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RICHARD D. REGER

THE ALASKA EARTHQUAKE, MARCH 27, 1964:
REGIONAL EFFECTS

Effects of the Earthquake Of March 27, 1964 In the Copper River Basin Area, Alaska

By OSCAR J. FERRIANS, JR.

A description and analysis of the earthquake-induced ground breakage, landsliding, regional uplift and subsidence, and damage to manmade structures in the Copper River Basin

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THE ALASKA EARTHQUAKE SERIES

The U.S. Geological Survey is publishing the results of its investigations of the Alaska earthquake of March 27, 1964, in a series of six professional papers. Professional Paper 543 describes the regional effects of the earthquake. In chapters of this volume already published, studies of slide-induced waves and seiching at Kenai Lake, geomorphic effects in the Martin-Bering Rivers area, gravity surveys of the Prince William Sound region, and effects of the earthquake on Kodiak and nearby islands have been reported.

Other professional papers in the series describe field investigations and reconstruction and the effects of the earthquake on communities, on the hydrologic regimen, and on transportation, utilities, and communications.

CONTENTS

	Page
Abstract	E1
Introduction and acknowledgments	2
Geographic setting	2
Physiography	2
Climate	3
Roads and settlements	3
Geologic setting	3
Bedrock	3
Major tectonic elements	3
Unconsolidated deposits	6
Permafrost and seasonal frost	6
The earthquake and its aftershocks	6
Seismic data	6
Ground motion	7
Sound	7
Geologic effects of the earthquake	E8
Regional uplift and subsidence	8
Changes in ground- and surface-water conditions	8
Ground water	8
Surface water	8
Cracking of lake and river ice	10
Ground cracks and associated landsliding	11
Terminology	11
General distribution	11
Geologic controls	11
Little Tonsina River site	13
Other landslide sites	13
Nelchina River outwash apron	17
Geologic effects—Continued	
Ground cracks and associated landsliding—Continued	
Nelchina River delta	E17
Origin	23
Lateral extension	23
Horizontal compaction	23
Differential vertical compaction	24
Snowslides, rockslides, and avalanches	24
Effects of the earthquake on manmade structures	25
Damage to buildings and associated structures	25
Damage to highways and bridges	25
References	27

ILLUSTRATIONS

FIGURES

	Page
1. Index map showing the location of the Copper River Basin area	E2
2. Generalized geologic map of the Copper River Basin area	4
3. Map showing major tectonic elements of south-central Alaska	5
4. Map showing recent regional uplift and subsidence in south-central Alaska	9
5. Aerial view of the northern end of Tonsina Lake	10
6. Aerial view showing intensely fractured ice along the eastern shore of Tazlina Lake	11
7. Map showing the distribution of ground cracks	12
8. Sketch map of the Little Tonsina River landslide site	14
9. View of pressure ridges on floor of Little Tonsina River valley	E14
10. Large ground crack paralleling north side of small hill near mile 65, Richardson Highway	15
11. Photograph of pressure ridge on flat surface bordering Little Tonsina River	15
12. Large ground crack formed in clearing along south shore of lake	16
13. Aerial view of the large braided flood plain of the Nelchina River	17
14. Photograph of typical ground crack in outwash apron of Nelchina River	18
15. Vertical aerial view of Nelchina River delta	19
16. Vertical aerial view of ground cracks along and paralleling hingeline on Nelchina River delta	20
17. Aerial view of north end of the large Nelchina River delta along the western shore of Tazlina Lake	E21
18. Aerial view of Kiana Creek delta along eastern shore of Tazlina Lake	21
19. Aerial view showing large inundated area along eastern shore of Tazlina Lake	22
20. Diagrammatic sections showing mechanism of formation of basic types of ground cracks	23
21. View of pavement surface of the Richardson Highway	26
22. Little Tonsina River bridge shoved from right to left by landslide movement	26
23. Small crack across abandoned section of road on a low gravel terrace	27

EFFECTS OF THE EARTHQUAKE OF MARCH 27, 1964, IN THE COPPER RIVER BASIN AREA, ALASKA

By Oscar J. Ferrians, Jr.

ABSTRACT

The Copper River Basin area is in south-central Alaska and covers 17,800 square miles. It includes most of the Copper River Basin and parts of the surrounding Alaska Range and the Talkeetna, Chugach, and Wrangell Mountains.

On March 27, 1964, shortly after 5:36 p.m. Alaska standard time, a great earthquake having a Richter magnitude of about 8.5 struck south-central Alaska. Computations by the U.S. Coast and Geodetic Survey place the epicenter of the main shock at lat 61.1° N. and long 147.7° W., and the hypocenter, or actual point of origin, from 20 to 50 kilometers below the surface. The epicenter is near the western shore of Unakwik Inlet in northern Prince William Sound; it is 30 miles from the closest point within the area of study and 180 miles from the farthest point.

Releveling data obtained in 1964 after the earthquake indicates that broad areas of south-central Alaska were warped by uplift and subsidence. The configuration of these areas generally parallels the trend of the major tectonic elements of the region. Presumably a large part of this change took place during and immediately after the 1964 earthquake.

The water level in several wells in the area lowered appreciably, and the water in many became turbid; generally, however, within a few days after the earthquake the water level returned to normal and the suspended sediment settled out. Newspaper reports that the Copper River was completely dammed and Tazlina Lake drained proved erroneous.

The ice on most lakes was cracked, especially around the margins of the lakes where floating ice broke free from the ice frozen to the shore. Ice on Tazlina, Klutina, and Tonsina Lakes was intensely fractured by waves generated by sublacustrine landslides off the fronts of deltas. These waves stranded large blocks of ice above water level along the shores. River ice was generally cracked in the southern half of the area and was locally cracked in the northern half.

In the area of study, the majority of the ground cracks occurred within a radius of 100 miles from the epicenter of the earthquake. Ground cracks formed in flood plains of rivers, in deltas, and along the toes of alluvial fans. They also occurred locally in low terraces adjacent to flood plains, in highway and other fill material, along the margins of lakes, along the faces of steep slopes of river bluffs and hillsides, and in areas cleared of vegetation for several years.

The ground cracks were restricted to areas underlain by unconsolidated deposits where one or more of the following conditions existed: (1) permafrost was absent or deep lying, (2) the ground-water table was near the surface, (3) bedrock was relatively deep lying, and (4) slopes were steep. Because the earthquake occurred in March, seasonal frost was present throughout the area.

Despite the diversity of local conditions, the origin of most of the ground cracks can be explained by the following mechanisms: (1) lateral extension, caused by materials moving toward an unconfined face such as a lakeshore, river bluff, hillside, or terrace escarpment; (2) horizontal compaction, caused by repeated alternate compression and dilation (in the horizontal direction) of materials in flat-lying areas where there are no unconfined faces; (3) differential vertical compaction, caused by the shaking of materials that vary laterally in thickness or character; and (4) combinations of the above.

Snowslides, avalanches, and rockslides were restricted to the mountainous areas surrounding the Copper River Basin. They were especially numerous in the Chugach Mountains which are closest to the epicenter of the earthquake. The large amount of snow and rock debris that has cascaded onto the icefield and glaciers of these mountains, and, probably even more important, the overall disturbance to the ice field will affect the regimen of the glaciers.

Most of the damage to manmade structures occurred in the southern half of the area, and, primarily because of the sparsity of population and manmade structures, property damage was not great and no lives were lost.

INTRODUCTION AND ACKNOWLEDGMENTS

The Copper River Basin area, as defined in this report, covers about 17,800 square miles in south-central Alaska (fig. 1); it includes most of the Copper River Basin and parts of the surrounding mountains.

1.—Location of Copper River Basin area.

Its boundary on the east is long 144°00′ W.; on the north, lat 63°-00′ N.; on the west, long 147°40′ W.; and on the south, approximately coincides with the axis of the Chugach Mountains.

The primary purpose of this investigation was to determine the effects of the great Alaska earthquake of 1964 in the Copper River Basin area and the geologic factors that tend to control the distribution and character of these effects. An understanding of these geologic factors is necessary to evaluate properly the engineering significance of the earthquake.

Because of the U.S. Geological Survey's geologic mapping of the Copper River Basin, in progress since 1952, the general distribution and character of unconsolidated deposits in the area are well known. Without this work, adequate evaluations of the effects of the earthquake would not have been possible during the short time available for field investigation.

Observations of the effects of the earthquake in the Copper River Basin were made between July 2 and July 23, 1964. During the 3¼-month interval between the occurrence of the earthquake and the time when observations were made, undoubtedly many earthquake-related features, especially subtle ones, were obliterated. Because of this time lag a large part of the discussion about earthquake damage to manmade structures is based on eyewitness accounts; however, most of the discussion concerning the natural earthquake-related features, as distinguished from damage to life and property, is based on the author's observations and on the study of postearthquake aerial photographs.

Since most of the people live near the highway, a systematic study along the roads provided fairly comprehensive coverage of damage to manmade structures. In the vast, inaccessible areas away from the highways, the distribution of earthquake-related features was determined by observation from light fixed-wing aircraft. At several sites where landings were possible, these features were examined on the ground.

I am greatly indebted to all of the individuals who provided eyewitness accounts of their experiences during and immediately after the earthquake. Rich Houston and Cleo McMahan, both bush pilots, not only did an excellent job of chauffeuring, but also contributed their own time and energy to making critical observations pertinent to this study. James B. Small of the U.S. Coast and Geodetic Survey provided releveling data, Robert M. Chapman of the U.S. Geological Survey made available an unpublished report which included his observations along the Richardson Highway made soon after the earthquake, and several individuals of the Alaska Department of Highways provided data concerning damage to the highways.

GEOGRAPHIC SETTING

PHYSIOGRAPHY

The Copper River Basin is bordered on the north by the Alaska Range, on the west by the Talkeetna Mountains, on the south by the Chugach Mountains, and on the east by the Wrangell Mountains.

The basin floor is a plain of low relief into which the major streams have cut steep-walled valleys as much as 400 feet deep. However, the bordering mountains are extremely rugged and they support numerous glaciers, which, along with their melt-water streams, have cut deep valleys opening into the basin.

The greater part of the area of study is drained by the Copper River, which originates from large glaciers on the northern side of the Wrangell Mountains. From its source the river flows in a large arc around the northern, western, and southwestern sides of the Wrangell Mountains, and then southward through the Chugach Mountains into the Gulf of Alaska. Major tributaries to the Copper River include the Chistochina, Sanford, Gakona, Gulkana, Tazlina, Klutina, Tonsina, and Chitina Rivers.

The northwestern corner of the area is drained by the Susitna River which originates from a large glacier in the Alaska Range. From its source this river drains southward to the Copper River Basin, then makes a sharp turn and flows westward through mountainous terrain to the north end of the Susitna Lowland; from here it flows southward to Cook Inlet. Within the area of study the major tributaries to the Susitna River are the Maclaren and Oshetna Rivers.

A small part of the southwestern corner of the area is drained by the Matanuska River which flows westward to Knik Arm of Knik Inlet.

The basin floor is dotted with lakes; the three largest are Lake Louise, Crosswind Lake, and Ewan Lake. Tazlina, Klutina, Tonsina, and Paxson Lakes are large water bodies occupying deep valleys in the mountainous areas surrounding the basin.

CLIMATE

The Copper River Basin area has an arctic continental weather regime with short warm summers and long cold winters. Mean annual temperature, as recorded at the Gulkana Federal Aviation Agency Station in the east-central part of the area of study, is 27°F., and mean annual precipitation is 12 inches. These climatic conditions are significant to this study because they are conducive to the formation and preservation of permafrost (perennially frozen ground)—and the presence or absence of permafrost is significant in relation to the distribution and character of earthquake effects.

ROADS AND SETTLEMENTS

Large segments of two major Alaska highways cross the Copper River Basin area. Both highways are paved two-lane roads which connect coastal cities in south-central Alaska with interior Alaska. The Glenn Highway, 314 miles long, extends from Anchorage to Tok Junction on the Alaska Highway; the Richardson Highway, 365 miles long, extends from the ice-free port of Valdez to Fairbanks. Locations along these highways are designated by the number of miles from the point of origin of the highway—along the Glenn Highway, miles from Anchorage, and along the Richardson Highway, miles from Valdez. Other roads within the area of study include the Edgerton Highway and the Lake Louise Road. The Edgerton Highway, a two-lane gravel road in the southeastern corner of the area, is 39 miles long and connects Chitina with the Richardson Highway. The Lake Louise Road, also a two-lane gravel road, leads north from mile 160, Glenn Highway, for approximately 19 miles to Lake Louise.

