Quaternary and Engineering Geology in the Central Part of the Alaska Range

A. Quaternary geology of the Nenana River valley and adjacent parts of the Alaska Range

By CLYDE WAHRHAFTIG

B. Engineering geology along part of the Alaska Railroad

By CLYDE WAHRHAFTIG *and* ROBERT F. BLACK

GEOLOGICAL SURVEY PROFESSIONAL PAPER 293

Studies of glacial features and periods of glaciation in the Nenana River valley and of landslides, icings, and frost heaving and settling affecting maintenance of track bed along 63 miles of the Alaska Railroad

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By CLYDE WAHRHAFTIG

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 293-A

A study of glacial features and periods of glaciation in an area on the northern margin of the Cordilleran ice sheet in Alaska

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By Clyde Wahrhaftig

ABSTRACT

The Nenana River flows northward across the Alaska Range near longitude 149° W. Sedimentary bedrock formations of its basin include schist of pre-Cambrian age, undifferentiated Paleozoic and Mesozoic rocks, continental Upper Cretaceous rocks and poorly consolidated continental Tertiary rocks. Igneous rocks include quartz-orthoclase schist of Mississippion (?) age, greenstone, granitic and basic intrusive rocks of pre-Late Cretaceous age, and doleritic and andesitic intrusive rocks of Late Cretaceous age.

The pre-Tertiary structure of the Alaska Range is a complexly faulted east-trending synclinorium. Upper Cretaceous rocks in the center are flanked on the north by schist of pre-Cambrian age and on the south by Paleozoic and Mesozoic sedimentary rocks. Middle Tertiary structures include step-like monoclines north of the range, and anticlines, synclines, and fault blocks within and south of the range. As a result of these two periods of deformation, the formations generally occur in broad bands parallel to the range.

Most streams of the Alaska Range have dendritic drainage systems and flow northward, alternately following narrow canyons through east-trending ridges of hard pre-Tertiary rocks and crossing broad plains and lowlands cut on Tertiary rocks. The plains and lowlands extend without interruption across drainage divides. The drainage is believed to have developed on a late Pliocene or early Pleistocene erosion surface, which extended across the Alaska range between longitude 148° W. and 149°30′ W. Mountains that rose above this surface to the west culminated in Mt. McKinley, then about 10,000 feet high, and those to the east in Mt. Hayes, then about 6,000 feet high. The only well-established remnant of the surface is the flat top of Mt. Wright. The present altitude of the surface is about 3,000 feet in the northern foothills, and 7,000 feet along the crest of the range.

Evidence of four distinct glacial advances has been recognized along the Nenana River, although in places deposits of two or more advances may be grouped together. During each glacial advance ice moved northward from within and south of the range to the northern foothills.

Deposits of the earliest advance, the Browne glaciation, include erratics that occur on a terrace 500 feet above the river at Browne and 1,000 feet above the river near Ferry. Several of the erratics are 40 feet across. Near Lignite, erratics occur 2,500 feet above the river. Most of the erratics consist of granite, which apparently was derived from a stock near the headwater glaciers. The erratics indicate that an ancient glacier extended at least to the northern foothills and was 16 miles wide. Between the Browne glaciation and the next glaciation the Nenana River downcut 200 feet at Browne and 700 feet at Healy. Presumably, this activity was caused by uplift of the Alaska Range, which increased the inclination of the surface 25 feet per mile near Browne and Healy. In response to this uplift, stream sculpture and periglacial processes produced, below the upland surfaces on which the Browne deposits lie, a topography that differs markedly from glacial topography.

Deposits attributed to a second advance—that of the Dry Creek glaciation—include a gravel outwash terrace, 100 feet thick, extending along the Nenana River northward from Lignite. The terrace is 500–1,700 feet below the surface containing the erratics and 350–500 feet above the outwash terrace of the following glaciation. Varved clay in the valley of Dry Creek, a stream established after the earliest ice advance, is also attributed to the Dry Creek glaciation because it lies 600 feet above the terminal moraine of the next younger advance, which stands immediately south of the mouth of Dry Creek. The varved clay was probably deposited in a glacier-dammed lake. Scattered till in the mountains south of McKinley Park station is several hundred feet above ice-margin deposits of the following glaciation. The terminus of the glacier probably was near Dry Creek. The height and slope of the outwash terrace indicate that between the Dry Creek glaciation and the next glaciation the Nenana River downcut at Healy about 500 feet, presumably in response to a northward tilting of 17 feet per mile.

The terminal moraine of the third advance—that of the Healy glaciation—is a prominent compound curved ridge of till on a terrace about 450 feet above the Nenana River 2 miles northwest of Healy. The spurs of the U-shaped gorge between Healy and McKinley Park station are truncated, but minor features of glacial abrasion have not been preserved. Modified lateral-moraine ridges and patches of till are preserved on gentle topography. Elsewhere, glacial deposits of the third advance were removed before the next glaciation. No lakes formed during the Healy glaciation remain. The outwash terrace is about 470 feet above the Nenana River near Healy and 85 feet above the river 20 miles north of Healy.

During retreat of the ice of the Healy glaciation, a proglacial lake that occupied the gorge between McKinley Park station and Healy was filled with sediments. Alluvial cones built by tributaries from the west forced the Nenana River, flowing on the lake sediments, to the east wall of part of its gorge. The river then cut into the wall, forming a narrower gorge. This superposed course lies about a quarter of a mile east of the sediment-filled glacial gorge.

Glacial deposits of the youngest major advance—that of the Riley Creek glaciation—are much better preserved than the

older deposits. The terminal moraine forms a ridge along the south bank of Riley Creek near its mouth. Lateral moraines and ice-margin deposits form irregular pond-pocked embankments for many miles up the valleys of the Yanert Fork and Nenana River. The ground moraine has well-preserved drumlinlike hills, a medial-moraine ridge, and many depressions in which lakes have formed. The valley-train outwash is preserved as a set of terraces the highest of which is 250 feet above the river. The outwash gravel beneath the terrace surfaces is 10–160 feet thick. Between McKinley Park station and Moody the outwash rests unconformably on eroded lake sediments. Between Moody and Healy the outwash terraces are in the gorge of the superposed Nenana River. On Healy Creek, bluffs cut terraces graded to this outwash and reveal only alluvium from creek level to terrace top. These exposures indicate that before the Riley Creek glaciation Healy Creek and the Nenana River flowed at or below their present elevations.

Valley-train outwash from an end moraine near Carlo forms a gravel terrace 200 feet high in a stream-cut canyon in till and outwash related to the terminal moraine at Riley Creek. These conditions suggest that the ice readvanced after its retreat from the terminal moraine at Riley Creek. No other valley on the north side of the Alaska Range shows evidence of this readvance. The deposits are explained by assuming that as the ice retreated, a proglacial lake formed near Carlo; that this lake was subsequently drained by erosion of its drift dam; that the ice readvanced a short distance and pushed forward the proglacial delta forming the end moraine, and that a new valley train was built by the heavily loaded glacial melt water.

Evidence of two recent cold periods is found in two rock glaciers at the head of Clear Creek. The older rock glacier, which is now stable and covered with vegetation, has been dissected by deep gullies into which the younger rock glacier is now moving. Presumably, rock glaciers are active during cold periods and are dissected during warm periods.

INTRODUCTION

PURPOSE AND SCOPE OF THE REPORT

It has long been known that Alaska was never completely covered by glacial ice during the Pleistocene. North of the Cordilleran ice sheet of southern Alaska was a great driftless area, which included the greater part of the drainage basins of the Yukon and Kuskokwim Rivers (Capps, 1931, pl. 1). The southern border of this driftless area lay along the north side of the Alaska Range. South of the Alaska Range, ice covered most of the low country during periods of glaciation; and on the north side of the Alaska Range, ice tongues moving down the valleys left deposits of till and outwash gravel on the valley floors. The Alaska Range, as will be shown, was being continuously uplifted throughout the Pleistocene. The effect of this uplift should have been to raise the deposits of early Pleistocene Time above the zone in which glacial erosion occurred later. Therefore, the north flank of the Alaska Range should be a favorable place for unravelling the Pleistocene history of Alaska.

Several rivers whose headwaters are in the low country on the south side of the Alaska Range cross the range and flow into the Tanana River. Glaciers that advanced down the valleys of these rivers are continuous with the Cordilleran ice sheet of southern Alaska; to a certain extent they were distributary glaciers fed by this ice sheet. The history of these glaciers reflects the history of the Cordilleran ice sheet. The government-operated Alaska Railroad follows the valley of one of these rivers, the Nenana, in crossing the range between Anchorage and Fairbanks.

This paper is concerned with the glacial history of the Nenana River valley and of the parts of the Alaska Range adjacent to it in an area 78 miles long (from east to west) and 70 miles wide (from north to south) between longitudes 147°30′ W. and 150°W. and latitudes 63°15′ N. and 64°15′ N. (fig. 1). A detailed study was made of part of this area—a strip 5–8 miles wide along the Alaska Railroad and Nenana River between latitudes 63°25′ N. and 64°15′ N. (fig. 2), and a reconnaissance was made of the rest of the area. The glacial sequence which was worked out for this narrow strip has been applied to the larger area. The area shown on plates 2–5, inclusive, lies between miles 328 and 385 on the Alaska Railroad,[1] and is about 214 miles by railroad north of Anchorage, and 90 miles by railroad south of Fairbanks. It includes the middle portion of the Nenana River, beginning at a point about 50 miles downstream from its source at the Nenana glacier and ending about 25 miles upstream from its confluence with the Tanana River.

Chapter B of this report, by Clyde Wahrhaftig and R. F. Black, applies the results of this geologic investigation to the study of landslides along the Alaska Railroad and to a general appraisal of the engineering geology along the Alaska Railroad between miles 328 and 384.

HISTORY AND METHODS OF THE INVESTIGATION

The attention of the Geological Survey was drawn to the Pleistocene geology along the Nenana River in response to a request made by the Alaska Railroad that the causes of landslides along the railroad between McKinley Park station and Healy be investigated. These landslides have hindered the operation of the railroad almost from the time of its opening. The author became interested in the Pleistocene problems of this area while studying the coal deposits of the Nenana coalfield.

On October 19, 1947, immediately after several severe earthquakes (St. Amand, 1948, p. 617), the railroad track at mile 351.4 in the gorge between McKinley Park station and Moody began to settle at a rate of about 4 feet per day. Col. J. P. Johnson, general manager

[1] Mileage is given in terms of mileposts on the Alaska Railroad.

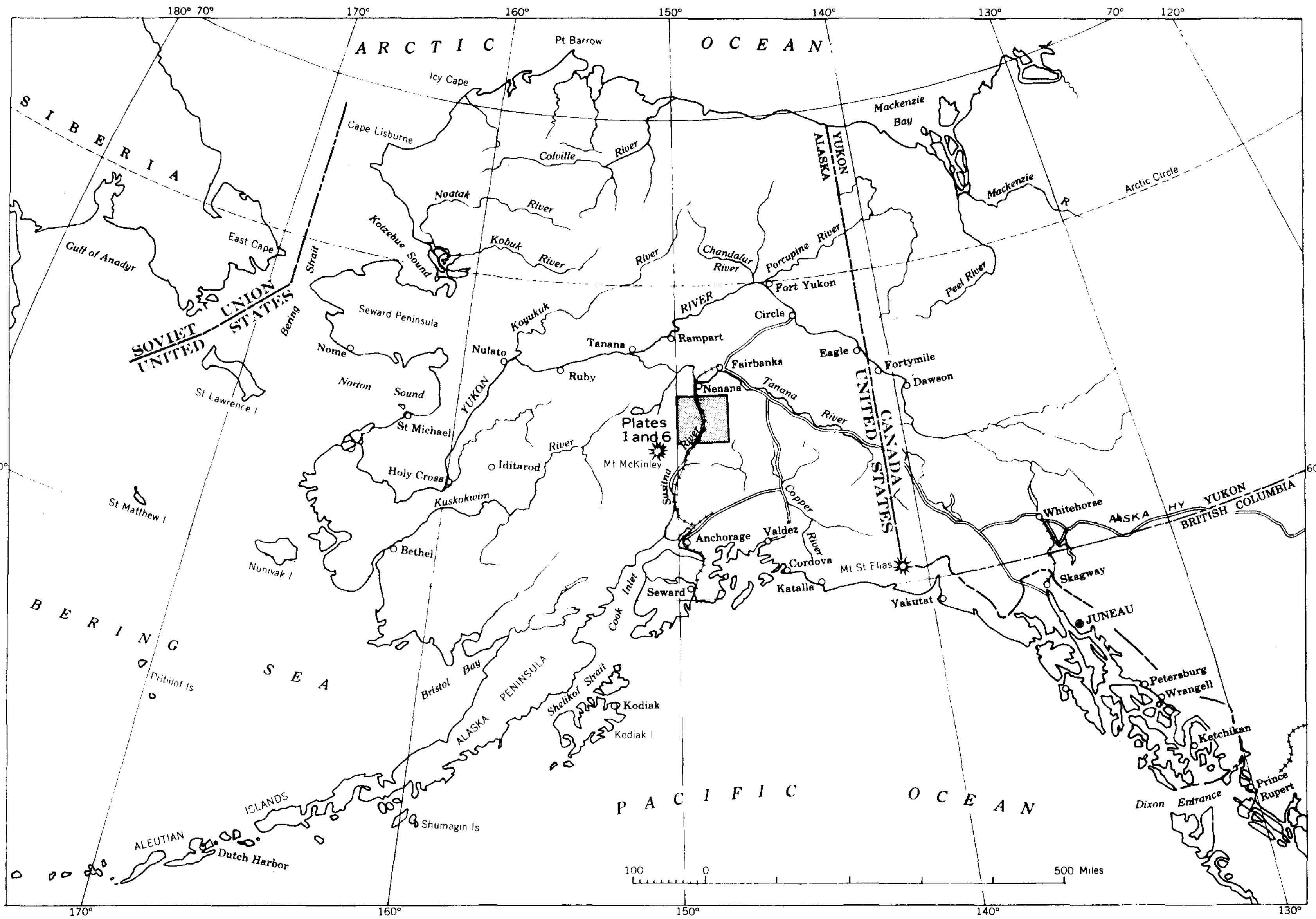

FIGURE 1.—Index map of Alaska, showing location of area covered by this report (see pls. 1 and 6).

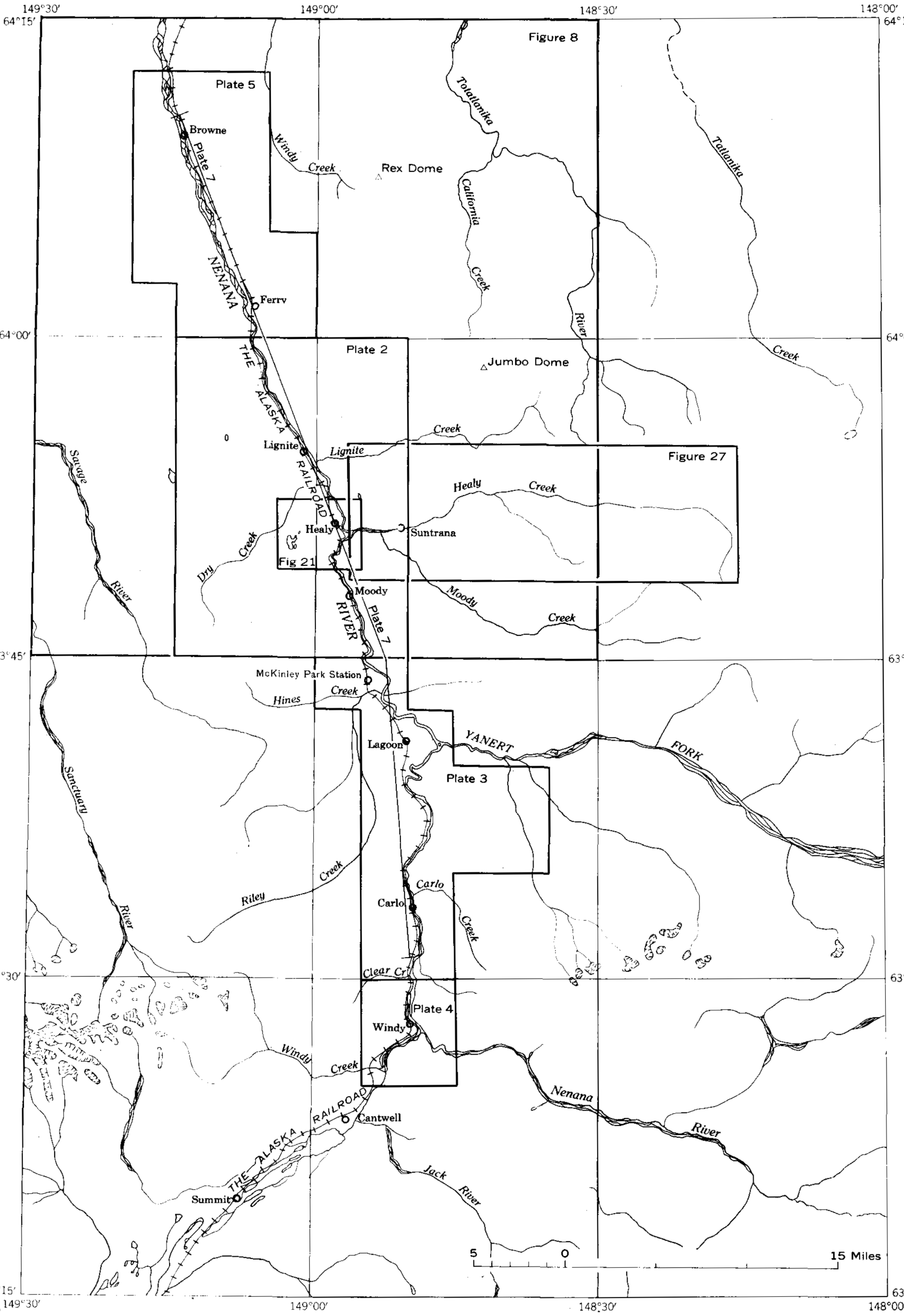

FIGURE 2.—Index map of the central part of the Alaska Range, showing areas covered on plates 2–5 and 7, and figures 8, 21, and 27.

of the Alaska Railroad, requested the Geological Survey to make an immediate investigation. The area of the landslide was visited by Robert F. Black and the author on October 31, 1947, and a geologic reconnaissance along the 9-mile stretch of track between McKinley Park station and Healy was made between October 31 and November 2.[1] As a result of this investigation, it was decided that a reconnaissance making special reference to Pleistocene deposits and engineering problems be undertaken along the Alaska Railroad between miles 328 and 385. This done in the summer of 1948; the author was in the area from June 15 to November 15, and John W. James was in the area from June 15 to August 27. Information gathered in 1944 and 1945 (Wahrhaftig, Hickcox, and Freedman, 1951) has also been incorporated in this professional paper. The author reexamined the area, particularly the landslide localities, in 1949, 1950, and 1951. The author, assisted by Allan V. Cox, spent several days mapping in an area east of the Nenana River and south of the Yanert Fork and in an area west of the river near Lignite. Observations on the glacial geology of the Wood River country were made in 1950 by the author and R. A. Eckhart, and observations on the glacial geology of the Yanert Fork and in Mount McKinley National Park were made in 1951 by the author and Allan V. Cox. In 1952, the author and J. H. Birman mapped country along lower Lignite Creek, along Moody Creek, and west of Ferry. The distribution of glacial erratics was a subject of special study.

Geologic features along the railroad were plotted in the field on maps and profiles supplied by the Alaska Railroad. The scale of these maps is 1:4,800, and the contour interval, 10 feet. Geologic features at greater distances from the railroad were plotted on vertical and oblique aerial photographs taken by the U. S. Army and Air Force in 1941, 1946, and 1949. Information gathered in the field was transferred to U. S. Geological Survey topographic maps, whose contour interval is 100 feet. These maps have been reproduced as plates 2–5. Wahrhaftig and James made transit traverses and planetable surveys in 1948 of the terraces and critical deposits along the Nenana River; these are the basis of plate 8, the longitudinal profile of the inner terraces of the Nenana River. Inasmuch as the course of the river at the time the terraces were deposited was probably different from its present course and can no longer be located, the line of the Alaska Railroad was selected to represent the average position of the river during later Pleistocene time. On plate 8, distances along the Alaska Railroad were used as ordinates, with the exception that the distance between miles 342 and 345 was doubled on the profile to allow for the arc of the river in the vicinity of Yanert Fork. The longitudinal profile of the terraces and glacial deposits (pl. 7) was prepared from the geologic maps (pls. 2–5).

The author wishes to acknowledge the cooperation of the management of the Alaska Railroad, who placed accommodations, transportation, and technical assistance at his disposal. He is grateful in particular for the cooperation of the following members of the staff of the railroad: Col. J. P. Johnson, general manager; R. A. Sharood, chief engineer; Charles Griffith, bridge engineer; Anton Anderson, engineer in charge of maintenance of way; James Morrison, resident engineer; Norval Miller and James Allen, surveyors; the late Joseph McNavish, roadmaster; Al Logsdon and Calvin Brown, roadmasters; Sven Bragstad, Frank Spadero, Ted Mommsen, and Al Cass, section foremen; and Jerry Marshall and John Witkowski, managers of the hotels at Healy and McKinley Park station.

GEOGRAPHIC SETTING

PHYSIOGRAPHIC DIVISIONS

Most of the area shown on plate 1 lies in the Alaska Range and its northern foothill belt (see fig. 3). This range of mountains is one of the dominant topographic features of Alaska. It forms a great arc about 600 miles long and 50–120 miles wide extending from a point near the Canadian boundary to Lake Clark and Lake Iliamna in southwestern Alaska, where it merges with the Aleutian Mountains. The highest point in

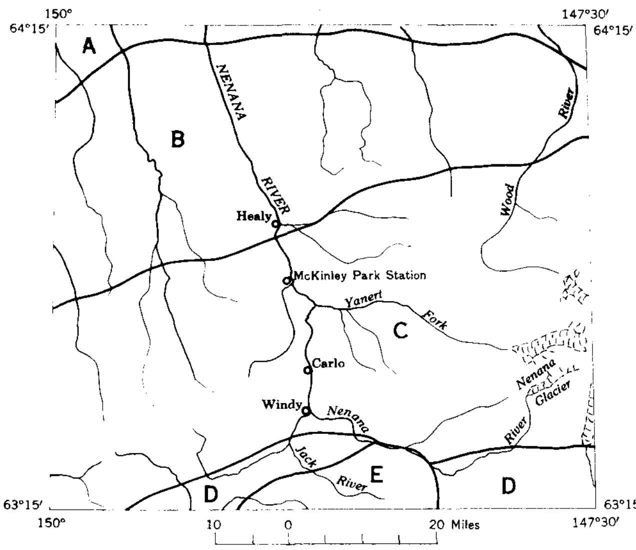

FIGURE 3.—Physiographic divisions of the area covered by this report (see pls. 1 and 2). *A*, Tanana Flats; *B*, northern foothill belt of the Alaska Range; *C*, Alaska Range; *D*, Broad Pass depression; *E*, northern Talkeetna Mountains.

[1] Black, R. F., and Wahrhaftig, Clyde, 1948, Preliminary geologic investigation of railroad track difficulties in the Nenana River gorge, Alaska: unpublished rept. in files of U. S. Geol. Survey.

the Alsaka Range and the highest point on the North American continent is Mt. McKinley, which is 20,300 feet high. This mountain is located 35 miles S. 35° W. of the southwest corner of the area shown on plate 1. However, the number of high mountains in the Alaska Range is comparatively small. Less than 40 peaks are higher than 10,000 feet, and the crest of most of the range is between 7,000 and 9,000 feet in altitude. The range is dominated by four great mountain masses: the Mt. Spurr–Mt. Gerdine group in the extreme southwest, culminating in Mt. Gerdine (12,600 feet high); the Mt. McKinley group, just west of the area shown on plate 1; the Mt. Hayes group, culminating in Mt. Hayes, 24 miles east of the area shown on plate 1; and the mountains around Mt. Kimball, 70 miles east of Mt. Hayes.

The Alaska Range is crossed by several low passes and by several rivers that head in the lowlands on the south side of the range and flow northward across the range into the Tanana River. These rivers are the Chisana and the Nabesna Rivers, east of longitude 143° W.; the Delta River, at longitude 146° W.; and the Nenana River. All other rivers of the range rise in the mountains and flow south into the Copper or Susitna Rivers, or north and west into the Tanana and Kuskokwim Rivers. Most of these rivers have short and steep courses, and nearly all those rising in the higher portions of the range head in glaciers. Mt. Spurr, Mt. McKinley, and Mt. Hayes support glaciers that extend 20 or 30 miles from their sources and spread out as great piedmont lobes at the edge of the plains bordering the range. Glaciers on the south side of the range are much larger than those on the north side, as the south side receives more precipitation. On the other hand, ice is found at lower altitudes in north-facing cirques than in south-facing cirques.

The northern foothill belt of the Alaska Range, which is about 20 miles wide (see fig. 3), consists of parallel east-trending ridges and valleys. The ridges are 3,000–5,000 feet in altitude, and the valleys are 1,000–2,500 feet in altitude. The foothill belt is crossed by north-flowing streams rising in the Alaska Range.

The southern edge of the Tanana lowland lies along the north border of the foothills (see pl. 1 and fig. 3). For a distance of 15–30 miles northward from this border the flats are made up of a series of coalescing alluvial fans.

The Broad Pass depression (fig. 3) is a flat-floored trench about 5 miles wide bordering the Alaska Range on the south. Its altitude is between 2,000 and 3,000 feet, although scattered mountains within it rise to higher altitudes. The Talkeetna Mountains, the southernmost of the physiographic divisions covering the area of plate 1, are a rugged upland that rises to altitudes of 6,000 feet.

THE NENANA RIVER

The Nenana River rises in the Nenana Glacier on the south side of the Alaska Range (pl. 1). It flows about 47 miles southwestward along a braided course through the Broad Pass depression to Windy, where it turns abruptly northward and flows directly across the Alaska Range. At Windy the Nenana River is joined by the Jack River, which drains the northwestern corner of the Talkeetna Mountains and part of the south flank of the Alaska Range.

For the next 10 miles of its course, to a point a few miles downstream from Carlo, the Nenana River occupies a U-shaped valley whose floor is nearly flat and almost a mile wide and whose walls rise to heights of 2,000–3,500 feet above the river. The gradient of the river in this stretch is gentle, and there are few rapids. At a point a few miles north of Carlo the river enters the Yanert Fork valley. The river flows along the west side of this depression through a narrow winding terraced gorge, 100–250 feet deep, cut in glacial deposits and bedrock hills that floor the Yanert Fork valley. About midway across this depression the river is joined by the Yanert Fork, its largest tributary, which rises in a large glacier 30 miles to the east and flows westward in a braided course to join the Nenana River. A few miles above its confluence with the Nenana the Yanert Fork also sinks into a narrow winding gorge cut in glacial deposits. The Nenana River leaves the northwest corner of the Yanert Fork valley at McKinley Park station.

From McKinley Park station to Healy, a distance of 10 miles along the river, the Nenana flows in a remarkable two-story canyon through a high ridge. The outer canyon is U-shaped, and its floor is ½–¾ of a mile wide; the broadly flaring walls and truncated spurs rise to a height of 2,500 feet above the canyon floor. In the downstream half of this canyon, and also for a short distance at the upstream end, the river flows in an inner gorge, about 500 feet wide, that has nearly vertical rock walls 200–300 feet high. In the other parts of the two-story canyon the inner gorge broadens to nearly the full width of the outer gorge.

North of Healy the river follows an almost straight course N. 25° W. about 28 miles across the northern foothill belt. Here it occupies a broad valley having gentle terraced walls that rise from a few hundred to 2,500 feet above the river. The valley, including its terraces, ranges in width from 6 to 10 miles; individual terraces are locally more than a mile wide. North of the foothills the Nenana River enters the Tanana lowland, which it crosses on a large alluvial cone nearly 20 miles long and 400 feet high at the apex. The Nenana River enters the Tanana River at Nenana, 30 miles downstream from the edge of the foothills. The total length of the river is thus about 150 miles, of which slightly more than half is in the area covered on plates 2–5.

CLIMATE

The climatic data for three stations on the Alaska Railroad are summarized in table 1. These stations (see pl. 1) are Summit, at the crest of Broad Pass; McKinley Park station; and Nenana, about 22 miles north of the north edge of the area shown on plate 1. The records for Summit represent conditions typical of the south side of the range; those for McKinley Park station, of the mountains; and those for Nenana, of the north edge of the Alaska Range foothills. As can be seen from these records, precipitation is considerably heavier on the south side of the Alaska Range than on the north side. Average annual temperatures are about the same for all three stations, but summers are much hotter and winters are far more severe at Nenana than at the two southern stations.

TABLE 1.—*Climatological data for three stations on the Alaska Railroad*

[From records of U. S. Weather Bureau (1950)]

Month	Average temperature (°F)			Total precipitation (inches)		
	Summit	McKinley Park sta.	Nenana	Summit	McKinley Park sta.	Nenana
January	4.3	3.0	−8.2	1.07	0.86	0.64
February	8.9	7.8	.2	1.13	.61	.48
March	11.4	12.9	8.8	1.48	.42	.56
April	21.6	26.6	27.2	.48	.70	.35
May	37.2	41.5	46.1	1.08	.85	.70
June	49.3	52.6	57.9	2.31	1.95	1.31
July	52.1	54.7	60.6	3.24	2.36	1.91
August	48.3	50.7	55.7	3.71	2.81	2.54
September	40.5	41.9	44.3	3.43	1.60	1.21
October	25.5	27.1	27.1	1.75	1.04	.72
November	8.7	11.0	4.3	.88	.68	.49
December	1.5	3.3	−7.4	1.37	.60	.44
Annual	25.9	27.7	26.4	21.83	14.58	11.34
Number of years of record	9	26	23	9	22	15

Snow falls on the high mountains during all months. The first snow can be expected to fall in the valleys around the middle of September. In the valleys snow remains on the ground until early May. Early summer weather is generally warm and dry, and is characterized by thunder showers of convective origin. Late summer and fall weather is characterized by periodic cyclonic storms from the south and west. Winters are reported to be generally clear for long periods of time. Prevailing winds are from the south, and are frequently of very great intensity.

BEDROCK GEOLOGY OF THE NENANA RIVER VALLEY

The bedrock formations of the Alaska Range occupy in general east-west bands parallel to the trend of the range and normal to the course of the Nenana River. The areal distribution of the bedrock formations is shown on plate 1. The bedrock formations along the Nenana River, where not overlain by Pleistocene deposits, are shown on plates 2–5. In terms of age, tectonic history, and degree of consolidation, they form two strongly contrasted groups: Rocks of the older group range in age from pre-Cambrian to Cretaceous, are well consolidated or metamorphosed, and contain schist, gneiss, phyllite, chert, argillite, limestone, conglomerate, slate, shale, and coal; greenstone, in part intrusive and in part derived from basic lava flows, is common. Rocks of the younger group are of Tertiary age, are poorly consolidated, and are now confined to the northern foothill belt and lowlands within the range, but were once much more extensive. A major unconformity separates the two groups.

The history of the older group of rocks is very complicated and includes several known periods of orogeny (Capps, 1940, p. 130–132); however, from the point of view of Pleistocene geology, all the rocks behave similarly in that they are all resistant to erosion. Their arrangement in bands across the courses of the rivers makes possible the distinction between material deposited by the rivers and that derived from adjacent hillsides. The younger group of rocks erodes easily to form broad plains and lowlands. The broad terraces along rivers that cross the area of Tertiary rocks are sensitive records of Pleistocene events.

The pre-Tertiary structure of the range is a great synclinorium, first recognized by Spurr (1900, p. 240), in which Cretaceous rocks at the center are bordered by Paleozoic and pre-Cambrian rocks on the flanks. The synclinorium is complex, having many subsidiary synclines and anticlines, especially within the area of the Cantwell formation. The east-trending trough in the south part of the range is a great fault zone, which complicates the structure of the Paleozoic rocks in the region of this report. The fault has been traced the length of the Alaska Range from a point near Mentasta Pass westward to a point about 60 miles beyond Mt. Foraker, and it probably extends much farther in both directions. Another fault in the northern part of the Alaska Range separates the Cantwell formation of Cretaceous age on the south from Birch Creek schist of pre-Cambrian age on the north (see pl. 3).

Structures have also been imposed by the mid-Tertiary orogeny. Essentially, these include an uplifted area that coincides with the higher parts of the Alaska Range and the bordering depressed areas on the south (Broad Pass) and north (Tanana Flats). On the north side of the range is a series of structural terraces and monoclines along which the Tertiary rocks decline northward. Several synclines of considerable closure exist in the northern foothills, however, and a cross-syncline is followed by the Nenana River northward from Lignite. A line of synclines and grabens that were formed during the mid-Tertiary orogeny and that are made up of early Tertiary rocks extends westward along the McKinley Park highway. Apparently these once extended the length of the Yanert Fork in the center of the range.

In the discussions of bedrock geology that follow, only those bedrock formations that crop out in the areas shown on plates 2–5 are described. The bedrock lithology of the much larger area shown on plate 1 is of little importance to the engineering problems along the Alaska Railroad discussed in chapter B and, except for a few intrusive bodies, is relevant only in a general way to the Pleistocene history of the Nenana River. Therefore, the discussion of these rocks in the preceding paragraphs and in the explanation on plate 1 is regarded as sufficient. Most of the lithologic descriptions of formations in the following sections, although based on exposures in the areas covered by plates 2–5, apply of course to outcrops of these formations shown on plate 1.

SEDIMENTARY ROCKS

BIRCH CREEK SCHIST

The oldest formation traversed by the Nenana River and the Alaska Railroad in crossing the Alaska Range is the Birch Creek schist (Capps, 1940, p. 95). This formation occupies an east-trending belt from 3 to 12 miles wide in the north part of the Alaska Range (pl. 1). It forms the bedrock in the Nenana River Gorge between mile 348 and mile 358 on the Alaska Railroad (pls. 2 and 3). The Birch Creek schist is predominantly quartz-sericite schist, but locally contains layers of quartzite and black carbonaceous schist. From mile 345.5 to mile 355.5 on the Alaska Railroad the schist contains abundant pyrite in well-formed cubes as large as a quarter of an inch on a side. Foliation in the schist, while not uniform, generally strikes eastward and dips 20°–40° southward (see pl. 2). The foliation is locally very irregular and highly contorted. The schist is traversed by well-developed joints that commonly strike northward and dip almost vertically. These joints are believed to be pre-Tertiary in age because some of them are filled with basalt dikes that are overlain unconformably by Tertiary rocks. According to Capps (1940, p. 97), the Birch Creek schist is early pre-Cambrian.

UNDIFFERENTIATED PALEOZOIC AND MESOZOIC ROCKS SOUTH OF WINDY

South of Windy (pl. 4) the bedrock along the Nenana River and the Alaska Railroad is a complex assemblage of argillite, shale, graywacke, phyllite, limestone, conglomerate, and chert. These rocks are either moderately indurated or are metamorphosed; some are considerably metamorphosed. They are intruded by granitic rocks, greenstone, and diabase and rhyolite dikes. Fossils ranging in age from Devonian to Jurassic have been collected from them at several localities. Fossils of Devonian and Triassic age have been collected from localities separated by short distances, and from rocks that cannot be distinguished lithologically (E. H. Cobb, oral communication, 1951). Because of their complex structure and the uncertainties regarding their age, the rock units in this group are shown on the geologic maps (pls. 1 and 4) as undifferentiated Paleozoic and Mesozoic rocks.

North of Bain Creek (pl. 4) the rocks of this group consist largely of dark-gray to purple argillite, but also contain interbedded graywacke and stretched conglomerates. Outcrops along the railroad consist largely of chert, argillite, and conglomerate. The ridge between Windy and Bain Creeks is made up of argillite, graywacke, and conglomerate that contains several large lenticular bodies of limestone. From a point near the mouth of Windy Creek southward along the east side of the Nenana River to the south edge of the area shown on plate 6, bedrock consists largely of highly deformed dark-gray to black shale, slate, and argillite, locally intruded by lamprophyre and rhyolite dikes.

