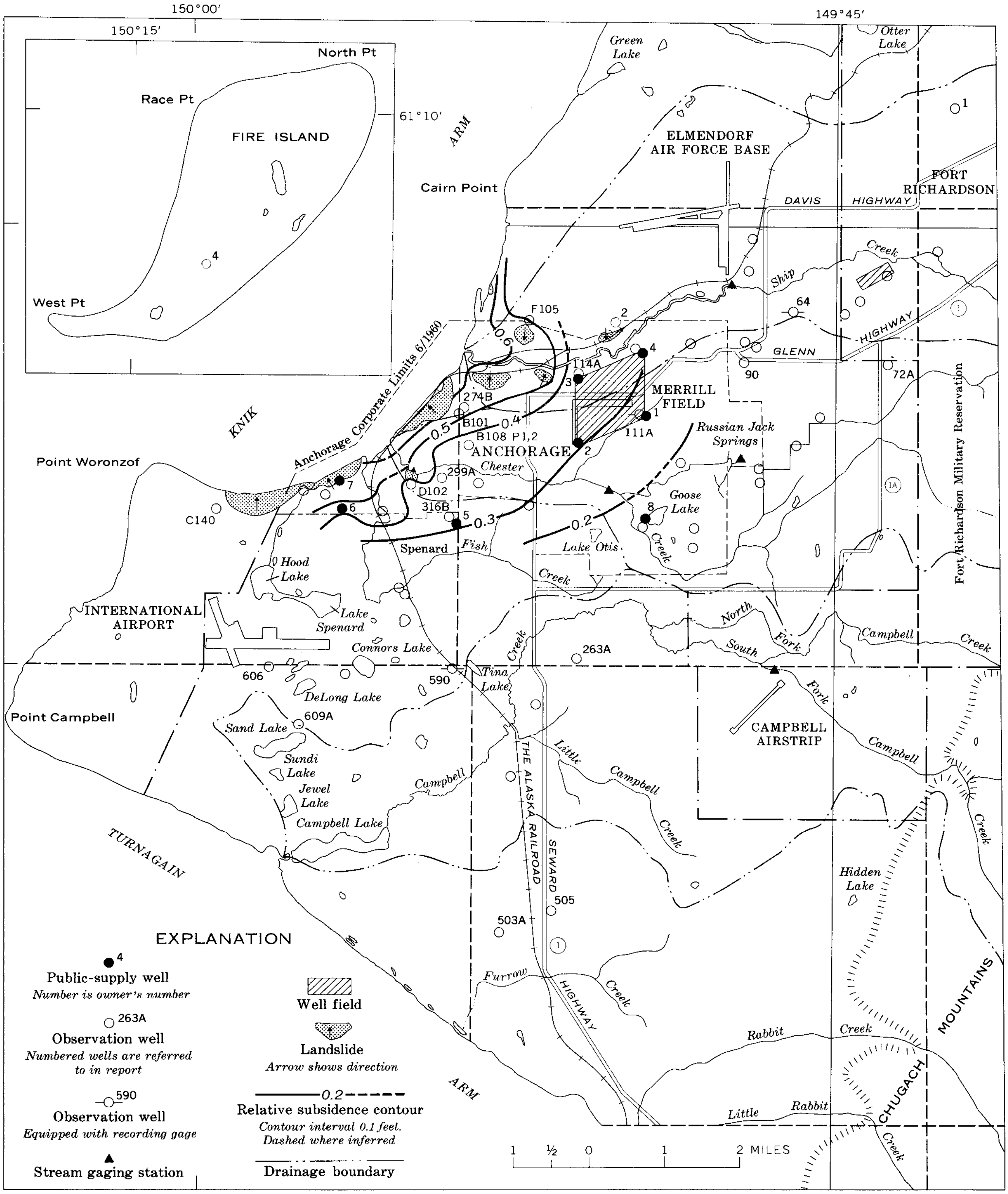
9.—Hydrographs of piezometer observations from June 1964 to May 1965. (See fig. 10 for location.)

slides is great. Dewatering is presumably desirable for engineering stability, but it may affect adversely the ground-water supply of the Anchorage area. If the formation is dewatered by pumping the sand and gravel aquifers beneath or within the clay to reduce water leakage into the clay, the problem of decreased piezometric level in the artesian system near the estuary would arise immediately. The result might be incursion of sea water into the aquifers. If, on the other hand, dewatering is restricted to the clay, the clay would become more stable and more impermeable, and dewatering might thus improve the capability of the clay to confine the artesian aquifers.

SUBSIDENCE

Subsidence of unconsolidated material by compaction during earthquakes has been reported from many previous earthquakes, notably the New Madrid earthquake of 1811 (Fuller, 1912). The Alaska earthquake of 1964 caused subsidence in many of the areas underlain by unconsolidated deposits in south-central Alaska (Grantz and others, 1964, p. 26). In the Anchorage area the land surface subsided 3.7 feet at the city dock according to tide-gage records (U.S. Coast and Geodetic Survey, 1964, 1965). This subsidence includes an unknown amount of tectonic subsidence of bedrock in the region, and probably local compaction as well. The tectonic subsidence is probably the larger factor.