The settlements within the area are concentrated along or near the major highways. Glennallen, the principal settlement of the area, with a population of around 200 people, is near the junction of the Glenn and Richardson Highways. Other settlements include Chitina, Copper Center, Gulkana, Gakona, Chistochina, and Paxson. Several roadhouses and some service enterprises are located along the highway between these settlements.

GEOLOGIC SETTING

BEDROCK

Mountainous areas around the margin of the Copper River Basin and prominent hills within the basin are underlain by altered volcanics and interbedded graywacke and slate, and by virtually unaltered sediments, all of which have been intruded locally by a wide variety of igneous rocks. Extensive areas are underlain also by a considerable thickness of unaltered basaltic and andesitic lava. These rocks range in age from middle Paleozoic to Pleistocene. The distribution of bedrock within the area of study is shown on figure 2 (next page).

MAJOR TECTONIC ELEMENTS

There are six major tectonic elements within the area of study (fig. 3, p. 6). From north to south, they consist of the Alaska Range geosyncline, the Talkeenta geanticline, the Matanuska geosyncline, the Seldovia geanticline,

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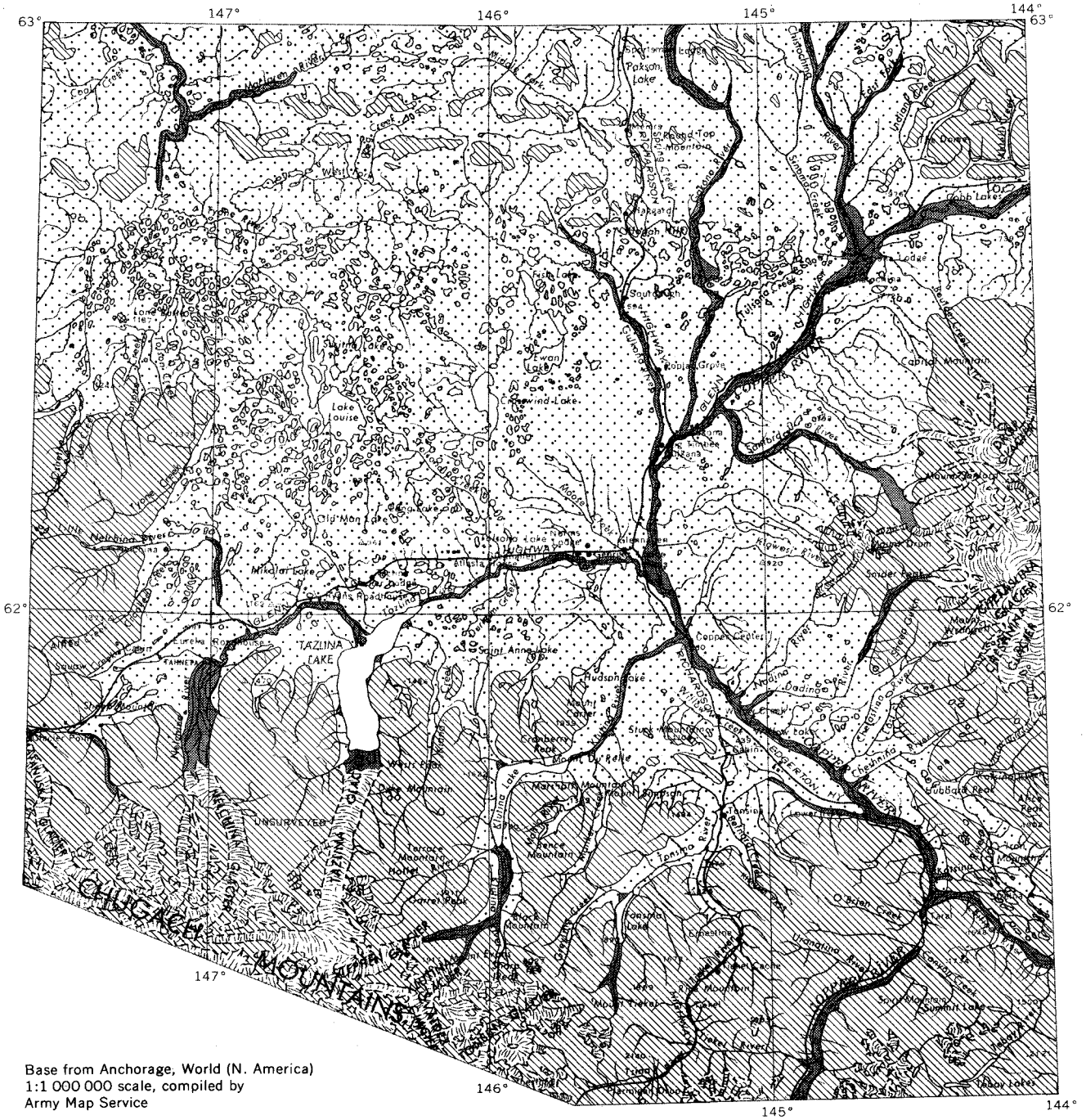


EXPLANATION

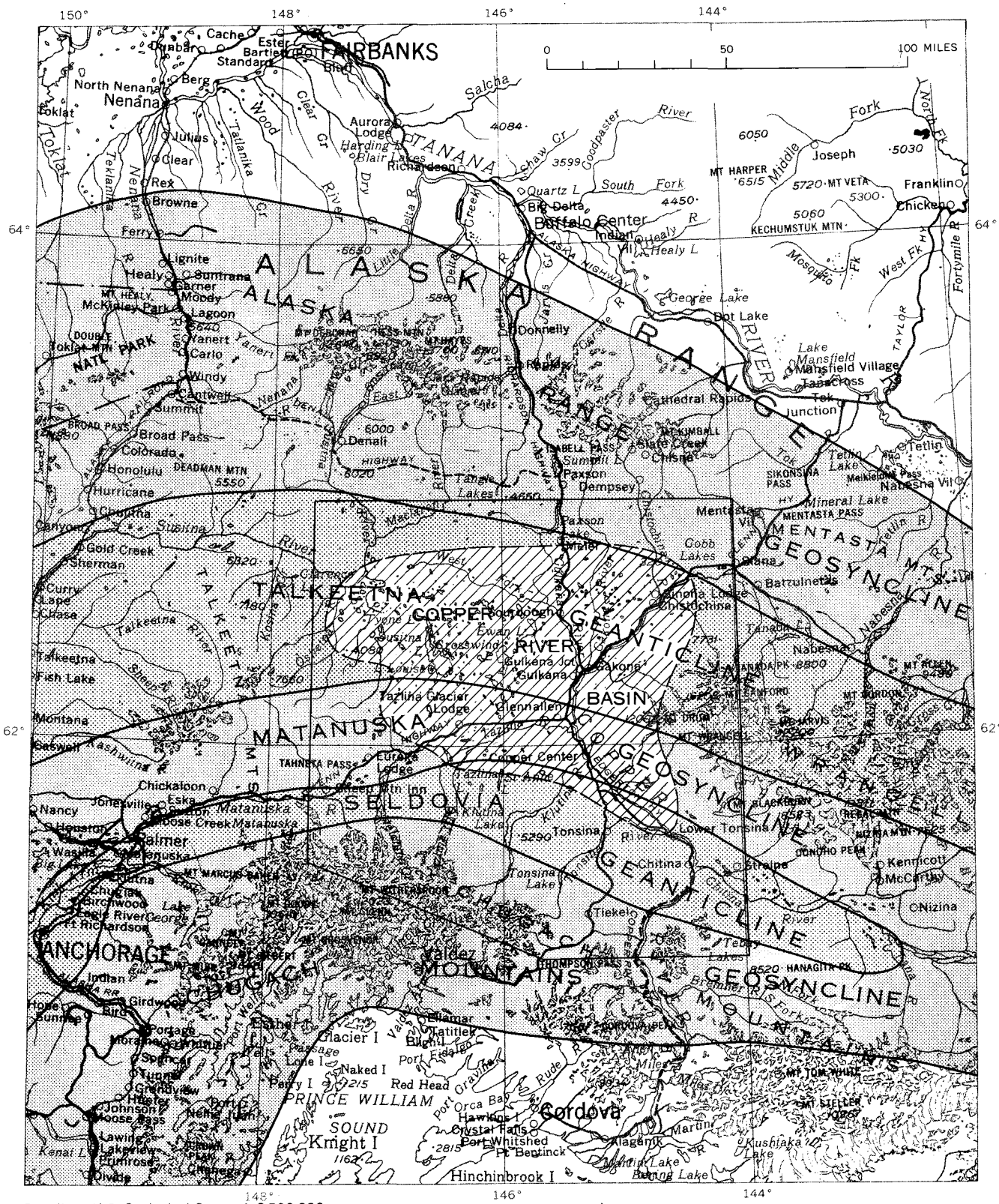
Coarse-grained unconsolidated deposits of Recent age

Fine- and coarse-grained unconsolidated deposits of Pleistocene age

Bedrock ranging in age from middle Paleozoic to Pleistocene

0 10 20 30 40 MILES

2.—Generalized geologic map of the Copper River Basin area. Geology compiled by Ferrians, Nichols, Williams, and Yehle; Grantz (pl. 23 in Andreason and others, 1964); and Coulter and Coulter (1962).


150°
148°
146°
144°
64°
62°
0
50
100 MILES
FAIRBANKS
Nenana
North Nenana
Cache
Ester
Fairbanks
Salcha
Tanana
Richardson
Aurora Lodge
Harding L
Blair Lakes
Julius
Clear
Rex
Browne
Ferry
Lignite
Healy
Suntrana
Carmer
Moody
Lagoon
Vanert
Carlo
Windy
Antwerp
Summit
Broad Pass
Colorado
Honolulu
Hurricane
Chulitna
Gold Creek
Sherman
Curry
Talkeetna
Fish Lake
Montana
Cantwell
Chickaloon
Eska
Palmer
Wasilla
Knik
Chugiak
Eagle River
Ft Richardson
ANCHORAGE
Girdwood
Portage
Moran
Spencer
Tunnel
Grandview
Hiller
Johnson
Moose Pass
Lawing
Lakeview
Primrose
Divide
Kenai L
Valdez
Glacier I
Naked I
Perry I
Red Head
PRINCE WILLIAM SOUND
Knight I
Hinchinbrook I
Cordova
Port Whitshed
Pt Bentinck
Port Gravina
Port Orca
Hawkins I
Crystal Falls
Alaganik
Martin L
Kushtaka Lake
Bering Lake
Miles L
Tatitlek
Port Fidalgo
Port Wells
Passage
Esther
Bligh I
Lone I
Tonsina
Lower Tonsina
Chitina
Tiekel
Strelna
Kennicott
McCarthy
Nizina
Glennallen
Gulkana
Paxson
Dempsey
Chistochina
Gakona
Tazlina Glacier
Lodge
Copper Center
Eureka Lodge
Tahneta Pass
Mt Wrangell Inn
Matanuska
Palmer
Nancy
Houston
Wasilla
Knik
Chugiak
Eagle River
Birchwood
Ft Richardson
Indian
Girdwood
Bird
Portage
Moran
Spencer
Tunnel
Grandview
Hiller
Johnson
Moose Pass
Lawing
Lakeview
Primrose
Divide
Kenai L
Cache
Ester
Bartlett
Standard
Blue
North Nenana
Berg
Toklat
Julius
Clear
Rex
Browne
Ferry
Lignite
Healy
Suntrana
Carmer
Moody
Lagoon
Vanert
Carlo
Windy
Antwerp
Summit
Broad Pass
Colorado
Honolulu
Hurricane
Chulitna
Gold Creek
Sherman
Curry
Talkeetna
Fish Lake
Montana
Cantwell
Chickaloon
Eska
Palmer
Wasilla
Knik
Chugiak
Eagle River
Birchwood
Ft Richardson
ANCHORAGE
Girdwood
Portage
Moran
Spencer
Tunnel
Grandview
Hiller
Johnson
Moose Pass
Lawing
Lakeview
Primrose
Divide
Kenai L
Valdez
Glacier I
Naked I
Perry I
Red Head
PRINCE WILLIAM SOUND
Knight I
Hinchinbrook I
Cordova
Port Whitshed
Pt Bentinck
Port Gravina
Port Orca
Hawkins I
Crystal Falls
Alaganik
Martin L
Kushtaka Lake
Bering Lake
Miles L
Tatitlek
Port Fidalgo
Port Wells
Passage
Esther
Bligh I
Lone I
Tonsina
Lower Tonsina
Chitina
Tiekel
Strelna
Kennicott
McCarthy
Nizina
Glennallen
Gulkana
Paxson
Dempsey
Chistochina
Gakona
Tazlina Glacier
Lodge
Copper Center
Eureka Lodge
Tahneta Pass
Mt Wrangell Inn
Matanuska
Palmer
Nancy
Houston
Wasilla
Knik
Chugiak
Eagle River
Birchwood
Ft Richardson
Indian
Girdwood
Bird

and the Chugach Mountains geosyncline (Payne and Dutro, in Miller, and others, 1959, pl. 2). In the central part of the area the Cenozoic Copper River Basin is superimposed on several of the other tectonic elements.