The structural relations within this area of sedimentary and metamorphic rocks are so complex the author was unable to define them in detail. Dips are steep, and at least one fault of large displacement cuts the rocks. The argillite and graywacke exposed along the east bank of the Nenana River opposite the mouth of Windy Creek have been folded into numerous isoclines and have been deformed and broken by many steeply dipping thrust faults. A few miles east of this area, conglomerates have been converted to schistose rocks through the stretching of pebbles (Moffit, 1915, p. 43).

CANTWELL FORMATION

The Cantwell formation was first described by Eldridge (1900, p. 16), who designated a locality on the Nenana River (then known as Cantwell River) about 3 or 4 miles above its junction with the Yanert Fork as the type locality. Since that time the formation has been found to extend from Big Grizzly Creek, a tributary of the Wood River, westward to a point about 30 miles beyond Mount Foraker (Capps, 1927, p. 93).

Where it is crossed by the Alaska Railroad the formation occupies a band 16 miles wide—from Clear Creek (mile 330) to McKinley Park station (mile 348) (pl. 3).

The Cantwell formation consists of conglomerate, sandstone, argillite, shale, coaly shale, and coal. Sandstone and conglomerate, which make up about 60 percent of the formation, occur together as massive beds as much as 300 feet thick. The numerous conglomeratic and pebbly layers in these beds range from 1 to 10 feet in thickness and comprise 10–20 percent of the sandstone-conglomerate sections. Pebbles in the conglomeratic layers average from half an inch to 2 inches in diameter, but locally are as large as 6 inches in diameter. Quartz and chert pebbles are the most common, but rhyolite, argillite, phyllite, granite, and gabbro pebbles are present in significant amounts in some layers. Many of the pebble layers are extremely well sorted and do not contain interstitial material smaller than one-half the average diameter of the pebbles. Compressive forces have pressed the pebbles in these well-sorted layers against each other, molding them into crude polyhedrons. Some pebbles have been deeply indented by others, but none have been fractured. As a result of these forces the original porosity of the conglomerate has been greatly reduced. Sandstone in the massive beds grades from light tan to very dark grayish brown and dark gray. It has a fairly high content of nonquartzose material, such as black chert, argillite, and feldspar, but at least half of it probably consists of quartz sand. Light-tan sandstone is common along Riley Creek (pl. 3) and along the Nenana River north of Carlo. Throughout the rest of the outcrop area of the Cantwell formation a very dark sandstone that looks like graywacke is the common type. The sandstone has been subjected to the same compressive forces that the conglomerate has, and its porosity has also been considerably reduced.

Claystone, shale, and coaly material together form zones in the Cantwell formation that are as much as 50–100 feet thick. The coaly material in these zones is in the form of beds of bone and coal that are 1–5 feet thick and 3–30 feet apart. Few, if any, of the coal beds appear to be economically minable. An attempt to mine the coal at mile 341 on the Alaska Railroad (pl. 3) was abandoned because of the disturbed nature of the beds and the poor quality of the coal (Capps, 1940, p. 114).

North of mile 336 the Cantwell formation is well consolidated but only moderately well cemented; the rock of fresh outcrops is soft enough to be scratched easily by a pick. Exposure to the weather toughens the rock. South of mile 336 it is more thoroughly cemented and more highly indurated; here the rocks are jointed into massive, resistant blocks that form rugged mountains and steep canyon walls.

The Cantwell formation occupies a large synclinorium in the center of the Alaska Range. On the north it is bounded by a vertical fault, which forms its contact with the Birch Creek schist. The south side of this fault is the dropped side. The amount of displacement on the fault is unknown, but at McKinley Park station it must be at least 7,000 feet, for a 5,000-foot-thick section of the Cantwell formation dips northward toward the fault, and the top of this section at the fault is 2,000 feet below the tops of adjacent mountains of Birch Creek schist to the north. The fault zone, which is several hundred feet wide, is made up of clayey gouge that contains "horses" (large blocks) of solid schist. On the south side of the fault the Cantwell formation is in contact with a band of greenstone. The exact nature of this contact is not certainly known, but it is probably an unconformity. Within the synclinorium the Cantwell formation is folded into synclines and anticlines, and is locally cut by steeply dipping faults. The axis of a complex, eastward-plunging anticline crosses the railroad near mile 341, and that of a broad syncline crosses the railroad near mile 336. A fault that cuts the Cantwell formation is followed by the Nenana River through the rock gorge east of mile 342 on the Alaska Railroad. It has a displacement of between 400 and 500 feet, the north side being down. The displacement is indicated by the offsetting of a diabase sill. The fact that the Nenana River followed that fault across the ridge of diabase suggests that weakened rock, possibly a wide zone of gouge, borders the fault. Small faults exposed in the rock walls of the gorge are parallel to the large fault, but have no gouge.

The Cantwell formation has been determined as Cretaceous in age on the basis of fossil leaves (Capps, 1940, p. 118).

TERTIARY COAL-BEARING FORMATION

The coal-bearing formation is a sequence of poorly consolidated sandstone, claystone, and subbituminous coal. It crops out in an eastward-trending band that crosses the Alaska Railroad between miles 357.7 and 358.6, and in an area about 3 miles wide that extends along Lignite Creek and westward across the Nenana River to lower Pangengi Creek (see pl. 2). A complete section of the coal-bearing formation is exposed at Suntrana, 4 miles east of Healy. This group of rocks has been described in detail by Wahrhaftig, Hickcox, and Freedman (1951). The lithology of the formation, which is divided into three members, is summarized briefly in the following three paragraphs.

At Suntrana the lower member is 600 feet thick and consists of about 20 percent subbituminous blocky coal in beds 5–30 feet thick, 40 percent claystone, and 40 percent somewhat clayey, medium- to coarse-grained pebbly sandstone. This member rests on an uneven erosion surface cut on Birch Creek schist. An intensely weathered zone, which is more than 100 feet thick in places, lies immediately beneath the coal-bearing formation. Weathering in this zone, which took place before the deposition of the coal-bearing rocks, reduced the schist to a soft sticky mass of clay, sericite flakes, and quartz grains. Consequently the contact between the coal-bearing formation and the Birch Creek schist is commonly marked by landslides and low saddles. At the top of the lower member of the coal-bearing formation is a bed of brown-weathering claystone. This bed is 80 feet thick at Suntrana. Where this claystone comes to the surface over areas as extensive as several acres, landslides are associated with it.

The middle member of the coal-bearing formation at Suntrana is a six-times-repeated sequence of sandstone, claystone, and coal, totaling 750 feet in thickness. One-fourth of the section consists of beds of coal as much as 40 feet thick. Well-sorted pebbly sandstone constitutes about two-thirds of the section. The remainder is made up of thin beds of claystone which commonly underlie the coal beds.

The upper member of the coal-bearing formation consists of medium-grained buff-colored pebbly sandstone in layers 30–100 feet thick, separated by zones of clay 10–50 feet thick that contain thin woody coal beds. It is 600 feet thick at Suntrana, but it thins abruptly westward, and is probably only about 400 feet thick at Healy, where it crosses the railroad. At the top is a persistent bed of greenish-gray shale and claystone about 50 feet thick.

The rocks of the coal-bearing formation are in general uncemented and poorly consolidated. They can be excavated easily with a pick or knife and can be scratched by a fingernail. Frequent freezing and thawing have caused them to disintegrate rapidly to their constituent particles, which can be transported easily by the smallest streams. Consequently, gullies, badlands, and landslides are common on exposures in this formation. Because of the ease with which the rocks are eroded, the areas underlain by this formation are marked by broad plains, wide stream valleys, and low passes.

The band of coal-bearing rocks that crosses the railroad at Healy is on the south limb of a large syncline, whose axis lies about 2 miles north of Healy. The formation in this band strikes about N. 60° E. and dips about 60° N. at Healy. Eastward, toward Suntrana, the formation strikes more to the east, and its dip decreases to about 35° N. The broad terrace south of Healy Creek and between Moody Creek and the Nenana River is underlain by the lower member of the coal-bearing formation. Here the lower member is apparently in a syncline, for the white basal sandstone and conglomerate of the member crop out at many places around the borders of this terrace and dip gently toward its center.

Near the west fork of Dry Creek the lower and middle members are cut out by an unconformity at the base of the upper member, which pinches out about 2 miles west of the west fork of Dry Creek (pl. 2). The patches of coal-bearing formation on the Dry Creek–Savage River divide near the national park boundary (pl. 2) belong in part to the lowermost part of the lower member, and in part to the upper member. An angular unconformity at the base of the upper member and another at the base of the Nenana gravel are responsible for the erratic and patchy distribution of the various members of the coal-bearing formation at this locality.

The coal-bearing formation on Lignite Creek and along the Nenana River between the mouth of Dry Creek and the mouth of Pangengi Creek (pl. 2) crops out along the crest and north side of a faulted anticline. West of the river only the upper member is exposed, but along Lignite Creek both the middle and upper members are exposed; the middle member is also present at the surface in the core of a subsidiary anticline exposed on the east side of the river opposite the mouth of Pangengi Creek. Dips in the coal-bearing formation west of the river are gentle. The beds are nearly horizontal in the vicinity of Lignite, and they dip 10°–20° N. and W. along Pangengi Creek. East of the river, dips in the formation are also gentle. Here, however, the formation is deformed—it has been warped into an anticline, which is exposed in the bluff opposite Pangengi Creek, and broken by the fault between Lignite and Poker Creeks, which bounds this area of the coal-bearing formation on the south. The fault passes westward into a monocline, in which the Tertiary rocks—both the coal-bearing formation and the overlying Nenana gravel—strike west and have nearly vertical dips for a distance of nearly half a mile along the river bluff.

The coal-bearing formation has always been classed as Tertiary. Its exact position within the Tertiary has not previously been determined. According to Roland W. Brown (oral communication, 1956) plant remains collected by him from a locality on the south bank of the Healy River about 3 miles east of Suntrana indicate an Eocene age for the formation.

NENANA GRAVEL

The Nenana gravel is the major bedrock formation along the Nenana River north of Healy. It consists largely of poorly consolidated, moderately well sorted conglomerate and sandstone. Capps (1912, p. 30) gave this formation its name for its exposures on the east bank of the Nenana River between Healy and Lignite Creeks. It has recently been described by Wahrhaftig, Hickcox, and Freedman (1951, p. 152–153) and by Wahrhaftig (1951, p. 176–179).

In the vicinity of Healy the Nenana gravel consists largely of conglomerate, the pebbles of which range in average size from 1–2 inches at the base to 3–4 inches near the top of the formation, and in maximum size from 4 inches at the base to 18 inches near the top. The pebbles are composed of sandstone and conglomerate from the Cantwell formation, schist, quartzite, and granite and other intrusive rocks that are abundant in the Alaska Range. Interstitial material is coarse- to very coarse-grained dark sandstone. Pebbles and sand grains are commonly coated with thin layers of iron oxide. Interbedded with the conglomerate are lenses of coarse sandstone 5–10 feet thick, 50–100 feet long, and spaced 30–50 feet apart. Locally, near the base and in the upper part of the formation, the Nenana gravel contains beds of claystone 3–5 feet thick, spaced 30–50 feet apart. The Nenana gravel east of Healy has a total thickness of 4,000 feet and appears to contain most of the stratigraphic units that have been recognized in this formation.

Northward from Lignite the lower part of the Nenana gravel is exposed in bluffs along the river. It consists of about equal parts of coarse dark sandstone and fine conglomerate. Most of the pebbles of the conglomerate range in size from ½ to 3 inches; pebbles larger than 5 inches are rare. Claystone layers are more abundant here than farther south, and fragments of coalified wood are abundant in the sandstone. Between miles 384 and 385 on the Alaska Railroad, about 3½ miles north of Browne station, a bed of lignite about 4 feet thick is exposed in the Nenana gravel at the crest of an anticline.

The pebbles in the Nenana gravel are generally slightly weathered. Most pebbles and boulders, especially those of graywacke and conglomerate, have weathered rinds as much as an inch thick, in which the rock is friable and iron-stained. The core of each pebble is generally unweathered. Pebbles of certain kinds of granite and volcanic rocks have been decomposed to angular sand or grüss. These decomposed pebbles are found in fresh outcrops in roadcuts and river banks. Presumably the weathering of the pebbles in the Nenana gravel took place during or shortly after deposition.

For the most part the Nenana gravel, although moderately well consolidated, is poorly cemented. It supports steep cliffs, 50–100 feet high, for long periods of time; however, when struck lightly with a hammer, it breaks into its constituent pebbles and grains. It is more resistant to erosion than the underlying coal-bearing formation, because its greater perviousness permits more of the water from rain and melting snow to sink into the ground, leaving less runoff for erosion, and because its constituent particles are coarse and therefore less easily removed by streams. Hence, the outcropping edge of the Nenana gravel, where underlain by the coal-bearing formation, forms hogbacks and ridges that rival in height nearby mountains of much harder rocks. On the other hand, in structural basins where the Nenana gravel is not underlain by the coal-bearing formation but rests instead directly on harder rocks, it forms rolling plains and valleys. An example of such a valley is the eastward-trending valley west of McKinley Park station that the McKinley Park highway follows for 20 miles.

The Nenana gravel along the Nenana River has about the same attitude as the coal-bearing formation beneath it. Elsewhere, however, there are indications that an angular unconformity separates the two formations (Wahrhaftig, 1951, p. 182–183). This unconformity represents only a minor orogeny compared with that which took place before the deposition of the coal-bearing rocks, for the formations above and below the unconformity are equally well consolidated, and throughout much of the Alaska Range they are parallel.

In the belt near Healy the Nenana gravel strikes about N. 60°–70° E. The dip at the south contact is about 45° N., but within a distance of about a mile northward it decreases to about 10° N. Just north of Poker Creek the Nenana gravel is broken by the large fault that forms the south boundary of the coal-bearing formation around Lignite Creek. Eastward, coal-bearing rocks and Birch Creek schist are brought up on the north side of the fault; and westward, the fault dies out and is replaced by the monocline that is described in the section on the coal-bearing formation. The Nenana gravel north of Pangengi Creek occupies a cross syncline that is parallel to the Nenana River. Dips are commonly gentle (10°–15°) toward the river, and beds along the river are nearly horizontal. An anticline in the Nenana gravel crosses the Alaska Railroad between mile 384 and 385 (see pl. 5).

Capps (1940, p. 126–128) regarded the Nenana gravel as definitely of Tertiary age and younger than the coal-bearing formation. In 1955 Roland W. Brown collected specimens of *Trapa* sp., from the Nenana gravel exposed along the Alaska Railroad about 3½ miles north of Browne station. According to Brown (oral communication, 1956) these fossils indicate that the Nenana gravel is Oligocene or Miocene in age, more likely Miocene than Oligocene, and that it was deposited in a warm temperate climate.

IGNEOUS ROCKS

TOTATLANIKA SCHIST

The Totatlanika schist crops out on Slate Creek, on Moose and Chicken Creeks, and in the mountains east of the Nenana River in the vicinity of Browne (see pls. 1, 2, and 5). The formation probably underlies the Nenana gravel from Slate Creek to the northern edge of the gravel. It forms a belt 5–20 miles wide that extends along the north edge of the Alaska Range from the Kantishna Hills, 40 miles west of the Nenana River, to the Little Delta River, 60 miles east of the Nenana River (Capps, 1940, pl. 3). The formation was named by Capps (1912, p. 22–23) for its exposures in the canyon of the Totatlanika River, 15 miles east of the Nenana River.

Two types of Totatlanika schist occur in the areas shown on plates 2 and 5. On Slate Creek, and on Chicken and Moose Creeks, the formation consists of fine-grained yellow slate, which contains scattered grains of feldspar and quartz less than 0.1 inch in diameter. In the mountains east of Browne the formation consists of coarse-grained gneiss, which is made up of subhedral porphyroblasts of orthoclase as much as half an inch in diameter and porphyroblasts of quartz as much as 0.1 inch in diameter; the porphyroblasts are set in a matrix consisting largely of sericite and quartz. It is thought that the Totatlanika schist resulted from the metamorphism of rhyolite flows and tuffs (Capps, 1940, p. 105). Foliation in both types of the schist is well developed and is commonly about parallel to the bedding in overlying rocks. This means only that the foliation at the time the younger rocks were laid down was nearly horizontal, not necessarily that it has always been nearly horizontal.

Capps (1940, p. 106–107) assigned the Totatlanika schist to the Paleozoic and stated that it is probably of an earlier age than Middle Devonian, based on its degree of metamorphism and on long-range correlations with other formations. At the time of his report no fossils had been found in the formation. In the summer of 1954 the writer found fossils in float from a limestone lens in the upper part of the Totatlanika schist. The fossil locality is just west of the junction of Rogers and Sheep Creeks (tributaries of the Wood River) at an altitude of 4,100 feet (pl. 1). These fossils were submitted to Helen Duncan, of the Geological Survey, who reported (May 20, 1955) as follows:

> I examined all the pieces of rock in this collection and sawed and polished several. The only things I could find that I am sure are organic are crinoid columnals, a small gastropod in section, and several pieces of a species of *Syringopora* that is closely similar to if not identical with a form that occurs in the Wachsmuth limestone of the Lisburne group. The specimens of *Syringopora* are a little distorted, but the internal structures are well preserved. . . .
>
> The presence of *Syringopora* (sensu stricto) indicates that the rock is post-Ordovician, and the chances are that it is not Silurian—at least I have not seen any good evidence that *Syringopora* in the strict sense occurs in the Silurian of Alaska. However, Silurian species of the genus have been described from the Arctic regions of the U. S. S. R. and might occur in Alaska. I have seen a few specimens from the Devonian of Alaska that I would refer to *Syringopora*, but they did not closely resemble the species in this collection. We do not have enough information on stratigraphic occurrences, however, to rule out the possibility of Devonian age in this case. Possibly because I am more familiar with the Mississippian Syringoporas of Alaska and because the species in this collection looks very much like a form that I know is common in the Mississippian, I favor a Mississippian assignment. Verification of that assignment will depend on getting other kinds of fossils.

On the basis of Miss Duncan's report, the Totatlanika schist is assigned to the Mississippian (?).

GREENSTONE

A band of greenstone crosses the Alaska Railroad between miles 327.5 and 329.5. It is shown on plates 3 and 4 (on plate 1 it is grouped with the undifferentiated Paleozoic and Mesozoic rocks). The greenstone apparently makes up Panorama Mountain and the Windy Peaks and extends westward to the head of Clear Creek. The rock is predominantly dark green, but weathered surfaces are dark brown. Where it crosses the railroad the greenstone appears to be of two types.

One of the two types of greenstone occupies the southern half of the greenstone body. It consists of blocks of massive unaltered gabbro surrounded by zones in which intense shearing and serpentinization have taken place. The rock is moderately close jointed, but massive enough to form the most rugged mountains in this part of the Alaska Range. Microscopic study of a fresh specimen collected from talus west of the railroad showed it to consist of about 55 percent calcic labradorite and 40 percent augite. The calcic labradorite occurs as euhedral grains 2–3 millimeters long, and the augite as aggregates of crystals, each of which is ⅓- to 1 inch in diameter. The aggregates of augite crystals generally fill the spaces between the feldspar crystals and are molded to their shape, giving the rock an ophitic texture. Five percent primary magnetite or ilmenite is present as skeleton crystals in the feldspar and augite. Locally the augite has been altered to a fine-grained mass of chlorite and serpentine, which contains some secondary quartz. The feldspar has cloudy patches that may represent incipient saussuritization. A specimen of coarse-grained greenstone was obtained 2 miles south of Slime Creek on the McKinley-Cantwell highway. The rock is fresh appearing and has an ophitic texture. It consists of grains of labradorite (An 54), augite, and ilmenite that are between 0.2 and 2 millimeters in diameter, but includes small amounts of chlorite and sericite as alteration products. This type of greenstone probably comprises most of the pebbles of the "green ophitic diorite" in the Nenana gravel (Wahrhaftig, Hickcox, and Freedman, 1951, p. 152–153; and Wahrhaftig, 1951, p. 178–179), and pebbles and boulders of similar material in gravels of Quaternary age.

The second of the two types of greenstone is a fine-grained rock that makes up the hills and jumbled area (known locally as the badland) through which the railroad passes between miles 328.5 and 329.5, south of Clear Creek. This is a dense, massive rock, and is cut by irregular veins of quartz and calcite. It is broken by irregular fractures 10–40 feet apart, and is locally altered to brown earthy material. The glacier that occupied the canyon of the Nenana River quarried great blocks of greenstone from hills on either side of the railroad track in the vicinity of mile 329 and transported them a short distance downstream, producing the chaotic topography along the railroad just south of Clear Creek. A specimen of the fine-grained type collected from a talus cone along the new highway on the east side of the Nenana River about 1 mile south of Slime Creek shows, in thin section, a relict porphyritic texture. The groundmass has been completely recrystallized and altered to a mass of fine-grained oligoclase, chlorite, epidote(?), and an unidentified mineral. The phenocrysts, which originally were probably of plagioclase, are indicated by masses of saussurite.

The contact of the greenstone with the Paleozoic and Mesozoic rocks on the south is probably nearly vertical; the greenstone presumably intruded these rocks. The greenstone body narrows westward and has an an irregular western contact with sedimentary rocks, which include ferruginous slates. On the north the greenstone is in contact with the Cantwell formation. Whether the greenstone intruded the Cantwell formation, or is overlain unconformably by it has not yet been definitely determined, although the author's present belief is that the contact is an unconformity. A one-day helicopter reconnaissance in 1951 of the region around the Yanert Glacier indicated that the Cantwell formation rests with marked angular unconformity on a sequence of slate, schist, phyllite, and limestone, intruded by large greenstone sills; these rocks are very similar lithologically to the rocks that are exposed at the head of Clear Creek and along the Nenana River between Clear Creek and Windy.

GRANITE INTRUSIVE ROCKS

A small body of quartz-diorite(?) occurs in the faulted area between Bain Creek and Windy Peaks (pl. 6). A hand specimen of this rock appears to consist of about 45 percent feldspar (largely plagioclase), 45 percent quartz, and about 10 percent dark minerals (mostly altered biotite). Shearing and crushing have locally reduced the rock to whitish mylonite. Similar material, probably mylonitized, occurs in a narrow band along the south base of Panorama Mountain. The quartz-diorite clearly intruded the undifferentiated Paleozoic and Mesozoic rocks north of Bain Creek. Its relation to the greenstone, however, is uncertain; although the map pattern of the body east of the Nenana River suggests that the quartz-diorite(?) intruded the greenstone, the quartz-diorite(?), long after it was originally emplaced, may have been forced upward along a fault zone into the greenstone.

Intrusive bodies a fraction of a mile to 5 miles across are common in the central part of the Alaska Range. The lithology of the intrusive body between the Yanert and Nenana Glaciers is important because that body is a possible source of erratic boulders along the Nenana River (see p. 23). This granite body was examined briefly in 1951. Study of two thin sections from it shows it to consist of about 50 percent orthoclase, which occurs as anhedral grains 5–10 millimeters across (the orthoclase has been partly replaced along crystallographic planes by albite); about 20 percent sodic oligoclase, which occurs as subhedral grains about 2 millimeters across, most of which have borders of albite; about 20 percent quartz, which occurs as partly rounded grains 2–4 millimeters across; and about 10 percent biotite, which occurs as clusters of irregular plates 0.5–1 millimeter across. Zircon is present as an accessory.

Thin sections of rocks collected by Pogue (1915, p. 54–66) from intrusive bodies in the Broad Pass region, by Capps (1932, p. 285) from a body 4 miles southwest of Easy Pass (pl. 1), by Bradford Washburn from the vicinity of Mount McKinley, and by the author from the Wood River district (pl. 1), all of which are in the files of the Geological Survey, were examined by the author. Most of these rocks have a much higher content of both plagioclase feldspar and dark minerals than has the intrusive body between the Nenana and

Yanert Glaciers, and hornblende is as abundant or more abundant than biotite. Pyroxene is present in some of the bodies, and in most of them the grain size is much smaller than in the body between the Nenana and Yanert Glaciers. The description by Pogue (1915, p. 57) of the granite body in the vicinity of Bruskasna Creek, for which thin sections were not available, is similar, however, to the granite body between the Nenana and Yanert Glaciers.

IGNEOUS ROCKS IN THE CANTWELL FORMATION

The Cantwell formation locally contains interbedded flows and tuffs; moreover, it is intruded by sills, dikes, and irregular bodies of rocks that range from diabase to rhyolite porphyry.

Although volcanic rocks are rare in the Cantwell formation near the Nenana River, they constitute a considerable part of the formation west of the Sanctuary River (Capps, 1932, p. 268). A layer of white rhyolite 100 feet wide crops out on the crest of the ridge between Riley Creek and the Nenana River about 1¾ miles due west of Lagoon section house and 3 miles due south of McKinley Park station.

The petrography of the rocks that intrude the Cantwell formation is summarized in table 2; the summary is based on a few thin sections from these rocks. Although the collection is not representative it does indicate the range in composition of the rocks. The most abundant intrusive rock in the Cantwell formation is diabase. This rock is dark green or black on fresh surfaces, and it weathers dark brown.

An irregular sill of diabase, about 200 feet thick, is well exposed in the north wall of the valley occupied by the lakes west of Yanert (pl. 3). Specimens 6 and 7 were collected from this sill.

Outcrops at the north end of the ridge east of Riley Creek (about 1 mile south of the mouth of Hines Creek), on the east side of this ridge about half a mile southwest of mile 343 on the Alaska Railroad, and in the walls of the gorge of the Nenana River 1 mile east of mile 342 on the Alaska Railroad appear to lie at about the same stratigraphic position within the Cantwell formation and may be parts of a large sill-like intrusive body (pl. 3). This sill-like body is about 500 feet thick where it crosses the Nenana River. It may be continuous with a dikelike body that lies along the fault between the Cantwell formation and the Birch Creek schist. The dikelike body extends from a point a few miles west of Mt. McKinley National Park headquarters eastward to the Nenana River.

Other sill-like and laccolithic bodies of diabase and associated igneous rocks are exposed on the banks of the Nenana River for 4 miles downstream from the mouth of the Yanert Fork. The contacts of some of these bodies with the enclosing sediments are extremely irregular. A wide range of rocks, from diabase to quartz-latite, is present in this small area.

Porphyry dikes and sills whose composition ranges from that of andesite to that of rhyolite and whose groundmass is commonly fine grained are common in the Cantwell formation. Sills and irregular intrusive bodies of diabase and andesite porphyry that contain small amounts of light-colored felsic porphyry are present in the mountain west of the Alaska Railroad between miles 337 and 341. These have been separately distinguished on plate 3 only on the east side of the mountain, but they are undoubtedly present on the west side of the mountain as well. South of mile 337 the Cantwell formation on both walls of the Nenana River canyon contains many sills and a few dikes of igneous rocks—chiefly andesite, latite, and rhyolite porphyry. These were not mapped separately. In general, diabase is more abundant north of latitude 63°37′30″ N., and andesite and latite are more abundant south of it.

IGNEOUS ROCKS INTRUDING THE BIRCH CREEK SCHIST

Basalt dikes are common in the Birch Creek schist. They are generally vertical, strike roughly between north and N. 30° W., and are 5–50 feet thick. They are spaced 1,000–2,000 feet apart on the average. The dikes intruded the Birch Creek schist along cross joints, which strike between N. 10° E. and N. 30° W. They do not extend into the Tertiary coal-bearing formation, which appears to overlie them unconformably.

An irregular body of greenish-gray basalt, evidently related to the dikes, is exposed on the east bank of the Nenana River opposite mile 354.8 on the Alaska Railroad (pl. 2). Apophyses of the body are exposed in the railroad cut west of the river. One minor apophysis is a thin dike that strikes eastward and dips northward, perpendicular to the planes of schistosity. It has been offset from a few inches to a couple of feet by many faults that coincide with the planes of schistosity.

A large body of white rhyolite and brown basalt makes up the top of Sugar Mountain, a white conical mountain about 8 miles southeast of Healy. The rhyolite body was visited by the author and R. A. Eckhart in 1950. The following description is summarized from their report.[3]

The main body is about 3,500 feet long and 2,000 feet wide. It consists largely of white fine-grained rhyolite, but includes small phenocrysts of quartz, oligoclase, and

[3] Wahrhaftig, Clyde, and Eckhart, R. A., 1952, Perlite deposit near Healy, Alaska: unpublished report in files of U. S. Geol. Survey.

TABLE 2.—*Petrography of the intrusive rocks in the Cantwell formation [percentages estimated]*

Specimen No.	Type of rock	Texture	Average grain size (mm)		Plagioclase		Orthoclase (percent)	Hornblende (percent)	Augite (percent)	Serpentine (percent)	Quartz (percent)	Accessories (percent)	Remarks
			Phenocrysts	Groundmass	Percent	Percent anorthite							
6	Diabase	Ophitic		1–2	40	57	10	35(?)				5	
7	do	do		1–5	60	55	[1]	8	20	10		2	
13	do	do		2	62		[1]	12	12	12		2	
14	Hornblende-pigeonite(?)-monzonite.	do			28	42	[2] 42	12	12			6	
24	Andesite	Porphyritic	1	0.3	[3] 5	[3] 28		[3] 10					85 percent groundmass, unidentified.
27	Latite porphyry	do	0.3–1	.1	[4] 50	[3] 38	[5] 40	[3] 10					
30	Andesite	do	1–5	.02	[3] 30	[3] 28	[3] 5	[3] 10			[3] 1		54 percent groundmass, unidentified.
33	Quartz latite	do		.1–.2	[3] 3	[3] 65	[3] 2				[3] 2		93 percent groundmass, unidentified.
37	Rhyolite	do	.5–1.5				[6] 62			[7] 10	[3] 4		
84	Soda rhyolite	Porphyritic (altered).	1	.1	[5] 30	8		[8] 25	[9]		[5] 30		Phenocrysts (altered) make up 15 percent of rock.

[1] Included with plagioclase.
[2] Replaces plagioclase.
[3] In phenocrysts.
[4] Twenty-five percent in phenocrysts, 25 percent in groundmass.
[5] In groundmass.
[6] Two percent in phenocrysts, 60 percent in groundmass.
[7] Calcite.
[8] Includes augite.
[9] Included with hornblende.

LOCALITIES FROM WHICH SPECIMENS WERE COLLECTED:

6. Northwest end of sill on north wall of lake valley west of Yanert.
7. Sill on north wall of lake valley west of Yanert.
13. East bank of tributary of Hines Creek, one-half mile southeast of Mount McKinley National Park headquarters.
14. South bank of Hines Creek at junction with tributary east of Mount McKinley National Park headquarters.
24. West bank of Nenana River, 1½ miles N. 82 E. of mile 345 on the Alaska Railroad.
27. West bank of Nenana River, 2¼ miles N. 87 E. of mile 344 on the Alaska Railroad.
30. Top of ridge, three-quarters of a mile N. 73 W. of mile 388 on the Alaska Railroad.
33. Three-quarters of a mile S. 85 W. of Carlo section house at an altitude of 3,100 feet.
37. North side of Clear Creek, 2⅓ miles west of the Alaska Railroad at an altitude of 3,150 feet.
84. Hill (altitude 2,200 feet) about 2 miles N. 20 E. of the mouth of Carlo Creek.

biotite. The rhyolite contains an abundance of nearly spherical vesicles, each filled with a single large crystal of calcite. In places the rhyolite exhibits platy structure. A body of basalt 700 feet wide and 2,000 feet long lies on the southwest side of Sugar Mountain in nearly vertical contact with the rhyolite body. It was impossible to determine which was the younger during the brief examination. The basalt is similar in appearance to the basalt of the dikes. A patch of the Tertiary coal-bearing formation that consists of conglomerate, containing pebbles of quartz and chert, and layers of brown, slightly silicified coal is exposed at the base of the southeast corner of the rhyolite body, outside the area shown on plate 2. The relationship of this patch of the coal-bearing formation to the rhyolite body, and the absence of rhyolite pebbles in the conglomerate, indicate that the rhyolite probably was extruded very early in the period of deposition of the coal-bearing formation. A small body of perlite, not of commercial size, rests on the coal-bearing formation.

The rhyolite was probably extruded as an endogenous dome while the basal beds of the coal-bearing formation were being laid down. It was later buried by the coal-bearing formation. Pebbles of rhyolite in the basal conglomerate of the coal-bearing formation, in exposures on the Teklanika and Savage Rivers 15–20 miles west of Sugar Mountain (Wahrhaftig, 1951, p. 174), may have been derived from this rhyolite. The extrusion of the rhyolite is the only igneous activity known to have occurred in the Alaska Range during the period of deposition of the Tertiary rocks.

The petrography of intrusive rocks in the Birch Creek schist is summarized in table 3.

SUMMARY OF THE PLEISTOCENE HISTORY

The following summary of Pleistocene history will give the reader a general picture of the events indicated by Pleistocene deposits and landforms, thus providing a frame of reference in which to relate the separate pieces of evidence described in other sections of the report. It will also enable the reader to evaluate more critically the pertinence of each item of evidence to the conclusions reached.

EVENTS LEADING TO THE ICE ADVANCES

The later phases of the mid-Tertiary orogeny that caused the deposition of the Nenana gravel caused also its deformation into synclines and anticlines, horsts and graben, structural terraces, monoclines, and tilted fault blocks. At the end of the mid-Tertiary orogeny the Alaska Range stood as a belt of generally high mountains, bounded on the north and south by de-

TABLE 3.—*Petrography of intrusive rocks in the Birch Creek Schist*

Specimen No.	Locality	Name of rock	Texture	Average grain size (mm)		Plagioclase		Augite (percent)	Biotite (percent)	Serpentine (percent)	Other constituents
				Phenocrysts	Groundmass	Percent	Percent anorthite or mineral name				
1	Ridge north of Gagnon Creek.	Diabase	Diabasic	0.3–0.5		50	60	15	1–2		Ilmenite, 5 percent; calcite, 2 percent; sphene(?), 25 percent.
22	Between Healy and Lignite Creeks.	do	Subophitic	1		50–60	70	20–25	5–8	10–15	Ilmenite, 5 percent.
7	Southeast corner of Sugar Mountain.	Rhyolite	Porphyritic	1	0.05	[1] 2	Oligoclase		1		Quartz, 7 percent [1]; groundmass contains quartz (30 percent) and orthoclase (60 percent.)
10	do	Basalt	Seriate-porphyritic.	.5	.05–.1	30	Labradorite			(2)	Basaltic hornblende, 10 percent; apatite and magnetite are also present.

[1] As phenocrysts.
[2] Unknown.

pressed areas filled with Tertiary sediments. Part of the range consisted of mountains of hard pre-Tertiary rocks—sedimentary, metamorphic, and igneous—from which the Tertiary rocks had been derived, and the remainder consisted of soft Tertiary rocks. Part of the latter had accumulated in the early stages of the orogeny and were deformed and uplifted in the later stages. Erosion quickly reduced the areas of Tertiary rocks to nearly featureless plains, but the areas of pre-Tertiary rocks, much more resistant to erosion, persisted as highlands. The centers of the greatest mid-Tertiary uplifts are believed to have persisted as highlands continuously to the present time (Wahrhaftig, 1950).

No record is left of the period between the mid-Tertiary orogeny and the completion in late Pliocene or early Pleistocene time of an extensive erosion surface of low relief, which covered most of the area shown on plate 6. Presumably, this part of the Alaska Range was slowly uplifted and eroded during this period. Isolated groups of high mountains dominated the landscape; a group to the west culminated in Mount McKinley, then probably about 10,000 feet high, and a group in the east culminated in Mounts Hayes and Deborah, then about 6,000 feet high. A few other widely scattered monadnocks rose above the plain.