Subsidence due to compaction of unconsolidated material is important because of its possible effect on the aquifer system. In order to determine whether compaction did take place in the Anchorage area, pre- and postearthquake-level data within the city



10.—Map showing relative subsidence, landslides, and well locations in Anchorage.

were obtained from the Anchorage Department of Public Works. These data were tied to the new U.S. Coast and Geodetic Survey tidal reference, and differential levels of some 70 bench marks were measured. Additional data on levels obtained from studies in the Turnagain area (Shannon and Wilson, Inc., 1964) suggested that compaction had indeed taken place. Well casings in the observation-well network also indicated minor compaction within the city area by the fact that after the quake many casings protruded farther above ground than they had earlier. The data (fig. 10) show that subsidence within the city limits was greatest along the shore bluffs behind the slides and was progressively less toward the east and south. The differential subsidence in this 2-mile zone parallel to Knik Arm ranges from 0.6 foot at the bluffs to 0.2 foot in the Lake Otis area. The direction of increasing subsidence of this zone is nearly opposite to the direction of regional tectonic subsidence (Plafker, 1965); thus the 0.6 foot of differential subsidence at the bluffs probably represents the minimum amount of compaction of the unconsolidated sediments underlying the city.

Compaction of unconsolidated deposits from seismic stresses can occur by the rearrangement of grains during lateral spreading of the deposit or during the shaking. Rearrangement at either time would very likely decrease the porosity and the permeability, and hence increase the piezometric gradient. However, inasmuch as water levels in the sand and gravel aquifers in the area of known compaction did not rise, compaction probably did not occur in the aquifers. Compaction of the clay part of the Bootlegger Cove Clay is also ruled out because its impermeability precludes instantaneous release of water during the earth movements. The only other types of material present that are capable of compaction are the silt and fine sand that occur as lenses and layers within the Bootlegger Cove Clay.

The parallelism of contour lines showing differential subsidence to the bluff line (fig. 10) suggests that the compaction occurred in the fine sand and silt lenses in the Bootlegger Cove Clay, including those associated with the landslides, and the slide investigations showed that liquefaction did take place in these lenses (Shannon and Wilson, Inc., 1964). According to Terzaghi's (1956) description of the process of compaction during liquefaction and slope failure, pore pressure is released and progressive liquefaction extends rapidly away from the point of release. Hence, perhaps the silt lenses within the Bootlegger Cove were progressively compacted behind and away from the slide areas. The gradual decrease in subsidence away from the bluffs, indicated by releveling, seems to support this postulation.

The general zonation and parallelism of the differential subsidence also correlate with the wedging out of the clay formation towards the east (Trainer and Waller, 1965). Differential compaction of the silt lenses throughout the formation could explain the decrease in subsidence to the east because the formation is thinner in that part of the area.

Differential subsidence may be caused by withdrawal of ground water from aquifers and the resulting leakage of water from clay deposits overlying the aquifers. The overall preearthquake lowering of artesian pressures, however, was only 3–5 feet between 1958 and 1964. Furthermore, the data on water levels indicate that the subsidence is not confined to the area of greatest ground-water withdrawals, so as yet there probably has been very little subsidence caused by pumping.

CONCLUSIONS

The Anchorage hydrologic system was materially affected by the seismic shock. Patterns of stream discharge were changed during the first months after the earthquake, but subsequently have not been affected either by the land subsidence of nearly 4 feet or by the lowered pressure head in the ground-water system. Permanent changes have resulted in an apparent increase in discharge from the ground-water system and a lowering of artesian pressure.

Water in the Bootlegger Cove Clay was the most important factor contributing to bluff failures along Knik Arm. Postearthquake piezometric data suggest that locally pore pressures are still high, but most are declining as expected. Land subsidence of 3.7 feet in the area probably occurred principally by tectonic readjustment and to a lesser degree by compaction of silt layers within the Bootlegger Cove Clay.

Ground-water supplies for municipal and private use were disrupted at first, and some long-term effects have been observed. Compaction appears to have affected water-saturated silt layers rather generally; this effect may mean that the total ground-water yield of the area will be reduced by a small amount. The concurrent lowering of the land and of the artesian pressure may have increased the possibility of sea-water encroachment into the aquifers. To date there has been no indication of such an encroachment on the mainland, but one Fire Island well that showed slowly increasing chloride concentrations before the earthquake now yields water in which chloride concentrations appear to be increasing at a much faster rate.

Dual use of surface and subsurface water supplies was proven a good insurance. Even though both sources were partially disrupted, together they provided a continuous supply of water.

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