UNCONSOLIDATED DEPOSITS

In the mountainous areas surrounding the Copper River Basin the floors of the major valleys are underlain predominantly by unconsolidated sediments of Pleistocene and Recent age. These sediments are chiefly outwash gravel deposited by glacier-fed streams and till deposited by glaciers which formerly covered the valley floors. Locally, significant thicknesses of colluvial deposits are present.

The greater part of the basin itself is underlain by lacustrine, glacial, and fluvial sediments of Pleistocene and Recent age (Karlstrom and others, 1964). In the east-central part of the basin, these deposits are quite thick. The exact thickness is unknown; however, as much as 400 feet is well exposed in bluffs along the deeply entrenched rivers, and near Glennallen a water well 502 feet deep bottomed in unconsolidated deposits. In the western part and along the margin of the basin, these deposits generally overlie bedrock at relatively shallow depths. The distribution of unconsolidated deposits within the area of study is shown on figure 2.

PERMAFROST AND SEASONAL FROST

Permafrost and seasonal frost were important factors in determining the distribution and character of ground cracks and landslides. Most fine-grained unconsolidated deposits in the Copper River Basin are perennially frozen from 1 to 5 feet below the surface to depths of as much as 200 feet. In similar areas that have been cleared of vegetation for several years, such as those along the highway net or in settled areas, the permafrost table (top of permafrost) occurs from 10 to 20 feet below the surface. In contrast to the fine-grained deposits, the coarse-grained gravel deposits along the major streams generally are free of permafrost. Permafrost generally is also absent near large deep lakes because of the enormous amount of heat held in these large bodies of water. In the Chugach Mountains south of the basin, permafrost occurs as isolated masses where local conditions are favorable for its formation and preservation (Ferrians, 1965).

Seasonal frost generally penetrates to depths from 2 to 4 feet in poorly drained environments such as marshes; however, in well-drained environments such as gravel terraces, seasonal frost generally penetrates from 10 to 20 feet.

THE EARTHQUAKE AND ITS AFTERSHOCKS

SEISMIC DATA

Computations by the U.S. Coast and Geodetic Survey (1964, p. 30) placed the time of origin of the earthquake at shortly after 5:36 p.m. Alaska standard time, March 27, 1964, the epicenter at lat 61.05° N. and long 147.50° W., and the hypocenter, or actual point of origin, at about 20 kilometers (about 12½ miles) below the surface. Later computations, based on more data, place the epicenter at lat 61.5° N. and long 147.7° W. and the hypocenter at a depth between 20 and 50 kilometers. Estimates of the Richter magnitude of the earthquake, from four United States stations, range from 8.4 to 8¾ and place it among the historically great earthquakes.

The epicenter, which is near the west shore of Unakwit Inlet in northern Prince William Sound, is 30 miles from the closest point within the area of study and 180 miles from the farthest point.

During the first month after the main shock more than 7,500 aftershocks were recorded at the five seismograph stations that were installed in the epicentral area soon after the main shock occurred (Algermissen, 1965, p. 2). Press and Jackson (1965, p. 867) reported that approximately 12,000 aftershocks, having a magnitude equal to or greater than 3.5, occurred during a 69-day period after the main shock.

Press and Jackson (1965, p. 868)

estimated that a line distribution of 100 underground nuclear explosions, totalling 100 megatons each, would be necessary to equal the seismic energy released by the Alaska earthquake.

GROUND MOTION

The tremendous amount of energy released during the earthquake caused severe ground shaking throughout most of the southern half of the area of study. However, locally there was variation in the reported intensity and duration of shaking. Most observers reported that the ground motion lasted 3–5 minutes. Gutenberg (1956, 1957) demonstrated that within a small area the duration and intensity of ground shaking can vary considerably depending upon the character of the underlying materials. For example, water - saturated unconsolidated deposits will be affected more than similar unconsolidated deposits which are dry, and much more than hard crystalline bedrock.

From Glennallen southward and westward the ground motion generally was described as having either a jarring effect or a strong rolling effect on most dwellings, whereas north of Glennallen most people reported a gentle rolling effect, like swells on the ocean.

People reported seeing trees and telephone and power poles being whipped back and forth by the ground motion.

Many people reported seeing the ground undulate in waves like those generated on large bodies of water. Unfortunately, during a great earthquake it is difficult for individuals to make objective observations. However, one observer estimated that at the junction of the Glenn and Richardson Highways, 100 miles from the main epicenter, these waves were about 10 feet apart and about 3 feet high. Other reliable witnesses estimated that the ground waves near Slana, 165 miles from the main epicenter, were 50–60 feet apart and 18–20 inches high. All the witnesses stated that the waves moved from the southwest to the northeast.

Even though many individuals have reported visible ground waves during major earthquakes, especially in flat-lying areas underlain by water-saturated unconsolidated deposits, many seismologists discount such occurrences. One of the main reasons for this skepticism is that ground waves recorded on seismographs have crests and troughs too small to be seen, commonly no more than 0.004 inch for large surface waves and hardly ever more than 0.020 inch (Leet and Leet, 1964, p. 79); furthermore, practically all of these waves travel too fast to be seen. Other explanations used to discount the existence of visible ground waves include optical, physiological, and psychological illusions.

The opinion of Eiby (1957, p. 26) is typical of that of many seismologists. He presents arguments against the existence of visible ground waves and then states, "However, something of the kind has so often been reported in good faith that it must be supposed that the violent shaking so effects a man as to produce an illusion of this kind. With this demonstration of human fallibility it is as well to pass to the problem of instrumental recording."

In spite of the difficulty of explaining the origin of such phenomena, many workers have concluded that visible ground waves do exist. These include Dutton (1890, p. 267–268), Oldham (1899, p. 4–41), the State Earthquake Investigation Commission (1908, v. 1, p. 380–381), Knott (1908, p. 18), Fuller (1912, p. 57), Imamura (1937, p. 75), and India Geological Survey Officers and Roy (1939, p. 29–30).

In a more recent publication, Richter (1958, p. 132) concludes that there is almost certainly a real phenomenon of visible progressing or standing waves on soft ground, but he thinks the effect may be associated with earth lurching, with which it may be confused. The phenomenon of visible ground waves obviously poses a perplexing problem that needs further study, but the evidence in the Copper River basin area tends to fortify the conclusion that visible ground waves do exist.

SOUND

A few people heard sounds which presumably were associated with the earthquake. Generally the sound was described as a rumbling or roaring like distant thunder. This type of phenomenon has occurred during many other great earthquakes. Thompson (1929) and Kingdon-Ward (1951, p. 130, and 1953, p. 172) have described unusually loud sounds heard during two such earthquakes.

Even though there is some disagreement on certain points, the perception of sound is fairly well explained by seismologists: the sound waves are produced directly by the transfer of elastic wave energy from the ground to the air (Richter, 1958, p. 128).

Some earthquakes have transferred enough energy to the air that sensitive barographs several hundred miles from the epicenter were affected. Gutenberg and Benioff (1939) first described this effect.

GEOLOGIC EFFECTS OF THE EARTHQUAKE

REGIONAL UPLIFT AND SUBSIDENCE

During the summer of 1964 the U.S. Coast and Geodetic Survey completed aproximately 900 miles of first-order leveling in Alaska areas affected by the earthquake. About 680 miles of this was releveling of previously established first-order leveling. Releveling was accomplished between Seward and Anchorage via The Alaska Railroad, between Anchorage and Glennallen via the Glenn Highway, and between Valdez and a point 15 miles southeast of Fairbanks via the Richardson Highway.

A large part of the resurveyed net was first leveled in 1922 and 1923; new stations were established and others releveled along parts of this net in 1943, 1944, and 1952. Examination of these data suggests that there have been minor changes in altitude prior to 1964; however, a large part of the change determined by the 1964 releveling must have occurred during and immediately after the earthquake. Changes in altitude of some stations, all on unconsolidated deposits, were obviously anomalous and undoubtedly represented changes caused by local phenomena such as frost heaving, slumping, or thawing of permafrost. These changes in altitude were not considered in evaluating regional uplift and subsidence.

Recent regional changes in altitude in south-central Alaska are shown in figure 4, compiled primarily from releveling data supplemented with data from Grantz, Plafker, and Kachadoorian (1964, p. 4). Because of the lack of control points, the location of the isobase lines are only approximate. In spite of the sparsity of control points, it is obvious that a broad area, including a large segment of the Chugach Mountains, part of the Talkeetna Mountains, most of the Copper River Basin, and the Cook Inlet Lowland, did subside, and that large areas to the south and north of the subsided area were uplifted. The subsided area forms an arcuate trough sloping gently to the west and to the southwest. The maximum determined amount of subsidence was about 6 feet near Portage. The available data indicate that the uplifted area north of the trough forms a gentle arch having a maximum determined uplift of almost 1 foot. Uplift to the south of the trough was much greater and was reported to be at least 33 feet on land (Plafker, 1965, p. 1679).

The fact that the configuration of the subsided and uplifted areas generally parallels the trend of the major elements of the region (see fig. 3) suggests a genetic relationship. The southern two-thirds of the area of study is within the eastern part of the trough, and the northern one-third of the area covers a part of the southern edge of the uplifted arch north of the trough (fig. 4).

CHANGES IN GROUND- AND SURFACE-WATER CONDITIONS

GROUND WATER

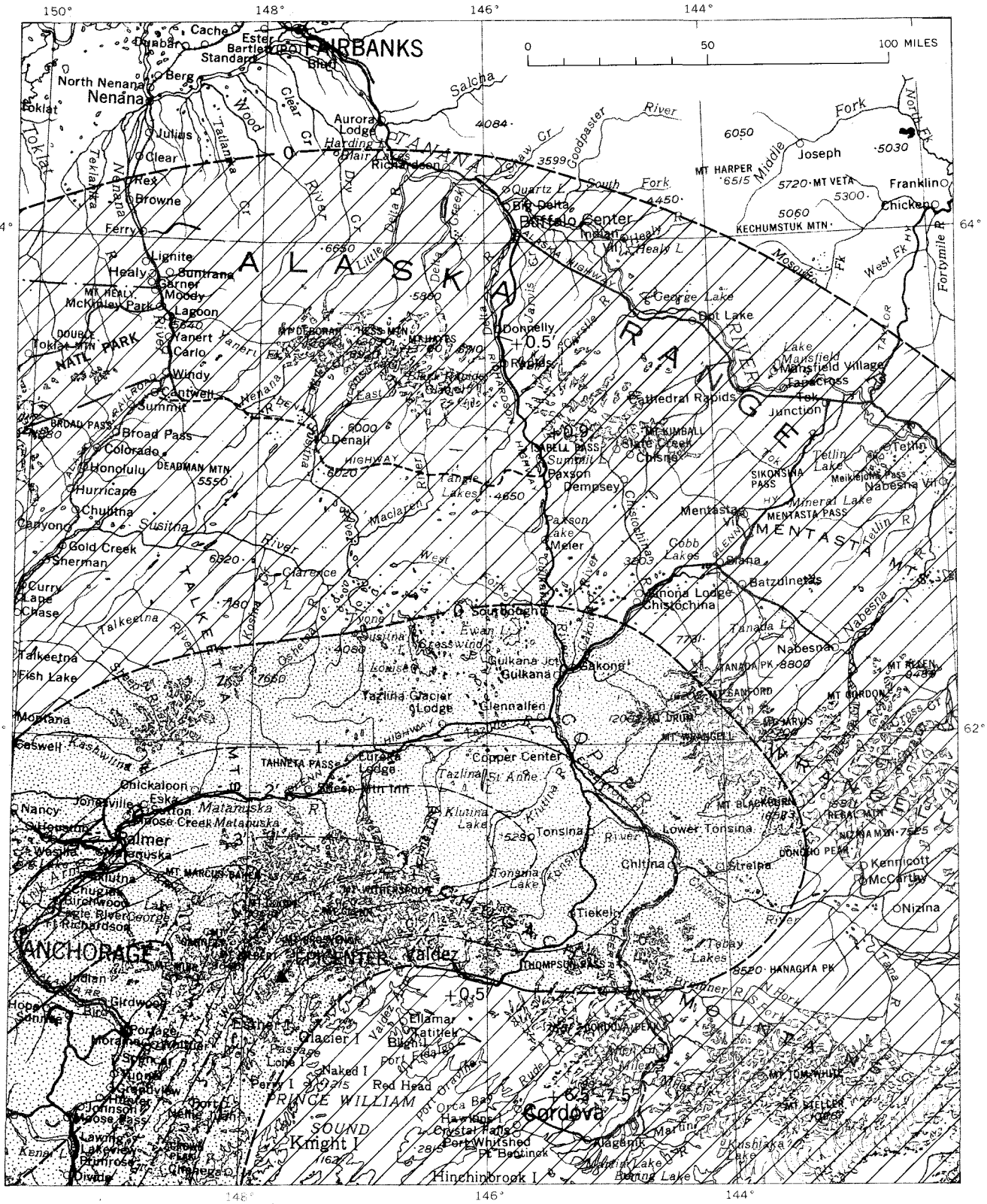
The water level in several wells in the area lowered appreciably, and the water from many wells became turbid. Generally within a few days after the earthquake, the water level returned to normal and the suspended sediment settled out. Three wells in the Glennallen area were reported to have gone dry after the earthquake.