Late in the Pliocene or early in the Pleistocene an uplift centered south of the Alaska Range inclined the erosion surface causing it to decline northward. By the time of the Browne glaciation, the earliest whose limits in the central part of the Alaska Range can be determined, the erosion surface had been uplifted more than 2,000 feet, and valleys at least 2,000 feet deep had been cut by the consequent streams flowing northward. This set the stage for the first of the four great glacial advances which have thus far been recognized with certainty in the central Alaska Range.

BROWNE GLACIATION

The Alaska Range at the time of the Browne glaciation was a rolling country of low ridges and broad valleys dominated by the Mount McKinley group of mountains to the west of the Nenana River and the Mount Hayes group to the east. In the eastern group and presumably in the higher western group, snow accumulated and formed glaciers, which, advancing down the valleys of rivers that drained these highlands, spread as piedmont ice lobes in the surrounding lowlands. This glacial advance is here called the Browne glaciation. Glaciers advancing down the Nenana and its main tributary, the Yanert Fork, coalesced to form a lobe which extended a few miles north of Browne, near the north edge of the foothills (see pl. 6). Near Lignite this lobe was at least 16 miles wide. A subsidiary lobe extending westward at this point may have poured its melt water down the Savage River. It extended farther downstream on the Nenana than that of any subsequent stage. Another glacier advanced northward down the ancestral Wood River and spread as a piedmont lobe 6 miles wide on the plains around Gold King Creek.

The uplift and northward inclination of the Alaska Range probably continued during the Browne glaciation and certainly continued after the disappearance of ice of this stage. The uplift of the Browne deposits before the next glaciation amounted to 700 feet at Healy; at Browne, 22 miles north, it amounted to about 200 feet. The average tilting in the north part of the range was about 25 feet per mile northward, but much of this was in a monoclinal flexure between Lignite and Ferry whose gradient was 37 feet per mile.

During the period of uplift between the Browne glaciation and the younger Dry Creek glaciation, streams and mass-wasting processes dissected the country which had been overridden by the Browne ice; streams deepened the canyons and broadened the valleys. The areas of soft Tertiary rocks were reduced to broad valleys and featureless plains, whereas the sides of mountains supported by the hard rocks in the cores of the mid-Tertiary anticlinal uplifts were barely trenched. The headward growth of subsequent tributaries along easily eroded zones, particularly at the base of the coal-bearing formation, apparently began during this period. The only drainage change which appears to have occurred at this time is that of the Wood River, which originally drained northward across the plain that is dissected by the canyons of Bonnifield and Gold King Creeks. The Wood River was probably diverted northeastward by capture, its new course describing a broad arc around this plain. The stream which effected the capture was enabled to do so because it was eroding headward along a soft zone within and at the base of the Tertiary coal-bearing formation, which extends along the present Wood River for several miles northeastward from Coal Creek.

DRY CREEK GLACIATION

Ice of the next glaciation, the Dry Creek, appears not to have advanced as far downstream as the Browne. Although the mountains of the Alaska Range were higher and presumably could have caught more snow during the Dry Creek glaciation than during the Browne glaciation, the mountains bordering the Gulf of Alaska were probably being uplifted during the Dry Creek glaciation and may have been sufficiently high to catch most of the moisture from the Pacific Ocean and to decrease the amount reaching the Alaska Range. Ice of the Dry Creek glaciation appears to have reached a locality a few miles north of Healy on the Nenana River, where it dammed Dry Creek, a tributary of the Nenana, and caused it to deposit varved clay. The glacial melt water deposited an outwash plain many miles wide that extended northward from Lignite.

The uplift of the Alaska Range, which presumably had been going on during the Dry Creek glaciation, continued after the disappearance of ice from the lowlands. Before the next glacial advance—the Healy—the northern foothill belt had been inclined northward about 17 feet per mile. The uplift at Healy was about 500 feet. During this inter-glacial episode many drainage changes took place in the Alaska Range. One of these was the enlargement of the drainage basin of the Nenana River at the expense of that of the Totatlanika River to the east. This enlargement was caused by the extension of Lignite Creek headward along the zone of soft rocks at the base of the coal-bearing formation, resulting in the capture of the headwaters of Marguerite Creek. At the same time Healy Creek eroded headward along the part of the coal-bearing formation that was brought to the surface by faulting farther south (pl. 1) to capture headwaters which for a short time flowed into Lignite Creek. Minor drainage changes took place elsewhere in the Alaska Range. These involved the capture of portions of northward-flowing consequent streams by short subsequent eastward- or westward-flowing streams; thus many streams now draining the north slope of the Alaska Range consist of long northward-flowing consequent segments, joined by short eastward- or westward-flowing subsequent segments.

HEALY GLACIATION

The following glaciation, the Healy, occurred when the topography of the Alaska Range was much as we know it today. Ice accumulated as glaciers in the higher mountains of the range and in the ranges to the south, as it had done at least twice previously. These glaciers advanced down the river valleys and coalesced to form a great intermontane ice sheet in southern Alaska. Most of the ice of the Nenana glacier probably moved southwestward down Broad Pass to join the great ice sheet of the Susitna Basin. A distributary branch of the Nenana glacier flowed northward down the Nenana Canyon and was swelled by ice from the Yanert Fork and Riley Creek. It spread out at the mouth of the narrow gorge between McKinley Park station and Healy to form a bulbous piedmont lobe about five miles wide. It is possible that during the Healy glaciation the Nenana glacier withdrew several miles from its point of maximum advance, and subsequently readvanced to that point, but at a slightly lower altitude. Glaciers advanced down the Sanctuary, Teklanika, and Savage Rivers almost to the McKinley Park highway, and down the East Fork of the Toklat River several miles beyond the McKinley Park highway. The glacier that advanced down the Wood River apparently reached the southern part of the Tanana Flats.

The Nenana River built an extensive outwash plain downstream from the terminus of the glacier, as did all other glacial streams. Periglacial tributaries, which were oversupplied with debris provided by intensified frost action, built gravel plains which were graded to the glacial outwash plains.

When the Healy ice front made its final retreat, a lake occupied the Nenana Gorge between McKinley Park station and Healy. This lake is here named glacial Lake Moody. Tributary streams built deltas in the lake, and the lake itself was completely filled with varved silt and clay. Presumably the Nenana River flowed out of the lake over a bedrock lip northeast of Garner. After the filling of the lake the river at first flowed on a gravel plain over the lake sediments, but the building of alluvial cones by tributaries from the west eventually forced it against the east wall of the glacial gorge between Moody and Garner. Downcutting resulted in the superposition of the Nenana River on the schist bedrock of the east wall of its former canyon; therefore, between Moody and Healy it now flows in a narrow bedrock gorge, whereas most of its course south of Moody is in the broad canyon that was once occupied by the lake. The retreat of the ice of the Healy glaciation may have been interrupted by standstills or even slight advances. Eventually the ice retreated far into the mountains. During the interglacial interval that ensued, congeliturbation, involving chiefly solifluction and accompanied by some stream erosion, removed most of the deposits left by the Healy ice. Deposits of the Healy glaciation are preserved only in gently sloping areas.

RILEY CREEK GLACIATION

The youngest recognized ice advance is the Riley Creek. Its extent, shown on plate 6, was considerably less than that of the Healy glaciation, and it is doubtful that glaciers covered all the lowlands of southern Alaska during the Riley Creek. Glaciers advanced down the Nenana River and Yanert Fork to the junction of these streams, where the lobes coalesced to form an intermontane ice sheet. The Nenana glacier was apparently the more vigorous of the two glaciers for the interlobate moraine which separates them is convex toward the Yanert Fork valley. The terminus stood at the mouth of Riley Creek, near McKinley Park station. One lobe of the glacier spilled over the pass north of Carlo into the Riley Creek drainage where its terminus coalesced with the terminus of the glacier that was advancing down Riley Creek. Glaciers on the Toklat, Teklanika, and Sanctuary Rivers reached only as far north as the McKinley Park highway. The Savage River valley appears not to have been occupied by a glacier during this glaciation. The glacier that advanced down the Wood River ended in the foothills several miles back of the terminus of the Healy glacier.

Evidence suggests that the ice advance of the Riley Creek was double or multiple, like that of the Healy, separate advances being interrupted by short periods of minor retreat. The advance which built the terminal moraine at the mouth of Riley Creek was complex, retreating and readvancing at least twice over a distance of several hundred yards. This moraine was built shortly before 8,600 B. C., based on a radiocarbon determination (Suess, 1954, p. 471, No. W–49).

Deposits of outwash gravel were several hundred feet thick at the glacier fronts, but tapered downstream, and 20–30 miles north of the glacier fronts were only a few feet thick. The periglacial streams aggraded their beds with gravel deposits to meet the main streams at grade, as they had done during the Healy glaciation.

The retreating Nenana glacier left, along the inner margin of its terminal moraine, a body of stagnant ice protected by a thick covering of superglacial moraine. South of this ice the glacial melt water built an outwash plain which abutted against the stagnant ice. That outwash plain now fronts the depression which was left when the stagnant ice melted. When the ice front stood at Windy, a proglacial lake apparently occupied the valley of the Nenana River for several miles north of Windy. Debris from the glacier was presumably deposited as a proglacial delta at the head of the lake. The lake was drained by the erosion of its dam of terrace gravel. Shortly thereafter the glacier readvanced to a point 4 miles north of Carlo, where it built a terminal moraine composed largely, perhaps, of the proglacial delta which had been built into the lake. The river again aggraded its bed, leaving an outwash plain; this plain has been preserved as a series of terraces, which can be traced continuously downstream to the foothills. The glacier again retreated and left a second proglacial lake. Finally the glacier retreated far into the mountains, the proglacial lake was drained, and the Nenana River and other streams eroded their beds to positions they now occupy.

The warm period which followed the Riley Creek glaciation was brought to a close many hundred or a few thousand years ago by a short, sharp, cold period, which caused a general glacial readvance and the growth of rock glaciers. This was followed by a warm period, then by a second cold period that began a few hundred years ago. This cold period reached its climax between 1880 and 1920, and is apparently now on the wane.

PREGLACIAL EROSION SURFACE

Throughout the foothill region of the Alaska Range, and in a few places in the higher parts of the range, are numerous flat mountaintops. An important event in the late Cenozoic history of the Alaska Range was the development of an erosion surface across the deformed Tertiary and pre-Tertiary rocks. Although most of the flat mountaintops belong to a much older erosional feature—the deformed and exhumed unconformity at the base of the Tertiary rocks—some may be remnants of the late Cenozoic surface. If it can be proved that some are actually remnants of the late Cenozoic surface, it will be possible to reconstruct that surface and determine its subsequent deformation fairly closely.

Before discussing the late Cenozoic erosion surface, the early Cenozoic surface will be described.

EXHUMED UNCONFORMITY AT THE BASE OF THE TERTIARY ROCKS

Many smooth surfaces and areas of low relief in the Alaska Range are parts of the folded and uncovered unconformity at the base of the Tertiary rocks. Triangular facets on the ends of truncated spurs on the north side of the ridge of Birch Creek schist north of the highway west of McKinley Park station are remnants of that unconformity. The facets truncate the schistosity at a considerable angle. The slope of these facets is as steep as and in places steeper than the dip of the Tertiary strata that are exposed at the base of the hills, and the facets coincide at their bases with the contact between the Tertiary rocks and the underlying Birch Creek schist. These truncated spurs are exceptionally well preserved west of the Savage River (pl. 6). Similar surfaces are exposed along the south side of Healy Creek for the first 12 miles above its mouth. The high north-sloping plateau which caps the mountain between Moody Creek and the Nenana River is also thought to be a part of the unconformity.

The Broad Pass depression, through which the railroad crosses the divide between the Pacific Ocean and the Bering Sea drainages just south of the Alaska Range, is an eroded graben in Tertiary rocks. Patches of Tertiary rocks lie on the floor of the depression, and the walls are fault-line scarps [3] that are much dissected and modified.

Nenana gravel underlies the plain which is followed by the McKinley Park highway from Savage River to Teklanika River, about 15 miles west of McKinley Park station. This body of Nenana gravel is connected with the broad valley of the Yanert Fork by a series of lowlands and passes. The valley of the Yanert Fork for 15 miles above its mouth has a lowland floor nearly 3 miles wide and broad flaring sides. This lowland could hardly have been carved out of hard pre-Tertiary rocks by the Yanert glacier of Pleistocene age, for the much larger Nenana glacier, which was active at the same time, failed to carve a canyon wider than 1 mile both above and below its confluence with the Yanert glacier.

The surface of the mountain southwest of McKinley Park station is broadly convex and has a slope of 1,000 feet to the mile eastward and northeastward. This slope is dissected by many canyons with steep walls. The slope truncates steeply dipping beds in the Cantwell formation. The mountain rises high above the highest levels reached by later glaciers that have left clear marks of their presence in the topography. Although erratic boulders deposited during some of the earlier glacial stages rest on the slope, any attempt to explain its origin through ice sculpture must account for the absence of such turtle-back slopes elsewhere along the Nenana Canyon at the same altitude. Likewise, any attempt to explain the slope through processes of solifluction similar to those operating elsewhere in Alaska (Taber, 1943, p. 1451–52; Eakin, 1916, p. 76–78), must also explain the general absence of such slopes when rocks of the same kind and the same age form mountains of the same age both east and west of this locality. The mountain lies just south of the pass between the Yanert Fork valley and the body of Nenana gravel along the McKinley Park highway. Its surface is thought, therefore, to be a portion of the unconformity, here deformed into an anticline, at the base of the Tertiary rocks.

Surfaces of similar origin are widely distributed throughout the Alaska Range. They occur where smooth-sided mountains in the shape of overturned canoes—such as the mountain north of All Gold Creek at the head of the Totatlanika River (pl. 1)—are flanked by terraced lowlands underlain by Tertiary rocks—rocks that dip away from the mountains at angles about equal to the slope of the mountainsides. Along the crests of the anticlines and along structural terraces these surfaces are essentially flat; and many of them, if traced far enough, will be found to coincide with the surface at the base of the Tertiary rocks elsewhere along the anticlines and structural terraces—for example, the surface at the top of the mountain cut by the lower Teklanika and Sushana Rivers (see pl. 1). Small patches of basal white quartz conglomerate resting on such flat surfaces coincide with the unconformity at the base of the coal-bearing formation.

Many flat surfaces cap mountains throughout the northern foothill belt of the Alaska Range. Examples are the flat top of Mount Wright and of the mountain east of it and north of the McKinley Park highway (pl. 6); the nearly flat top of the mountains through which the Teklanika and Sushana Rivers flow at about latitude 63°55′N. (pl. 6); Jumbo Dome and the mountains around the headwaters of California and Buzzard Creeks north and east of Jumbo Dome; and the top of Rex Dome and the mountaintops near Rex Dome. Although all these surfaces truncate the structure of the underlying schist, they are not necessarily remnants of the late Cenozoic preglacial erosion surface: in fact most of them are parts of the exhumed unconformity at the base of the Tertiary rocks.

[3] Wahrhaftig, Clyde, 1944, Coal deposits in the Costello Creek coal basin: unpublished report in files of U. S. Geol. Survey.

EVIDENCE OF EXISTENCE OF THE LATE CENOZOIC PREGLACIAL EROSION SURFACE

In a few places there is evidence to support the contention that some of the flat mountaintops are remnants of a late Cenozoic preglacial erosion surface. Mount Wright and its neighboring mountains provide the strongest evidence. In the first place, the surface on the tops of these mountains makes a sharp angle with the triangular facets on the spurs along the north side of the mountains—facets which are the upward extensions of the unconformity at the base of the Tertiary coal-bearing formation. This alone does not prove that the flat tops of the mountains are not part of an exhumed unconformity—specifically, the one at the base of the Nenana gravel, which is unconformable on the coal-bearing formation in this vicinity (Wahrhaftig, 1951, p. 182). However, the Nenana gravel, which was deposited from the south (Wahrhaftig, 1951, p. 179), has at its top a thick layer of conglomerate made up largely of boulders of Birch Creek schist. This schist could have come only from Mt. Wright and its neighboring mountains north of the McKinley Park highway, for no Birch Creek schist occurs south of the highway. The layer of conglomerate containing the schist is deformed, as is the rest of the conglomerate, and dips 30° S. near the mouth of the Savage River. The mountains from which the boulders of schist were derived could not have been buried by the Nenana gravel, for the layer of schist pebbles lies near the top of that formation. Furthermore, as will be shown in the next paragraph, the surface on which the Savage, Sanctuary, and Teklanika Rivers were consequent was formed after the deformation of the Nenana gravel and truncated folds and fault blocks in the Nenana gravel. It is very likely that the flat surface that truncates the structure of the schist in Mount Wright and its neighboring mountains is part of the late Cenozoic preglacial erosion surface.

FIGURE 4.—Aerial view, looking west, of the Teklanika and Sanctuary Rivers, showing superposed northward-flowing streams crossing eastward-trending structurally controlled ridges and valleys. Mount Wright is in the center of the photograph. Photograph by the U. S. Army Air Corps, 1941.

The evidence that best demonstrates that the flat top of Mount Wright is part of an ancient erosion surface is the remarkable discordance between drainage pattern on the one hand and topography and structure on the other, a discordance which can be explained only by postulating the existence of such a surface. The simple dendritic pattern of the northward flowing streams—the forks of the Toklat River, the Teklanika River and its tributaries, the Nenana River and Riley Creek, and Totatlanika and Tatlanika Creeks—gives no clue to the fact that the predominant trend of the ridges is eastward (pl. 6). More than that, several of the streams—the Nenana, Savage, Teklanika, Sanctuary, and East Fork of the Toklat—are remarkably parallel, trending about N. 15°–25° W., almost perpendicular to the structure (fig. 4). Clearly, these streams originated on topography or rock formations that had no similarity to the topography of the present Alaska Range. It is unlikely that the eastward-trending ridges were formed by faulting and folding which took place after this stream pattern was established, for many of the streams were too feeble to cut through rising ridges of schist and gneiss, and would quickly have been diverted, by capture, toward more vigorous streams. The upper Sushana, some of the forks of Totatlanika Creek, and Gold King Creek, for instance, have cut deep canyons in ridges of hard rock just a few miles downstream from their sources, although much easier courses exist to left or right of them along valleys and low passes underlain by softer rocks (pl. 1). It seems certain, therefore, that at one time a relatively smooth plain existed across at least part of the Alaska Range—a plain which may or may not have been covered by late Tertiary sedimentary rocks that were little deformed—that this plain was subsequently inclined northward, and that a consequent drainage developed on it. The tops of Mount Wright and its neighbors are probably remnants of this plain. It remains to be determined whether any other remnants of this plain exist, what its original limits were, and the amount of its subsequent deformation.

NATURE AND TOPOGRAPHY OF THE PREGLACIAL EROSION SURFACE

It is not possible to demonstrate conclusively that flat mountaintops other than those of Mt. Wright and its neighboring mountains are part of the preglacial erosion surface. The mountaintops of this part of the range, however, are probably not far below the level of the erosion surface, for the elevations of summits between longitude 148°10′ W. and longitude 149°30′ W., are between 6,500 and 7,000 feet. A reconstruction of the erosion surface at its present position is shown on figure 5. This reconstruction is based on the assumption that the top of Mt. Wright is a remnant of the surface and that the surface, if restored, would have a gentle northward slope, just clearing the tops of the mountains in this part of the Alaska Range. As figure 5 shows, the erosion surface is 3,000 feet high in the northern foothills and 6,000–7,000 feet high near the crest of the range, and it slopes about 90 feet per mile about N. 20° W.

Figure 5 also shows that certain mountains project above the level of the restored erosion surface. One of these is Rex Dome, which is believed to be the core of an anticlinal mountain of Totatlanika schist that rose above the erosion surface as a monadnock. Large areas, well to the east and west of the Nenana River, also rise above the reconstructed erosion surface. The mountains around the head of the Yanert Fork, 1,000–1,600 feet above the erosion surface, have a moderately well developed trellised drainage, and their rivers and glaciers flow westward. They probably were not reduced by erosion at the time the erosion surface was

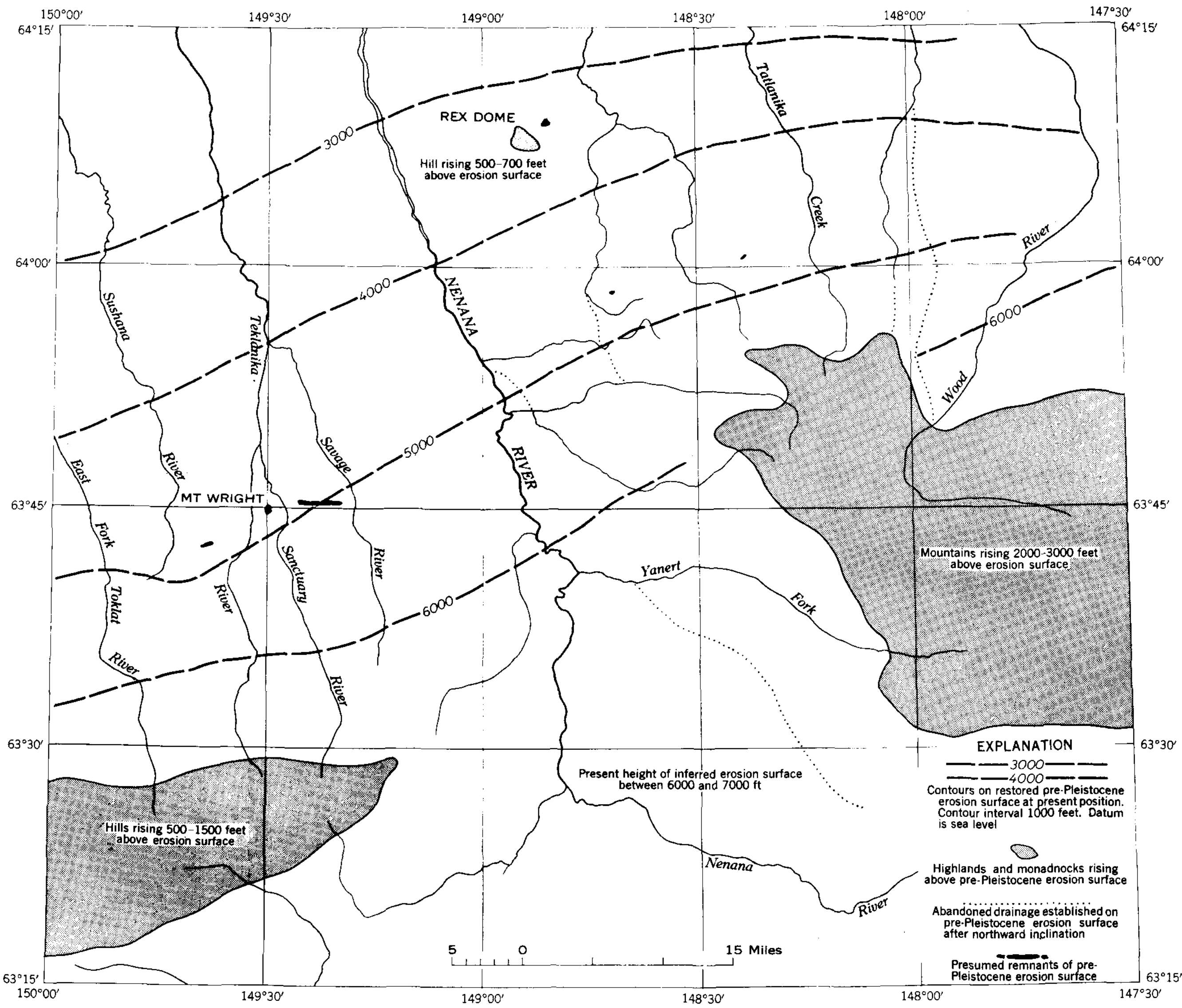

FIGURE 5.—Geography of the Alaska Range before the Browne glaciation.

being carved because they consisted largely of hard pre-Tertiary rocks, already possessing considerable relief, whereas the surfaces to the northwest and southwest were underlain largely by soft Tertiary rocks.

Similarly, the crest of the Alaska Range west of the head of the Sanctuary River rises above the restored erosion surface. It forms a drainage divide along a band of hard rocks a little north of what may have been the main drainage divide for this part of Alaska. This part of the range is the east end of a large group of high mountains rising above the erosion surface and culminating in Mt. McKinley, which probably had an altitude of 10,000–13,000 feet at the time the erosion surface was completed.

SUBSEQUENT DEFORMATION OF THE EROSION SURFACE

In preceding paragraphs it was shown that the present altitude of the erosion surface is 3,000–7,000 feet, and its northward slope is 90 feet per mile. If the gradient of the surface as a whole was no greater than the average gradient of streams now draining the Alaska Range and if the shoreline was near its present position, the erosion surface would have had an altitude between 1,000 and 2,000 feet in the Alaska Range. It has, therefore, apparently been uplifted at least 5,000 feet and possibly 6,000 feet in the central part of the range. As will be shown in the following sections, much of this uplift took place gradually throughout the Pleistocene, during and between successive glaciations.

The reader may wonder whether the present drainage of this part of the Alaska Range has been inherited from the drainage that carved the erosion surface. Although it seems likely that the westward courses of the upper Yanert Fork and the upper Wood River, adjusted as they are to the structure of the crystalline mountains, have persisted since the time these mountains were first eroded, the northward courses do not appear to have. The rivers that carved the erosion surface, which was probably very smooth, would be expected to have meandered considerably. Parallel development of stream courses, except on the most general plan, would have been fortuitous. The larger and more aggressive streams would have captured many of the smaller streams and developed a palmate dendritic pattern. Instead, the streams, with the exception of the Wood River and Totatlanika Creek, are remarkably straight and parallel, trending about N. 15°–25° W., almost perpendicular to the contours on the restored erosion surface. This remarkable parallelism is best explained by assuming that the streams flowed northwestward as a result of the northwestward tilting of the erosion surface. It is unlikely that any of the streams inherited a course which existed before the tilting. The pattern of the streams that carved the erosion surface still remains a mystery.

BROWNE GLACIATION

GLACIAL DEPOSITS ALONG THE NENANA RIVER

The oldest recognized glacial deposits consist of scattered boulders and blocks of granite on some of the higher mountains on either side of the Nenana River. The boulders measure as much as 40 feet on a side. Most of them are of rocks which occur only in the higher parts of the Alaska Range, at the headwaters of the Nenana River and the Yanert Fork. They are certainly too large to have been transported to their present positions by streams. They are found on terrains of Nenana gravel, coal-bearing formation, Totatlanika and Birch Creek schist, and Cantwell formation. Hence they were not deposited by mudflows or glaciers as an episode in the deposition of one of the Tertiary formations. The most likely explanation for their occurrence is that they are glacial erratics, the only remnants of ancient till sheets of an early glacial advance.

These boulders were first described by Capps (1912, p. 35), who recognized them as evidence for a glacial stage much older than the Wisconsin (Capps, 1931, p. 7). The boulders on the terrace near Browne define this glacial advance which in this report is called the Browne glaciation (fig. 6).

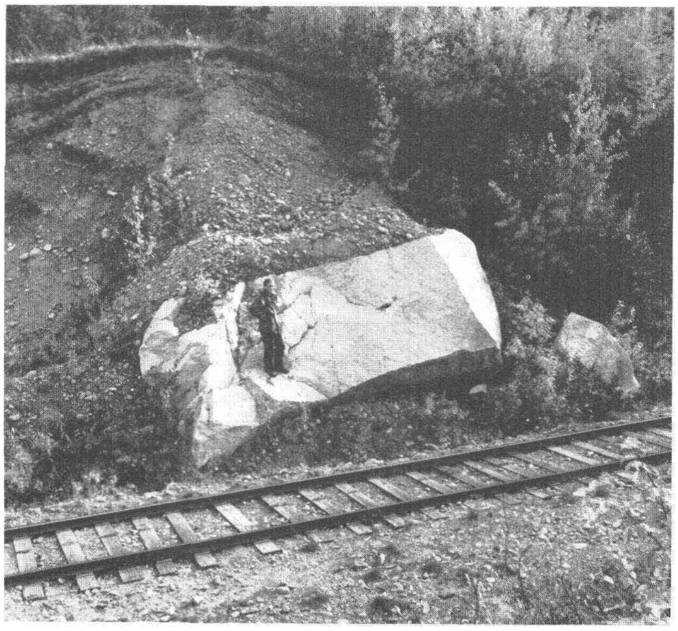

FIGURE 6.—Erratic of the Browne glaciation at mile 382 on the Alaska Railroad. This boulder has rolled or slid to the level of the railroad track from the terrace 400 feet above. The granite is sufficiently fresh to require blasting to make the railroad cut. The man standing on the boulder is 5 feet 7 inches tall.

Most of the boulders are of granite; many are of gabbro similar to that of the greenstone body between Windy and Clear Creek; and a few are of conglomerate and sandstone from the Cantwell formation. The granite of these boulders is strikingly similar petrographically to that from the large stock between the Yanert and Nenana Glaciers. Except for the presence of a dark-brown mineral which resembles allanite in the thin sections from the erratics, the granite is identical in appearance to that of the thin sections from the stock. Presumably it was derived in part from this stock, and possibly also from the stock at the head of Bruskasna Creek, which, according to Pogue (1915, p. 57), has a similar lithology. The granite is unlike that of thin sections of igneous rocks occurring elsewhere in the Alaska Range (see section on granitic intrusive rocks).

The distribution of the glacial erratics is shown on figure 8 and on plates 2, 3, and 5. In those areas mapped thoroughly on the ground (the area east of the Nenana River and in the basins of Dry Creek and Savage River) the erratics were plotted individually on the field maps. A record was kept of the number of foreign boulders larger than 5 feet in diameter observed between selected points in the bed of Lignite Creek and in the bed of Moody Creek. From these records graphs were prepared (fig. 7), showing the density of the boulders (presumably glacial erratics).

The counts, and the positions of the points between which they were made, were recorded on the sketch maps directly below the graphs. The points were then projected to the projection lines drawn on each of the sketch maps, and the intercepts between projections of the points were measured. The number of boulders in each intercept, divided by the intercept distance in thousands of feet, gave the number of boulders per 1,000 feet. This number was plotted at the midpoint of the intercept on the graphs. The points were then connected by a curve to give the graphs. The graphs have been reduced and reprinted in their correct geographic positions, on figure 8. Thus the locations of the very high concentrations of boulders on each creek may be compared with the general pattern of distribution of glacial erratics along the Nenana River. On Lignite Creek, the foreign boulders consist of granite, greenstone, and conglomerate. On Moody Creek they are of granite and greenstone.

The distribution of boulders in the area west of the Nenana River and north of Fish Creek and Pangengi Creek (including all of the area shown on figure 8) was determined from closely spaced helicopter flights, 100–500 feet above the ground. Landings were made at selected localities and samples of the boulders collected. It is felt that at least 70 percent of all the boulders in this area were located, probably a higher percentage than that located in the area covered by foot.

The glacial erratics which have been assigned to the Browne glaciation are found from McKinley Park station northward to the north edge of the foothills. The greatest concentrations are north of Healy. The distribution of the erratics is peculiar in that between distances of about 3 and 6 miles from the river on either side of it is a belt of very abundant boulders, while beyond, to east and west, only a few widely scattered boulders of the same types of rock occur. The western belt of high concentration occurs on top of the hill,

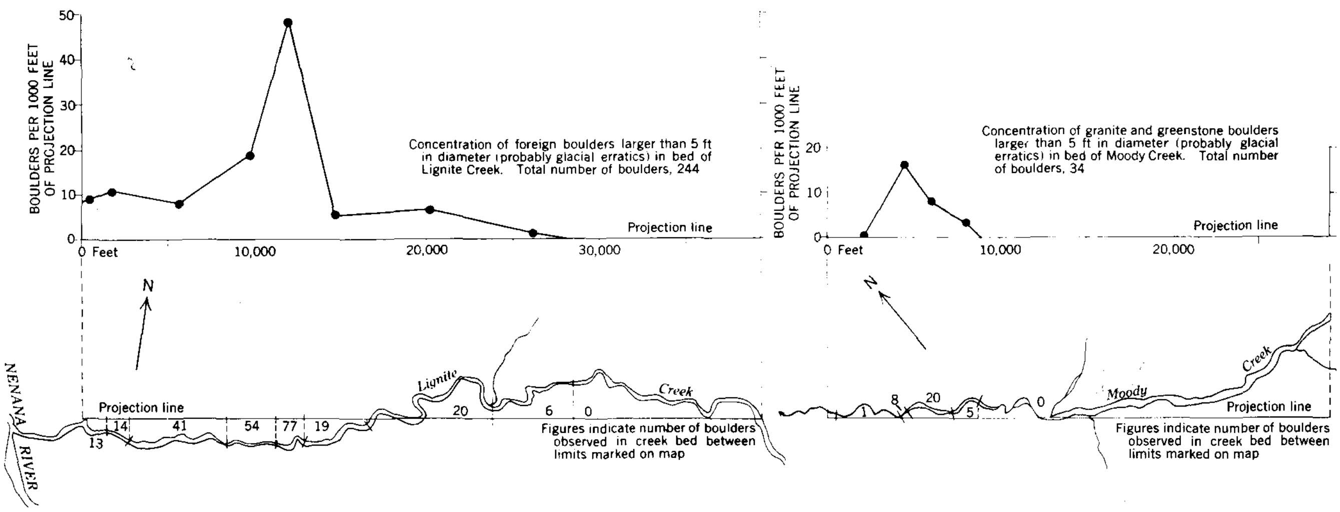

FIGURE 7.—Graphs showing the distribution of probable glacial erratics in the beds of parts of Lignite and Moody Creeks. The sketch map below each graph shows the position of the projection line of the graph with respect to each creek. The boulder counts on which the graphs are based are shown on the sketch maps. In order to make clear the significance of the distribution of the boulders, the graphs are shown at a reduced scale in their proper geographic positions on figure 8.

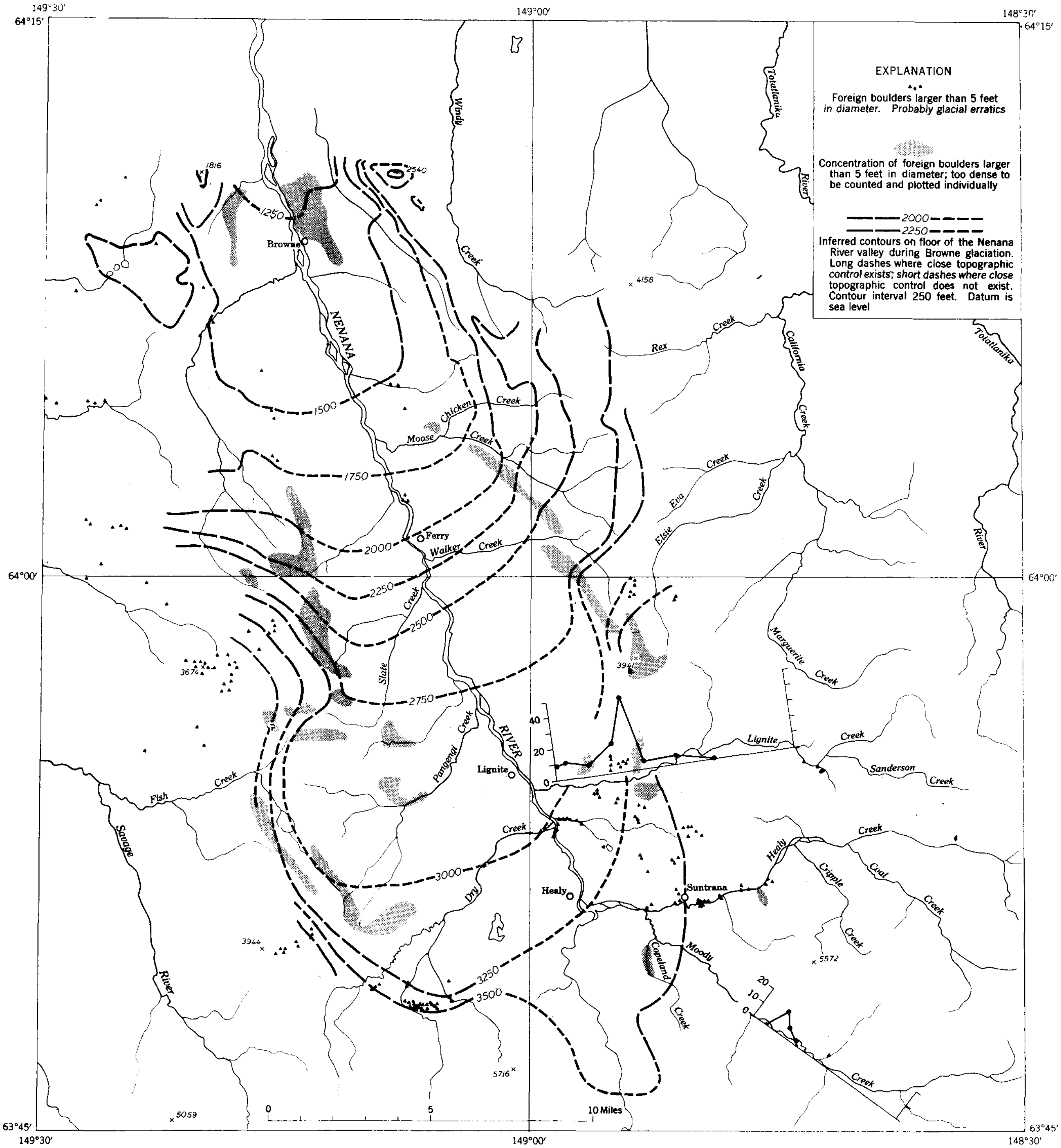

FIGURE 8.—Map showing distribution of probable glacial erratics of the Browne glaciation along the Nenana River, and contours on the inferred floor of the Brown glacial valley of the Nenana River. The graphs shown on figure 7 have been reduced and reprinted in their proper geographic positions on this map. For explanation of the graphs see figure 7.

3,120 feet in altitude, between the forks of Dry Creek, about 6 miles southwest of Healy; and along the ridge north of Dry Creek between altitudes of 2,700 and 3,000 feet, 5–7 miles west of Healy (see pl. 6 and fig. 8). It continues northwestward along the watershed between Pangengi and Fish Creeks; two low ridges along either side of the lake at the head of Fish Creek have numerous boulders. The belt extends around the flank of the mountain west of Slate Creek between altitudes of 2,500–3,000 feet, where the boulders litter the remnants of a high terrace. The belt continues northward along this bench for about a mile beyond the latitude of Ferry (see pl. 5). North of this bench is a gap in the belt about 7 miles wide, in which there are very few boulders. Beyond the gap, granite boulders again occur in abundance, littering the surface of a terrace 1,200–1,350 feet in altitude, 1 to 2 miles west of the Nenana River. This segment of the belt extends from the north edge of the foothills, at a point opposite Browne, northward to the bluff facing the Tanana Flats.

West of this band of boulders a few boulders of granite, gabbro, and conglomerate are widely scattered for a distance of from 5 to 7 miles. A few granite boulders, 3–5 feet across, occur on the top of the 3,944-foot mountain north of Dry Creek, about 9 miles west of Healy. Three granite erratics are on the ridge north of Fish Creek, the farthest west boulder being 10 miles from the Nenana River and only 2 miles from the Savage River.

Many granite and gabbro boulders litter the top of the 3,674-foot mountain west of Slate Creek (see fig. 8). This is the greatest concentration of these boulders outside the belt of abundant boulders. A few boulders of granite and conglomerate were spotted in the rolling upland country in the western part of Fairbanks A–4 quadrangle; the concentration of erratics averages one every 4 square miles, far less than the concentration of boulders in the belt of abundant boulders nearer the Nenana River.

On the east side of the Nenana River the belt of abundant boulders begins on Moody Creek, where boulders of granite, gabbro, and conglomerate, from 1 to 10 feet in diameter, are found as far upstream as a point 6½ miles southeast of the stream mouth. The rocks from which these boulders were derived are foreign to the drainage basin of Moody Creek. No foreign boulders were observed beyond that point, although the creek was carefully examined as far as its headwaters. One of the graphs on figures 7 and 8 shows the concentration of boulders observed on Moody Creek. Boulders are common on Healy Creek as far as 3 miles east of Suntrana. None are present on Healy Creek above this point, nor in the basins of Coal and Cripple Creeks. Erratics, the largest 30 feet long and 15 feet high, are found as high as 3,200 feet on the ridge north of Suntrana (see pl. 2). Erratics are very abundant in the bed of Lignite Creek, where they have probably been deposited by mudflows from the surrounding highlands. Their concentration is greatest 3 miles east of the mouth of the creek, above which point it falls off abruptly. East of a point 6 miles above the mouth of the creek there are no large boulders except that 9 miles above the mouth of Lignite Creek, 4 large boulders of granite and gabbro occur. (See fig. 8.) The largest of these is 15 feet across. Granite erratics are common along the ridges on either side of Walker Creek, about 5 miles east of the Nenana River. From this locality, the belt of abundant erratics continues northward to the junction of Chicken and Moose Creeks. A deposit of coarse sand and gravel, containing scattered erratics, caps the 1,600-foot terrace just north of the junction of Moose and Chicken Creeks (see pl. 5). This may be coarse till or outwash of the Browne glaciation. Extending northward from this terrace almost to Browne is a 5-mile gap in the belt. Between Browne and the north edge of the hills, abundant granite erratics are associated with a deposit of sand and gravel about 50 feet thick, which covers part of a terrace 500 feet high on the east side of the Nenana River. Boulders have slid down the face of this terrace into the Nenana River, where they may be seen on both sides of the railroad track. One and a half miles north of Browne it was necessary to blast through one large boulder for the right-of-way of the Alaska Railroad (see fig. 6).

There are very few boulders east of the eastern belt of abundant boulders. One was observed on top of the 2,540-foot mountain 4 miles northeast of Browne; a few occur east of the head of Elsie Creek; and 4 boulders, which have already been mentioned, were found 9 miles above the mouth of Lignite Creek.

The belts of abundant boulders which have been described coincide with what appear to be the borders of an ancient valley of the Nenana River, incised about 2,000 feet below the preglacial erosion surface. The most striking remnant of this valley is the prominent terrace which occurs on both sides of the Nenana River. On the east side of the river it can be traced from the north edge of the foothills southward to Moose Creek; and on the west side, from the north edge of the foothills to Slate Creek. This terrace defines a valley about 4 miles wide at Browne and about 6 miles wide at Ferry. It is about 450 feet above the river at the north edge of the foothills, and rises southward to about 1,700 feet above the river in the vicinity of Slate Creek.

South of Slate Creek the remnants of the ancient valley floor consist largely of ridge crests. The most prominent of these ridge crests is north of Dry Creek. It has an abrupt change in altitude about 6 miles west of Healy, close to the western limit of abundant glacial erratics. West of this point the altitude of the crest is about 3,800 feet, and the ridge is a simple hogback having a smooth north slope. The crest is held up by a zone of beds of boulder conglomerate in the Nenana gravel. The crest of the lower eastern part ranges in altitude from 2,800 to 3,200 feet, and trends in part transverse to the strike of the beds. Extending northward from the low eastern part of the ridge are several long even-crested spurs, which end abruptly at the zone of coarse boulder conglomerate which holds up the higher western part. The strike and dip of the beds in the Nenana gravel are constant through the entire ridge. There is no break in structure or change in lithology to account for the abrupt change in the height and character of the ridge. The change is thought, therefore, to be due to erosion, either by the Nenana River, or by a glacier moving down the Nenana River valley. The western limit of abundant boulders coincides closely with the west wall of this ancient valley.

Between McKinley Park station and Healy between miles 349 and 352 on the Alaska Railroad are four even-crested ridges having altitudes of 3,000–3,500 feet (see pl. 2). They are on the east wall of the Nenana gorge and at right angles to the gorge. They give the impression of marking an ancient valley floor or terrace of an open-valley stage. This open-valley stage is probably the same as that indicated by the ridge crest north of Dry Creek.

The glacial erratics of the Browne glaciation are remarkably fresh. Thin sections ground from chips taken from the surface of several erratics show very little development of weathering products. The erratic shown on fig. 6 was so firm that explosives were necessary in constructing the roadbed for the Alaska Railroad through it. Thus it would appear that the weathering of the erratics has been negligible, a surprising fact if true, for the Browne glaciation was followed by three major glaciations. Judging by the amount of uplift and erosion that occurred after the Browne glaciation, the author would be inclined to assign the Browne glaciation to an early glacial stage in the Pleistocene, possibly Kansan or Nebraskan. Actually, however, the weathering of these boulders has been considerable. In fact, the boulders which now litter the hillsides and terraces on either side of the Nenana River are only remnants and fragments of the original boulders which were carried out by the glacier. The weathering was predominately mechanical, since even in interglacial times the climate in this area was either cold-temperate or subarctic. The fine-grained weathering products were removed as fast as they were formed.

Several of the glacial erratics have fantastic and irregular projections as much as 5 feet long. These are usually upheld by dark inclusions in the granite, apparently more resistant to mechanical disintegration than the granite itself. If the boulders had been transported in this condition by the glacier the projections would have probably broken off. Boulders having such projections are not found on modern glaciers. It seems clear, therefore, that the erratics owe their unusual shapes to weathering of the surface layer, probably by frost disintegration.

The ground surrounding granite boulders in the gravel flood plain of Lignite Creek has an accumulation of thin spalls of granite, which can be crushed in the hand. They have apparently accumulated over a period of not more than 20 years, for the creek, which probably swept the base of each boulder within that time, would have removed the spalls. One boulder on Lignite Creek is exposed in the side of a gravel terrace about 15 feet high. The boulder itself is nearly 15 feet high. The lower part of the boulder has been smoothly polished by the stream for about 5 feet above low water on the creek. Above this level the surface of the boulder is rough and pitted, indicating that considerable spalling of the surface has occurred since it was last polished by the stream.

Many of the erratics on the terraces and high mountainsides occur in clusters of a half dozen or more, which are separated by some distance from each other. A large cluster of this kind occurs on the north side of the ridge north of Suntrana. Others were found on the terrace north of Browne. Some of the boulders of these clusters have plane sides, although the edges and corners are slightly rounded; on close examination they are seen to fit together. They were probably derived by frost riving of much larger boulders—the original glacial erratics. Although there are no weathered boulders here such as those common to the older tills of temperate regions, that is, none of the types of boulders on which weathering counts are made to distinguish separate glaciations (Blackwelder, 1931), the erratics of the Browne glaciation have, nevertheless, been considerably eroded.

GLACIAL LOBE DEFINED BY THE GLACIAL DEPOSITS

The distribution of the glacial erratics of the Browne glaciation indicates that a great glacier advanced from the highlands around the Yanert and Nenana Glaciers westward and northward down the Nenana River to a locality a few miles north of Browne. The floor on which the glacier advanced has been fairly well preserved northward from Moose Creek as the high terrace on which the glacial erratics occur. At Moose Creek this floor has an altitude of 1,600 feet, and 9 miles farther north it has an altitude of 1,200 feet. Its present slope in this distance is, therefore, 45 feet per mile. This part of the glacier lobe occupied a broad valley 500–1,000 feet below the hills on either side. The valley had been incised by the Nenana River almost 2,000 feet below the level of the preglacial erosion surface. Southward from Moose Creek the topography formed by the Browne glaciation near the Nenana River has been destroyed, although the level of the valley floor is indicated by the low part of the ridge crest north of Dry Creek and by the accordant ridge crests on the east side of the Nenana gorge between Moody and McKinley Park station. Using the terrace and accordant ridge crests as control, contours were drawn on figure 8 to show the inferred valley floor of the Nenana River during the Browne glaciation.

The close association of the deposits of abundant boulders with the remnants of the ancient open-valley stage suggests a close genetic relation. Presumably, the great concentrations of boulders represent lateral moraines. The deposits lie close to the walls of the ancient valley. This suggests that the valley walls confined the ancient glacier. If this relation between valley walls and glacier existed, the occurrence of widely scattered boulders far beyond the limits of the valley is difficult to explain in terms of a single glacial advance. The glacier could have expanded greatly during a short period, during which it carried little till, then retreated within the valley and there accumulated massive moraines. A more reasonable explanation, the author believes, is that the widely scattered boulders represent a glaciation that occurred earlier than the Browne glaciation and that was separated from it by a long interglacial period. In an effort to determine whether or not the widely scattered boulders on the high mountaintops could have been deposited by the glacier of the Browne glaciation, an attempt was made to estimate the probable thickness of the glacier. It was assumed that the Browne glacier in the Nenana River valley would have had about the same structure and thickness as the glaciers of the later glacial periods and that it would have occupied a similar topographic position. To determine the thickness of ice during these later periods, well-defined ice-contact features high on the sides of valley walls were measured at several localities on many of the rivers in the Alaska Range. These measurements are presented in table 4.

TABLE 4.—*Thickness of ice of the Healy and Riley Creek glaciations along rivers of the Alaska Range*

River	Distance from terminus to point of measurement (miles)	Thickness at point of measurement (feet)	Average downstream decrease in thickness (feet per mile)
Healy glaciation:			
Nenana	19	1,000	53
Wood	19	1,800	95
East Fork of the Toklat	12	1,000	85
Riley Creek glaciation:			
Nenana	4	600	150
Nenana	12	1,500	125
Yanert Fork	16	1,600	100
Wood	16	1,200	75
East Fork of the Toklat	5	800	160
Teklanika	9 (?)	600	70
Delta	12	1,200	100
Delta	22	1,400	65

From these data it appears that, in general, the thickness of the Browne glacier increased roughly 100 feet per mile for about 15 miles south of its terminus, and beyond that point it remained relatively constant. The maximum thickness in the vicinity of Lignite was probably 1,000–1,500 feet, as it was more nearly like the Delta River glacier in ground plan than any of the other ice streams listed in the table. It could, therefore, have overridden the 3,941-foot mountain at the head of Elsie Creek, as well as the 3,674-foot mountain southwest of Ferry and the 3,944-foot ridge west of Healy; thus it could have deposited all the boulders which have yet been found, with the possible exception of the boulder on the 2,540-foot mountain west of Windy Creek. If it overrode these mountains, it is difficult to understand why the glacier should have left only a few scattered boulders on and beyond these mountains and a great abundance of boulders on the valley floor at their base. It is unlikely that erosion subsequent to the Browne glaciation removed most of these boulders, for the 3,674-foot mountain is graded to the terrace formed during the Browne glaciation on the east side of the mountain. Furthermore, if such erosion took place, streams should have delivered many boulders to the Teklanika and Totatlanika drainage; yet, although a careful search for foreign boulders was made along these streams and the streams draining into them, none were found.

There thus appears to be some evidence to suggest that the erratics here grouped under the Browne glaciation along the Nenana River were deposited during two separate glacial advances; nevertheless, it is entirely possible that they were deposited during a single advance.

UPLIFT OF THE ALASKA RANGE SINCE THE GLACIATION

The present slope of the valley floor formed by the Browne glaciation between Moose Creek and Lignite is about 100 feet per mile (see fig. 8). North of Moose Creek and south of Lignite it is about 60 feet per mile. The over-all slope of the present-day Nenana River across the Alaska Range is about 25 feet per mile, projected to a straight line parallel to the river. The Nenana River during the Browne glaciation very likely had a similar slope. Therefore, the total northward inclination since the Browne has amounted to 75 feet per mile in the stretch from Moose Creek to Lignite, and about 35 feet per mile from McKinley Park station to Lignite and from Moose Creek to Browne.

GLACIATION ON THE WOOD RIVER

Very large boulders of granite and gabbro mantle the plateau surfaces to the east and west of Gold King and

Bonnifield Creeks at altitudes of 3,000–4,000 feet. (See pl. 2.) The sources of these rocks were the granite bodies on the tributaries of the Wood River (pl. 1) and a gabbro beneath the Cantwell formation on Young Creek (pl. 1). Thus a glacier moved from the headwaters of the Wood River to the plateau surface around Gold King Creek (see pl. 6). As no granite boulders were observed mantling the plateau surface north of the head of Coal Creek (tributary to Wood River), the main valley down which the glacier flowed must have been west of Coal Creek. It probably extended through the pass between Mystic Creek and Bonnifield Creek. This implies a considerable change in drainage, as well as downcutting by the Wood River of 2,000 feet since the glacier which deposited these boulders advanced down the Wood River. The downcutting is comparable to that of the Nenana River and its tributaries through deposits of the Browne glaciation in the vicinity of Healy. Hence, the boulder deposits are tentatively correlated with the Browne glaciation on the Nenana River.

TOPOGRAPHY DURING THE GLACIATION

Figure 8 indicates clearly that the part of the Alaska Range which was truncated by the erosion surface had a relief of about 2,000 feet during the Browne glaciation. During the Browne glaciation the appearance of the inner parts of the range, around McKinley Park station and Carlo, must have been similar to the present appearance of the northern foothills west of the Nenana River, where the relief is of the same order of magnitude. Low, rolling ridges, probably having smooth, nearly flat summits, marked the emerging pre-Tertiary cores of the anticlines, which later became the rugged east-west ridges of the Alaska Range. The intervening valleys, cut on Tertiary rocks, which at that time must have covered most of this part of the Alaska Range, either were nearly featureless plains or had broadly terraced slopes. The mountains of the Mount Hayes group probably stood 5,000–9,000 feet above the valley bottoms, and may have been 10,000–11,000 feet in altitude. They were high enough for ice to have accumulated on them. The mountains of the Mount McKinley group were even higher, Mount McKinley being perhaps 16,000 or 17,000 feet in altitude. The mountains between the Alaska Range and the Pacific ocean probably were much lower than they now are, and may not have blocked the passage of moist winds. Hence the Browne glaciation could have been more extensive in the Alaska Range than the succeeding stages, even though the mountains were not nearly as high as they were later.

DRY CREEK GLACIATION

DEPOSITS ALONG THE NENANA RIVER

The next glacial advance in the Alaska Range is named the Dry Creek glaciation and is described for the first time in this paper. Glacial and related deposits which are assigned to the Dry Creek glaciation lie on hillsides at a level well below that of glacial erratics of the Browne glaciation but above deposits of the younger Healy glaciation, described in the following section.

A deposit of yellowish-brown varved clay on the east side of the valley of Dry Creek serves best to define the altitude of the ice during the Dry Creek glaciation and the amount of uplift and erosion which occurred between the ice advance of this stage and the ice advances before and after it. It is at an altitude of 2,400 feet at about latitude 63°49′ N., longitude 149°05′ W. (pl. 2). The varved clay is flat-lying, and it appears to be a remnant of a deposit which may once have filled the valley of Dry Creek. It was apparently deposited in a lake dammed by ice moving down the Nenana River, although all other vestiges of this lake have been destroyed. The terminal moraine of the Healy glacier is well preserved on a broad terrace about 2 miles northeast of the varved-clay deposit, at an altitude of 1,850 feet (pl. 2), and makes up the south bank of the lower course of Dry Creek. It is clear that the Healy glacier could not have been responsible for the damming of the lake, for its upper level lay well below the level of the clay, and adequate drainage was provided around the ice terminus. On the other hand, the valley of Dry Creek is 400 feet below the lowest ridges on which boulders assigned to the Browne glaciation occur and about 700 feet below the supposed level of the valley floor of the Browne glaciation at this locality. Furthermore, Dry Creek and the ridge north of it trend at right angles to the direction of flow of the Browne glacier, and the topography on which the lake deposit rests was very probably formed after the ice advance of the Browne. Therefore, if the varved clay was deposited in a glacially dammed lake, it is younger than the ice advance of the Browne and older than the ice advance of the Healy, and was deposited caused by a glacier whose restored upper surface would be at least 500 feet higher than the restored upper surface of the Healy ice.

The broad flat-topped mountain between the Nenana River and Riley Creek about 4 miles due north of Carlo rises to an altitude of 3,700 feet. (See pl. 3.) Glacial erratics are strewn over its top. On its southwest side, at an altitude of 3,175 feet, is a low rounded ridge of till, which is probably a remnant of a lateral moraine of a lobe of the Nenana glacier of the Healy glaciation.

Therefore, the erratic boulders on the mountains above this moraine ridge were probably deposited by a glacier which stood at least 500 feet higher than the Healy glacier. They could have been deposited by the glacier which dammed Dry Creek to form the varved-clay deposit.

In 1951 the author observed large rounded white boulders, presumably granite, wasting out of a deposit on a bench at an altitude of 4,000 feet, about 1¼ miles north of Carlo triangulation station (VABM 4929, between Carlo Creek and Revine Creek, on pl. 3). These boulders are about 500 feet higher than a ridge of till which, as observed from the air, appeared to dam the valley just east of Carlo triangulation station. The ridge is correlated with the Healy glaciation, and is regarded as marking the ice limit of that glaciation. The deposit of white boulders is, therefore, regarded as marking the ice limit of an earlier glaciation which stood 500 feet higher on the mountain sides than the Healy ice. A similar deposit of boulders occurs at an altitude of 4,000–4,300 feet on the west wall of the Nenana River gorge, 1½ miles west of the mouth of Carlo Creek.

The position of these deposits and their relations to the profile of the glacier they represent, and to older and younger glaciers, are shown in the longitudinal profile of the Nenana River (see pl. 7).

OUTWASH GRAVEL ON THE NENANA RIVER

The glacial outwash deposits of the Dry Creek glaciation are believed to be represented by a prominent terrace, which has a thick cap of terrace gravel, on either side of the Nenana River. This terrace extends from about Lignite Creek to a point a short distance north of Ferry. (See pls. 2 and 5.) In the vicinity of Lignite, the top of the gravel on the outwash terrace of the Dry Creek glaciation lies at an altitude of 2,200 feet, about 450 feet above the highest of the terraces which appear to be associated with the Healy (fig. 9), and about 500 feet below the restored profile of the Nenana River of the Browne glaciation. In the vicinity of Ferry, about 8 miles north, it is about 350 feet above the terraces of the Healy. Farther north the terrace has been removed by erosion.

Exposures of gravel underlying the terrace are poor, but east of the Nenana River, opposite Lignite, gravel appears to be 50–100 feet thick (see fig. 9). This gravel appears to have been deposited by the Nenana River, for it is blue gray in color, as is the gravel now being deposited by the Nenana River, and consists of boulders of unweathered gabbro, granite, Birch Creek schist, dark-gray conglomerate, and coarse sandstone from the Cantwell formation. It is completely unlike gravel deposits derived from the Nenana gravel. The latter, which form alluvial cones resting on the distal parts of the terrace, are commonly buff to brown in color. Boulders derived from the Nenana gravel—although also consisting of schist, gabbro, granite, conglomerate, and dark sandstone—are commonly deeply weathered and iron-stained, and terrace gravel derived from the Nenana gravel is quite similar in color and appearance to the Nenana gravel itself.

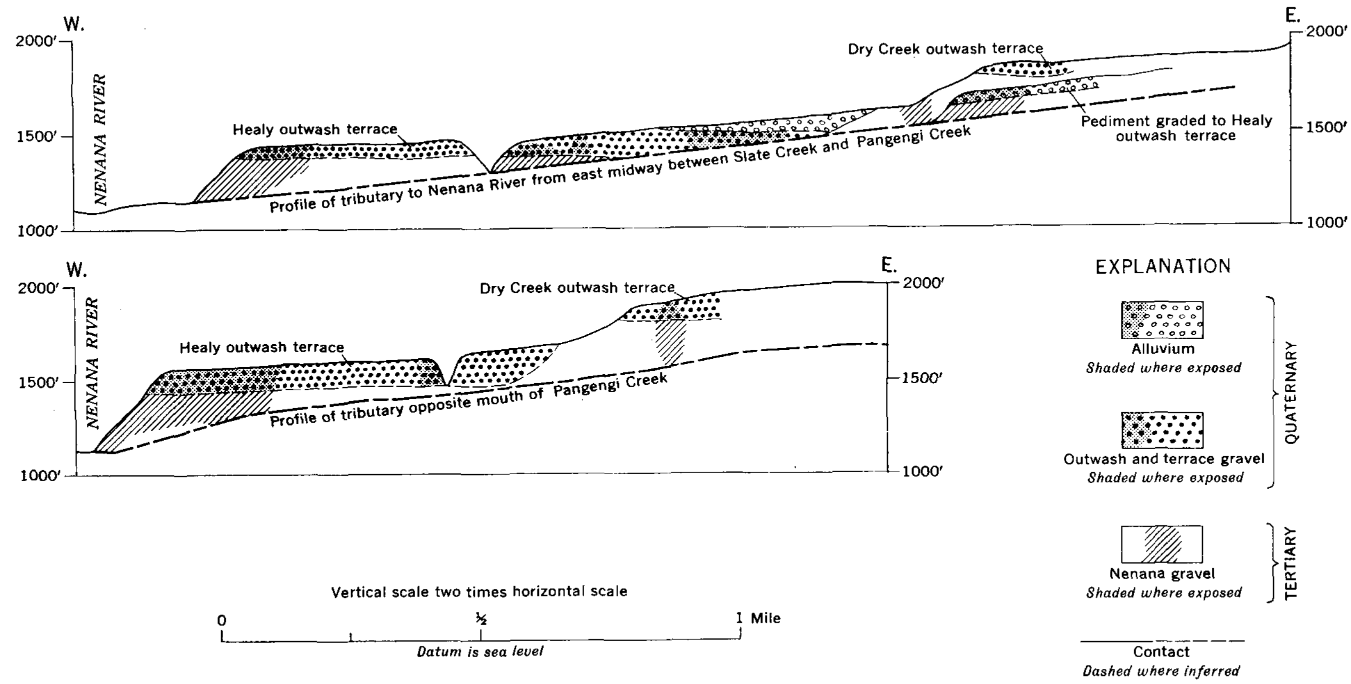

FIGURE 9.—Cross sections of terraces on the east side of the Nenana River between Lignite Creek and Ferry.

The terrace on the west side of the river forms the flat top of the mountain just north of Pangengi Creek, 3 miles due west of Lignite. Many white granite boulders litter the top and south side of this mountain, down which they are slowly sliding into the bed of Pangengi Creek. These boulders could be remnants of till of the Dry Creek glacier. If so, they would indicate the approximate northern limit of this glaciation, for the terrace gravels north of this point clearly were deposited by river and must represent an outwash plain. It is more likely, however, that these boulders were deposited by ice of the Browne glaciation, and later were partly reworked by the Nenana River and its tributaries. They remained on the terrace at this point because they were too large to be moved any farther.

An indistinct bench that appears to be a remnant of a terrace is preserved at an altitude of 2,500 feet about a mile east of the lake at the head of Poker Creek and about 2 miles north of the junction of Moody and Healy Creeks. If it is a terrace remnant, it would correlate with the outwash terrace of the Dry Creek glaciation.

GLACIAL ADVANCES ON OTHER RIVERS

Climatic conditions that could cause a glacial advance down the Nenana River as far as Healy would, in all likelihood, have caused ice advances of comparable magnitude on other rivers of the Alaska Range. Deposits of till and erratics that are assigned to this glaciation because of their topographic position and relations to other glacial deposits have been found on the East Fork of the Toklat River, on Igloo Creek, Savage River, and Moose Creek (tributary to Tatlanika Creek). These deposits lie only a few hundred feet above the adjacent streams, on topography which appears to be younger than the Browne glaciation. The uplift and tilting that caused the valleys of the Nenana and Wood Rivers to be deepened 1,000 to 2,000 feet also affected the East Fork of the Toklat River, Igloo Creek, the Savage River, and Moose Creek. Although not all of these streams deepened their valleys as rapidly as did the Nenana and Wood Rivers, they must all have deepened their valleys many hundreds of feet since the Browne glaciation, and therefore these deposits are thought to lie considerably below the level that must have prevailed in these valleys during Browne time. If, instead, we assume that the glacial deposits in question are of Browne age, then the valleys in which they lie would have been so deep during Browne time that they should have captured the drainage of both the Nenana and Wood Rivers. On the other hand, the deposits lie above and beyond the limits of the Healy glaciation, or occupy ancient valleys which probably were abandoned before the advent of the Healy glaciation.

Glacial deposits at two localities in the drainage basin of the East Fork of the Toklat River have been assigned to the Dry Creek glaciation. One of the deposits is at an altitude of about 2,600 feet on the west bank of a tributary stream at about latitude 63°43′N. and longitude 149°53′W. (pl. 6). It consists of till, largely boulders of andesite and rhyolite. According to Capps (1932, pl. 4), the drainage basin of the tributary consists almost entirely of Birch Creek schist and Paleozoic and Mesozoic sedimentary rocks. The mountains at the headwaters of the creek are not as high as other mountains nearby which appear not to have supported glaciers during the Healy and Riley Creek glaciations. The volcanic rocks could have been derived from volcanic terrain of the main valley of the East Fork of the Toklat River. Although rock types exactly like those of the till have not been found in place where the McKinley Park highway crosses the volcanic terrain, they may crop out farther downstream.

If the till was brought to its present position by a glacier advancing down the tributary valley, the surface over which the glacier advanced must have been largely destroyed. This is indicated by the narrow V-shaped gorge having interlocking spurs several hundred feet high that extends 3 miles southward (upstream) from the deposit. Above the inner canyon is a broad canyon having straight flaring walls and a floor about a quarter of a mile wide, which could have been occupied by a glacier. However, this upper canyon is far narrower than the broad U-shaped valley of the East Fork of the Toklat, which ends abruptly downstream about 5 miles south of the till deposit. It would appear therefore that the glacier which deposited the till, if it advanced down the East Fork of the Toklat, is very old, and that uplift and erosion amounting to several hundred feet have occurred since its advance. Evidence presented in the following sections indicates that two separate glacial advances have taken place on the East Fork of the Toklat River since the deposition of the till. These are correlated with the Healy and Riley Creek glaciations on the Nenana River. On the other hand, the deposit could hardly be as old as the Browne glaciation, for it is only 400 feet above the present level of the nearby East Fork of the Toklat River. Presumably, the valley floor of the East Fork of the Toklat River during the Browne glaciation would have been much higher than the present river level.

Although the till deposit is correlated with the Dry Creek glaciation on the Nenana River, the evidence for the ice advance in the tributary valley is still tentative. The geology at the head of the tributary was studied only in reconnaissance fashion by Capps and Brooks. The absence of volcanic rocks in situ in the basin of this tributary must be proved before it can be stated with certainty that the volcanic rocks that make up the till deposit came from the basin of the East Fork of the Toklat.

The second glacial deposit assigned to the Dry Creek glaciation in the drainage basin of the East Fork of the Toklat River is at the top of the 4,900-foot mountain about 3 miles S. 20° E. of Sable Mountain in Mount McKinley National Park. Here, large boulders of limestone and of a clastic breccia consisting of limestone pebbles in a matrix of well-cemented graywacke litter the surface. Some of these boulders are more than 10 feet long. As they are not found in the Nenana gravel, which makes up this mountain, they must have been brought here by glaciers advancing down the East Fork of the Toklat River from mountains to the south, where these rock types are present. The boulders are 1,500 feet above the bed of the East Fork of the Toklat River, and about 500 feet above benches which are regarded by the author as ice-contact benches formed at the maximum extent of the next younger glaciation—The Healy. They are believed to be younger than the Browne ice advance because they rest on topography which is believed to have been carved later than the Browne glaciation. Hence, they are regarded, together with the deposit of till 14 miles north, as evidence of a glacial advance whose height, extent, and age were about the same as those of the Dry Creek ice advance on the Nenana River. This ice advance is, therefore, correlated with that of the Dry Creek.

A field of boulders, about 50 percent of which are of Birch Creek schist and the remainder of granite, gabbro, conglomerate and basalt, lies in a creek about half a mile north of a point on the McKinley Park highway 3 miles east of the Savage River bridge. Boulders 3 feet across are common, and the largest one observed was an angular boulder of conglomerate 6 feet long. The schist could have been deposited by streams draining the ridge of Birch Creek schist north of the highway, but the other rocks could have been deposited only by glaciers advancing out of the mountains to the south. The terrain on which the other rocks rest is underlain by Birch Creek schist and the Tertiary coal-bearing formation, neither of which contains boulders of granite, gabbro, or conglomerate of this size. It is unlikely that the till could have been deposited by a glacier advancing down the Nenana River, for no similar deposits were observed east of this creek, although every stream bed crossing the highway as far east as the head of Hines Creek was carefully examined. The deposition of these boulders by a lobe of the Sanctuary glacier seems unlikely also. If the Sanctuary glacier had advanced to this point, one would suppose that a lobe of the glacier would have moved down the Sanctuary canyon north of the highway; yet, no evidence of glacial erosion was found in this canyon, which is a narrow V-shaped one, 2,000 feet deep, having interlocking spurs. The only remaining hypothesis is that the boulders were deposited by ice advancing down the Savage River. This ice may have reworked till of the Browne glaciation containing granite boulders, for no bodies of granite are known to occur at the head of the Savage River. Reasons for concluding that the Savage River canyon was not occupied by ice during the last (Riley Creek) glaciation are given in another section of this report. It seems likely that the U-shaped gorge of the Savage River south of the McKinley Park highway was formed during the Healy glaciation. The deposit of boulders is believed to be beyond the terminus of the Healy ice, although all topographic evidence of the terminal moraine of the Healy has been destroyed. Therefore, the glacial advance which deposited the erratic boulders is tentatively assigned to the Dry Creek glaciation.

Boulders of Birch Creek schist, the largest of which is 8 feet long, are strewn over the flat saddle (altitude, 4,000 feet) between the head of Moose Creek and the head of Gold King Creek, about 3 miles due north of Keevy Peak. The saddle is underlain by Totatlanika schist, and the contact between the two schists is almost 2 miles south, on the flanks of Keevy Peak. Presumably these boulders are erratics left by a glacier which advanced northward from the cirque at the head of Moose Creek. In all likelihood, Moose Creek drained northward to Gold King Creek at the time of this glacial advance, but has since been diverted by headward capture toward Tatlanika Creek. The stream bed is now several hundred feet below the boulders. The boulder deposit is tentatively correlated with the Dry Creek glaciation, although it is possible also that it was formed during the Browne glaciation.

No glacial deposits definitely assignable to the Dry Creek glaciation were found on the Wood River.

UPLIFT AND EROSION DURING THE INTERVAL BETWEEN THE BROWNE AND DRY CREEK GLACIATIONS

Comparison of contours on the restored valley of the Nenana River during the Browne glacial advance (fig. 8) with the profile of the Dry Creek outwash terrace (pl. 7) shows that the Nenana River of the Browne glaciation had a slope of about 25 feet more per mile between Lignite and Browne than had the outwash terrace of the Dry Creek glaciation (see table 5). The greatest divergence in slope—37 feet per mile—was between Ferry and Lignite. Table 5 indicates that the Alaska Range was uplifted 700 feet during the interval between the Browne and Dry Creek glaciations, and that the displacement was largely restricted to a narrow monoclinal belt, about 8 miles wide, along the north side of the range. Presumably, this belt extends eastward from the Nenana River, passing just north of the high plateau near Gold King Creek, where deposits of the Browne glaciation indicate that the valley floor was 2,000 feet above the present river level. The monoclinal flexure probably trends southwestward from the Nenana River toward the Kantishna Hills.

TABLE 5.—*Differences in present altitude of Nenana River profiles of Browne and Dry Creek glaciations*

Locality	Distance from Browne (miles)	Altitude of the restored profile of the river formed during the Browne glaciation (feet)	Altitude of the restored profile of the river formed during Dry Creek glaciation (feet)	Difference (feet)
Browne	0	1,300	[1] 1,100	200
Ferry	10	2,000	1,650	350
Lignite	18	2,850	2,200	650
Healy	22	3,200	[1] 2,500	700

[1] Approximate altitude.