Water from a spring on the north side of the Glenn Highway near mile 140 was reported to have been turbid and salty to the taste after the earthquake, but within a few days the condition of the water returned to normal.

Ground water near the surface caused an increase in the intensity and duration of ground motion which, in turn, caused ground breakage. In many areas the ground water, along with fine-grained sediments, was ejected to the surface through cracks and was sprayed into the air. These phenomena are called "earthquake fountains" and have been reported in many areas during major earthquakes, for example: the Charleston earthquake of 1886 (Dutton, 1904, p. 296–298); the California earthquake of 1906 (State Earthquake Investigation Commission, 1908, p. 402–404); the Pleasant Valley, Nev., earthquake of 1915 (Jones, 1915, p. 196); the Japanese earthquake of 1923 (Imamura, 1937, p. 74); the Bihar-Nepal earthquake of 1934 (India Geological Survey officers and Roy, 1939, p. 33–34, 185–187); and the Alaska earthquake of 1958 (Davis and Sanders, 1960, p. 248–250).

SURFACE WATER

Soon after the earthquake, newspapers reported that the Copper River was dry in its lower reaches and that Tazlina Lake had


150°
148°
146°
144°
64°
62°
0
50
100 MILES
FAIRBANKS
Nenana
North Nenana
Cache
Ester
Bartlett
Standard
Berg
Julius
Clear
Rex
Browne
Ferry
Lignite
Healy
Suntrana
Garner
Moody
Lagoon
Yanert
Carlo
Windy
Cantwell
Summit
Broad Pass
Colorado
Honolulu
Hurricane
Chulitna
Gold Creek
Sherman
Curry
Chase
Talkeetna
Fish Lake
Montana
Caswell
Chickaloon
Nancy
Palmer
Wasilla
Chugiak
Eagle River
Richardson
ANCHORAGE
Girdwood
Portage
Whittier
Cordova
Valdez
Glennallen
Copper Center
Gulkana
Paxson
Meiers
Chistochina
Batzulnetas
Nabesna
Tonsina
Chitina
Strelna
Kennicott
McCarthy
Nizina
Tiekel
Aurora Lodge
Richardson
Buffalo Center
Big Delta
Donnelly
Delta
Healy
Denali
Tanana
Clearwater
Tok Junction
Mentasta Vil
Tetlin
Nabesna Vil
Tazlina Glacier Lodge
Kluti Kaah
Lower Tonsina
Knight I
Hinchinbrook I
Hawkins I
Port Whitshed
Pt Bentinck
Naked I
Red Head
Perry I
Glacier I
Ellamar
Tatitlek
Bligh I
Esther I
Lone I
Port Fidalgo
Port Orca
Crystal Falls
Port Gravina
Port Chalmers
Port Ashton
Port Wells
Port Fidalgo
Port Nellie Juan
Port Bainbridge
Port Dick
Port Fidalgo
Port Ashton
Port Wells
Port Gravina
Port Chalmers

5.—View, to the northeast, of the northern end of Tonsina Lake showing intensely fractured ice and large blocks of ice stranded above water level along the shore. The lake is about half a mile wide at this point. Photograph by U.S. Army, April 8, 1964.

drained. Examinations by personnel of the U.S. Geological Survey and the Alaska Department of Highways, several days after the earthquake, produced no evidence that the Copper River was, or had been, completely dammed. Water was flowing in the main channels of the Copper River and the water in Tazlina Lake was near its normal level for that time of the year.

Large waves were generated on Tazlina, Klutina, and Tonsina Lakes by sublacustrine landslides off the fronts of deltas. These waves stranded large blocks of ice above water level along the shores (fig. 5), and at the outlet of Tazlina Lake, sediment and large blocks of ice were carried over the rapids and a short distance down the Tazlina River.

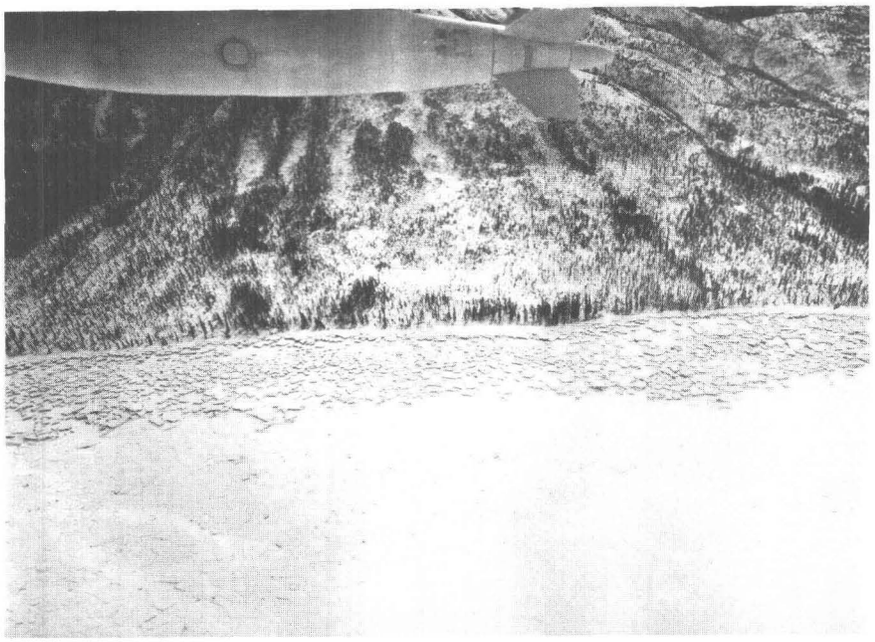
A large snowslide near mile 50, Richardson Highway, dammed the Tiekel River, and ice jams near miles 74 and 78.5, Richardson Highway, dammed the Tonsina River. In both places, explosives were used to blast channels through the obstructions to prevent the river from flooding the highway.

CRACKING OF LAKE AND RIVER ICE

The earthquake caused the ice on most lakes to crack, especially around the margins of the lakes where the floating ice broke free from the ice frozen to the shore. In addition to the breakage along the shores of the lakes, a few linear cracks commonly formed at a tangent to the shorelines. In many places these linear cracks extended completely across the lakes.

Tazlina, Klutina, and Tonsina Lakes were major exceptions to this general pattern. Ice on Klutina Lake and Tonsina Lake was highly fractured throughout (fig. 5). On Tazlina Lake the ice on the northern half of the lake was highly fractured (fig. 6), but ice on the southern half was fractured only around the margin, and a few linear cracks were formed across the lake. The greater intensity of the cracking of ice on these lakes was caused by water waves generated by sublacustrine landsliding off the fronts of large deltas built out into the lakes.

River ice cracked locally throughout the area of investigation. At several places along the Nelchina, Sanford, and Copper Rivers the cracks formed a systematic reticulate pattern, easily recognized on aerial photographs.



6.—View, to the east, showing intensely fractured ice along the eastern shore of Tazlina Lake, across from the large Nelchina River delta. Large blocks of ice stranded above water level along the shore are easily discernible, but the intense fracturing of ice away from the shore is obscured by the refreezing of the lake water and by a postearthquake snowfall. The segment of shoreline shown in this photograph is about half a mile long. Photograph by U.S. Army, April 8, 1964.

GROUND CRACKS AND ASSOCIATED LANDSLIDING

TERMINOLOGY

The terminology for ground cracks caused by earthquakes has been inconsistently used in the literature. The terms "fissure," "fracture," "furrow," and "ground crack" have been used more or less synonymously. However, on the basis of priority the terms "fissure" and "fracture" should be reserved for two types of ground cracks of different origin. Oldham (1899, p. 86) proposed the use of the term "fissure" for ground cracks formed by forces acting at the surface, and the term "fracture" for ground cracks formed by forces acting at depth, such as movement along a buried fault. In many places it would obviously be difficult to distinguish between the two types of ground cracks. For this reason and because of other inherent difficulties with this classification, I have used the general term "ground crack" which has no specific generic connotation.

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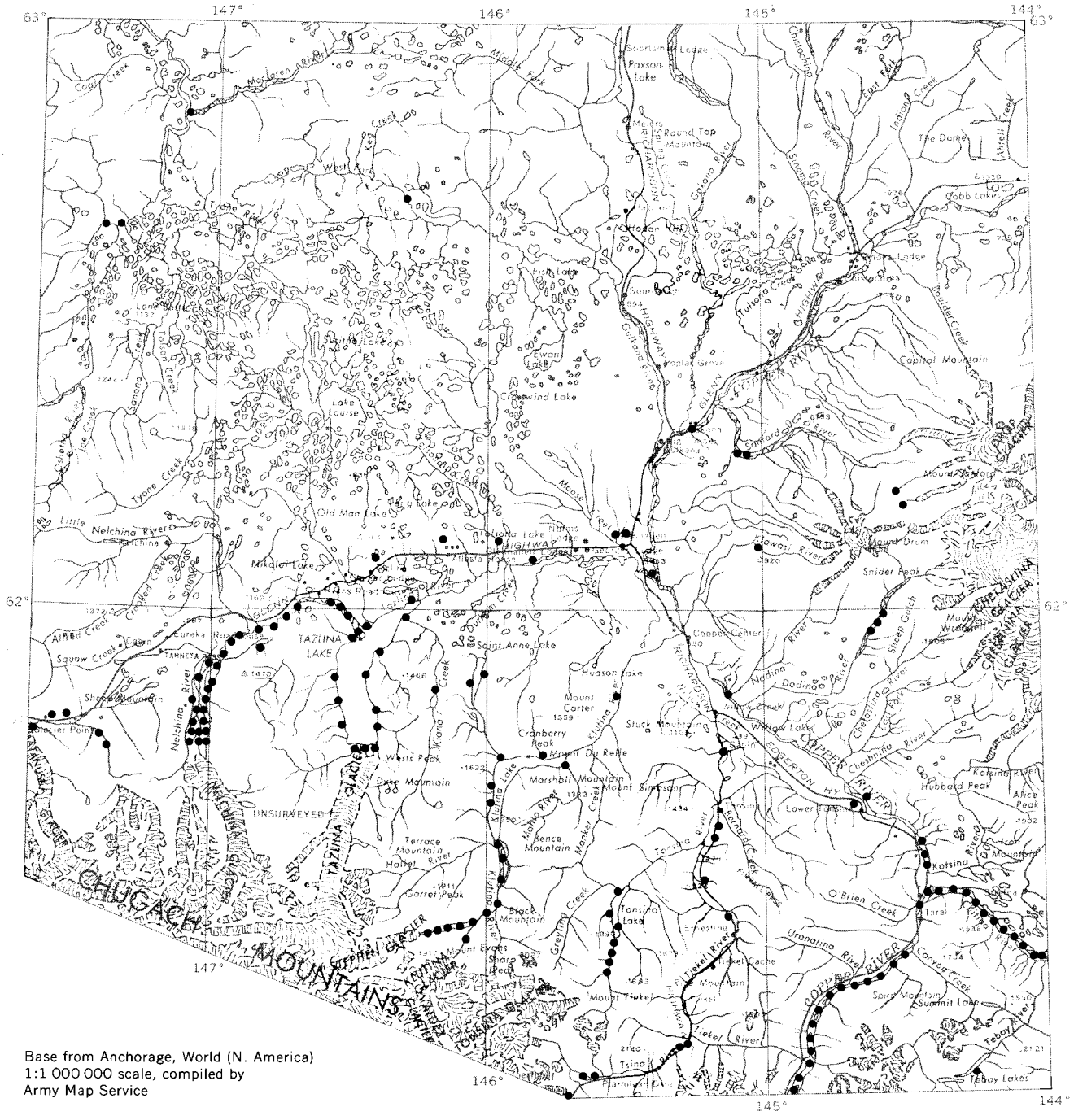
GENERAL DISTRIBUTION

In the area of study, the majority of the ground cracks occurred within a radius of 100 miles from the epicenter of the earthquake. Ground cracks formed in the flood plains of rivers, in deltas, and along the toes of alluvial fans. They also occurred locally in low terraces adjacent to flood plains, in highway and other fill material, along the margins of lakes, along the face of steep slopes of river bluffs and hillsides, and in areas cleared of vegetation.