The uplift in the interval between the Browne and Dry Creek glaciations was accompanied by extensive nonglacial erosion, chiefly mass wasting and stream erosion. The surface over which the Browne glaciers had advanced was dissected by streams chiefly along belts of soft Tertiary rocks. Consequently, the original surface of the Browne glaciation in the vicinity of Lignite Creek is now preserved only on high mountaintops. The slopes of these mountains are graded to extensive pediments—surfaces of stream abrasion, sloping away from the mountains at angles of 7°–10°, which are mantled with a thin layer of stream gravel derived from the mountains. These pediments, in turn, are graded to the Dry Creek outwash terrace and to younger terraces along the Nenana River. Nonglacial erosion was responsible for the sculpture of most of the Alaska Range, particularly the foothill country, in the interval between the Browne and Dry Creek glaciations.

One significant drainage change appears to have occurred. During the Browne glaciation, the Wood River drained northward through the pass at the head of Mystic Creek, then flowed approximately along the present course of either Bonnifield or Gold King Creeks. A stream eroding headward in a southwesterly direction along soft rocks in the coal-bearing formation captured the Wood River and diverted it in a broad arc a few miles east of its original course.

HEALY GLACIATION

GLACIAL DEPOSITS ALONG THE NENANA RIVER

The Healy glaciation, the type locality of which consists of terminal moraine deposits along the Nenana River near Healy, followed the Dry Creek glaciation. No deposits have been found which indicate that a separate glacial advance occurred between the two. The deposits of the Healy ice advance are much more abundant and much better preserved than those of earlier advances.

Part of the terminal moraine of the Nenana River glacier of the Healy glaciation is preserved as six or seven parallel arcuate ridges resting on a terrace 1,650–1,800 feet above sea level, about 2–2½ miles due west of Healy. These ridges are about 2 miles long, have a total width of a third of a mile, and rise to a height of 25–50 feet above the intervening depressions.

An exposure in a roadcut in the south end of the outermost of these ridges shows rudely stratified, coarse, clean gravel, including boulders of gabbro, conglomerate, and granite. The granite is disintegrated. Pebbles in the gravel average 3 inches in size. The boulders are as much as 3 feet across. The surface of the ridge is mantled with a layer of mixed silt and pebbles about 2 feet thick. Presumably, windblown silt was deposited on an upper layer of pebbles, and these were mixed by intensive frost action. Roadcuts in other ridges are largely in till. The till consists commonly of rounded pebbles and boulders of conglomerate, greenstone, and granite, scattered through a matrix of greenish-gray silty clay.

The arcuate ridges were recognized by S. R. Capps (1932, p. 290) as marking the maximum extent of a great glacial advance, which he assumed to be the most recent in this area.

The arcuate ridges have smoothly rounded crests and gentle slopes, and are markedly different in appearance from the more angular depositional landforms of the younger Riley Creek glaciation. They obviously have been considerably modified by mass wasting since they were deposited.

Southward from the arcuate ridges, the terrace on which they rest has many irregular, closed depressions, the largest of which is more than 50 feet deep. Most of these depressions are dry. Large boulders of conglomerate, the largest nearly 10 feet across, are on the terrace surface.

On the east side of the Nenana River, near latitude 63°50′ N., a terrace 1,800–1,900 feet in altitude lies between the river and Moody Creek (pl. 2). It is shown on figure 21 as terrace 14. Its upper surface has many hillocks and undrained depressions. The material at the surface appears, from poor exposures, to be largely gravel. This terrace may be a pitted kame terrace that was deposited along the margin of the terminal lobe of the Nenana River glacier at the maximum advance of the Healy glaciation.

Till is exposed on the north wall of the canyon at mile 355 on the Alaska Railroad, about one mile south of Garner (pl. 2). It rests on Birch Creek schist and lies against the east wall of an ancient gorge, now filled with blue clay, of the Nenana River. As explained in a later section, the clay is believed to have been deposited by a lake that was left by the retreat of the Healy glacier, and the till, therefore, was probably deposited during the Healy glaciation.

Till is exposed on the east bank of the Nenana River about 1 mile north of McKinley Park station (pl. 3, and fig. 15). Here, also, it rests on Birch Creek schist and is overlain by blue clay.

A small body of till of the Healy glaciation, overlain unconformably by blue-gray outwash gravel of the Riley Creek glaciation, is exposed in a railroad cut about a mile north of McKinley Park station.

Deposits of till, assigned to the Healy glaciation, mantle much of the floor of the valley drained by Hines Creek and its tributaries in the vicinity of Mount McKinley National Park headquarters. The flat area at about 2,500 feet altitude, about half a mile northwest of the National Park headquarters (pl. 3), is underlain by till containing large boulders of granite and conglomerate, some more than 10 feet across. This till must have been brought to this position by a glacier flowing down the Nenana River valley.

An excavation for a water pipe, made in 1951 along the McKinley Park highway about three-quarters of a mile west of the National Park headquarters, disclosed fresh-appearing blue-gray till containing boulders of granite, conglomerate, gabbro, and other rocks in a matrix of blue-gray sand and clay. The till interfingers westward with stream-deposited gravel which contains abundant boulders of Birch Creek schist in addition to the other rocks. The excavation was about 8 feet deep, and neither the base of the till nor the base of the gravel was exposed. The altitude of this exposure is about 2,200 feet. Presumably, the deposits of till and gravel represent the margin of the Nenana River glacier of the Healy glaciation, as very little evidence of glacial deposition was observed farther up the valley of Hines Creek. This fixes the upper surface of the glacier at McKinley Park station during the maximum advance of the Healy ice at about 2,500 feet. Southward, a prominent bench rises along the west side of the valley of Riley Creek from the level of these deposits.

A similar deposit of till, interfingering laterally westward with stream-deposited gravel, underlies a triangular terrace remnant between Riley Creek and Hines Creek (pl. 3) at 2,000 feet altitude, or 500 feet below the upper surface of the ice at the maximum of the Healy glaciation. The relationship of till to stream-deposited gravel at this place suggests that these, also, are ice-margin deposits. They may have been deposited during a pause in the retreat of the Healy ice or during a short readvance of the ice.

Till remnants of the Healy glaciation south of McKinley Park station consists largely of ice-contact deposits in protected positions on mountains high above the younger Riley Creek deposits.

A smoothly rounded ridge of till, 90 feet high, lies on the relatively flat shoulder on the southwest side of the mountain between Riley Creek and the Nenana River about 3–4 miles north of Carlo (see pl. 3). The top of this ridge ranges in altitude from 3,175 feet at the south end to about 3,000 feet at the north end, 2 miles away. Its base is about 300 feet above the sharply defined ice-margin deposits of the Riley Creek glaciation in the pass southwest of this mountain. The ridge is believed to be a remnant of a lateral moraine of a lobe of the Nenana River-Riley Creek glacier of the Healy advance.

Kirtley F. Mather, Troy L. Péwé, and the writer, on an airplane flight in 1951, observed a morainelike ridge that blocks the mouth of a small creek near Carlo triangulation station (pl. 3). At one time the creek flowed eastward into Revine Creek, but, because of the ridge, it now flows northward, parallel to Revine Creek, into the Yanert Fork. This ridge stood about 3,600 feet in altitude, about 200 feet above the well-defined morainal ridges of the Riley Creek. It is believed to mark the ice limit of the Healy glaciation at this point.

The position of the ice surface, indicated by these scattered deposits of till, is shown on the longitudinal profile of the Nenana River (see pl. 7).

LANDFORMS OF THE HEALY GLACIATION ALONG THE NENANA RIVER

Landforms of the Healy glaciation along the Nenana River are poorly preserved, compared with the landforms of the younger Riley Creek glaciation. The outer gorge of the Nenana River between McKinley Park station and Healy is straight and has faceted spurs (fig. 10). Evidently, the spurs have been planed away by the glacial ice of the Healy and, possibly, the Dry Creek glaciations. However, no glacial grooves or rounded roches moutonees are preserved. The triangular facets of the spurs facing the river are rough and hummocky in detail.

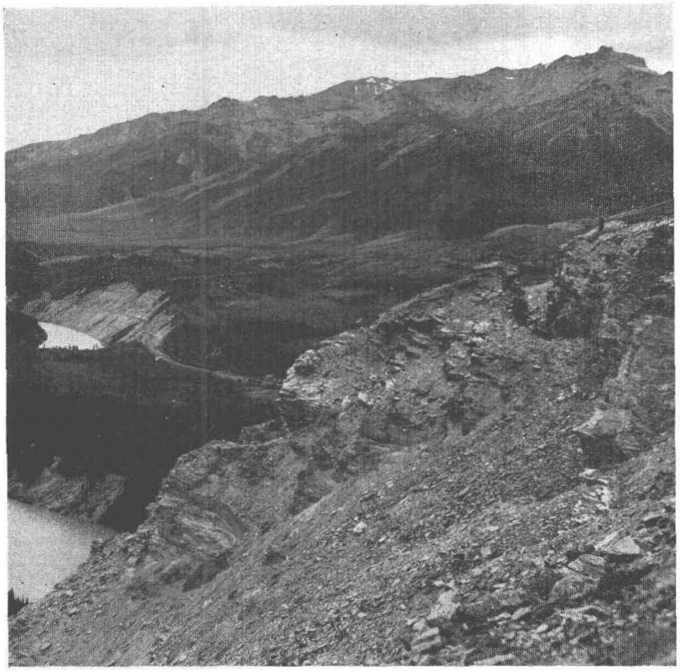

FIGURE 10.—View southwestward from mountain north of Garner, showing the two-story canyon of the Nenana River. The broad floor of the outer gorge, to the right, is underlain by alluvium and lake-deposited clay. The gorge to the left was cut after the Healy glaciation by the superposed Nenana River. The terrace gravel on the west wall of the inner gorge is Riley Creek outwash.

These landforms are quite unlike the part of the Nenana River gorge between Windy and Carlo, which was occupied by ice of the later Riley Creek glaciation. There, the side walls have distinct horizontal grooves and benches parallel to the river, and the lower slopes of the spurs are gently rounded. The absence of minor glacial landforms could be attributed to the greater susceptibility of the Birch Creek schist to weathering than rocks that make up the mountains of the upper gorge of the Nenana. However, the canyon of the Wood River, 30 miles east, and of the Delta River, 80 miles east, both of which were occupied by glaciers of the last advance (Troy L. Péwé, oral communication, 1951), have excellently preserved glacial grooves on their walls and well-rounded roches moutonees on their walls and floors. Both canyons are cut in Birch Creek schist that is similar in every respect to the Birch Creek schist of the lower gorge of the Nenana River. This difference in degree of preservation between the glacial landforms in the gorge of the Nenana between McKinley Park station and Healy on the one hand, and those on other rivers and farther upstream on the Nenana on the other hand, is evidence that the period during which ice occupied the lower Nenana gorge (that is, the Healy glaciation) is much older than the latest ice advance in this region.

LAKE DEPOSITS OF THE HEALY GLACIATION ALONG THE NENANA RIVER

During the retreat of the ice of the Healy glaciation, the Nenana River gorge was occupied by glacial Lake Moody. This lake, about one-third of a mile wide, and at least 9 miles long, extended from Riley Creek northward to a point beyond Garner. Its surface stood at an altitude of about 1,750 feet. Before the river began to cut down its outlet, the lake was completely filled with clay and gravel. Between Riley Creek and Moody, the lake coincided closely with the present canyon of the Nenana River. North of Moody, however, the lake was from 1/8 to 1/2 mile west of the present Nenana River, which flows in a narrow gorge that was cut after the lake was filled with sediments. The lake deposits consist largely of blue- and yellowish-gray horizontally varved silty clay, but each stream flowing into the lake built a delta of coarse sand and gravel. Some of the deltas are exposed in cross section along the Alaska Railroad, and others are undoubtedly buried beneath younger deposits.

The northernmost exposure of clay deposited in glacial Lake Moody is in the forks of the creek half a mile west of Garner (pl. 2), and also in frost-polygons on a hillside as high as 1,750 feet in altitude. Clay is exposed on both banks of the canyon that the Alaska Railroad crosses at mile 355, about 1 mile south of Garner, between a point one-sixth of a mile up the canyon from the railroad bridge and a point half a mile up the canyon from the railroad bridge. The lower one-sixth of a mile of the canyon is in Birch Creek schist. Along the contact between the clay beds and the Birch Creek schist, the outcrops indicate an irregular mass of till and gravel, the deposit mentioned on page 33. The clay in this canyon is found from the level of the canyon floor (1,470 feet) to an altitude of about 1,670 feet on the canyon walls. It is overlain on the north side of the canyon by a layer of gravel, 50–70 feet thick, consisting entirely of Birch Creek schist. The upper surface of this gravel is the surface of a sloping terrace, which has the appearance of part of a low cone radiating from the point at which this canyon emerges from the mountain wall to the west. Apparently, the deposit is an alluvial fan that was built by this canyon across the upper surface of the clay and later partly dissected. The exposures of clay are very poor, extensive slumping of the walls of the canyon having obscured them. Enough clay is exposed, however, to demonstrate conclusively that the upper part of this canyon, where it crosses the broad floor of the outer gorge of the Nenana River, crosses a body of clay.

Similar exposures of blue-gray clay occur along the north side of the canyon at mile 354 (pl. 2), about 1½

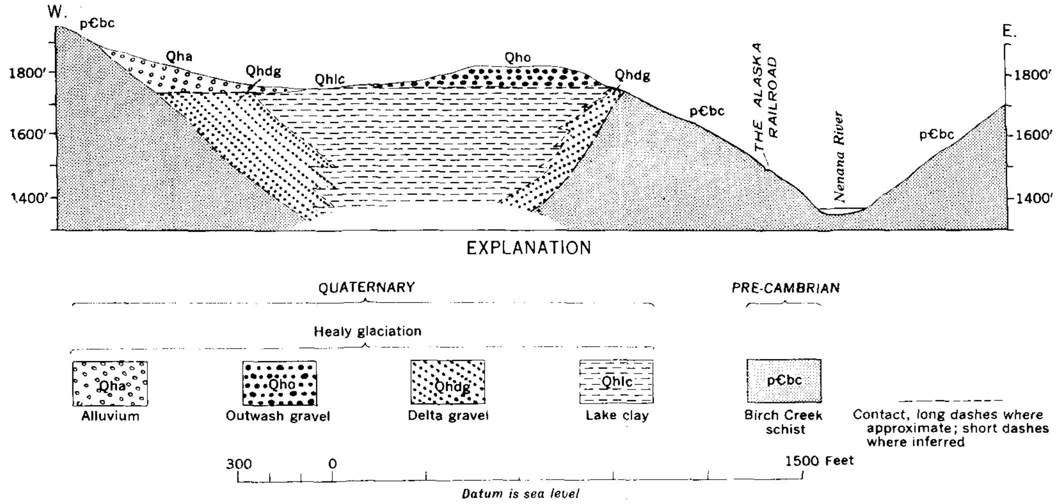

FIGURE 11.—Geologic cross section of the floor of the buried Nenana River gorge at mile 354 on the Alaska Railroad, showing buried lake deposits west of the river. Topography from Alaska Railroad bridge engineer's map (scale, 1 : 4,800).

miles south of Garner and half a mile north of Moody. They extend along the canyon wall ⅛–½ mile above the railroad bridge. The clay ranges in altitude from about 1,600 to 1,700 feet. Geologic conditions near this canyon are indicated on figure 11.

From about mile 353, just south of Moody (pl. 2), to mile 353.5, north of Moody, the Alaska Railroad crosses a deposit of blue glacial-lake clay. An excellent exposure of the clay and interbedded sand near the north end of this outcrop shows that the clay is flat-lying and varved. Poor exposures of the clay along the railroad track near Moody also indicate that it is varved. The clay is the locus of many landslides.

Between mile 353 and Sheep Creek the clay is confined to a narrow band between the railroad track and the river. West of the railroad track is a bank of gravel 165 feet high, rising about 280 feet above the river. A cross section of this bank is shown on figure 13. Between the railroad track and a level about 50 feet above it (altitude, 1,540 feet) the gravel is well bedded and consists almost entirely of boulders of Birch Creek schist. The beds dip 35°–40° toward the river (see fig. 12). Apparently they are foreset beds of a delta built by Sheep Creek into glacial Lake Moody. Resting unconformably on the channeled surface of the foreset beds is a 35- to 40-foot layer of coarse blue-gray gravel, consisiting of boulders of conglomerate, coarse dark sandstone, andesite, gabbro, and granite, derived from the Cantwell formation and other rock bodies many miles up the Nenana River. This gravel is identical to the gravel in the bed of the modern Nenana River. The blue-gray gravel is overlain in turn by a layer of brown silty gravel, consisting entirely of boulders of Birch Creek schist, the upper surface of which has a slope of about 15 feet per 100 feet northeast and east, away from the mouth of the gorge of Sheep Creek. This upper layer of gravel is probably an alluvial fan built by Sheep Creek on gravels deposited by the Nenana River. The layer of blue-gray gravel, resting on clay, can be traced northward to the vicinity of the railroad tunnel, where it is about 20 feet lower than it is at Sheep Creek. Between the buried delta of Sheep Creek and the railroad tunnel this gravel rests on clay. As will be shown in the following section, the layer of blue-gray gravel is the outwash gravel of the later Riley Creek glaciation, which rests unconformably on partly eroded lake deposits of the Healy glaciation.

Lake deposits, including delta gravel, are exposed at the railroad bridge at mile 351.4 on the Alaska Railroad (see pl. 2 and fig. 13). Along the railroad and between the railroad and the Nenana river, horizontally bedded, varved, blue and gray glacial clay is exposed. The clay interfingers westward with coarse gravel that consists almost entirely of Birch Creek schist and that dips 20°–25° toward the river. The gravel is the foreset part of a delta built into glacial Lake Moody by the creek that flows under the bridge. This gravel extends to an altitude of 1,600 feet, about 30 feet above the railroad track. It is overlain by a layer of blue-gray gravel, similar to the blue-gray outwash gravel at Moody, about 15–20 feet thick. This layer is overlain in turn by yellowish-brown silty gravel, consisting of Birch Creek schist, apparently deposited as an alluvial cone on the gravel that was laid down by the Nenana River. Churn drilling done in 1948 in the material on which the bridge rests, disclosed that the clay extends to a depth of as much as 100 feet below the railroad track,

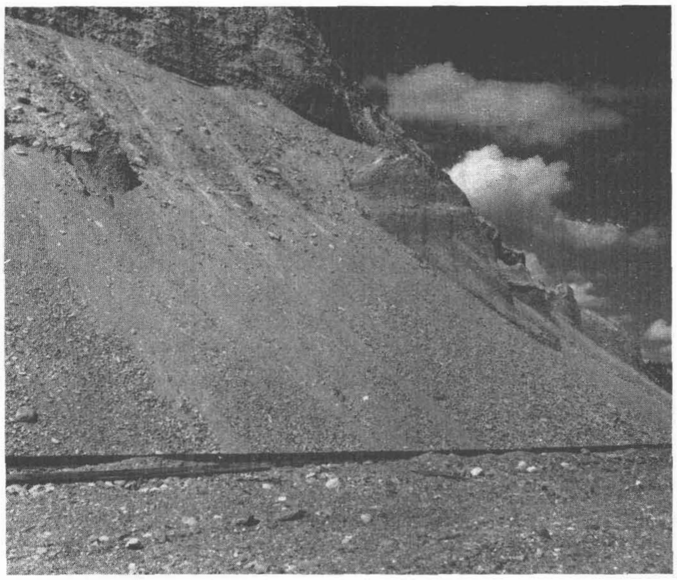

FIGURE 12.—Steeply dipping foreset beds of the delta built by Sheep Creek into glacial Lake Moody overlain by outwash gravel of the Riley Creek glaciation. The vertical bluff above the sharp break in slope is formed of alluvium resting on outwash gravel. Compare with fig. 13.

or 70 feet above river level, where it is underlain by coarse clean water-bearing blue-gray gravel.

Clay is exposed downstream along the creek from the railroad bridge at mile 350.3 (pl. 2), and a small body of clay was exposed on the north bank of the creek just west of the bridge during construction of a trestle in 1948. Gravel that dips 15° toward the river makes up the south wall of this canyon just west of the railroad. It is overlain unconformably by horizontal blue-gray gravel at track level. Presumably, the same explanation applies to these deposits as does to those at Sheep Creek and mile 351.4; that is, a delta built into glacial Lake Moody was partly destroyed at a later time by the Nenana River, which deposited outwash gravel across the truncated delta beds.

Between miles 349 and 350.3 (pl. 2), both the Nenana River and the Alaska Railroad swing in a broad arc around a low bench that projects eastward from the west wall of the Nenana River gorge. Most of the bench is underlain at depth by varved clay of glacial Lake Moody. The clay is exposed between the river and the railroad track on the south side of the bench between miles 349 and 349.6, and on the north side of the bench 100 feet east of mile 350 and between miles 350 and 350.25. At all these points the clay outcrops have been the loci of landslides. Between miles 349.6 and 350, the west wall of the gorge is Birch Creek schist, which apparently forms a narrow septum of schist between the rock-walled gorge of the Nenana River and the clay-filled glacial gorge west of the railroad track. The bench is an almost perfectly preserved alluvial cone deposited by the creek at mile 350.3. The alluvial gravels of the bench consist almost entirely of Birch Creek schist. They rest on a thin layer of blue-gray gravel deposited by the Nenana River, which rests in turn unconformably on the glacial-lake clay and the wall of schist east of the clay. Geologic conditions beneath this bench are illustrated on figure 14, which represents an east-west section through the bench.

Clay, overlying till, is exposed on the east bank of the Nenana River about 1 mile north of McKinley Park station (see pl. 3). The relations of the clay and till are indicated on figure 15. The terrace east of the railroad and about half a mile north of McKinley Park station is underlain by clay. The terrace consists of blue-gray gravel, 100 feet thick, deposited by the Nenana River. Clay exposed on the north bank of Riley Creek about half a mile east of the railroad bridge, at an altitude of 1,640 feet, is probably the southernmost exposure of clay of glacial Lake Moody.

The alluvial cones, resting on clay, north of the canyon at mile 354 were probably deposited shortly after glacial Lake Moody had been destroyed by silting. Presumably, the lake drained northeastward over a ledge of Birch Creek schist, probably just south of the tunnel at Garner. Had the lake drained northward over the terminal moraine at Dry Creek, it would have eroded the moraine before the lake was completely filled with clay and silt. The deposition of alluvium by canyons at miles 354 and 355 was sufficiently rapid to force the Nenana River against the east bank of its canyon between Moody and Garner; no comparable tributaries enter the Nenana River from the east in this 3-mile stretch. After the Healy glaciation, when the lake was filled with silt and downcutting was resumed, the river was superposed on the east bedrock wall of the sediment-filled glacial gorge, where it carved a narrow postglacial gorge.

OUTWASH GRAVEL ALONG THE NENANA RIVER

Outwash gravel of the Healy glaciation extends downstream along the Nenana River from Garner. Locally the gravel is as much as 180 feet thick, and the upper surface of the outwash plain near the terminus of the glacier at Healy is 400–500 feet above the present river level. The terraces on which the gravel rests were formed by the Nenana River during the advance and retreat of the Healy ice. They are complex, for they occur at three and possibly five different levels.

A gravel-covered terrace about 400 feet above the present river level, and about 1½ miles wide, extends northward on the west side of the Nenana River from

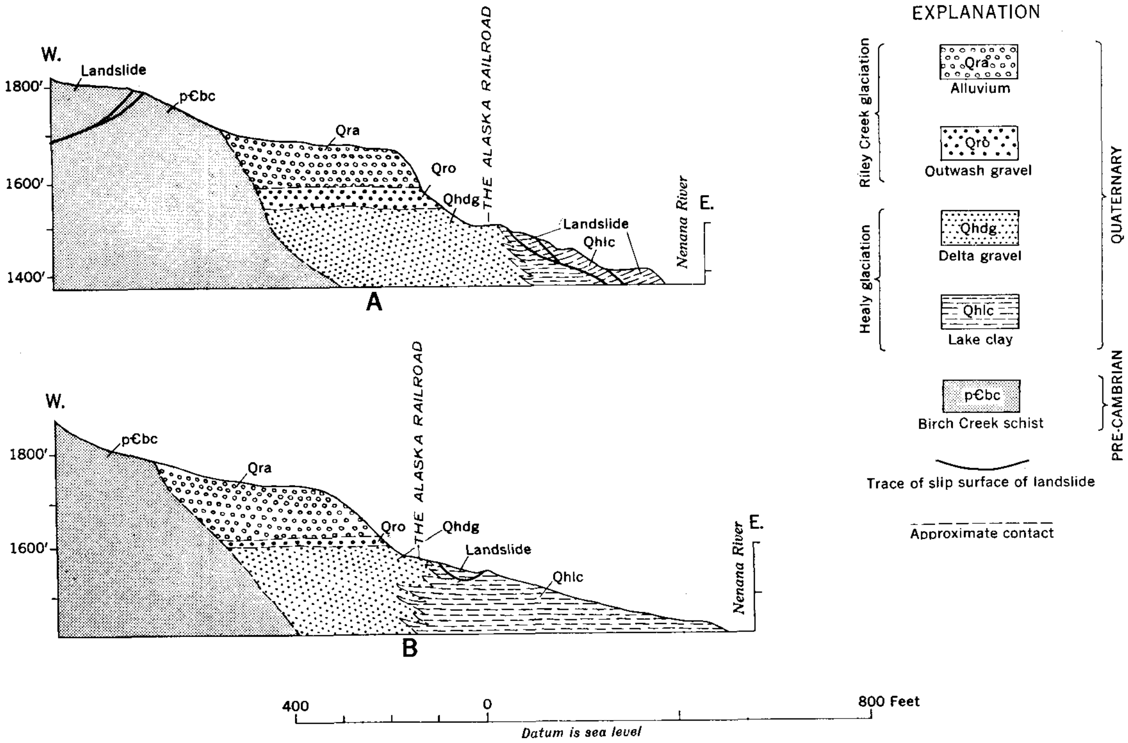

FIGURE 13.—Geologic cross sections of delta deposits of glacial Lake Moody, based on planetable surveys at a scale of 1 : 1,200. *A*, Cross section of bluff on north side of the mouth of Sheep Creek, mile 352.7 on the Alaska Railroad, showing outwash gravel and alluvium of the Riley Creek glaciation resting on the eroded surface of the delta gravel built by Sheep Creek into glacial Lake Moody. *B*, Cross section of bluff on south side of mouth of creek at mile 351.4 on the Alaska Railroad, showing outwash gravel and alluvium of the Riley Creek glaciation resting on the eroded surface of gravel deposits built into glacial Lake Moody.

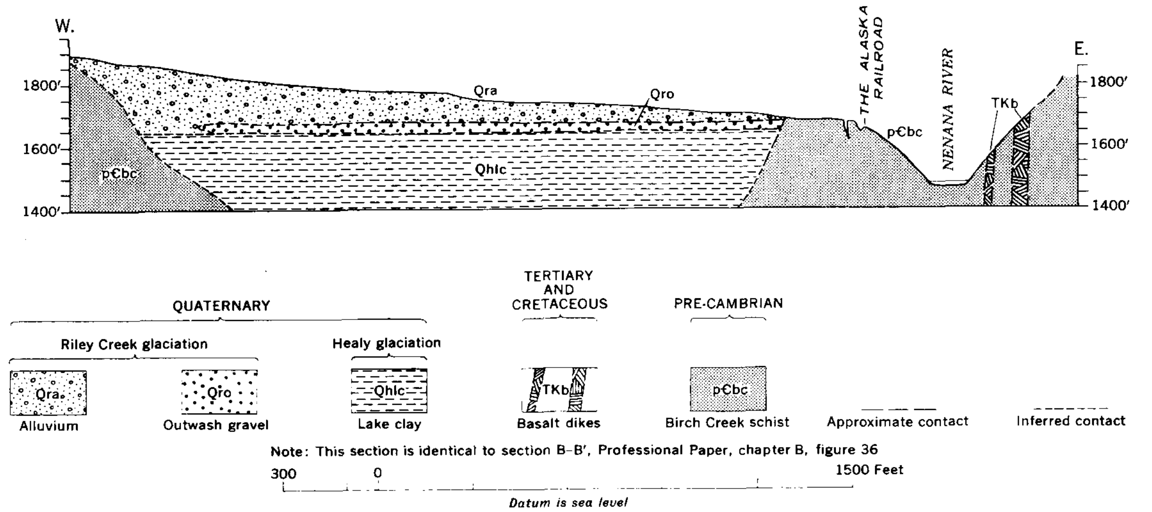

FIGURE 14.—Geologic cross section of the point of land around which the Nenana River and the Alaska Railroad curve between mile 349.5 and mile 350.3, showing outwash gravel and alluvium of the Riley Creek glaciation resting on eroded lake deposits of glacial Lake Moody. Topography from Alaska Railroad bridge engineer's map (scale, 1 : 4,800).

Dry Creek to Pangengi Creek (see pls. 2, 7, 8). This is the high, well-defined terrace shown on figure 16. (On the plate the top of the terrace is invisible because it is slightly above the level of the observer.) The topographic position of the terrace along Dry Creek suggests strongly that the layer of gravel at its top is part of the outwash plain of the terminal moraine of the Healy glacier, and it is so considered here. The terrace continues northward along the hillside from Pangengi Creek almost to Ferry, where it is about 260 feet above the river. Northward from Ferry (pl. 5) the outwash plain of the Healy glaciation is probably

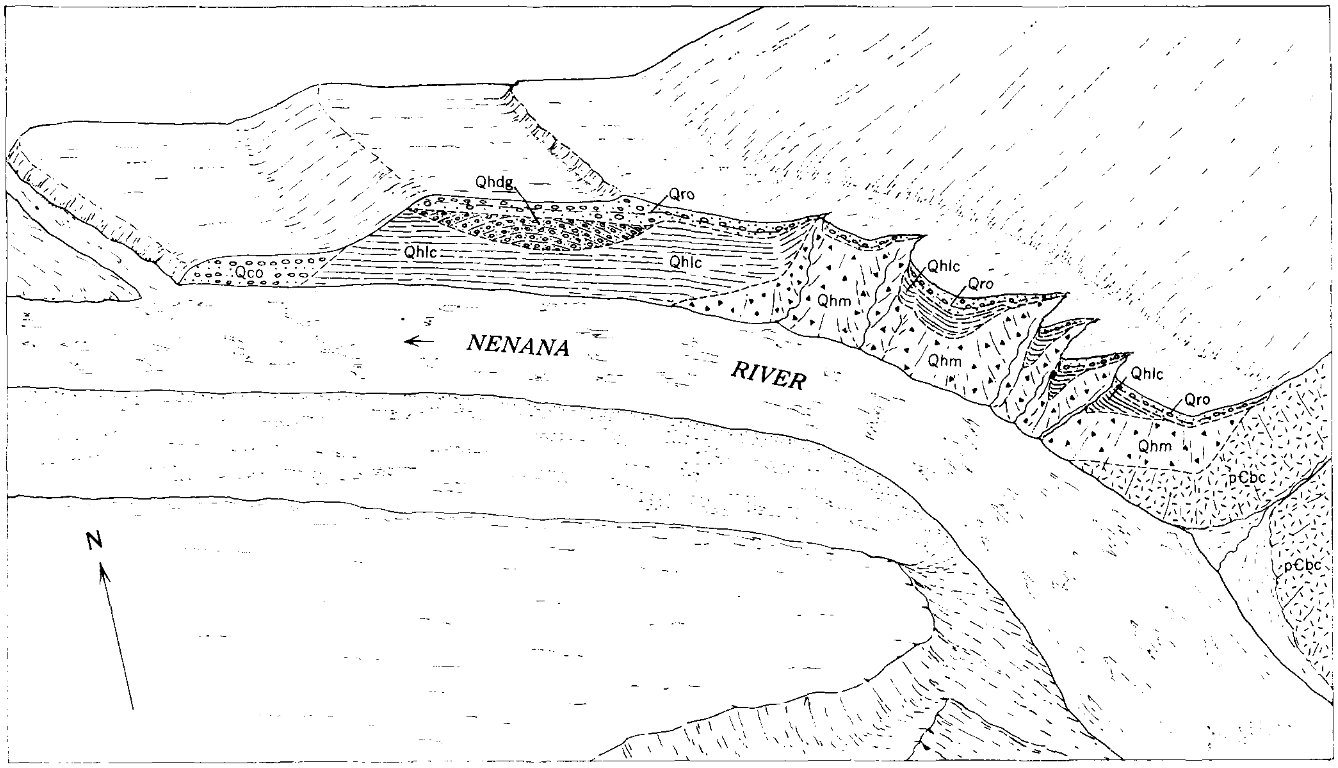

FIGURE 15.—Field sketch of the northeast bank of the Nenana River 1 mile north of McKinley Park station. *Qco*, outwash of the Carlo readvance; *Qro*, outwash of the Riley Creek glaciation; *Qhdg*, delta gravel of glacial Lake Moody; *Qhlc*, lake clay of glacial Lake Moody, *Qhm*, till of the Healy glaciation; *pЄbc*, Birch Creek schist. Geologic contacts shown by dashed lines.

preserved as a layer of gravel on one of a complex series of terraces along the west side of the river. It stands about 250 feet above the river opposite Ferry and 100 feet above the river opposite Browne. The thickness of gravel on this terrace is unknown, but it is probably between 50 and 100 feet.

The outwash terrace of the Healy glaciation on the east side of the river at Lignite stands nearly 100 feet higher than the terrace on the west side, or 500 feet above the river. It has a steeper northward slope than the terrace of the west side, and at Ferry is only about 250 feet above the river, the same height as the terrace on the west side. The thickness of gravel on this terrace, in the excellent exposure opposite the mouth of Pangengi Creek, is 180 feet. Thus, the base of the gravel on the east side of the river is 80 feet below the terrace top on the west side. Despite the disparity in slope and altitude, the two terraces could easily have been formed during the same episode of filling and cutting. On the west side of the river north of Pangengi Creek, a terrace segment about 1½ miles long is about 450 feet above the river, the same height as the higher Healy terrace on the east side of the river. Presumably this is a remnant of the higher terrace of the Healy glaciation.

A terrace about 60 feet lower than the terrace on which the terminal moraine of the Healy glaciation rests, begins about half a mile north of the road west of Healy and has a slope of nearly 100 feet per mile (Terrace 13 of fig. 21). It is thought to have been cut during the period of erosion that followed the retreat of the ice of the Healy glaciation. A terrace one mile due south of Healy (fig. 21) is correlated with this terrace. It has a surface altitude of 1,680 feet and is underlain by about 150 feet of terrace gravel. It is also believed to have been cut during the retreat of the Healy ice, although the gravel may have been deposited by the proglacial stream during the advance of the ice and may have been overridden by the ice. A gravel bank, as much as 1,800 feet in altitude, on the north side of the creek flowing through Garner station, may also have been deposited during the advance of the ice. The surface of the terrace north of this gravel bank has many features which suggest it was overridden by ice.