The overall distribution pattern of ground cracks within the area of study indicates that the cracks were not localized in regional linear zones (fig. 7), and thus suggests that they were not caused by fault movement in bedrock beneath the unconsolidated deposits. Rather, the distribution pattern indicates that local geologic factors controlled the distribution of the cracks. Nevertheless, the possibility that fault movement at depth did cause ground cracks to form locally can not be definitely eliminated.

GEOLOGIC CONTROLS

The ground cracks were restricted to areas underlain by unconsolidated deposits (see fig. 2) where one or more of the following conditions existed: (1) permafrost was absent or deep lying, (2) the ground-water table was near the surface, (3) bedrock was relatively deep lying, and (4) slopes were steep. Because the earthquake occurred in March, there


63°
147°
146°
145°
144°
62°
Paxson Lake
Round Top Mountain
The Dome
Gobb Lake
Capitol Mountain
Lake Louise
Tyone Creek
Little Nelchina River
Nelchina River
Middle Lake
Old Man Lake
Alfred Creek
Squaw Creek
Eureka Roadhouse
TAHNETA
TAZLINA LAKE
Saint Anne Lake
Hudson Lake
Mount Carter
Cranberry Peak
Mount Du Relle
Marshall Mountain
Mount Simpson
Wests Peak
Dave Mountain
UNSURVEYED
Terrace Mountain
Hatter River
Garret Peak
Bence Mountain
Black Mountain
Mount Evans
Sharp Peak
Tonsina Lake
Mount Tiekel
Tiekel River
Tsina
Harmina Lake
Copper Center
Willow Lake
Lower Tonsina
Kotsina
O'Brien Creek
Uranalina River
Conroy Creek
Spirit Mountain
Summit Lake
Tebay River
Tebay Lakes
Hubbard Peak
Alice Peak
Snider Peak
Mount Drum
Mount Wrangell
Sheep Gulch
Chetaslina River
Dadina River
Nadina River
Lowell River
Chistochina River
Indian Creek
Sinona Creek
Gulkana River
Gulkana Glacier
Moore Creek
Moderna Creek
Coal Creek
Tyone River
Ice Creek
Sanona Creek
Crawford Creek
Sheep Mountain
Nelchina Glacier
Tazlina Glacier
Chugach Mountains
Copper River
Copper River Highway
Richardson Highway
Glenn Highway
Alaska Highway
Chistochina Glacier
Chetaslina Glacier
Klutina Glacier
Klutina River
Tiekel River
Tonsina River
Bernard Creek
Greyling Creek
Marker Creek
Mahna River
Klutina Lake
Tebay Glacier
Copper Glacier
Sheep Creek
Chistochina Lodge
Sourdough Lodge
Gulkana Glacier Lodge
Sportsman's Lodge
Meiers Spring Lodge
Tolsona Lodge
Tolsona River
Tuhona Creek
Boulder Creek
Moore Creek
Lake Louise
Crosswind Lake
Fish Lake
Lewis Lake
Long Lake
Sanona Creek
Tyone River
Nelchina River
Squaw Creek
Eureka Roadhouse
Sheep Mountain
Nelchina Glacier
Tazlina Glacier
Chugach Mountains
Copper River
Copper River Highway
Richardson Highway
Glenn Highway
Alaska Highway
Chistochina Glacier
Chetaslina Glacier
Klutina Glacier
Klutina River
Tiekel River

was a variable thickness of seasonal frost throughout the area.

Most ground cracks occurred in coarse-grained unconsolidated deposits, but some occurred in fine-grained deposits, generally in proximity to steep slopes, along the shores of lakes, or in areas cleared of vegetation for several years. Where well-drained unconsolidated deposits were thin, overlying bedrock at shallow depths, grounds cracks generally did not form.

Permafrost which extends from near the surface to depths as great as 200 feet is widespread in the Copper River Basin area, but generally was absent in areas underlain by coarse-grained deposits in which ground cracks formed (see figs. 2, 7). Permafrost generally was absent also near large deep lakes, and consequently, ground cracks occurred locally along the shores. In areas where ground cracks formed in fine-grained deposits, the impervious permafrost table generally was from 10 to 20 feet below the surface; in flat-lying areas this situation permitted a water-saturated zone to exist between the permafrost table and the base of the seasonal frost at the surface.

The effect of permafrost on the distribution of ground cracks becomes apparent if one considers that a thick layer of ice-rich permafrost behaves more like bedrock than like unconsolidated deposits and that, according to Gutenberg (1956, 1957), the intensity and duration of ground motion at the same distance from the epicenter may be 10 times as great in water-saturated unconsolidated deposits as in crystalline bedrock. Naturally, other conditions being equal, ground breakage will be most severe in areas receiving the greatest intensity of ground motion for the longest period of time.

When the earthquake occurred in the latter part of March, seasonal frost, which was near its annual maximum penetration, formed a thin, brittle layer extending from the surface of the ground to variable depths, depending upon local conditions. The ground motion, where it was intense, broke this brittle layer, and thereby formed the ground cracks. At many places along slopes (unconfined faces), the seasonal frost probably prevented ground breakage, whereas in flat-lying areas underlain by permafrost-free water-saturated materials, the seasonal frost facilitated ground breakage.

In most areas where severe ground breakage occurred, the ground-water table was no more than 15 feet from the surface, and generally just a few feet. In some places, large concentrations of vadose water were perched on top of the impervious permafrost. In areas where the ground-water table was within a few feet of the surface, permafrost generally was absent; in areas where vadose water was perched on top of permafrost, the permafrost table was relatively deep lying. Under both conditions the unconsolidated deposits beneath the seasonal frost were saturated with water, and consequently, were subjected to greater intensity and duration of ground motion than unconsolidated deposits perennially frozen or those not saturated with water.

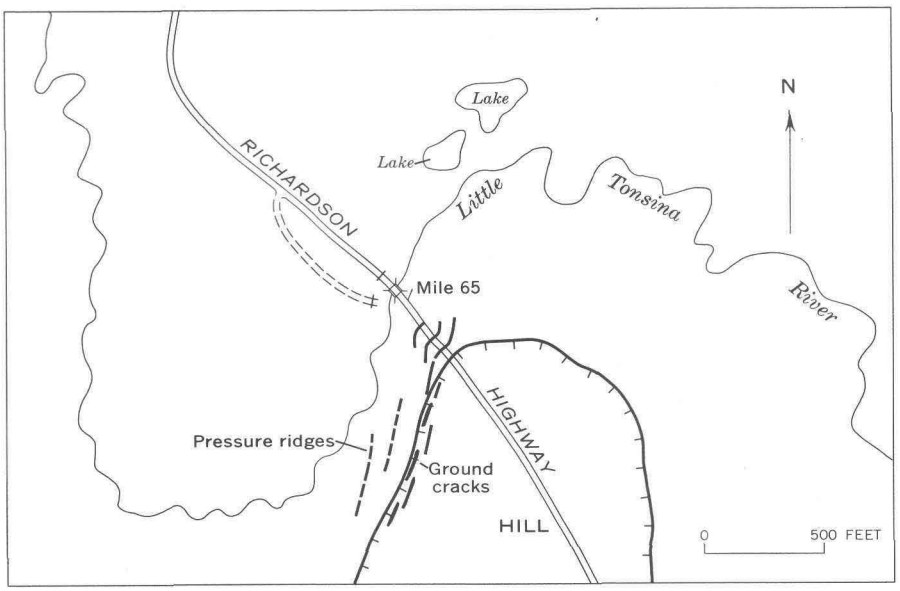
In many parts of the area, ground cracks formed on or near a steep slope, which provided an unconfined face for the lateral extension of materials. These ground cracks generally paralleled the slope and occurred either on the face of the slope or behind it. Landforms with relatively steep slopes, along which ground cracks occurred, include hillsides, lakeshores, river bluffs, and terrace escarpments.

LITTLE TONSINA RIVER SITE

The Little Tonsina River landslide site (fig. 8, next page) is in the southern part of the area, on the southwestern side of the Richardson Highway at mile 65. Landsliding occurred along the northwestern side of a small hill underlain by unconsolidated silt, sand, and gravel deposits. Lateral movement of segments of the hill toward the northwest caused several large ground cracks to form on and parallel to the face of the hill and pressure ridges to develop on the floor of the Little Tonsina River valley (fig. 9). One of the large ground cracks formed by the lateral extension of materials toward an unconfined face (hillside) is shown in figure 10, and a pressure ridge developed in front of the slide area is shown in figure 11. The horizontal forces that formed the ridge were transmitted through a layer of seasonally frozen peat and silty sand, approximately 2 feet thick, overlying water-saturated silty sand. Locally, water-saturated silty sand was ejected to the surface through cracks in the seasonally frozen layer.

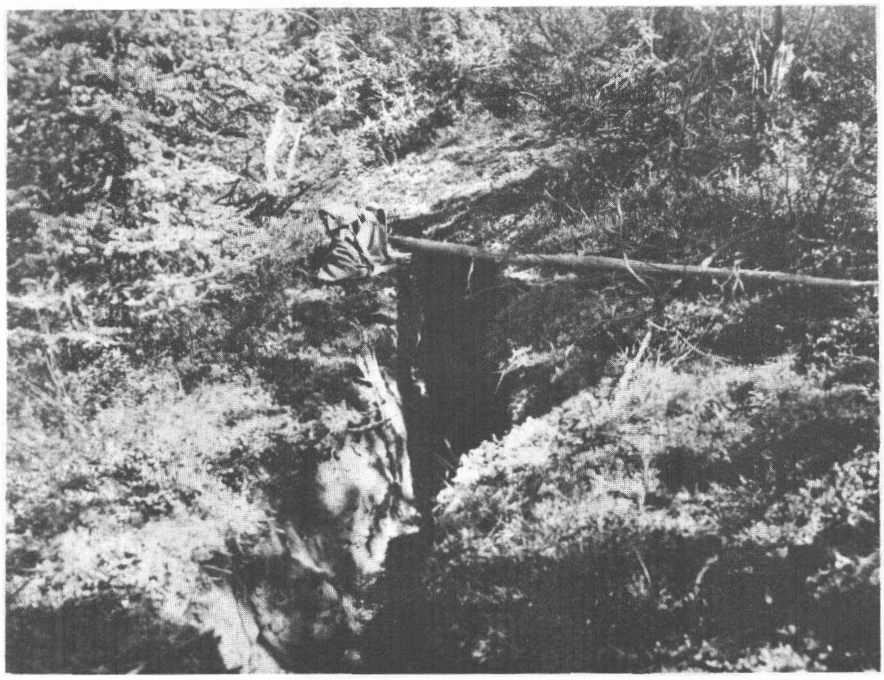
OTHER LANDSLIDE SITES

Other landslides include a large one at the mouth of Klutina Lake which caused the Klutina River to be diverted, several small ones along bluffs of the major rivers of the area, and numerous small slides marginal to lakes (see fig. 7). Ground cracks formed along margins of lakes by lateral movement of materials. An example is shown in figure 12 (p. 16).

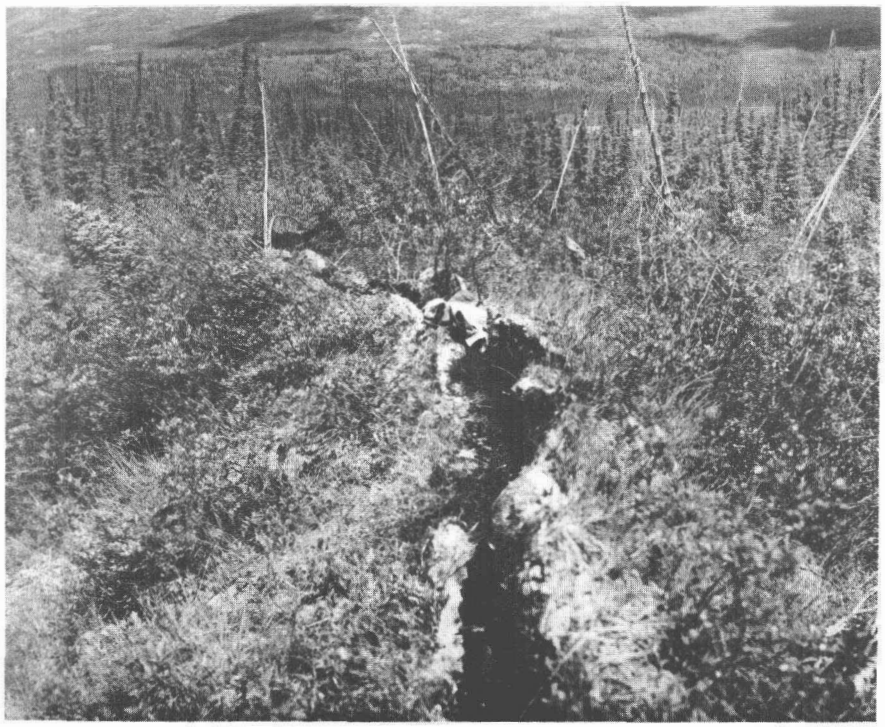


8. Sketch map of the Little Tonsina River landslide site.

9.—View, to the northwest, showing pressure ridges on floor of Little Tonsina River valley near mile 65, Richardson Highway; pressure ridges (indicated by arrows) caused by landsliding on face of hill.

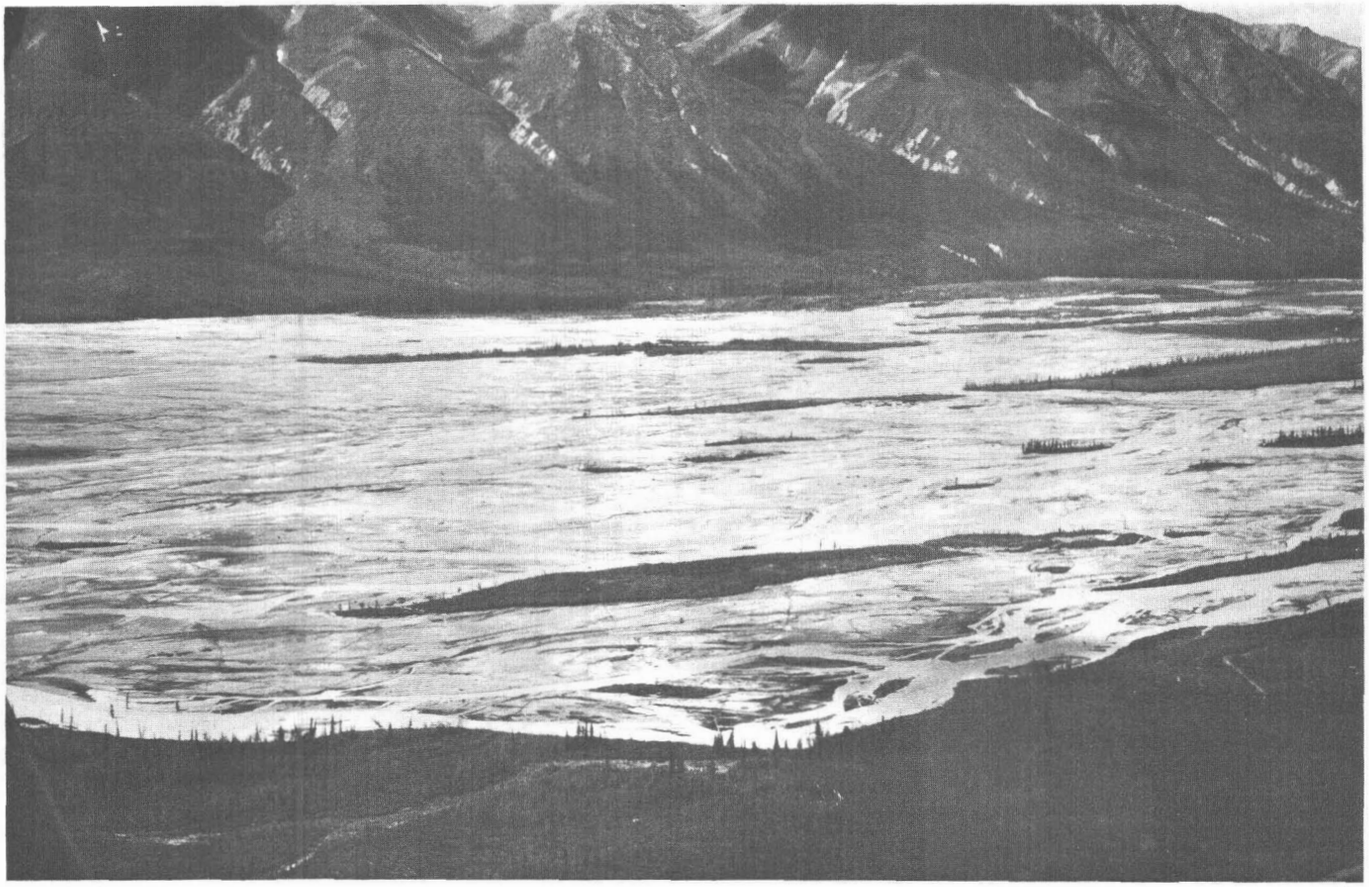


10.—One of several large ground cracks paralleling northwest side of small hill near mile 65, Richardson Highway. Crack, formed in fine- to medium-grained sand, has maximum width of 3 feet and depth of about 5 feet. The lateral extension of materials down the side of the hill caused the ground cracks and also caused pressure ridges to form on level ground several hundred feet in front of the base of hill.



11.—Pressure ridge, 6 feet high, on flat surface bordering Little Tonsina River near mile 65, Richardson Highway. Crest of ridge broken irregularly by upward flexing of frozen peat caused by landsliding on a nearby hillside.

12.—Large ground crack formed in clearing along south shore of lake about two-tenths of a mile north of mile 158, Glenn Highway. Maximum width of crack is 4 feet and depth is 6 feet. This ground crack is one of several that generally parallel the lakeshore.



13.—View, to the east, of the large braided flood plain of the Nelchina River 8 miles north of the terminus of the Nelchina Glacier.

NELCHINA RIVER OUTWASH APRON

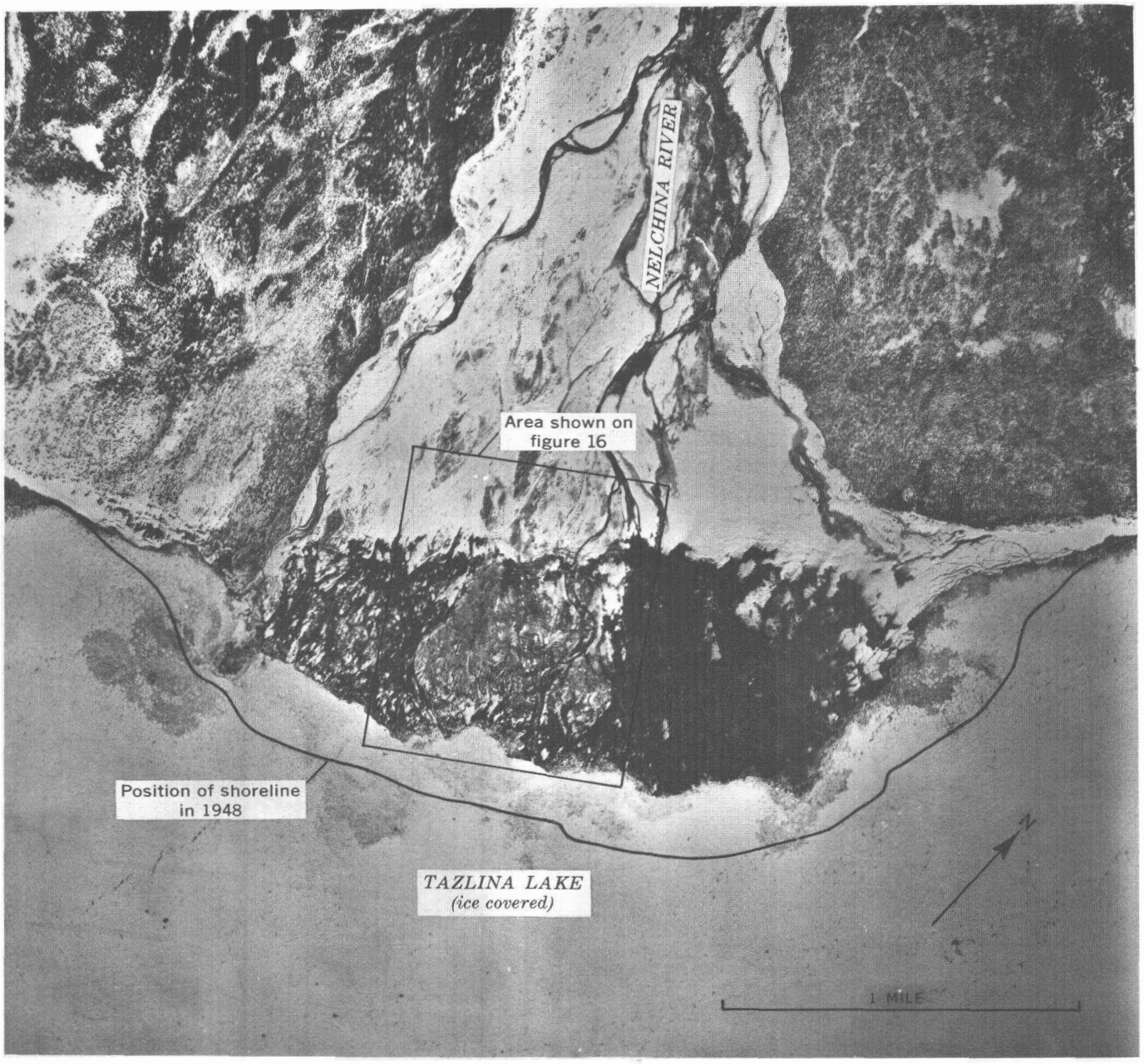
The Nelchina River outwash apron, in the southwestern part of the area, is underlain by silty sand and gravel, is approximately 10 miles in length, and averages about 2 miles in width (fig. 13). The unvegetated parts of this outwash apron were literally crisscrossed with ground cracks that generally ranged from 1 to 2 feet in width and extended for great distances across the flood plain (fig. 14, next page). Measurement of the rather systematic reticulate pattern of ground breakage at several points suggested a preferred orientation of N. 35° W. and N. 50° E. Silty sand, locally including pebbles, and large quantities of water were ejected from many of the cracks during the earthquake. One of the most significant characteristics of this site was the absence of any unconfined face toward which the materials could move, and consequently, form ground cracks. An explanation for the origin of ground cracks in such flat-lying areas is given below on page E23.

Extensive ground breakage, similar to that in the Nelchina River outwash apron, also occurred in the flood plains of the lower parts of the Chitina and Copper Rivers, and, locally, in flood plains of other streams (see fig. 7).