Terraces capped with alluvium as much as 50 feet thick and graded to the terraces of the Healy glaciation on the Nenana River can be traced up Healy and Lignite Creeks and their tributaries (see fig. 25). These terraces are about 500 feet above the present creek beds. Information concerning these terraces is used in a subsequent part of this section of the report

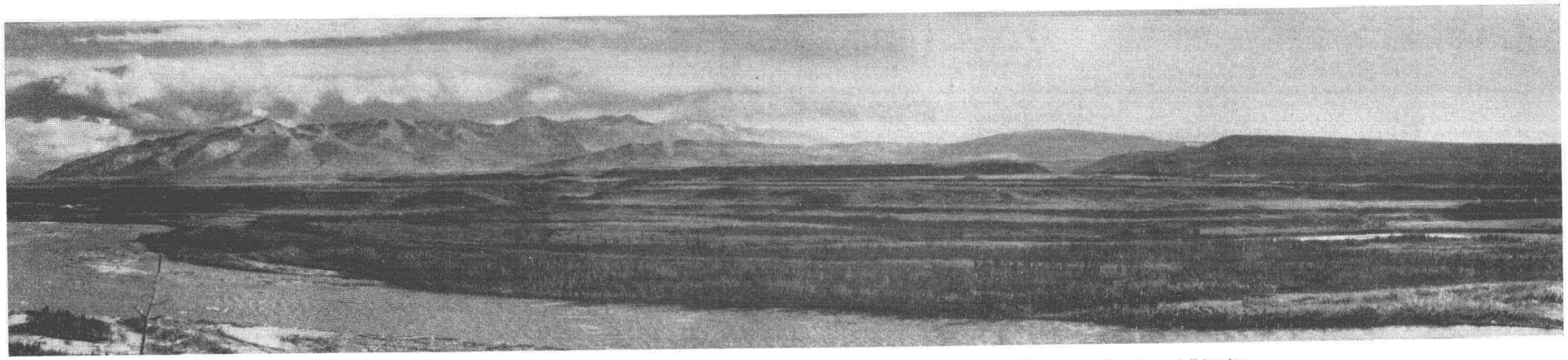

FIGURE 16.—Panorama of the terraces on the west bank of the Nenana River between Pangengi Creek and Lignite.

in dating the capture of streams east of the Nenana River.

GLACIAL DEPOSITS ALONG OTHER RIVERS

Glacial deposits and landforms in other river valleys lying above and beyond the well-marked limits of the Riley Creek glaciation, but on topography which has been little modified since the deposits and landforms were created, are probably equivalent in age to those resulting from the Healy glaciation on the Nenana River (see pl. 6). These deposits have been observed on the Wood River, the Sanctuary River, and the East Fork of the Toklat River. Glaciated valleys that are thought to have been carved, in part, during the Healy glaciation are present at the headwaters of Last Chance Creek and the Savage River.

The deposits on the Wood River are best preserved in the valley of Mystic Creek (see pl. 6). The flat at altitudes of 3,500–3,800 feet between the forks of Mystic Creek, 4–5 miles above its mouth, has deposits of large granite boulders as much as 8–10 feet in diameter strewn over it. Similar boulders are found on the flat about a mile due south of the fork at altitudes of 3,500–3,800 feet. The point farthest from the river at which boulders were observed was 1½ miles northwest of the fork of Mystic Creek. Similar boulders are also found at an altitude of about 3,600 feet at the headwaters of Coal Creek (see pl. 6). Apparently the ice that carried the boulders did not extend farther west than the farthest west boulders in the valley of Mystic Creek, and did not reach an altitude of more than 3,900 feet. The source of the boulders was a body of granodiorite on the west side of the Wood River about halfway between Copper Creek and Cody Creek. The boulders are about 300–500 feet above the well-defined upper limit of well-preserved glacial grooves and scoured surfaces on the walls of the valley of the Wood River. They probably were deposited during the Healy glaciation.

A very low arcuate ridge on the flat on the east side of the Wood River at an altitude of 1,400 feet, near latitude 64°11′ N., longitude 147°30′ W. (pl. 6), was identified on aerial photographs as possibly the terminal moraine of the glacier which deposited the boulders in the valley of Mystic Creek. If it is, it has been almost completely buried by outwash of a younger stage, for the present ridge is not more than 20 or 30 feet high.

The deposits of the Healy glaciation on the Sanctuary River (pl. 6) consist of scattered giant boulders of graywacke, greenstone, conglomerate, and gabbro, as much as several feet in diameter. These boulders litter the crest of the ridge east of the river and 2–4 miles south of McKinley Park highway at altitudes of 3,200–3,400 feet. The ridge is about 300 feet higher than a well-preserved terminal and lateral moraine of the youngest great glacial advance on the Sanctuary River, which is correlated with the Riley Creek glaciation. Therefore, these boulders are probably remnants of a lateral moraine of a glacier of the Healy glaciation which may have advanced down the Sanctuary River as far as the McKinley Park highway.

The only place on the East Fork of the Toklat River where till of the Healy glaciation has been examined is about 4 miles southeast of Sable Mountain in the pass at the head of Igloo Creek (see pl. 6). Ridges of till lie on either side of the broad valley at the head of Igloo Creek from the 4,500-foot pass northward for about 2 miles. Boulders in the till are largely limestone breccia, like that from the Dry Creek till near this locality. These deposits appear to be of much more recent origin than the scattered till and erratics of the Dry Creek advance that mantle the mountaintop west of the head of Igloo Creek, for their upper limit is well-defined. They appear to be remnants of lateral and terminal moraines defining a glacial lobe that extended down Igloo Creek 2 miles northward from the pass. They were probably deposited by an advance of the small glacier that occupies the valley south of and in line with the upper part of Igloo Creek. However, the most recent ice advance down this valley appears to have followed the canyon which turns sharply westward to join the ice of the East Fork of the Toklat at a level considerably below the pass. The deposits at the head of Igloo Creek are believed to have been laid down when the tributary to the East Fork of the Toklat drained northward, before Igloo Creek was beheaded. They probably were laid down during the Healy glaciation.

No glacial deposits correlated with the Healy glaciation have been positively identified elsewhere in this part of the Alaska Range. There are, however, many U-shaped valleys that are transverse to structural trends and therefore cannot be explained as having been eroded along bands of soft rock. No morainal deposits remain in these valleys. Some of the valleys are floored with periglacial terrace gravel. Judging from the freshness and abundance of deposits of the Riley Creek glaciation (where it has been recognized), and the well-preserved morainal topography in the valleys known to have contained Riley Creek glaciers, it appears unlikely that the few north-trending U-shaped valleys that contain no morainal deposits were occupied by ice during that glaciation. The U-shape of these valleys is, therefore, attributed to ice-scour during the Healy glaciation. The morainal material deposited in these valleys during the Healy advance was presumably removed during the interval between Healy and Riley Creek glaciations.

Examples of these valleys are the valley of the East Fork of the Toklat River between the McKinley Park highway and a point 6 miles north of the highway; the valley of the Savage River south of the McKinley Park highway (pl. 6); the valley of Last Chance Creek south of its junction with Moose Creek; and the headwater valleys of Cody and Healy Creeks (although the shapes of these valleys may be explained in part by the removal of Tertiary rocks along extensions of the Healy Creek syncline). All of these valleys are believed to have been eroded by Healy ice, although the possibility that they were eroded by ice of an earlier glaciation cannot be completely eliminated.

UPLIFT AND EROSION BETWEEN THE DRY CREEK AND HEALY GLACIATIONS

The estimates of uplift along the Nenana River in the following paragraphs are based largely on comparison of the height and gradient of outwash terraces formed at the times of glacial maxima. The divergence in gradient of these terraces is greatest north of Healy. In comparing these terraces it is assumed that the profile of the river at the time of the early ice advances would have been the same as the profile of the river during the later ice advances, and that the difference in the present slope of the outwash terraces is the result of deformation. Implicit in this assumption is the assumption that the river was essentially in equilibrium at the times of glacial advance. It may be questioned whether a river whose valley is subjected to continual uplift, climatic variation, and glaciation over much of its length is ever in equilibrium. Perhaps, instead, the terraces represent stages in the adjustment the stream made to an uplift which had ceased by late Tertiary time; however, a careful consideration of the evidence in the Nenana River valley and in other parts of the Alaska Range leads to the conclusion that this is not the case, but that the river was essentially in equilibrium throughout most of its history.

North of Healy the Nenana River now flows on a flood plain which averages half a mile in width, or 4–8 times the width of the river. On this flood plain the river has a winding, somewhat braided course; the bends are incipient meanders, and the river is eroding vigorously wherever it impinges on the bedrock margins of the flood plain. The Nenana River of the past also flowed on a flood plain that was much wider than the river itself. The outwash plains of the various glaciations were plains 2–5 miles wide, which could hardly have been occupied over their whole width by the braided Nenana River. They probably were carved, in part, by a laterally migrating stream, just as the flood plain is being carved today.

The bedrock formations of the Nenana River valley north of Healy are made up of soft, easily eroded Tertiary rocks. The size of the constituent particles of these poorly consolidated formations ranges from that of clay particles to that of cobbles 3–4 inches in diameter. Most of the bedrock formations, except some coarse Nenana gravel between Healy Creek and Lignite Creek, consist of fine pebble gravel, sand, and clay. On the other hand, the bedload of the river, and its channel gravels, derived from well-consolidated and crystalline rocks south of Healy, consist largely of cobbles and boulders. According to Mackin (1948, p. 474), the gradient of a stream traversing easily erodible fine-grained rocks is a function of its coarse bedload only. This is presumably true of the Nenana River, and it seems reasonable to assume that the stretch of the Nenana from Healy to Browne is graded to transport the coarse debris delivered at its upper end.

Many small streams in this part of the Alaska Range which drain basins wholly within the Tertiary rocks have profiles that are gently concave upward to within a mile or two of their heads. There, the even, "graded" profile is terminated by an abrupt nickpoint, usually a steep gully, in large part free of vegetation. Above the nickpoint the surface on which the headwater part of the stream flows is smoothly graded, and below the nickpoint this surface is usually a terrace which can be traced downstream to coincide with the terrace of the Healy or Dry Creek glaciation. Lignite Creek, whose nickpoint is in the SW¼ sec. 29, T. 11 S., R. 5 W., is an especially fine example of this type of creek. MacAdam and Marguerite Creeks, tributaries of the Totatlanika River, are other examples. Where these streams flow eastward or westward, as Lignite, Healy, and MacAdam Creeks do, the terraces are parallel to each other and to the present stream. If anything, they diverge downstream (see fig. 25). Only at the upper end, just below the nickpoint, is there a pronounced difference in gradient. This indicates that the minor tributaries, which erode Tertiary rocks largely with the Tertiary rocks they carry, were able to establish equilibrium (graded) profiles within the short period of time that elapsed since the last glaciation. Similar evidence for the rapid establishment of graded profiles is provided by the extensive pediments and flat plains truncating the Tertiary rocks. Remnants of pediments graded to the outwash terraces of the Healy and Dry Creek glaciations are found at the headwaters of Dry Creek and north of Lignite Creek (see pl. 2). Broad alluvial flats on some of the canyons draining into Lignite Creek appear to be incipient pediments, and indicate strongly that the pediment gravels on the interstream divides north of Lignite Creek were deposited by the same fluviatile and mudflow processes that operate today. Here, also, the evidence that relatively feeble erosional agencies were able to establish graded profiles is impressive. It seems natural to suppose, therefore, that the Nenana River and other major north-flowing streams in the Alaska Range which cross foothills of Tertiary rocks were quickly graded to transport their coarse bedrock load, and that they are probably graded at the present time. The Nenana River from Healy northward probably has had a graded profile for at least part of every glacial cycle.

Evidence which tends to confirm the supposition that the Nenana River has had a graded profile is revealed by the behavior of the river itself during the glacial advances. It has already been shown that the thickest deposits of outwash gravel and the highest terraces of both the Healy and Dry Creek glaciations were formed at about the time of the maximum ice advance of those glaciations. Even ice advances of only a few miles have been accompanied by the building of terraces 10–20 feet high, extending 30–40 miles downstream from the glacier front. Thus the Nenana has aggraded its bed in response to slight glacial advances and has re-excavated the gravel during interglacial periods. Studies made by the author along the Totatlanika River, Healy and Lignite Creeks, and the Teklanika River and its tributaries, as yet unpublished, show that all the periglacial streams and other glacial streams have done likewise. The sensitive response of the stream profiles to climatic variation suggests that most of the streams in this area were very nearly graded during most of the Pleistocene. If they had not been, changes in climate would not have altered the regimen of the streams so strikingly. One must assume, therefore, that during at least some part of each glaciation, the course of the Nenana River was graded, and it is very likely that the river's course from Healy northward has always been graded, or nearly so. If the river had had an ungraded profile, it could have handled the greater quantity of debris supplied to it by the glaciers without aggrading its bed to give it the necessary slope.

Mackin (1948, p. 498) has pointed out that the successive profiles of equilibrium in a stream successively adjusted to a lower base level are essentially parallel. The river on which he based his analysis, the Greybull River in Wyoming, is similar to the Nenana in that it derives its bedload from hard-rock sources at its head and transports that load over easily eroded Tertiary rocks. The terraces of the east- and west-flowing streams in the Alaska Range, such as Healy Creek (fig. 25), are essentially parallel to each other. The terraces on the Nenana, as plates 7 and 8 show, diverge rapidly upstream. Unpublished investigations by the author reveal that terraces on the Totalanika and on the Teklanika and its tributaries do likewise. This marked southward divergence of terrace profiles is considered by the author to be due largely to tilting of the north flank of the Alaska Range. The tilting probably was a result of uplift in the main part of the range to the south, which may have been accompanied by downsinking of the Tanana flats to the north. The initial stage of this uplift has already been described as taking place before and during the Browne glaciation and in the interval between the Browne and Dry Creek glaciations.

Before attributing the greater part of the southward divergence of terrace profiles to tilting, another possible cause of this divergence will be considered, namely the effect of the glacial advances. If we could compare the interglacial profiles of the river we would not have to consider this effect. However these profiles lay in the center of the river valley, where the older profiles have been destroyed through later downcutting by the river. The only profiles that have been preserved are those on the tops of the outwash-gravel terraces, formed at the height of the glacial advances.

The tremendous effect glacial advances have had on the profile of the Nenana River raises the question whether the profiles and heights of the terraces formed at the maximum advances of the ice were essentially similar at the times of maximum advance, or whether, instead, the greater height of the older outwash terraces reflects the greater extent of these older glaciers. The terminus of the Nenana glacier of the Dry Creek glaciation was only 3–5 miles downstream from the terminus of the Nenana glacier of the Healy glaciation, and only 15 miles downstream from the terminus of the Nenana glacier of the Riley Creek glaciation. The ice terminus of the Riley Creek glacier was 57 miles downstream from the present terminus of the Nenana glacier. Hence, in the vicinity of Ferry, for instance, about 9 miles downstream from the terminus of the Nenana glacier at the height of the Dry Creek glaciation, the outwash terrace of the Dry Creek glaciation should be only slightly higher than the outwash terrace of the Healy glaciation, and only one-fourth higher than the outwash terrace of the Riley Creek glaciation. The gravel on the older terraces has about the same range in size and the same average size as the gravel on the younger terraces and in the present channel of the Nenana River. As plate 7 shows, however, the outwash terrace of the Dry Creek glaciation at Ferry is more than twice as high as the outwash terrace of the Healy glaciation, and four times as high as the outwash terrace of the Riley Creek glaciation. Therefore, the great difference in heights of the outwash terraces is probably due not only to climatic fluctuations, but also to deformation.

At Lignite the outwash terrace of the Dry Creek glaciation is 450 feet higher than that of the Healy glaciation (see pl. 7). Eight miles north of Lignite, the terrace of the Dry Creek is 350 feet higher than that of the Healy. Near Browne station, 10 miles farther north, the Dry Creek outwash plain is probably not more than 150 feet above the Healy outwash plain. This difference in northward slope of 300 feet in 18 miles, or about 17 feet per mile, indicates a tilting of like amount between the two stages, for no change in the characteristics of the Nenana River drainage basin adequate to account for this remarkable difference has occurred. The uplift at Healy during the interval between the Dry Creek and Healy glaciations amounted to about 500 feet. South of Healy the profiles of the upper surfaces of the two glaciers, as nearly as can be determined, appear to have been parallel (pl. 7). It is likely that that part of the Alaska Range south of Healy was not tilted, but rather that it was bodily uplifted. Comparable amounts of uplift in the Alaska range near the East Fork of the Toklat River are indicated by the difference between the altitudes of Healy till and Dry Creek till along this river.

The Nenana River, in response to the uplift and tilting of the Alaska Range during the interval between the Dry Creek and Healy glaciations, eroded its bed to establish a graded profile, probably close to the base of the outwash gravel of the Healy outwash plain. The north-flowing Toklat, Teklanika, Sanctuary, Savage, Totatlanika and Wood Rivers and Tatlanika Creek did likewise wherever they could overcome the resistance provided by hard pre-Tertiary rocks across their courses. As the main rivers lowered their channels, their tributaries—subsequent streams developed along bands of soft rock, as well as older consequent streams established on the tilted peneplain—incised their channels to meet the local base level provided by the main streams, and eroded headward, chiefly by headwater gullying along bands of soft rock. The Nenana River crosses only soft Tertiary rocks north of Healy, whereas the Totatlanika, to the east, crosses three bands of crystalline schist before reaching the Tanana Flats. By the latter part of the interval between the Dry Creek and Healy glaciations, the Nenana in response to the uplift, had deepened its bed to the extent that its tributaries, eroding headward along bands of soft Tertiary rocks, were able to capture some of the headwater streams of the Totatlanika. Later, these tributaries effected substantial drainage adjustments among themselves.

It appears likely that the headwaters of Lignite Creek drained northward into Marguerite Creek (pl. 6) during the Dry Creek glaciation. The slope of pediments graded to the outwash terrace of the Dry Creek glaciation suggests that a north-south ridge may have existed across the course of lower Lignite Creek, and pediments correlated with this terrace along the pass between Marguerite and Lignite Creeks are continuous across the pass, suggesting a drainage to the north. On the other hand, pediments north of Lignite Creek are graded to the outwash terrace of the Healy glaciation and slope gently southward, away from this pass, indicating that Lignite Creek had captured the headwaters of Marguerite Creek before the Healy advance.

Shortly after Lignite Creek captured the headwaters of Marguerite Creek, Healy Creek, eroding headward along a band of soft Tertiary rocks, captured a large part of the headwaters of Lignite Creek. The pass between Healy and Lignite Creeks, about 1¼ miles north of the mouth of Coal Creek (pl. 6), is floored with coarse gravel. The gravel consists largely of Birch Creek schist, but contains boulders of basalt which are also in the gravels of Coal Creek. The terraces at the level of this pass but near the junction of Sanderson and Lignite Creeks are graded to terraces that are lower than the pass between Lignite and Marguerite Creeks. The pass between Healy and Lignite Creeks is about 100 feet above terraces on Healy Creek that grade to the Healy outwash plain. Consequently, this capture, also, is thought to have taken place during the interval between the Dry Creek and Healy glaciations.

Drainage diversion of the lower course of Healy Creek appears to have taken place during the retreat of the Healy ice. The pass at the head of Poker Creek, at the level of the Healy outwash terrace, is floored with gravel made up mostly of pebbles of Birch Creek schist. Presumably, before the Healy glaciation, Healy and Moody Creeks flowed northward through this pass to enter the Nenana River near Poker Creek. The headward erosion of a stream, probably along an anticlinal axis in the coal-bearing formation east of Healy, resulted in the capture of these waters, causing them to flow into the Nenana River at Healy. The drainage diversions during the Dry Creek and Healy glaciations are indicated on figure 17.

SUMMARY OF HISTORY

During the Healy glaciation, glaciers advanced over a topography similar to that existing in the Alaska Range today. Since the retreat of the Healy ice, main streams have not deepened their channels more than 300 feet. Although the gross landscape features produced by the Healy glaciation have been preserved,

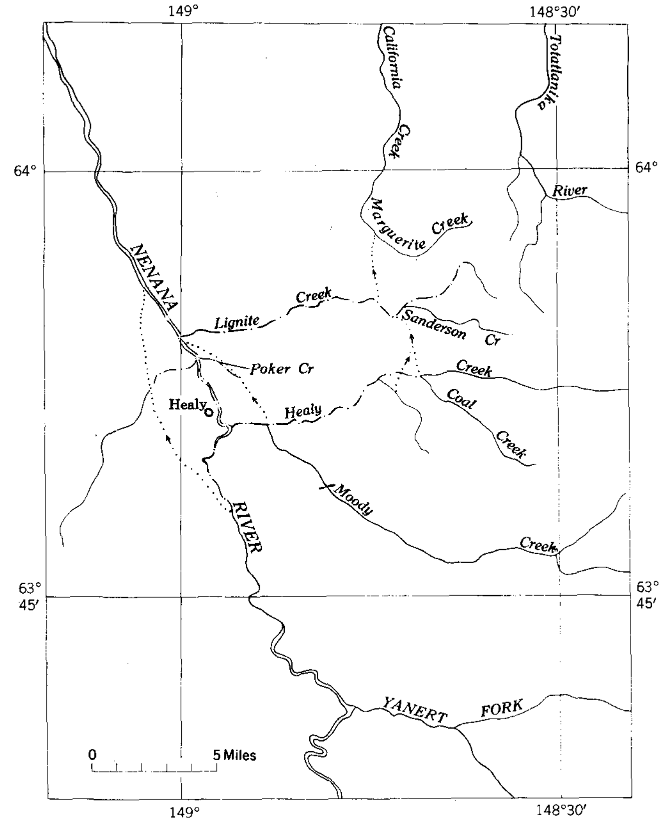

FIGURE 17.—Drainage changes on tributaries of the Nenana River from the beginning of the Dry Creek to the end of the Healy glaciation. Solid lines indicate stream courses relatively unchanged from the beginning of the Dry Creek glaciation to the present; dash-dot lines, stream courses developed since the Dry Creek; dotted lines, stream courses abandoned since the Dry Creek glaciation.

glacial deposits have been preserved only in favorable localities. Consequently, many of the events of the Healy glaciation cannot be determined with certainty.

Ice advanced down the Nenana River to Healy, down the Wood River to the Tanana Flats, and down the East Fork of the Toklat River to a locality about 6 miles north of the McKinley Park highway. Ice also filled the valleys of the Savage, Sanctuary, and Teklanika Rivers as far north as the McKinley Park highway.

The discordance in terrace heights on either side of the Nenana can be explained by assuming that two separate ice advances occurred during the Healy glaciation, and that in the intervening period the ice retreated an unknown distance. This period of retreat was very much shorter than the interglacial periods before and after the Healy. During this period of retreat the glacial melt water removed the terminal moraine of the first advance and lowered the level of the outwash plain nearly 100 feet, but did not remove all the outwash deposits. During the second ice advance the glacial front returned to the position it had reached at the height of the first advance. But, whereas the ice of the first advance carried a tremendous amount of debris (which was deposited to form the thick outwash plain of that advance), the ice of the second advance carried a relatively small amount. After the complex terminal moraine of the second advance was deposited, the glacier retreated, leaving glacial Lake Moody, a lake about 400 feet deep occupying the canyon of the Nenana River between Garner and McKinley Park station.

Glacial Lake Moody drained northeastward over a bedrock lip near Garner. When the lake was completely filled with sediments, the Nenana River began building an outwash plain across them. The river, which formerly had been unable to erode the bedrock lip because it had not carried much abrasive material, probably cascaded down a bedrock slope near Healy. However, once the outwash plain had been built, the river began to move more coarse material and to erode vigorously the bedrock barrier. At the same time, streams emerging from canyons on the west side of the glacial gorge were building alluvial fans across the lake deposits and the outwash plain. As no comparable streams emerged from the east side of the gorge, the river was forced to flow against the bedrock wall of the gorge along the east side of the outwash plain. As down-cutting progressed, the river's course was superposed on the bedrock from Moody northward to Garner and for a short distance near mile 350 (see fig. 10). Elsewhere, the river was able to cut its channel in the deposits of glacial Lake Moody.

Icecaps of the Healy glaciation apparently melted at least as far back as the limits of ice at the present time and may have melted completely away. Evidence to support this contention is presented in the section on outwash gravel deposits of the Riley Creek glaciation along the Nenana River. The period between the Healy and the Riley Creek glaciations appears to have been long, for the glacial deposits of the Healy have been completely destroyed, except where they have been preserved on isolated areas of gentle topography. Presumably, they were removed by solifluction and creep before the advance of the Riley Creek ice. Had they been removed during the Riley Creek advance, thick deposits of talus and debris would have formed slopes graded to the ice margin of that stage. Such landforms, however, are rare. It is possible that the great period of mass wasting which removed the Healy deposits coincided with the early stages of growth of the Riley Creek glaciers. It is equally likely, however, that the removal of Healy deposits took place during the interglacial period between the Healy and Riley Creek.

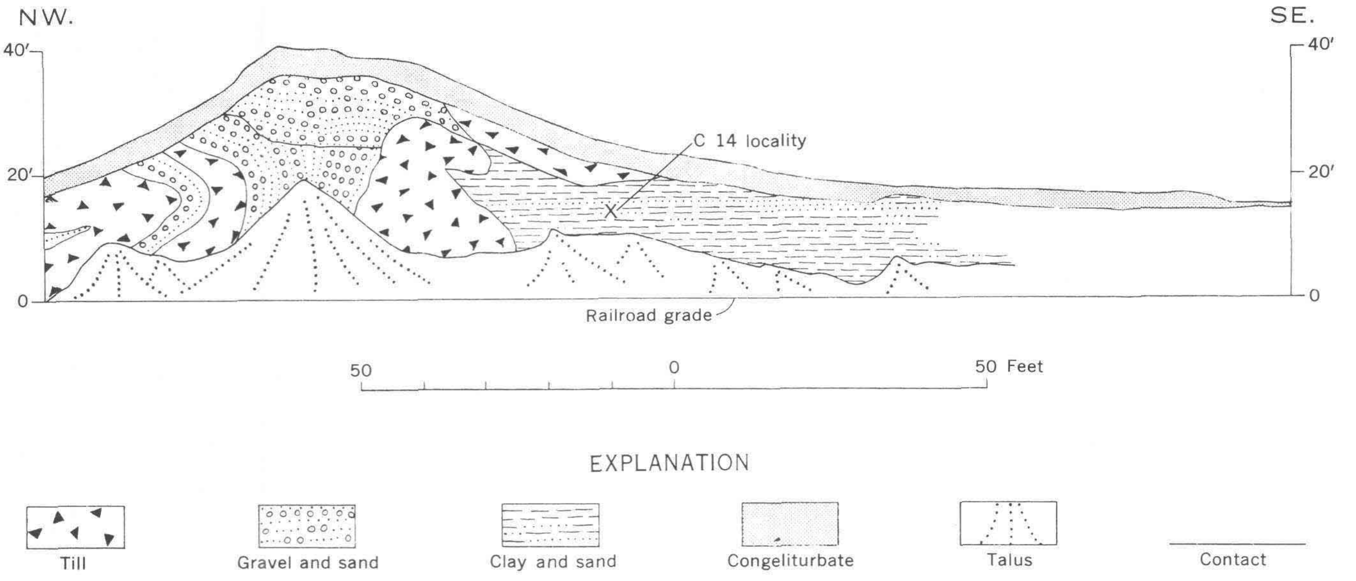

FIGURE 18.—Field sketch of north bank of the railroad cut through the terminal moraine of the Riley Creek glaciation, at mile 347.2 on the Alaska Railroad.

RILEY CREEK GLACIATION

DEPOSITS ALONG THE NENANA RIVER

The Riley Creek was probably the last extensive glaciation of the Alaska Range. The morainal deposits of this stage are much better preserved than the deposits of any earlier stage. The lateral moraines have been so little dissected, it is likely that those parts that appear to be missing may never have been deposited; if they were deposited, they probably were removed as the glacier ice, which supported them on the glacier side, melted down. Lakes in basins on the moraines of the Riley Creek glaciation have not been lowered appreciably; no integrated drainage is present, except where large streams cross morainal areas. The remarkable freshness of the topographic features makes them easily identifiable and sets them off from deposits of all earlier stages.

Ice of the Riley Creek glaciation advanced down the Nenana River to the mouth of Riley Creek, where a terminal moraine 70–180 feet high is preserved as an irregular ridge extending along the south bank of Riley Creek for about three-fourths of a mile. This large ridge of till and gravel probably owes its preservation partly to the fact that it was deposited behind an irregular ridge of Birch Creek schist. Parts of this ridge of schist are exposed in the bank of Riley Creek, where the schist is capped with till. The structure of the terminal moraine is well displayed in a railroad cut. The moraine here comprises two structural units: a body of deformed till and outwash on the northwest, and, plastered against the southeast side of this body, undeformed till and horizontally bedded clay containing layers of peat (figs. 18, 19). Immediately south of the terminal moraine is a belt of irregular, dry, closed depressions about 500 feet wide and 10–20 feet deep. These are bounded on the south by an irregular wall, 20–50 feet high, which is the front of a gravel plain extending southward for about a mile along the railroad.

These deposits are interpreted to represent the following sequence of events: (1) During its advance, the glacier deposited outwash gravel and till at the site of the terminal moraine. (2) The glacier retreated. (3)

FIGURE 19.—North bank of the railroad cut in the terminal moraine of the Riley Creek glaciation. Compare with figure 18. The man in the photograph is 5 feet 7 inches tall.

The glacier re-advanced, shoving the already deposited gravel and till forward into a recumbent syncline, which makes up the core of the moraine. (4) The glacier retreated again, leaving till plastered over the deformed gravel; the area between the glacier and the moraine was occupied by a lake, in which some peat accumulated for a short time. (5) Till was deposited on the lake sediments, probably by grounded icebergs. At this time the ice for about 500 feet behind the front of the glacier was thickly covered by superglacial till, which protected it from the sun's rays. Behind the till-covered ice was an area of bare ice at least a mile wide. The bare ice melted faster than the till-covered ice, and, when it disappeared, outwash gravel built an interior flat (Tarr and Martin, 1914, p. 209–211) behind the ridge of till-covered ice. Much later, when the till-covered ice melted away, it left a depression between the moraine and the interior flat.

The lake sediments, which included peat, could have been deposited only during a period between the maximum advance of ice of the Riley Creek and the melting of the till-covered stagnant ice, an event which probably occurred only a few hundred years after the maximum advance. A sample of the peat was collected at the locality marked "C 14 locality" on figure 18. A radiocarbon analysis of this sample was made by H. E. Suess. His statement on the results of the analysis is as follows (H. E. Suess, written communication, Jan. 6, 1954):

> This peat formed 820±160 years after the Two Creeks advance of the Mankato glaciation in Wisconsin. This figure for the age difference is derived from a direct comparison with a Two Creeks sample and is more accurate than the absolute value for the age which is 10,560±200 years. Undoubtedly your "Riley Creek" stage correlates with the continental Mankato glaciation, Naptowne on the Kenai Peninsula, and the younger Dryas in Europe.

The lateral moraines of the Riley Creek glaciation are well preserved as irregular hummocky benches or as smooth even-crested ridges. These extend for miles along the sides of the valley of Yanert Fork and its tributaries and along the east side of the canyon of the Nenana River, except on the steeper slopes. Lateral-moraine deposits are rare along the west side of the Nenana River. However, the low pass at an altitude of 2,450 feet between the Nenana River and Riley Creek (pl. 3), about 3 miles north of Carlo, was apparently occupied by ice of the Riley Creek glaciation. Irregular arcuate moraines that block the northwest end of this pass merge with moraines deposited by ice advancing down Riley Creek to about this point. The pass itself is a gravel plain about 500 feet above the Nenana River. The bluff, about 200 feet high, facing the river at the southeast end of this plain, indicates that the gravel is about 200 feet thick. Near the southeast border of the plain, next to the bluff, are several steep-walled dry closed pits, the largest about 50 feet deep. These are apparently kettle holes that resulted from the melting of ice buried by the gravel of the plain. This plain is probably a kame terrace deposited by the melt water of the Nenana River glacier in a depression at the side of the glacier. The depression was formed by the melting away of a small distributary lobe of ice between the morainal ridges deposited at the maximum extent of that lobe and the still-existing Nenana River glacier.

Southward along the west wall of the Nenana River gorge, discontinuous patches of till and gravel plastered against the wall form a bench that rises gradually from 2,900 feet in altitude at the pass to about 3,400 feet in altitude on the mountainside west of Carlo (pl. 3), 3 miles south. A small amount of till preserved on the north side of Clear Creek (pl. 3), may be a remnant of the lateral moraine.

The east side of the Nenana River north of Yanert Fork was not examined on the ground. Careful inspection of aerial photographs, and distant observation from hills on the west side of the river, failed to disclose any large body of well-preserved lateral moraine. Eastward from a point about 2 miles up the Yanert Fork (pl. 6), a prominent bench having irregular topography and many small lakes can be traced for many miles along the north side of the valley of the Yanert Fork. It probably marks the upper limit of ice of the Riley Creek glaciation. The limits of ice shown on plate 6 have been drawn to follow this bench.

The lateral moraine along the south side of Yanert Fork valley west of Revine Creek (pl. 3) is a prominent even-topped gravel bench, about 2,700 feet in altitude, paralleled on its uphill side by a depression about 50 feet deep. Lateral moraines extend for 3 miles up Revine Creek and can be clearly recognized on the topographic map of Healy C–4 quadrangle (see pl. 3). Farther upstream, the canyon walls of this creek are apparently either too steep to support continuous morainal deposits or are the areas from which the deposits along the lower part of the creek were derived.

An arcuate ridge extends northeastward from the lateral moraine on the south side of Yanert Fork valley near the point where the moraine crosses the 148°46′ meridian, and forms in plan a large bow convex toward the Yanert Fork (see pl. 3). It ends near the Yanert Fork about 2 miles (airline) above the mouth of that stream. This ridge appears to be an interlobate moraine of the Nenana and Yanert glaciers, deposited where the expanding lobes of the two glaciers coalesced in the great valley of the Yanert Fork.

Ground moraine and pitted outwash cover the entire valley floor in the vicinity of the junction of the Nenana River and the Yanert Fork, with the exception of rounded bedrock hills and a narrow band of river-deposited gravel in terraces and flood plains along each river. The ground moraine has an irregular hummock-and-hollow topography. The depressions of some parts of the ground moraine are dry most of the year or have very small marshes at their bottoms. Those of other parts are occupied by deep lakes. The areas in which all depressions are either dry or lake-filled are extensive; probably they are areas in which the moraine is either porous or impervious. The porous moraine presumably consists largely of outwash sand and gravel from which most of the clay-size particles have been removed by melt water. It may have been deposited over irregular bodies of ice, thus owing its hummocky topography to the melting of that ice. It is mapped as outwash on plate 3. The impervious moraine probably consists largely of clayey till that may or may not include small bodies of lake-deposited clay and gravel.

Several drumlinlike hills in the ground moraine of the Nenana glacier have been exposed in cross section by railroad cuts on the Alaska Railroad. Sketches of fresh exposures on these road cuts, made shortly after the excavations were enlarged, are shown on figure 20. As can be seen from the sketches, most of the ground-moraine hills on the floor of the Nenana River valley consists of stream-deposited gravel or lake silt having a thin and, in part, discontinuous veneer of till. The structure of these hills suggests a complex series of retreats and readvances at the lower end of the Nenana River glacier during the Riley Creek glaciation. Presumably, the lake deposits and outwash gravels, which include masses of till and probably rest on till, were rounded by ice advances that occurred after the proglacial deposits were laid down.

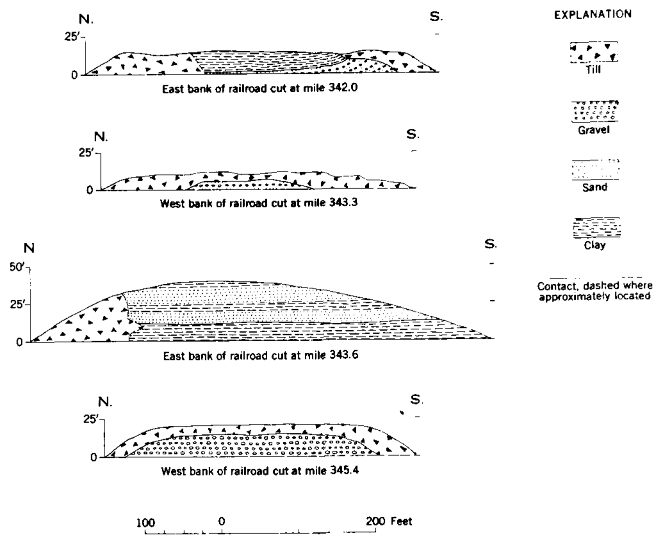

FIGURE 20.—Field sketches of fresh exposures in railroad cuts through drumlike hills in the ground moraine of the Riley Creek glaciation between Yanert and McKinley Park station, made in August 1948. Sketches of west banks of cuts have been reversed so that north in each section is to the left. Direction of ice flow was from right to left. The straight line at the base of each cut is the railroad grade.