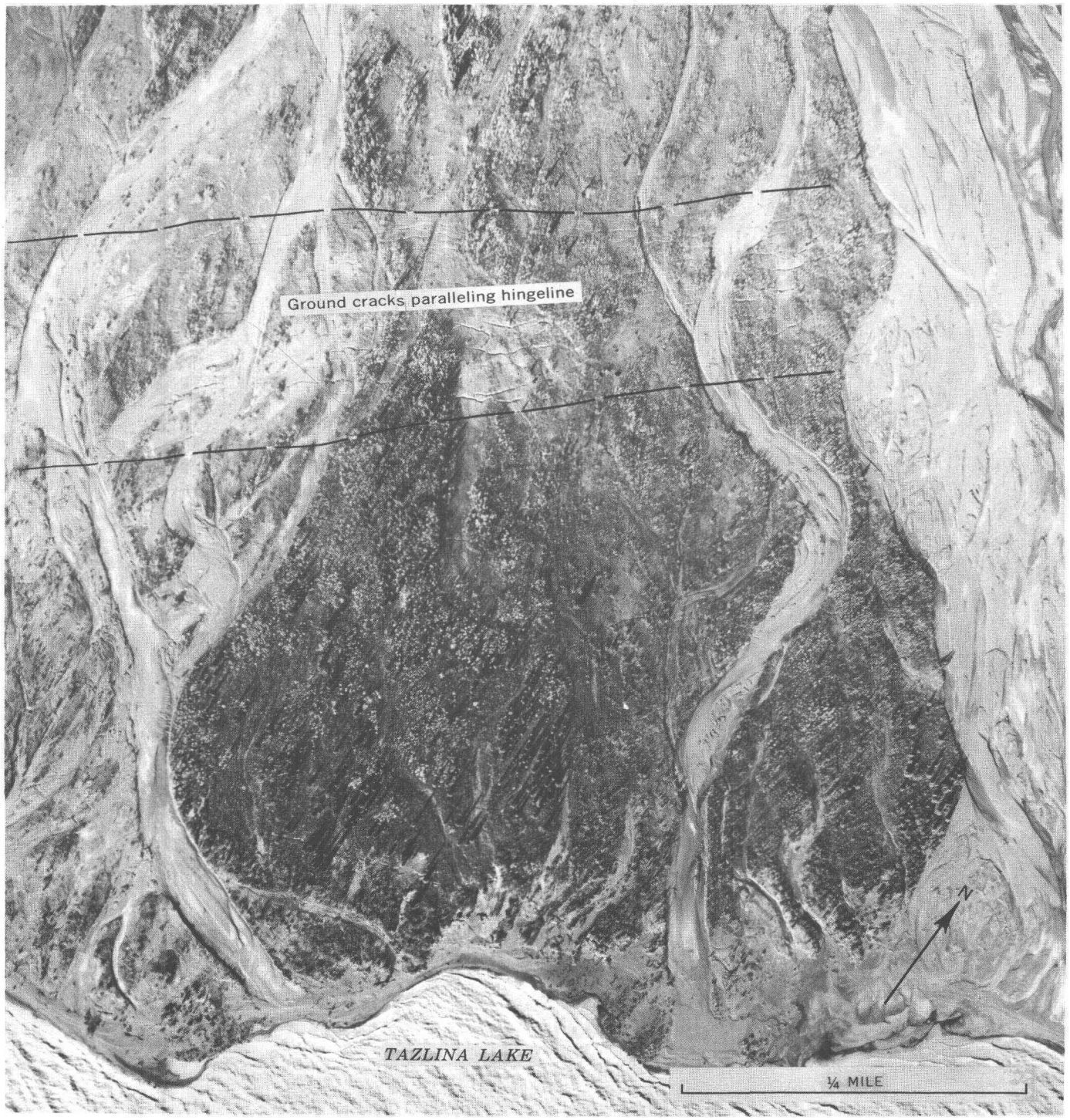
NELCHINA RIVER DELTA

The Nelchina River delta (figs. 15–17, p. 19–21) is along the northwestern side of Tazlina Lake in the southwestern part of the area. The delta is approximately 2½ miles wide at its widest point and generally is underlain by silty sand and gravel. Undoubtedly, finer grained deltaic deposits are present at depth. All of these deposits are free of permafrost, and the ground-water table is within a few feet of the surface. Extensive ground breakage in the delta included a concentration of cracks along, and generally parallel to, a hingeline that crossed the delta. This hingeline is conspicuous in figure 15 because most of the snow cover on the downslope side has been removed by water and sediment ejected from ground cracks. Figure 16 shows ground cracks in the central part of the hingeline, and figure 17 shows cracks at the northern end of the delta.

14.—Typical ground crack in outwash apron of Nelchina River 2 miles north of terminus of Nelchina Glacier; crack about 2 feet wide at widest point. Note how crack was deflected slightly in crossing swale in foreground. Standing water in swale marks the shallow ground-water table. Dark line behind man is trace of intersecting crack.



15.—The Nelchina River delta. Hingeline across the delta is conspicuous because most of the snow has been removed from the downslope side by water and sediment ejected from ground cracks. The position and character of the water-delta interface or shoreline in 1948 compared with the postearthquake shoreline indicate that large segments of the delta front slid into the lake. Photograph by U.S. Coast and Geodetic Survey, April 10, 1964.



16.—Ground cracks along and paralleling hingeline on Nelchina River delta. Photograph by U.S. Geological Survey, October 1964.

17.—North end of the large Nelchina River delta along the western shore of Tazlina Lake. Note the reticulate pattern of ground cracks which are as much as 6 feet wide.

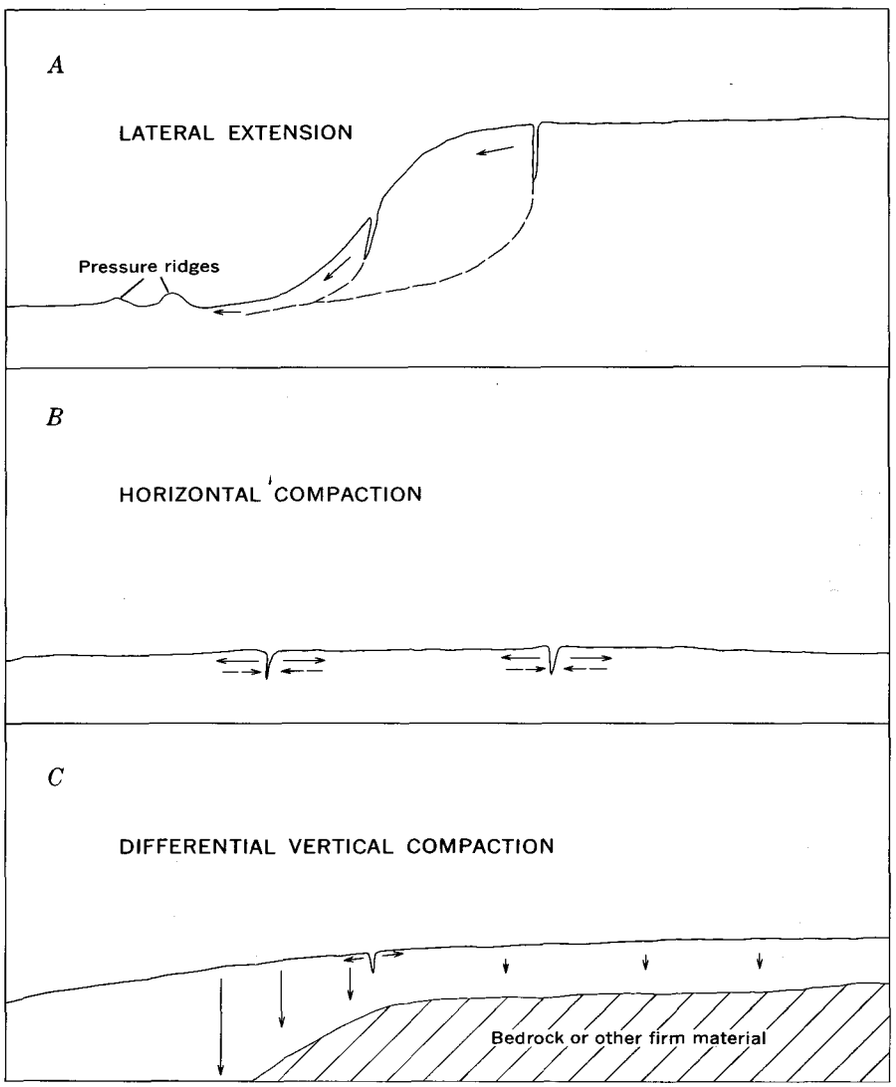
18.—View showing flooding of Kiana Creek delta along eastern shore of Tazlina Lake.

The available evidence suggests that the delta surface subsided—the greatest amount of subsidence occurring at the front of the delta and progressively lesser amounts upslope from the front. This differential subsidence resulted in a broad cambering of the delta surface which caused the concentration of tension cracks along the hingeline.

The position and character of the water-delta interface in 1948 as compared with the position and scalloped character of the post-earthquake interface (see fig. 15) indicate that not only was there subsidence but that large segments of the delta front slid into the lake. This sublacustrine landsliding generated large waves that severely fractured the ice on the northern part of the lake and stranded large blocks of ice above water level along the shore. Large quantities of sediment and ice were discharged through the outlet of the lake into the channel of Tazlina River. Similar sublacustrine landsliding occurred off the fronts of deltas in Klutina Lake and in Tonsina Lake.

The flooded delta of Kiana Creek along the eastern shore of Tazlina Lake is shown in figure 18. Subsidence, probably caused by compaction of unconsolidated sediments, and lateral movement of materials toward the lakeshore caused flooding of the delta and the formation of numerous ground cracks. A large area along the eastern shore of Tazlina Lake just south of the Kiana Creek delta was inundated (fig. 19). This area, which is part of an old alluvial-fan delta of Kiana Creek formed when the creek was a much larger stream, was subjected to changes similar to those that occurred at the Kiana Creek delta.

19.—Large inundated area along eastern shore of Tazlina Lake just south of the Kiana Creek delta. Lateral movement and vertical compaction of materials along lakeshore caused numerous ground cracks to form and the area to subside. Note normal beach (indicated by arrow) in the distance.



20.—Diagrammatic sections showing mechanism of formation of basic types of ground cracks in unconsolidated deposits in the Copper River Basin area.

ORIGIN

As already explained, the ground cracks within the area of study were formed in unconsolidated deposits under a variety of geologic conditions. Despite this diversity of local conditions, the origin of most of the ground cracks can be explained by the following mechanisms: (1) lateral extension, caused by materials moving toward an unconfined face such as a lakeshore, river bluff, hillside, or terrace escarpment; (2) horizontal compaction, caused by repeated alternate compression and dilation (in the horizontal direction) of materials in flat-lying areas where there are no unconfined faces; (3) differential vertical compaction, caused by the shaking of materials that vary laterally in thickness or character; and (4) combinations of the above. Figure 20 shows the mechanism of formation of the three basic types of ground cracks.

LATERAL EXTENSION

Lateral-extension ground cracks occurred on and behind relatively steep slopes (fig. 20, section *A*). These steep slopes provided an unconfined face toward which materials moved laterally, and in some places the movement was great enough to be considered landsliding. Generally the cracks formed parallel to the slope or unconfined face.

HORIZONTAL COMPACTION

The term "horizontal compaction" is used in this report for the earthquake-induced mechanism that causes unconsolidated materials to lose volume in the horizon-

tal direction, and consequently, causes ground cracks to form (fig. 20, section *B*). In flat-lying areas where there are no unconfined faces toward which the materials can move laterally, the very presence of numerous ground cracks, that extend for great distances indicates that the materials have lost volume in the horizontal direction.

In March when the earthquake occurred, seasonal frost had penetrated the surficial materials to a depth of several feet and formed a hard brittle surface layer. Because of the extremely cold weather in the area, the frozen surficial materials were in a state of tension. This frozen layer probably was initially cracked by ground waves flexing the surface.

The earthquake-induced ground waves must have subjected the water-saturated sediments beneath the seasonal frost to repeated alternate compression and dilation in the horizontal direction, the net result of these forces being horizontal compaction. Large quantities of water and silt- and sand-sized material were ejected from the cracks, and sediment particles were rearranged so that they occupied less space. The high mobility of the fine-grained materials ejected from the cracks suggests that they were liquefied spontaneously by the ground motion. Terzaghi (1950, p. 100) describes spontaneous liquefaction as the transformation of fine sand or coarse silt into a liquid state.

Similar mechanisms of formation have been postulated for earthquake-induced ground cracks in South Carolina (Dutton, 1889, p. 267–268), in India (Oldham, 1899, p. 88–92), in south-central United States (Fuller, 1912, p. 57), and in Japan (Imamura, 1937, p. 75).

DIFFERENTIAL VERTICAL COMPACTION

Without detailed data it is difficult to determine the degree to which differential vertical compaction contributed to the formation of ground cracks throughout the area; nevertheless, in certain areas this mechanism appears to have been dominant in their formation.

In a typical bedrock-confined valley underlain by unconsolidated deposits, the materials are much thinner along the margins of the valley wall than in the center of the valley. Where this condition exists and where the deposits are susceptible to vertical compaction, the materials in the center of the valley subside more than the materials along the valley walls because they are thicker. Consequently, ground cracks form generally near and parallel to the valley wall. Ground cracks such as these were observed along the eastern margin of the outwash apron of Tazlina Glacier and locally along the eastern margin of the outwash apron of Nelchina Glacier. Lateral variation in the texture and in void ratios of the unconsolidated deposits also can cause differential compaction.

The broad cambering of the surface of the Nelchina River delta (fig. 15) and the concentration of ground cracks along and parallel to the hingeline (fig. 16) can be explained by differential vertical compaction caused by lateral variation in the thickness of unconsolidated deposits.

The wedge-shaped body of deltaic deposits was laid down over the lip of a valley wall, and the thicker deposits toward the front of the delta were compacted more than those toward the apex. The hingeline formed above and parallel to the lip of the buried valley wall—under conditions similar to those depicted in figure 20, section *C*.

SNOWSLIDES, ROCKSLIDES, AND AVALANCHES

Within the area, snowslides, rockslides, and avalanches were restricted to the mountains surrounding the Copper River Basin. They were especially numerous in the Chugach Mountains which are closest to the epicenter of the earthquake. Many glaciers emanate from an extensive icefield in the higher reaches of these rugged mountains.

The remoteness of this vast mountainous region made it impractical to make a comprehensive study of the slides. However, reconnaissance flights over the area, reports of slides along the Richardson Highway where it crosses the Chugach Mountains, and study of postearthquake aerial photographs of the area indicate that slide activity was much greater than that in past years when no earthquakes occurred.

The large amount of snow and rock debris that has cascaded onto the icefield and glaciers, and, probably even more important, the overall disturbance to the icefield will affect the regimen of the glaciers emanating from it. According to Tarr and Martin (1912, p. 51–61), several glaciers in the Yakutat area advanced abnormally after the Yakutat earthquake of 1899 because of earthquake-induced changes in the regimen of the glaciers. If their hypothesis is true, it is not unreasonable to expect that some of the glaciers in the Chugach Mountains will advance an abnormal amount within the next few years.

EFFECTS OF THE EARTHQUAKE ON MANMADE STRUCTURES

DAMAGE TO BUILDINGS AND ASSOCIATED STRUCTURES

The greatest amount of damage to buildings, which were mostly of wood-frame or log construction, occurred within the southern half of the area, primarily because of proximity to the epicenter of the earthquake. Within this part of the area, breakage of fragile items inside buildings was widespread. However, major structural damage to buildings was restricted to localities where the intensity and duration of ground motion was greatest.

The following descriptions of damage to buildings and associated structures at various sites within the area were selected to give a representative picture of the range of damage:

Sheep Mountain Inn, at mile 113, Glenn Highway, is on the toe of an alluvial fan at the base of Sheep Mountain. Several ground cracks, oriented in a general east-west direction and paralleling the toe of the fan, formed in the cleared area where the buildings were located. The ground movement caused severe damage to underground pipes, a small cabin was shaken off its foundation, and other buildings shifted position. A diesel engine was shaken off a concrete slab to which it was bolted.

Tazlina Glacier Lodge, at mile 156, Glenn Highway, had only minor damage. There was considerable breakage inside, however, and most loose objects shifted position.

Lee's Guide Service, a short distance north of the Glenn Highway at mile 158, was severly damaged. Several large crescent-shaped ground cracks formed in a cleared area adjacent and parallel to a lake. This area is underlain by gravelly silt. A small building was partly submerged in water when the ground upon which it was erected moved laterally toward the lake. When the ground cracks opened, water was ejected to the surface and flowed down the gentle slope to the lake.

Glennallen, whose center is at mile 186, Glenn Highway, near the southern junction of the Glenn and Richardson Highways, is the largest community in the area. Breakage of fragile items inside buildings was widespread, but structural damage to buildings generally was not severe.

A 5-unit motel, a barracks-type building, and a trailer house were shaken off their foundations. The foundation of the elementary school building also was severely damaged. Several relatively small ground cracks formed in cleared areas and locally damaged structures. At the Copper Valley Electric Co. station, damage to the plant foundation, flooring, and equipment caused a power disruption for a little more than 4 hours while repairs were being made and generating equipment was being checked. The Glennallen Road Camp of the Alaska Department of Highways, the largest installation in Glennallen, sustained damage to underground sewers, steam and water lines, well casings, windows, and a boiler.

Gulkana Airfield, at mile 120, Richardson Highway, received only minor damage, even to fragile items inside buildings. A few small cracks formed in a paved runway and in roads, and a water pipe broke under one house.

Chistochina Lodge, at mile 238, Glenn Highway, had no significant damage; even glasses on a shelf did not tip over.

Tsina Lodge, at mile 34.5, Richardson Highway, in the southern part of the area of study had no major structural damage. However, a few fragile items inside the building were broken, and many loose items were moved.

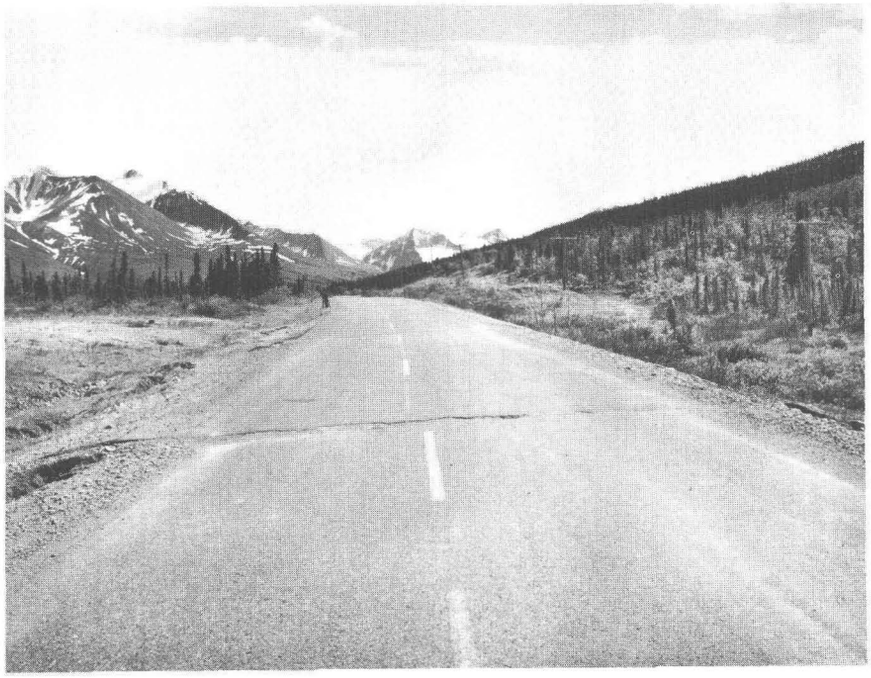
Tonsina Lodge, at mile 79, Richardson Highway, had minor structural damage; a fireplace and 2 chimneys were cracked severely, windows were broken, walls cracked, and some differential settlement occurred. Numerous fragile items inside the building were broken.

DAMAGE TO HIGHWAYS AND BRIDGES

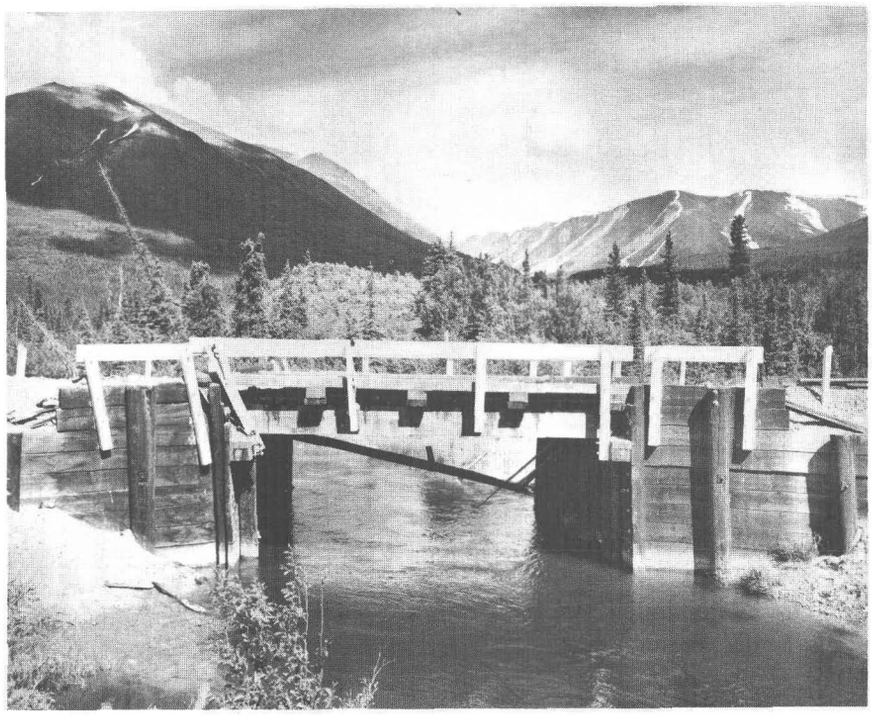
Along the Glenn Highway from the Matanuska Glacier at the western edge of the area of study to the junction of the Glenn and Richardson Highways near Glennallen, several small cracks formed in the pavement, and at a few places minor slumping of roadcuts occurred. The majority of these cracks were less than 6 inches wide, and no major differential movement took place. From the junction north along the Glenn Highway, only a few small cracks formed in the pavement—none that required major repair.

No damage was reported along the Lake Louise Road which extends from about mile 160 on the Glenn Highway to the southern end of Lake Louise, a distance of 19 miles.

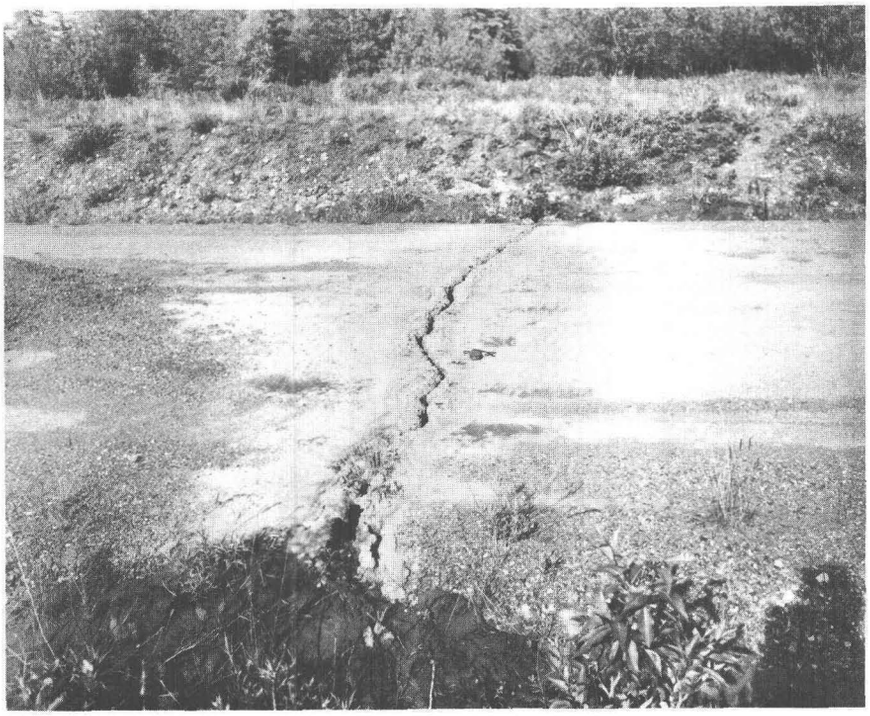
Along the Richardson Highway, however, serious road damage occurred at several places between mile 27 near the southern edge of the area of study and mile 91 near the junction of the Richardson and Edgerton Highways. A large crack formed in the roadway at mile 28 near Worthington Glacier, and severe road damage occurred along a 22-mile segment between mile 64, 1 mile south of the Little Tonsina River bridge, and mile 86 near the Rock Creek bridge. Cracks as wide as 8 inches formed in the pavement, and 30- to 50-foot segments of the roadbed were moved differentially (fig. 21). This differential movement was caused by landsliding which occurred in unconsolidated deposits on steep slopes near the highway. The Little Tonsina River bridge also was damaged primarily by this landsliding (fig. 22). At mile 79.8 the slump of a long segment of the roadbed on a sidehill cut restricted vehicles to one-way traffic. At mile 86.1 just north of Rock Creek a small crack formed in an abandoned section of road, and therefore, the feature was well preserved. Because of the granular nature of the underlying materials and because of the high ground-water table, the earthquake-induced ground motion caused silt and fine sand, along with water, to be ejected from the crack onto the road surface (fig. 23). Only a few small cracks formed in the pavement and road fill along the Richardson Highway north of mile 91.



21.—View, to the southeast, showing the pavement surface of the Richardson Highway just south of the Little Tonsina River bridge at mile 65. Note the 8-inch horizontal offset of the centerline; vertical displacement is as much as 3 inches.



22.—Landslide movement on a hillside approximately two-tenths of a mile away caused the Little Tonsina River bridge to be shoved from the right to the left. Minor slumping occurred in road fill to the left of the bridge. Immediately after the earthquake the pavement was buckled more than 3 feet high at the left end of the bridge.



23.—Small crack across abandoned section of road on a low gravel terrace adjacent to Rock Creek at mile 86.1, Richardson Highway. Note the fine sand and silt along both sides of the crack.

Snowslides covered the Richardson Highway near mile 38, mile 39, and mile 42, and a rockslide blocked the road near mile 44; a large snowslide near mile 50 dammed the Tiekel River, and because of the danger of flooding the highway, explosives were used to blast a channel in the slide. Ice jams on the Tonsina River near mile 75 and mile 78.5 caused the river to rise and to erode highway fill near mile 76 and mile 77; explosives were used to remedy this condition also. Between mile 66 and mile 73, accelerated surface drainage from the steep mountain slope paralleling the highway on the east caused large icings to form on the highway.

The Edgerton Highway was damaged very little, except for a 200-foot landslide on the Lower Tonsina Hill, a short distance north of Lower Tonsina. The Lower Tonsina River bridge, which was shifted about 6 inches to the southeast, sustained considerable structural damage.

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