EROSIONAL LANDFORMS OF GLACIAL ORIGIN

Erosional landforms of the Riley Creek glaciation are well preserved in many parts of the drainage basin of the Nenana River. The amount of erosion of bedrock below an altitude of 3,000 feet since the retreat of the glaciers has been small. Large-scale horizontal grooves, parallel to the direction of movement of the ice, mark the walls of the canyon between Windy and Carlo. Spectacular U-shaped glacial gorges, such as that of the Nenana, are common in the fretted upland around the Nenana River near Carlo. Clear Creek, Slime Creek, Carlo Creek, Revine Creek, and many other creeks have such gorges. The headwall cirques of these creeks are impressive. Rock-basin lakes in these cirques are rare, except in a small area between the headwaters of Clear Creek and Riley Creek. Elsewhere the cirques are filled with great masses of rubble. As is indicated in the next section, the rubble originated long after the time of the Riley Creek glaciation.

Roches moutonneés and rounded spurs are present in the pass between upper Yanert Lake and the Nenana River at Yanert. The shoulder on the west side of the Nenana River at Windy, which received the full pressure of the ice from the Nenana glacier, is similarly well rounded. The walls of Panorama Mountain, on the other hand, are jagged and angular and have numerous couloirs. The mountain was probably sculptured, in part, before the Riley Creek ice advance. During that advance, it may have been protected by a veneer of talus fragments and till caught along the concave side of the glacial bend. Erosion of the mountain probably took place after the retreat of the ice.

LAKE DEPOSITS

Glacial lake deposits of the Riley Creek advance are not common in the valley of the Nenana River. A morainal hill about 1½ miles south of Lagoon station on the Alaska Railroad consists largely of deformed clay. (See fig. 20, east bank of railroad cut at mile 342.0). For a distance of about 1 mile, along the west bank of the river, below the railroad at mile 338 (about 4 miles north of Carlo), varved, slightly calcareous silt and clay are exposed. The silt and clay, which are about 40 feet thick, are overlain by terrace gravel, which is about 25 feet thick. Landslide topography on the opposite river bank suggests that the clay is also present there. The clay is believed to have been deposited in a lake left by retreating ice of the Riley Creek glaciation.

OUTWASH GRAVEL ALONG THE NENANA RIVER

Outwash gravel of the Riley Creek glaciation forms a complex series of terraces extending downstream from the terminal moraine on Riley Creek to the northern edge of the foothills. Outwash gravel, deposited during the retreat of the glacier from its point of maximum advance at Riley Creek, forms terraces and pitted plains along the river from Riley Creek southward to a point a few miles north of Carlo.

McKinley Park station and hotel are built on two terraces; one about 200 feet above the river, and the other 250 feet above the river. The lower terrace is clearly the outwash plain that extends downstream from the terminal moraine on the south side of Riley Creek. The upper terrace is a few feet too high to be the outwash plain from this terminal moraine; however, it could either have been formed during a slightly earlier advance, or it could have been built by the outwash stream draining the glacial lobes in Riley Creek canyon and the valley 1 mile west of Yanert siding. Presumably, most of the lateral drainage on the west side of the Nenana glacier passed through the Yanert Lakes and not down the west side of the terminal moraine. This kept the terminal moraine from being leveled by the outwash stream of the retreating glacier, a fate common to the terminal moraines of valley glaciers. Outwash from the terminal-moraine lobe itself could have eroded part of the higher outwash terrace to establish the terrace graded to the present terminal moraine.

Downstream, the upper outwash terrace loses altitude more rapidly than the lower, and the two coincide near Moody. The thickness of gravel beneath the outwash plain at McKinley Park station is at least 80 feet (pl. 8), and the base of the gravel is 120 feet above the present river level. At mile 350.3 the thickness of gravel appears to be at least 110 feet, and the base is not more than 70 feet above river level. Additional remnants of the outwash plain are found in the canyon between McKinley Park station and Healy. The layers of blue-gray river gravel resting unconformably on eroded lake deposits of the Healy glaciation at miles 351.4 and 353 (Moody) (fig. 13) are remnants of the Riley Creek outwash plain. North of Moody, the terrace remnants of the Riley Creek are found on both sides of the canyon that is cut in Birch Creek schist, at about 180–190 feet above the river (pls. 2 and 8). They are commonly underlain by about 25–40 feet of blue-gray terrace gravel. The terrace above the railroad track extending 1 mile southward from Garner is part of the Riley Creek outwash, as is the terrace about 90 feet above the railroad track extending 1 mile northward from Garner.

The flight of terraces at Healy is probably one of the most complex to be found anywhere (see fig. 16). Fourteen terraces have been identified between the Healy glacial moraine and the river. These are shown on the map and section on figure 21 numbered consecutively from river level upward. At Healy remnants of most of the terraces are preserved on both sides of the Nenana River, as matching pairs of terrace remnants. They could not, therefore, be slip-off slope terraces, such as are formed by a meandering stream during a period of continuous downcutting. Instead, they represent extensive plains formed by the river during pauses in downcutting after the maximum advance of the Riley Creek ice. The Healy terminal moraine rests on terrace 14. Terraces 13 and 14 are clearly related to the Healy glaciation, but all lower terraces must have been deposited after the course of the Nenana was established in the bedrock gorge between Moody and Healy, as they originate in this gorge (see fig. 21). If the Riley Creek terraces are projected downstream through the Nenana River gorge at a height of about 180 feet above the river, they correlate with terrace 7 or terrace 8 at Healy. Above these terraces are four terraces, each 15–30 feet above the next lower terrace. These are tentatively correlated with the Riley Creek outwash, rather than with the Healy outwash, because of their altitude, geographic position, and relative preservation. However, their extreme height at this point is difficult to understand. It is possible that the gradient of the Nenana River during the Riley Creek glaciation was less than it is at the present time. The river could certainly have been dammed for a short time by large amounts of alluvium being brought down Moody, Healy, and Dry Creeks. It is also possible that Nenana River glacier of the Riley Creek glaciation, may have advanced to a point 3 or 4 miles north of Riley Creek, a distance sufficient to give the river a grade parallel to that of the present river, yet allowing it to coincide in altitude with terrace 12 at Healy. The terminal moraine of this supposed advance is not preserved. Another explanation is that some of the terraces may have been carved during the retreat of the Healy ice after the Nenana River was firmly established in the bedrock gorge.

Terraces at Healy and downstream from Healy are similar in that they generally consist, where exposed, of nearly plane, rock-cut benches overlain by 5–50 feet of river-deposited gravel. Judging from exposures on

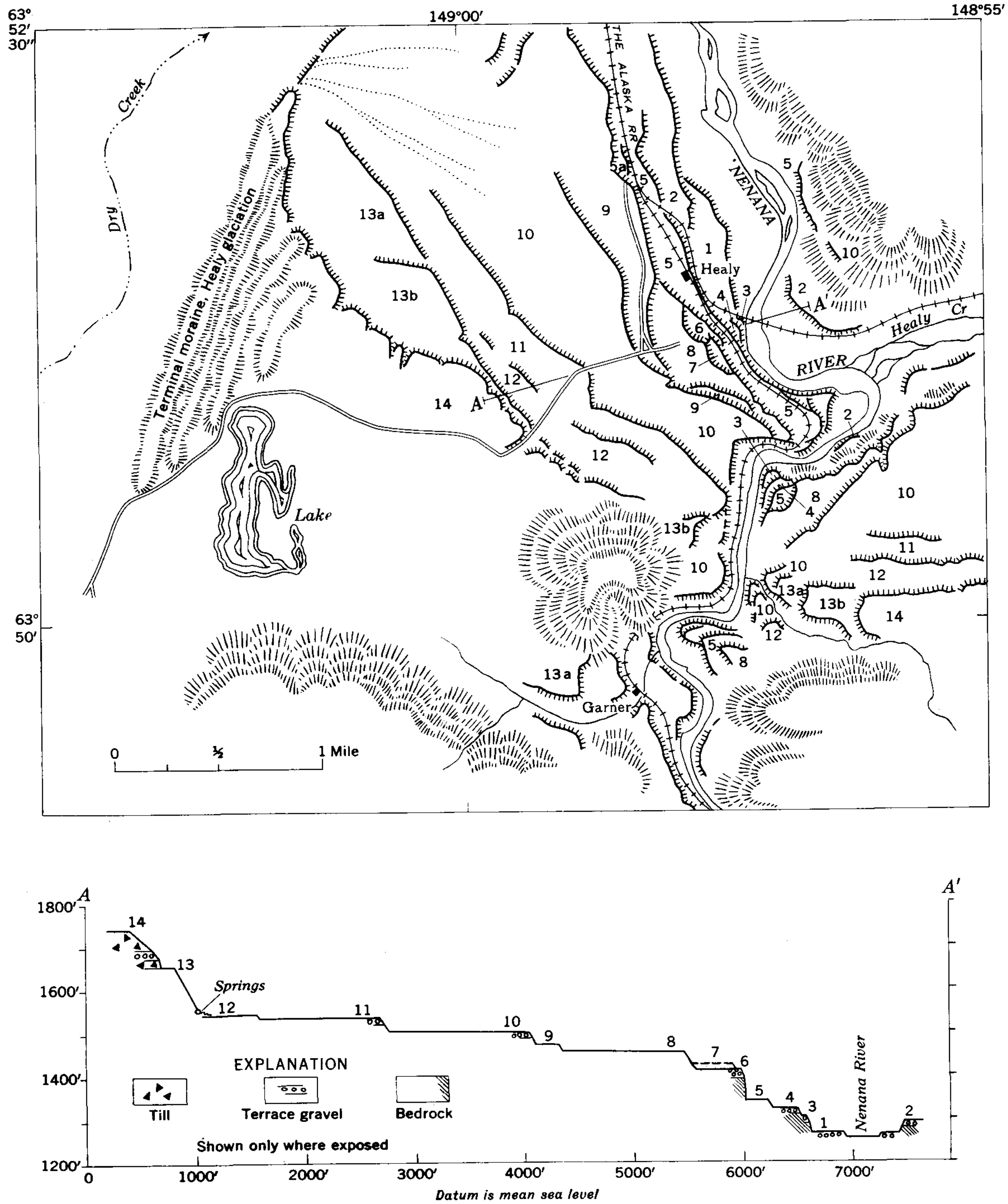

FIGURE 21.—Sketch map of terraces on the Nenana River in the vicinity of Healy, Alaska, and profile along line $A-A'$. Numbers designate terraces which are also shown on plate 8. Profile survey by transit and level rod.

the banks of the Nenana River, the thickness of the gravel on each terrace is fairly uniform from the terrace face to the back of the terrace; the back of each terrace lies against the bedrock front of the next higher terrace (see figs. 21–23). If we assume that the Nenana River formed all these terraces during a single episode of down-cutting, we must assume that the rock benches on which the terrace gravels rest were cut by the river as it aggraded its bed during the onset of the Riley Creek glaciation, and that the terrace surfaces were formed by removal of the outwash gravel during the retreat of the Nenana River glacier of the Riley Creek glaciation. Such assumptions imply that the river removed the excess thickness of gravel over each lower terrace exactly up to the buried base of bedrock beneath the upper terrace, at least at every locality

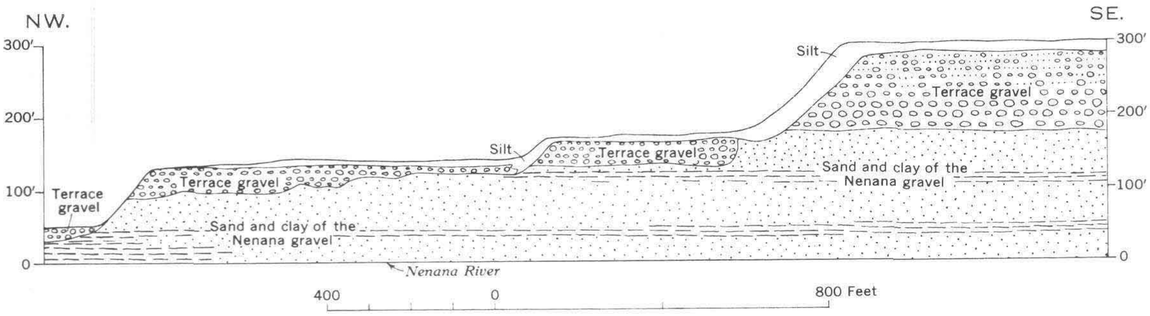

FIGURE 22.—Field sketch of bluff on east bank of the Nenana River opposite the mouth of Slate Creek.

where this relation is exposed. This requires a degree of coincidence of two essentially different processes—the cutting of bedrock benches during aggradation, and the erosion of gravel during degradation—that is rather unlikely. Therefore it is probable that the gravel on most of the terraces was deposited either at the same time or immediately after the terraces were cut, and that each terrace represents a short pause in the retreat of the Nenana River glacier of the Riley Creek glaciation, or even a short re-advance. In all, 7 terraces at Healy (terraces 6–12 on pl. 8)—these do not include terraces assigned to the Carlo readvance (see p. 53–54)—4 at Lignite, and 3 at Ferry are assigned to the Riley Creek glaciation.

ALLUVIUM DEPOSITED BY TRIBUTARIES OF THE NENANA RIVER

Terraces graded to the terraces of the Riley Creek glaciation on the Nenana River are well developed along the tributaries of the river, particularly on Healy and Lignite Creeks. Those along Healy Creek are especially prominent. Terrace 10 has been traced up Healy Creek for about 14 miles (fig. 24). Where Healy Creek flows across the coal-bearing formation, this terrace is a level bench cut across bedrock, veneered with a thin layer of gravel, similar to the terraces at Healy. Above the area underlain by the coal-bearing formation, however, the material exposed in the creek banks between the level of Healy Creek and the terrace, and presumably underlying the terrace surface, is gravel. The gradients of the terrace and of Healy Creek are parallel, and the gravel exposed in the creek banks beneath the top of the terrace is about as coarse as the gravel in the modern stream beds. Therefore, it is likely that Healy Creek flowed in a canyon along its present course, and at its present level before the terraces were cut, and that it aggraded its valley with debris provided by increased solifluction. The new slope of the valley was parallel to the old one and met the Nenana River valley at the level of the Riley Creek terrace. At its maximum altitude the stream cut a new bench across the coal-bearing deposits. The terraces below the bench on Healy Creek and Coal Creek (fig. 24) were cut during the period of downcutting that followed the retreat of the Riley Creek glacier.

Alluvium deposited by the torrents entering the Nenana River between McKinley Park station and Healy consists almost entirely of yellowish-brown pebbles and fragments of Birch Creek schist resting on a layer of blue-gray gravel deposited by the Nenana River. (See p. 34–36.) These deposits are found at miles 349–350, 351.4, and 353 (Moody) on the Alaska Railroad (figs. 11, 13, and 14), and in the canyons crossed by the railroad at miles 354 and 355. Truncated remnants of alluvial cones deposited by two such streams are shown on figure 25.

Alluvium deposited by tributaries north of Healy can generally be recognized by its strong resemblance to Nenana gravel. A good example of such alluvium is exposed in the bluff of the Nenana River opposite

FIGURE 23.—Terraces on the east bank of the Nenana River at Ferry. The lower part of the bluff is sandstone of the Nenana gravel, overlain by outwash gravel of the Riley Creek glaciation (upper terrace) and Carlo readvance (lower terrace). The terraces are mantled with a layer of interbedded peat and wind-blown silt. Note that the thick layer of Carlo outwash gravel on the lower terrace ends abruptly at the base of the higher terrace and that the peat layers in the silt of the upper terrace continue unbroken down the terrace front to the low terrace.

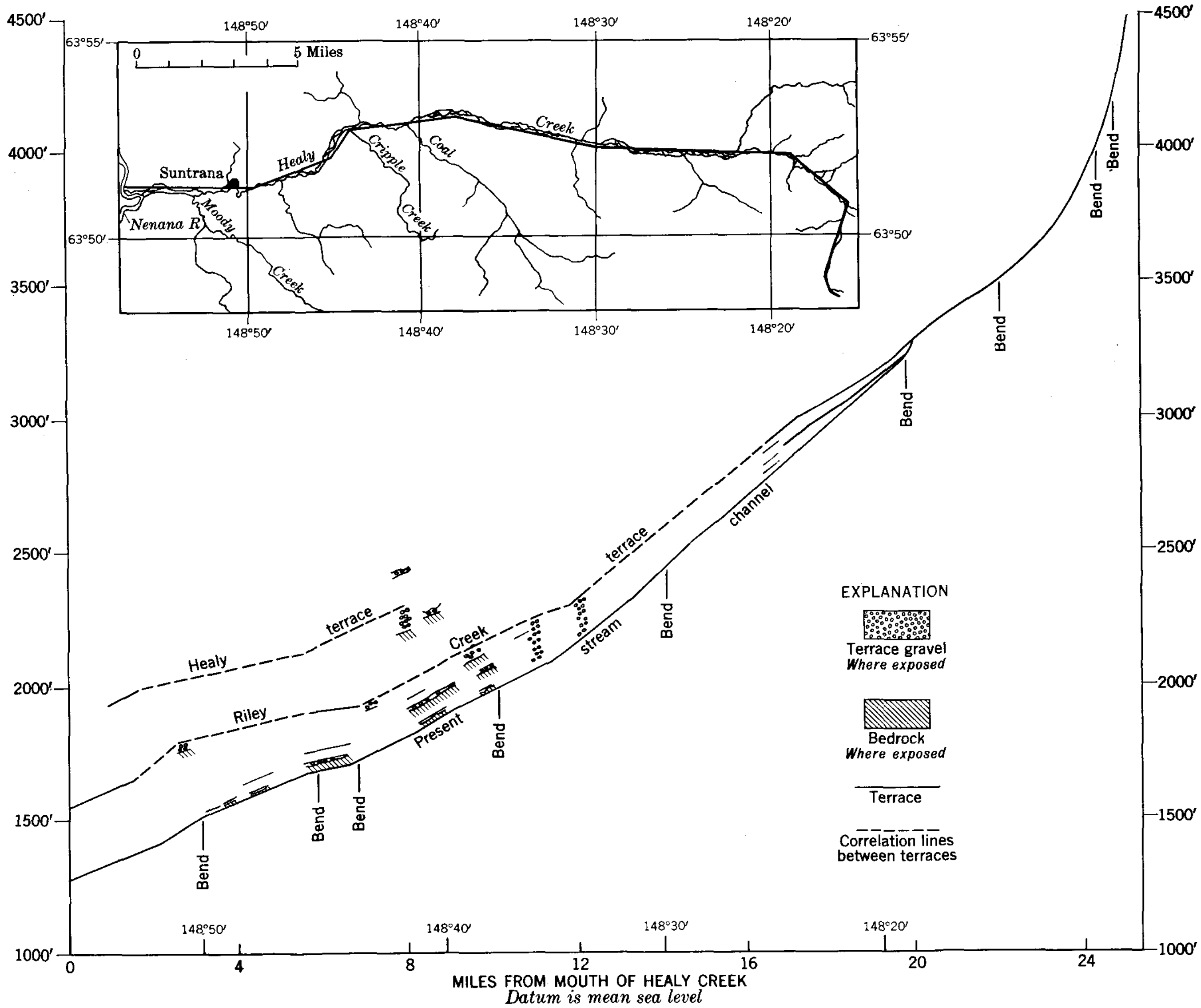

FIGURE 24.—Projected profile of terraces on Healy Creek

Healy (fig. 26). There, a flat-lying layer of blue-gray gravel deposited by the Nenana River rests on a steeply dipping layer of Nenana gravel; the blue-gray gravel is overlain by about 50 feet of brown gravel, which, although identical in appearance to the Nenana gravel, dips about 7° toward the river. The brown gravel apparently made up a group of coalescing alluvial fans built by the small torrents eroding the bluff east of the river. Apparently, the fans extended across the river bed when the Nenana River stood as high as terraces 10 and 5.

DEPOSITS ON OTHER RIVERS

Because the Riley Creek is the youngest extensive glaciation and its deposits are well preserved, it has been possible to recognize with considerable certainty the limits of this stage on several rivers.

The most striking evidence of Riley Creek glaciation on the Wood River (pl. 6) is the remarkable U-shaped canyon that extends from the river's source to the northern edge of the mountains. Although most of the sculpturing of this canyon was done by earlier glaciers, evidence of recent occupancy of the canyon by ice is impressive. This is in the form of glacial grooves and scratches and remarkably smooth roches moutonneés on the canyon walls of Birch Creek Schist. On the east side of the river, north of the mouth of Sheep Creek, a jumble of low hills and lake-filled depressions, partly buried by alluvial fans deposited by creeks entering the river from the east, make up the lateral and, in part, terminal moraine of the Wood River glacier of the Riley Creek ice advance. The terminus of this glacier at its maximum extent prob-

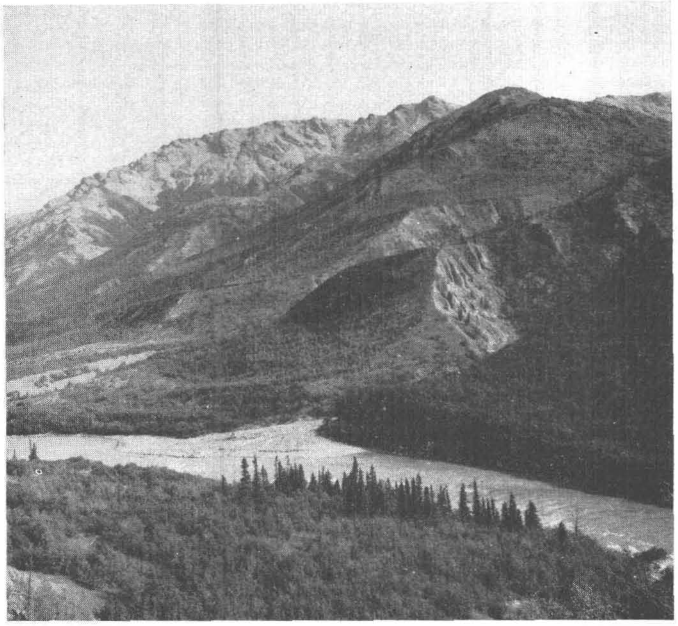

FIGURE 25.—Truncated alluvial cones on the east side of the Nenana River opposite mile 351 on the Alaska Railroad.

ably stood at latitude 64°07′ N., at an altitude of 1,800 feet. The surface of the glacier stood at an altitude of about 3,000 feet just south of Coal Creek, about 3,900 feet at the mouth of Copper Creek, and about 4,500 feet near the mouth of Cody Creek. The glacier was thus nearly 1,500 feet thick for much of its length.

Till, made conspicuous by its content of large white granodiorite boulders, forms a thick lateral moraine on both sides of Kansas Creek (pl. 6) from the present terminus of the glacier to a locality about 3 miles downstream, where the altitude is 3,600 feet. Similar till, which consists of conspicuous light-gray granodiorite boulders and rests on the brown canyon walls of Virginia Creek (pl. 6), extends down that creek to its junction with the Wood River, thus indicating that the two glaciers coalesced. Judging from till deposits, the glaciers on Keevy Peak (pl. 6) were not more than half a mile longer during the Riley Creek glaciation than they are now, and the glaciers at the head of Copper Creek (pl. 6) were only about a quarter of a mile longer than at present.

The valley of the Sanctuary River (pl. 6) is almost completely blocked about 2 miles south of the McKinley Park highway by a crescent-shaped area of hummocky topography rising about 75 feet above the surrounding plains and containing many ponds. This crescent-shaped area is clearly shown on the Healy C–5 quadrangle. It was recognized by S. R. Capps (1932, p. 290, and pl. 4) as the terminal moraine of the glacier that advanced down the Sanctuary River. The excellently preserved U-shaped gorge of the Sanctuary River in the mountains south of the terminal moraine is about 1½–2 miles wide. The freshness of the glacial topography, both of the moraine and of the gorge, the abundance of ponds, and the absence of terminal moraines of any younger glaciation on the Sanctuary River, indicate that this terminal moraine represents the maximum extent of the Sanctuary glacier of the Riley Creek glaciation.

No terminal moraine of the Riley Creek glaciation was recognized in the valley of the Teklanika River, although glacially scoured lake basins indicate that the ice must have advanced northward beyond the mouth of Igloo Creek. Presumably the terminal moraine was destroyed by the glacial melt water.

The terminal moraine of the Riley Creek glaciation on the East Fork of the Toklat River (pl. 6) appears to be crossed by the river about 1 mile south of the highway bridge. At this point, the broad river flat is constricted by a group of low, parallel, arcuate ridges, on which are several ponds. The lateral moraine which joins this terminal moraine forms a prominent bench, or low ridge, along the east mountain wall of the river valley. The bench rises from an altitude of 3,200 feet at its north end to an altitude of 4,200 feet 4 miles southward.

Several branches of the East Fork of the Toklat River join just south of the McKinley Park highway bridge. (See pl. 6.) The easternmost of these streams is the main branch, but the branch just west of it is almost as large. West of the two large branches are four small streams, which head in small glaciers in the mountains south of Polychrome Pass. The braided courses of these streams cross a plain underlain by Nenana gravel and unite at the base of the bluff south of the McKinley Park highway. The interstream areas of that part of the plain between the main fork of the East Fork of the Toklat River and the two branches immediately west of it, are covered with thin ground moraine. The most conspicuous objects on this moraine are several giant blocks of limestone, the largest nearly 35 feet high. These were moved to their present position from a belt of limestone about 6 miles southward, presumably by a glacier of the Riley Creek advance. The absence of any sign of moraine on the part of the plain crossed by the three western tributaries indicates that the glaciers at the head of these tributaries did not extend beyond the edge of the hills during the Riley Creek glaciation.

CARLO READVANCE ALONG THE NENANA RIVER

A group of deposits along the Nenana River, in part glacial and in part fluviatile, appear to indicate that

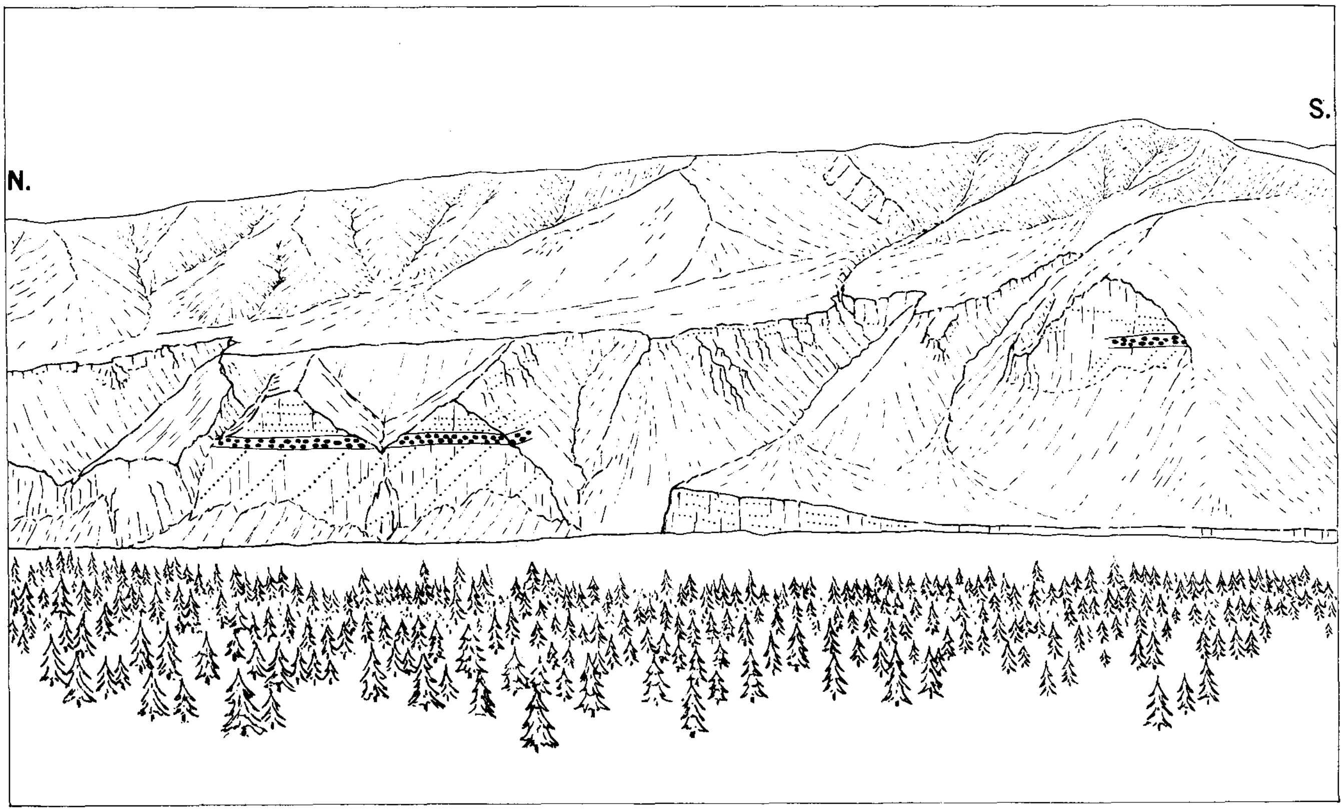

FIGURE 26.—East bank of the Nenana River, looking east from Healy, showing layers of blue-gray terrace gravel deposited by the Nenana River (heavy dots) resting on truncated beds of Nenana gravel dipping 45° north, and overlain by thick deposits of yellowish-brown alluvium derived from the mountain of Nenana gravel in the background. The lower gravel corresponds to the Carlo readvance, and the upper gravel to the Riley Creek glaciation. Sketched from a photograph.

a glacial advance occurred along this river after the glaciers of the Riley Creek glaciation had almost completely melted away; and that the advance brought the ice down the Nenana River to within 9 miles of the terminal moraine of the Riley Creek glaciation, or almost 50 miles from the present terminus of the Nenana glacier. These deposits are unique and present a difficult problem, for along no other river on the north side of the Alaska Range have glacial deposits been discovered that indicate such an ice advance occurred. A careful search for such deposits has been made along the Wood River, the Delta River, and along several streams in the western part of Mount McKinley National Park. Along all of these streams, the last great glacial advance appears to correlate with the Riley Creek glaciation along the Nenana.

The "terminal moraine" of this younger advance is an area of irregular hummocks and hollows, roughly crescent-shaped, extending along the east side of the Nenana River about 3 miles northward from Carlo Creek (see pl. 3). Some of the hollows are nearly 100 feet deep; most of these are undrained. Exposures in roadcuts made during the summer of 1951 indicate that the till in the north part of this morainal area consists chiefly of large and small subrounded boulders and pebbles, but includes interstitial sand and a small amount of clay. In the south part, clay-rich till is common in roadcuts. Between this moraine and Carlo Creek is a gravel plain, standing about 250 feet above the Nenana River and consisting entirely of coarse gravel. This gravel extends from river level to the surface of the plain. A tongue of the plain extends northward from Carlo Creek between the moraine and the Nenana River. On the west side of the river, from Carlo station northward for 3 miles, is a prominent terrace, which, at mile 336 on the Alaska Railroad, consists entirely of interbedded coarse sand and gravel from river level to the terrace-top. This terrace stands about 300 feet above the river at this point, and its surface is about 250 feet below the terrace of the Riley Creek glaciation that forms the pass about 1 mile northwest of mile 336. This terrace correlates in height with a terrace on the east side of the Nenana River which extends northward from the north edge of the Carlo moraine as a gravel plain, about a mile wide. The gravel beneath this plain is 100–150 feet thick, and rests on bedrock, till, or well-

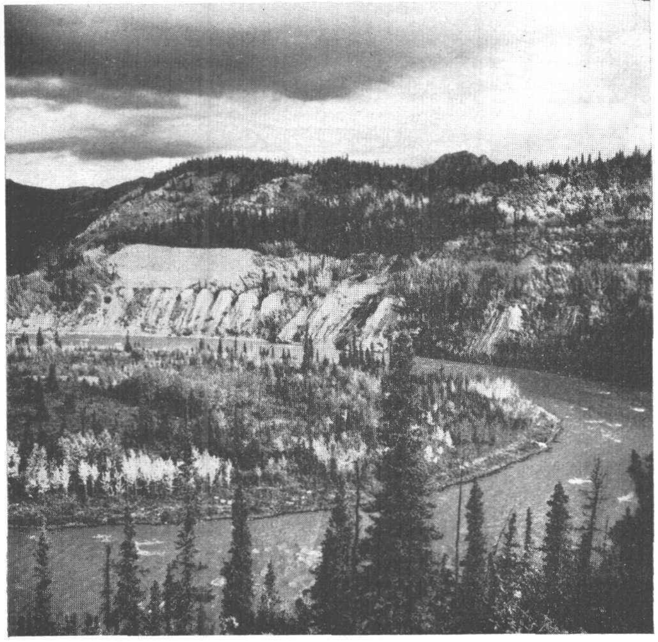

FIGURE 27.—Outwash of the Carlo readvance resting on till of the Riley Creek glaciation on the east bank of the Nenana River one mile above the mouth of the Yanert Fork.

bedded fine sand (possibly a lake deposit). The base of the gravel in all exposures appears to be a level surface, presumably cut by the streams that deposited the gravel. The cutbank of a meander about half a mile downstream from the new highway bridge at Yanert exposes about 100 feet of this gravel and 100 feet of till, presumably of the Riley Creek glaciation, upon which the gravel rests (see fig. 27).

A terrace, triangular in plan, on the west side of the Nenana River opposite the mouth of Yanert Fork, consists of terrace gravel from river level to its top, about 150 feet above the river. The relations of this gravel body to other land forms suggest that it occupies part of a valley cut by the Nenana River in till and outwash of the Riley Creek glaciation. At the south end of the terrace are large steep-walled closed dry depressions formed as a result of the melting of stagnant ice blocks. One of these depressions lies partly in the triangular terrace and partly in a higher area of the pitted Riley Creek outwash. It indicates that the triangular terrace was deposited before all the stagnant ice blocks of the lower 5 miles of the Riley Creek glacier on the Nenana River had melted away.

Gravel terraces about 100 feet high form the river bank just north of Riley Creek and appear to occupy valleys cut in Riley Creek outwash. Remnants of terraces lower than the terraces of the Riley Creek glaciation can be found at several localities in the Nenana River canyon between McKinley Park station and Healy. The broad terrace remnant a few feet lower than the railroad track at Garner is probably the largest.

Terraces 3, 4, and 5 (fig. 21, pl. 8) at Healy are tentatively assigned to the fluviatile deposits of the Carlo readvance.

Terraces correlated with terraces 3, 4, and 5 occur locally at several places on Healy Creek and its tributaries (fig. 24). No such terraces have yet been recognized on the Yanert Fork. Well-defined glacial deposits, similar to the Carlo "terminal moraine", are also absent on the Yanert Fork; however, a steeply sloping lateral-moraine ridge intersects the river about 15 miles above its junction with the Nenana and about 15 miles downstream from the present terminus of the Yanert glacier; it may represent a readvance of ice, but it may equally well represent simply a short pause in the melting back of the glaciers of the Riley Creek glaciation.

Upstream from Carlo, on the west side of the Nenana River, terraces consisting almost entirely of sand, capped with a thin layer of stream gravel, border the railroad and river for about 2 miles. These terraces are about 60 feet high. The extremely flat floor of the Nenana River valley between the mouth of Clear Creek and Carlo, the steep mountain walls that rise abruptly from it, the low gradient and gentle meandering flow of the river in this stretch, and the deposits of sand all suggest that the moraine at Carlo dammed the river, causing a lake to form. If so, the lake, which probably extended a few miles up the valley, was drained before it was completely filled with sediments and before the glacier retreated so far that sand could no longer be deposited on the lake floor.

The glacial and fluviatile deposits that are shown on the map (pls. 2–5) as Carlo deposits indicate unequivocally the following events:

(1) After the maximum Riley Creek advance, the glacier retreated southward at least as far as Carlo.

(2) After the southward retreat, the Nenana River excavated a canyon nearly 50 miles long through morainal deposits of the Riley Creek glaciation and through the outwash train extending northward from these deposits. This canyon must have been as deep as the present canyon of the Nenana, for the Carlo terraces in many places consist entirely of stream gravel.

(3) After cutting the canyon, the river filled it with gravel to the level of the Carlo outwash plain—a thickness of 250 feet at a point 3 miles north of Carlo. At the same time, the glacier deposited the body of till here called the Carlo moraine.

(4) The glacier continued to retreat from the Carlo moraine, leaving a lake dammed by the moraine and outwash deposits. This lake extended southward at

least as far as Clear Creek and possibly as far as the mouth of Windy Creek.

This sequence of events could be explained by a gradual retreat of the glacier to a position near the present glacier front. During this retreat the river, always maintaining a gradient sufficient to move the material supplied to it by the ever-retreating ice front, could have eroded the deposits of the Riley Creek outwash terrace. When the ice front stood near the present terminus of the Nenana glacier, the river could have been flowing at about its present level, as it must have north of Carlo in order to cut the canyon. Following the retreat of the ice, a readvance of about 50 miles—to the position of the Carlo terminal moraine—could have occurred, during which the river could have filled the canyon with outwash gravel of the Carlo glaciation.

The foregoing explanation of the relationships of the Carlo till and outwash assumes (1) that the glacier and the river system draining it always tend to a condition of equilibrium in which the glacial melt water deposits outwash gravel until it establishes a slope steep enough to remove all the debris supplied to it; (2) that during the advance and retreat of the glacier, barring such accidents and interruptions in the course of the river as superposition across a bedrock ridge and the formation of a proglacial lake, a series of graded profiles, essentially parallel to one another but converging downstream, are formed in turn by the river; and (3) that the height of each profile is determined by the position of the glacier front and by the amount and coarseness of gravel supplied to the river (Mackin, 1948, p. 475–477).

The preceding explanation of the Carlo deposits would be the most likely one if deposits similarly situated were found along other rivers of the Alaska Range. However, they have not been found, although the East Fork of the Toklat, Sanctuary, Wood, and lower Delta Rivers were carefully searched for them (Péwé, oral communication, 1951). Therefore, another explanation for the deposits must be found.

If, on melting back along the canyon between Windy and Yanert, the Nenana River glacier of the Riley Creek glaciation left a proglacial lake, the river draining that lake would no longer have been graded to the glacier front. The coarse debris carried by the glacier would have been deposited in the lake, and the river draining the lake would have been clear. The river would have tended to erode the gravel deposits downstream from the lake without replenishing its bedload from upstream sources. This erosion would have to have been rapid enough to remove, in a short time, the till and gravel filling a valley nearly 50 miles long to a depth ranging from 250 feet at the upper end to about 30 feet at the lower end. (Erosion of the outlet of a proglacial lake was used by MacClintock (1922) to explain the double terrace sequence on the Wisconsin River.) Presumably, the lake would have been formed shortly after the glacier front melted back southward, beyond Yanert station. The glacier front may have retreated to Windy before it began readvancing. The advancing glacier would have incorporated in its lower part much of the delta gravel which had been built into the lake, and would have carried this gravel forward as the mass of porous bouldery till which choked the canyon of the Nenana River north of Carlo Creek. Once the lake had drained, the Nenana River would have aggraded its bed with gravel, forming the Carlo outwash deposits. When the glacier retreated from the position of the Carlo till, another lake was formed in the canyon between Windy and Carlo. In this lake, the sand deposits west of the railroad, south of Carlo, were deposited. Subsequently, the glacier melted back almost to its source.

Varved clay deposits, overlain by the Carlo outwash, extending a few miles northward from the Carlo moraine, indicate that a lake must have existed exactly where the hypothesis requires one. Presumably these deposits were laid down after the Riley Creek ice melted away from this area; otherwise they would be deformed. Furthermore, the pits in the triangular terrace opposite the mouth of Yanert Fork indicate that the period of time between the retreat of Riley Creek ice from this point and the deposition of the Carlo outwash terrace was short. The Carlo deposits are, therefore, regarded as evidence for a minor readvance during the general retreat of the Riley Creek glacial ice.

SUMMARY OF HISTORY

The rivers of the Alaska Range appear to have established their positions at or below their present positions by the beginning of Riley Creek glaciation. This is certainly true for the Nenana north of Healy, and it appears to be true for the Sanctuary, Toklat and Wood Rivers. The topography of the Alaska Range at the beginning of the Riley Creek advance differed little from its present topography. In the interval between the Healy and Riley Creek glaciations, the ice presumably had retreated as far back as the present glacier fronts, or farther. It may have disappeared altogether from the area shown on plate 6.

With the general cooling of climate, ice began accumulating in the Alaska Range. Most of that which accumulated in the mountains near the headwaters of the Nenana River probably moved southwestward down Broad Pass into the Susitna basin. However, enough flowed down the Nenana River for the front of that ice to reach a position near McKinley Park station. Many reversals in the direction of movement of the ice front, and short episodes during which the ice front was stationary, may have occurred. At the same time that the ice was moving down the Nenana River, ice moved down the Yanert Fork and Riley Creek to coalesce with lobes of the Nenana glacier. This ice advance coincided with that of late Wisconsin age in the Continental United States—the Mankato substage or the Cary and Mankato substages combined.

Ice moved down the Wood River to the edge of the mountains, and down the Sanctuary to within 2 miles of the McKinley Park highway. Ice advanced down the Teklanika River to a locality a few miles beyond the mouth of Igloo Creek, and down the Toklat almost as far as the highway bridge. The small glaciers in the foothills of the Alaska Range, at the head of Kansas Creek and Copper Creek, and on Keevy Peak, advanced little if at all beyond their present positions. The great range in the lengths of the glaciers during the Riley Creek glaciation beyond their present lengths—the Nenana glacier, 60 miles; The Wood River glacier, 38 miles; the Yanert glacier, 30 miles; the Sanctuary glacier, 16 miles; the East Fork Toklat glacier, only 9 miles; and the glaciers around Keevy Peak and Copper Creek, less than a mile—indicates that orographic factors were important in controlling the growth of the glaciers. This is also apparent when the depression of the orographic snowline in this region (determined from the position of cirques) is considered. In the latitude of Windy, the orographic snowline appears to have lowered about 1,000 feet, judging from the difference in altitude of cirques now occupied by ice and those formerly occupied by ice. In the latitude of Keevy Peak it does not appear to have shifted more than a few hundred feet, if that much. Winters are much more severe north of Windy than south of Windy, and, under conditions of extensive glaciation in southern Alaska, they were more severe than they are at the present time. This indicates that snowfall and summer cloudiness, rather than mean temperature or winter extremes, are major, and possibly predominant, factors in the accumulation of ice in Alaska.

The glacier front fluctuated over a distance of at least a few hundred yards, and possibly a few miles, during the period when it was near the mouth of Riley Creek. These fluctuations occurred as repeated short, rapid advances, followed by gradual wasting away of the ice. Certianly at least three such episodes, and possibly many more, occurred when the ice front was near the mouth of Riley Creek. This alternation of advance and retreat may have been the characteristic pattern of glacier behavior during the entire period of waxing and waning of the ice sheet. Moffit reported that such movements were made by the Black Rapids Glacier (1942, p. 146–157), and Tarr and Martin reported that they were made by the Yakutat Bay Glaciers (1914, p. 168–197), the Childs Glacier (1914, p. 400–409), and the Columbia Glacier (1914, p. 261–282). The cause of the fluctuations of the front of the Nenana glacier of the Riley Creek advance is not necessarily the same as any of the causes—chiefly earthquake-induced avalanches—attributed by Moffit and by Tarr and Martin (1914, p. 168–197) to the fluctuations they reported.

The retreat of the glacier was, naturally, a process of melting down and melting back of the glacial ice. Areas of clear ice exposed to the rays of the sun melted first, and the depressions they had occupied were filled with outwash gravel. Continued melting of the ice exposed irregular moraines over much of the lowland country at the junction of the Yanert Fork and the Nenana. South of Yanert, a lake formed. This lake was quickly drained, as it was dammed solely by glacial debris and outwash. A readvance of the glacier brought the ice front northward to Carlo and caused the river to aggrade its bed. As the glacier again melted back, a lake formed between Carlo and Windy. This lake, also, existed for only a short time.

Similar events were presumably going on along other river systems, although their record is not so clearly preserved, nor was it so carefully studied. Nevertheless, it is known that as the glaciers advanced, the glacial rivers aggraded their beds as a result of the increased amount of coarse material provided them by the ice. At the same time, periglacial processes were supplying the periglacial tributaries of the Nenana River and other streams of the Alaska Range with so much material that they also aggraded their beds, more or less in step with the aggradations of the master streams. As the ice retreated, it no longer supplied the streams with vast quantities of coarse debris at their heads; therefore, the streams eroded their outwash terraces and cut elaborate terrace flights.

DEPOSITS AND LANDFORMS YOUNGER THAN THE DEPOSITS OF THE CARLO READVANCE

TERRACES

Some of the terraces along the Nenana River are much lower than the terraces assigned to the Carlo readvance. They have been separately distinguished on plates 2–5, from the mouth of Dry Creek southward. Northward from Dry Creek, the terraces assigned to the Carlo readvance are so close in height to the younger terraces that it was difficult to distinguish them. These terraces, like most of the higher terraces, occur in pairs; that is, the same terrace can be recognized on both sides of the river at many points along its course. They occur only as remnants, parts of them having been removed where the river erodes steep banks or where it flows in narrow rock-walled gorges; and in places these remnants are buried neneath alluvial fans that were built by the tributaries of the Nenana; for example, burial under the alluvial fan at the mouth of Dry Creek interrupts the continuity of the terraces between Healy and Lignite. The terraces have irregularities in height above the river that result from variations in the depth of erosion or thickness of gravel bedload when the river was forming the terraces. These irregularities approach in magnitude the difference in height of the terraces and the height of the lowest of them above the river. As a result of the existence of these irregularities, the terrace surfaces cannot be projected with confidence across the gaps between the terrace remnants, and correlation of these remnants is full of doubts.

At Healy, where the terraces along the Nenana River are most fully developed, two terraces lie below the lowest terrace assigned to the Carlo readvance. Terrace 1 stands 10 feet above the flood plain and consists entirely of river gravel. (See fig. 21.) Terrace 2 stands 28 feet above the flood plain; exposures on the east bank of the river, north of the railroad bridge, show it to consist of 18–20 feet of bedrock overlain by 8–10 feet of gravel similar to that on the present flood plain. (See fig. 21.)

Two terraces, 10 and 25 feet high, are present on the west side of the river at Lignite. The railroad track and village of Lignite are built on the lower terrace. The terrace on which the village of Ferry is located is about 15 feet high and consists of 10 feet of bedrock capped by 5 feet of terrace gravel. This terrace continues northward to Browne.

A rock-cut bench veneered with gravel 20 feet above the river occurs near mile 350 on the Alaska Railroad. About 1 mile north of McKinley Park station, a terrace 18 feet high on the east side of the river consists entirely of gravel. The terraces on which the railroad between miles 337 and 341 is built are much lower than the Carlo outwash plain on the east side of the river; however, they are 65–110 feet above river level, and are probably best explained as having been cut by the river during excavation of gravel deposited during the Carlo readvance. At mile 338.6, 15 feet of terrace gravel rests on 40 feet of clay. At mile 340 there is a terrace 50 feet high that is made up entirely of gravel. Terraces on the east side of the river and about 15 feet above river level, on the other hand, are probably correlated with the low terraces along the Nenana River near Healy.

Terraces 5–20 feet above stream level are present on most of the tributaries of the Nenana River and on many other streams in the Alaska Range. At many localities, especially on Healy and Lignite Creeks, these are rock-cut benches having a veneer of stream gravel. More commonly, however, they appear to consist entirely of gravel, from stream level to their tops. Similar low terraces have been observed on many other rivers, both glacial and periglacial, in this part of the Alaska Range. Because of their ubiquitousness, their nearly uniform height, and their position along the rivers—far below the lowest terraces of the Riley Creek glaciation—it is unlikely that they were formed merely as an incident in the degradation of rivers during the retreat of the Riley Creek ice. The fact that in many places they consist entirely of gravel suggests that they were formed as a result of a change in climate, rather than as a result of tilting or uplift. Along with other features, to be described subsequently, they are regarded as evidence of minor cold periods that occurred after the thermal maximum which followed the glacial retreat of the Riley Creek glaciation.

TALUS

Large or small amounts of talus occur at the base of all the rock cliffs except those that are periodically swept by the Nenana River or its tributaries. Slopes steeper than 35° are commonly veneered by talus which presumably rolled or slid to the slopes. Slopes less steep are covered with congeliturbate, which will be described in the following section.

Talus accumulated below cliffs and cirque headwalls throughout the Pleistocene. Most of the talus which formed in areas which were subsequently glaciated was swept from its resting places by the glaciers and incorporated in till or was distributed by the melt water as outwash gravel. Outside the areas covered by the successive ice sheets some of the talus which accumulated at the base of cliffs during the Pleistocene has remained there to the present day. However, most of the talus which accumulated in canyon bottoms along the periglacial streams during each glaciation was swept away when these streams subsequently re-excavated and deepened their canyons, and the talus which accumulated on valley sides during interglacial periods was frequently moved to the stream beds during periods of glaciation by periglacial processes of creep and mass wasting. Hence, in the area outside the ice limits of each glaciation are some talus deposits which were formed in part before that glaciation and later mantled with younger talus, and some talus deposits which have formed since that glaciation. For instance, the walls of the Nenana River gorge between Healy and McKinley Park station are mantled in many places with talus of the Riley Creek glaciation which rests on and interfingers with the outwash gravel of the Riley Creek glaciation. On the other hand, much of the talus in the tributary canyons rests on canyon walls which were probably buried beneath gravel graded to the outwash of the Riley Creek glaciation, but which have since been re-exposed. The talus in these canyons is for the most part younger than the Riley Creek glaciation.

Many of the most conspicuous talus deposits lie in valleys which were occupied by ice during the Carlo readvance, or on valley and canyon walls which were buried beneath outwash gravel of the Carlo readvance. These deposits are clearly younger than the Carlo readvance. Large deposits of coarse blocky talus have accumulated below cliffs and cirque headwalls in conglomerate, greenstone, granitic rocks, and Birch Creek schist. The new highway on the east side of the Nenana River between Slime Creek and the bridge opposite Windy is excavated, in part, in talus cones. On the west side of the river, about half a mile north of Clear Creek, the Alaska Railroad obtained blocks for riprap from a quarry dug in talus. The blocks of conglomerate and sandstone obtained from this quarry were used as shaped riprap along the river bank at the north end of the tunnel at Garner; they show no noticeable weathering or displacement. The supply of very coarse blocks was quickly exhausted, and the quarry was abandoned after a few years. The surface of this talus apron is dark, as the upper surfaces of the boulders are completely covered with lichen. However, lichens do not grow on boulders of the quarry face although the quarry has been abandoned since 1925. The quarry face, consequently, is light tan in color. This can mean either that conditions for lichen growth no longer prevail at this locality, which is unlikely, or that the time required for lichens to establish themselves is greater than the time that has elapsed since 1925.

CONGELITURBATE

Congeliturbate, defined by Bryan (1946, p. 640) as "a body of material disturbed by frost-action," forms a thin, almost continuous mantle over all the land surface of this part of the Alaska Range, except where actual outcrops of other formations are present. Because it is of great extent and rarely more than a few feet thick, it is not mapped separately on plates 2, 3, 4, and 5, except where it is of great thickness.

Congeliturbate is the result of intense deformation and displacement of a film of surface material through the heaving and settling effect of alternate freezing and thawing. Solifluction (Andersson, 1906), which takes place when soil viscosity is temporarily reduced by the presence of large amounts of melt water, also plays an important part in the development of congeliturbate. The accumulation in the soil of the large amounts of water necessary for congeliturbation requires the presence of an impervious substratum. In arctic regions this is provided by the layer of perennially frozen ground (Taber, 1943), or pergelisol (Bryan, 1946, p. 640), which is present nearly everywhere from the crest of the Alaska Range northward (Black, 1950, p. 249).

Congeliturbate of solifluction origin—material that has moved down slopes whose angles are gentler than the angle of repose—can be recognized at many places in the Alaska Range. In very coarse solifluction deposits at high altitudes, the blocks pried loose from the outcrops by frost action slide directly downslope from their source. Where the source rock varies slightly in color from place to place, the rocks extending downslope from it streak the slope with those colors. Such streaking is the outstanding feature of the mountaintops of Birch Creek schist on both sides of the Nenana River gorge, and can be seen clearly from McKinley Park station. In cross section, solifluction deposits are a heterogeneous mass of angular fragments and boulders mixed with sand and silt and appreciable amounts of peat and wind-borne material. They consist almost entirely of material derived from directly up the slope from their present resting place, and so can be readily distinguished from till. Commonly, also, they are not as compact as till. Although stratification due to water and wind action is absent, the deposits may exhibit a crude flow-layering and preferred orientation of inequant fragments resulting from the downslope movement of the congeliturbate.

On level surfaces, congeliturbate can be recognized in cross section by typical structures in the soil. In soils whose grains have a wide range in size (from boulders or pebbles to fine sand, silt, or clay), congeliturbation effects a sorting of the soil. On level ground it causes the stones in the soil to gather into rings or polygons, each of which surrounds soil rich in clay. On sloping ground it causes the formation of alternate stripes of stones and finer grained particles that extend down the slope (*cf.* Washburn, 1950, p. 89). Where the coarse particles in the soil are rare or absent the effect of congeliturbation can be seen in frost scars, peat rings, and allied forms (Hopkins and Sigafoos, 1951), and, in cross section, in the involutions of differently colored bands of soil (Schafer, 1949, p. 156–165). Even where there are no exposures, congeliturbation may be recognized, for it causes the development of a special microtopography. This topography consists of mounds or hummocks 6 inches to 3 feet high and a few feet to 10 feet across on level ground, and of lobes and terracettes on sloping ground. All these features are present in the Alaska Range. Their great extent makes it clear that most of the land surface of the range is mantled by a layer of material which has undergone congeliturbation.

Presumably, movement of rocks and soil by congeliturbation inhibits plant growth over the active bare areas; if congeliturbation decreases in intensity or ceases, plants will cover the bare areas in a few years, provided the slope is not too steep and rocky and the altitude not too great (Hopkins and Sigafoos, 1951). Even at an altitude of about 5,500 feet, 2,500 feet above timberline, there are a few lichens and small, nearly level patches of turf, which indicate that plant growth of one type or another would be continuous over most of this area were it not inhibited by intense movement of the soil. The only vegetation supported by coarse congeliturbate in Birch Creek schist above 4,500 feet is a sparse growth of weeds with long roots adapted to growing in moving talus. Lichens are absent from bare rock surfaces. A few boulders show by the presence of dead lichens on their undersides that they have been recently overturned after a long period of stability. Above 4,500 feet, therefore, active congeliturbate covers the entire surface except on outcrops and scattered patches of turf. At lower altitudes the talus and solifluction deposits are covered with a dense turf, which is interrupted at only a few localities—by landslides, badlands, outcrops, or frost scars (Hopkins and Sigafoos, 1951, p. 65–70). Therefore, although congeliturbation is occurring below 4,500 feet at the present time, it is affecting surfaces locally, not generally.

LANDSLIDE DEPOSITS

Deposits of ancient landslides are to be found at several places along the Alaska Railroad and Nenana River. Landslide activity in the Nenana River gorge has led to serious maintenance problems on the railroad. Landslides are of two types: rotational shear slips, and detritus slides or mud runs (Ward, 1945). The rotational shear slips occur where a thick layer of coarse material or a block of rock or soil behaving essentially as a rigid unit, is underlain either by a layer of fine-grained material (clay or clay-rich till) or by a gently inclined fracture. A landslide of this type, between the Alaska railroad and the river, about 1 mile southeast of McKinley Park station, consists of a series of arcuate blocks several hundred feet long and 50–100 feet wide, which have been rotated so that their originally horizontal surfaces now slope back toward the railroad at angles of 10°–25°. At the same time the blocks were rotated, they were moved downward and outward toward the river, creating a series of asymmetrical ridges at successively lower altitudes below the railroad track. This landslide occurred because the Nenana River eroded the base of a bluff, about 150 feet high, that consisted of a layer of clay-rich till 65 feet thick, overlain by a layer of outwash gravel 85 feet thick. The till flowed out toward the river, undermining the gravel and dragging blocks of gravel with it. As the blocks of gravel moved downward and outward, their originally horizontal upper surfaces were rotated away from the river. The landslide occurred on a surface close to river level. Clearly, this surface is younger than the outwash terrace of the Carlo readvance, remnants of which are nearly 100 feet high both north and south of the landslide. Therefore, the landsliding occurred since the Carlo readvance. The landslide is now stable.

Between 1949 and 1951 a landslide started on the mountain wall 1,500 feet west of the Alaska Railroad at mile 338.2, extending from 2,300 feet to 3,000 feet in altitude. This landslide is a rotational shear slip involving a block of the Cantwell formation and intrusive andesite. Below it is a mass of loose talus accumulated by rockfall from the front part of the block. This landslide appeared after the field work in this part of the area was completed and has not been examined. Its causes are unknown. When seen from a distance in 1951 and 1952 it did not appear to have moved forward more than a few hundred feet, nor did it appear to pose any immediate danger to the railroad.

Landslides in the Tertiary coal-bearing formation are common along the walls of the canyons of Lignite Creek and its tributaries. (see pl. 2). The landslides start where ground water is concentrated along the tops of impervious beds which slope gently toward the creek or its tributaries. The landslides along Lignite Creek rest on the canyon floor or on terraces correlated with or younger than the outwash terrace of the Carlo readvance. The landslides are therefore no older than the Carlo readvance. Vegetation on many of the landslides is disturbed, indicating that the landslides are still active.

Evidence of ancient landslides has been found along the bluff between the Healy outwash terrace and the Riley Creek terrace from Dry Creek northward to the road west of Lignite. This consists of a number of narrow irregular ridges and terraces parallel to the trend of the bluff. Presumably, the thick outwash gravel of the Healy glaciation here rests on a layer consisting mostly of clay, deposited either as till, proglacial lake sediment, or as a layer within the Tertiary rocks. The clay flowed out from beneath the gravel, causing the gravel to settle as irregular blocks. The landslides rest on the Riley Creek outwash terrace. The blocks appear more rounded than those of active landslides, and they are overgrown with vegetation which does not appear to be disturbed. The landslides could have occurred at any time since the Riley Creek glaciation. However, because they appear to be older than the other landslides, the author believes they probably occurred before the end of the Carlo readvance.

Detritus slides and mud runs generally flow into streams, which redeposit the debris as alluvium or remove it altogether. Small mud runs on hillsides are quickly overgrown with vegetation and are, therefore, difficult to recognize. Although no detritus slides or mud runs were found, it is believed that many badland areas resulted from the exposure of Tertiary rocks to active erosion after the vegetation was removed by such landslides.

ROCK GLACIERS

Rock glaciers similar in every respect to those in the Wrangell Mountains, described by Capps (1910), are common in the Alaska Range. These are usually lobate mounds of intermixed coarse and fine angular detritus, similar to talus in composition and grain size. They extend downslope from the base of talus cones and talus aprons on declivities as gentle as 5°. They strikingly resemble glaciers in appearance in that they are commonly elongate downslope, have steep fronts and sides facing lower country, and bear on their upper surfaces arcuate ridges that are convex downstream, and straight ridges that are parallel to the direction of flow.

Rock glaciers occupy the headwater cirques of Clear, Riley, Slime, Carlo, and Revine Creeks, all tributaries of the Nenana River and Yanert Fork. They are common in cirques draining into the Yanert glacier, at the headwaters of Virginia Creek in the Wood River country, and at the headwaters of the Sanctuary River. At all these localities the rock glaciers occupy cirques formerly occupied by ice of the Riley Creek glaciation, and those on the tributaries of the Nenana occupy cirques which were probably filled by ice at the time of the Carlo readvance. They are therefore younger than the Riley Creek glaciation and the Carlo readvance.

Part of the deposits of andesite blocks surrounding Jumbo Dome (Wahrhaftig, 1949) are regarded as ancient rock glacier deposits. The frost-moved rubbles surrounding Jumbo Dome were undoubtedly formed, in part as rock glaciers and in part as sheets of congeliturbate, during many of the glacial advances which took place on the Nenana River, only 10 miles away. Correlation of the glacial sequence on the Nenana River with the sequence of rubble deposits surounding Jumbo Dome may be possible when the pediments and terraces on Marguerite Creek, which can be dated with respect to periods of rubble movement, have been correlated with the pediments and terraces on Lignite Creek and the Nenana River.

Rocks which break into coarse angular blocks seem to be the most favorable for the occurrence of rock glaciers. Hence, rock glaciers are most common in the granite terrain between the Wood River and Kansas Creek, and in mountains of greenstone along the crest of the Alaska Range and in the vicinity of the Yanert Glacier.

Exposures of the interiors of rock glaciers are rare; loose, angular debris from the top and sides quickly slides into any openings that are made. An exposure of the side of an active rock glacier—the down-valley extension of the terminal moraine of the glacier at the head of Kansas Creek—shows that this rock glacier consists of solidly frozen clay and gravel in which numerous blocks of granite are embedded like plums in a pudding. The surface layer of this rock glacier is made up mostly of large blocks of granite. Similar interior and surface materials were seen in an exposure of a rock glacier at the head of one of the forks of Virginia Creek. An exposure in the side of an inactive rock glacier on Jumbo Dome (Wahrhaftig, 1949) shows that the material of the interior is of much finer grain size than that on the upper surface.

Preliminary results of measurements, now in progress, of the movement of a rock glacier at the head of Clear Creek, show that the upper surface of this rock glacier is moving forward at rate of about 2½ feet per year along the medial axis, and 1–1½ feet per year along the sides.

According to Richmond (1952), rock glaciers of the La Sal Mountains, Utah, have cores of till and other features of glacial origin. He believes that they are "residual from small glacial readvances, retaining the essential configuration and structure of the ice." The results of studies of the motion of the Clear Creek rock glacier indicate that its motion today is probably the result of glacierlike flow of interstitial ice. The surface of the rock glacier, however, is free of snow during the latter half of the summer, and the ice in the rock glacier, therefore, probably accumulates from freezing of interstitial water within the talus, rather than from compaction of snow.

Capps (1910) regarded rock glaciers as the last stages of the melting away of enfeebled glaciers, and thought them to be essentially the deposits left by the last glacial ice during a period of deglaciation. It appears more likely, however, that rock glaciers are newly formed and are independent of the last glaciation.

The rock glaciers which now occupy the cirques that were once filled by the Riley Creek ice probably originated long after that ice completely disappeared from those cirques and are a result of recent cooler climate. A rock glacier whose origin is clearly recent is at the head of Clear Creek. This rock glacier, whose motion is being measured, is advancing over a turf-covered mound which fills the floor of the cirque. The mound has steep sides that face downvalley as well as toward the valley walls, and an upper surface that slopes gently northward down the valley of Clear Creek. It is dissected by deep gulches, whose walls, also, are partly covered by turf. From the appearance of this mound and of exposures along the walls of the gulches that dissect it, it is evident that it is an ancient rock glacier, now completely stabilized and overgrown and partly dissected by tributaries of Clear Creek. The upper part of the mound is buried by the active rock glacier, the sides of which are free of turf, and the upper surface of which is partly covered by turf that is torn and broken by numerous fresh cracks. The active rock glacier is advancing over the older rock glacier and filling the gulches which dissect it. A period of time in which the older rock glacier was formed and later dissected, separated the formation of the younger rock glacier from the melting away of ice from this cirque, and, by analogy, a period in which there were no deposits of this type in this cirque is believed to have separated the formation of the older rock glacier from the disappearance of glacial ice.

TILL

A well-preserved low moraine crosses the Yanert Fork about 2 miles downstream from the present terminus of the Yanert Glacier. (See pl. 6.) Where it crosses the river it consists of several irregular hills, covered with spruce forest, rising like islands out of the braided outwash plain of the Yanert Fork. Large granite blocks are strewn over the surface of the hills, and presumably the hills themselves are composed largely of this granite. These hills form a double arc, convex downstream, where they cross the river. Upstream from that point, along the walls of Yanert valley, the moraine consists of two low continuous ridges of till, generally about 200 feet apart but merging locally. These ridges rise about 200 feet above the glacier surface, which position they maintain far back into the headward portions of the Yanert Glacier, especially along the north mountain wall of the valley. A dense growth of mature spruce covers the terminal moraine. This forest continues upstream for about a mile, where it grades into a forest of cottonwood and willow, which extends almost to the base of the glacier. At about the point where the two forests grade into each other, about a mile below the glacier terminus, another moraine crosses the river. On the mountainsides near the terminus of the glacier, this moraine is a thin sheet of till. The glacier abuts against the till-covered slopes, which are overgrown by alders and low tundra vegetation. The contact between moraine-covered ice and vegetation-covered till is abrupt.

Recent till covers stagnant ice a few tens of feet downslope from the glaciers on Keevy Peak. At the head of Copper, Virginia, and Kansas Creeks, recently deposited till is now separated from the glaciers that deposited it by narrow outwash plains. This till merges downslope with rock glaciers.

GLACIERS

There are no active glaciers in the area immediately adjacent to the Alaska Railroad; however, the Nenana River, Yanert Fork, Sanctuary River, Teklanika River, East Fork of the Toklat River, Wood River, and many of their tributaries, head in glaciers (see pl. 6). Less than one-twentieth of the area that was covered by ice during the height of the Riley Creek ice advance is covered today. Existing glaciers range in length from half a mile to 20 miles; the longest and largest is the Yanert Glacier, which heads on Mount Deborah, 12,540 feet high, just east of the area shown on plate 6. The existing glaciers are one-tenth to one-third as long as they were at the height of the Riley Creek glaciation. Historical records (Taliaferro, 1932, p. 764) and biological data (Cooper, 1942, p. 17–20) show that the glaciers of southern and southeastern Alaska during most of post-Wisconsin time were much smaller than they now are; and that, beginning a few thousand years ago, an ice advance took place which reached its culmination about 100–200 years ago in southeastern Alaska, and about 20–50 years ago along the southern Alaska coast. Since this culmination, the glaciers have been melting back for distances of from a few hundred feet to scores of miles. For instance, according to Barnes (1943), the Portage Glacier retreated 3,000 feet during the 25-year period from 1914 to 1939. Similarly, the Spencer Glacier retreated about 2,100 feet between 1906 and 1931, and the Bartlett Glacier about 1,000 feet between 1911 and 1931 (Wentworth and Ray, 1936, p. 898–903).

The glaciers of this part of the Alaska Range show evidence of similar recent advance and retreat. However, as will be shown in a following paragraph, all the recent deposits—glacial and other types—considered together, suggest a somewhat more complicated climatic history for Alaska than that outlined by Cooper. Presumably, the vegetation on the 1-mile moraine against which the moraine-covered ice of the Yanert Glacier is in sharp contact, took a considerable time to establish itself. The sharp contact of the ice with this moraine implies either a long period of standstill or a recent advance. At the present time, however, the lower part of the Yanert Glacier appears to be slowly wasting away, as the clear ice surface is smooth for many miles above its terminus, and ridges of till-covered ice rise as high as 50 feet above this surface. Similar conditions were observed by Tarr and Martin (1914) on stagnant glaciers of the Yakutat Bay region. The Yanert Glacier had a similar appearance in 1913, as photographs taken then attest (Moffit, 1915, pls. 4 and 5). The glacier was photographed in 1941 by Bradford Washburn, who has kindly given these photographs for study. At that time its surface was freshly crevassed, and the surface of the moraine-covered ice was flush with that of the clear ice. Apparently the glacier was active during 1941, but was dormant in 1913 and in 1950 and 1951.

Tarr and Martin (1914) have shown that rapidly advancing glaciers have deeply crevassed surfaces, whereas glaciers whose ice is either stagnant or moving forward only slowly have relatively smooth surfaces. When the Yanert Glacier was examined in 1951, its surface was remarkably smooth for at least 8 miles above its terminus, and crevasses were absent (shown by the large melt water streams flowing on it), indicating that the lower part of the glacier had not advanced for several years.

The small glaciers on Keevy Peak and around the Wood River show signs of recent retreat. On nearly all these glaciers, the areas of visible ice are smaller than the areas covered by glaciers shown on topographic maps made in 1910 (Capps, 1912, pl. 1). The ice surface of the glaciers on Keevy Peak was observed in 1950 to be much lower than the ridges of fresh till in front of the glaciers. The easternmost of the two glaciers on Keevy Peak was separated from till-covered stagnant ice by a small proglacial or superglacial lake. The large, nearly circular glacier at the head of Virginia Creek was bordered by a band of bare till and bedrock 200 feet wide. Beyond the band of bare rock, the till and granite were covered with lichens and had a dark appearance.

PEAT

Peat is accumulating in boggy areas along the Alaska Railroad. Small closed basins in till in the vicinity of Lagoon appear to be filled with sphagnum and *Carex* bog, which rests on peat. The thickness of the peat is unknown, for the ground was frozen at a depth of a little more than 1 foot, and no further digging was attempted. Peat 1–2 feet thick mantles bog-covered hillsides on the west side of the Nenana River canyon from Moody northwestward to the Diamond coal mine (see pl. 2). The bogs on the surface of the high terrace east of Browne and north of Ferry are presumably underlain by peat (see pl. 5). The thickness of this peat is unknown. Layers of peat from a fraction of an inch to more than a foot thick are interbedded with the silt that mantles many of the terraces. Woody plant remains are found in the peat, along with remains of herbaceous plants. Where the peat was observed to occur in two layers, the lower layer was black and involuted, and the upper layer was brown and only slightly disturbed by frost action. This relationship was observed at Moody and on the north bank of Dry Creek about 1 mile above its mouth; it is believed to be fairly common.

AEOLIAN DEPOSITS

Aeolian deposits, in the form of sand dunes and loess layers, are common along the Nenana River and in adjacent parts of the Alaska Range. They are not distinguished on the maps (pls. 2–6), but the locations of the more significant outcrops are given below. Sand dunes are restricted to the immediate vicinity of cliffheads and to the lee sides of "badland" areas, where they accumulate as true cliff-head dunes. They are present along the tops of all south-facing "badland" bluffs in the Tertiary rocks of Nenana coalfield, but have not been observed along the tops of north-facing bluffs. The sand composing the dunes has been derived from sandstone or conglomerate of the adjacent "badland," which is in the Tertiary coal-bearing formation and overlying Nenana gravel. Sand dunes range from 10 to 40 feet in thickness and may extend several hundred feet to the lee of the cliff-head. Cliff-head dunes show all gradations of stability, from bare, rapidly growing dunes, some of nearly perfect sigmoid shape, to dunes completely stabilized and overgrown with dense spruce forest. In places where they have been dissected by wind, water, or railroad cuts, the dunes show 1, 2, or 3 peat and forest layers.

Cliff-head dunes containing interbedded forest layers are exposed in section along the railroad about a quarter of a mile northeast of Moody (pl. 2) and about half a mile south of Garner (at the south end of the siding). At both localities they rest on outwash of the Carlo readvance. Cliff-head dunes occur on the high bluff above the railroad track about 1–1½ miles along the railroad south of Healy. At this locality they rest on outwash of the Riley Creek glaciation, and may in part be as old as that glaciation. The high bluff on the east side of the Nenana River has many cliff-head dunes. These may be in part as old as the Healy and Riley Creek glaciations, although it is probable that they are much younger. Most of the dunes are close to the edge of the terrace on the top of the bluff.

A dune deposit at the top of the mountain above the Garner tunnel (pl. 2) contains platy fragments of schist half an inch thick and as much as 4 inches in long diameter. These have been blown or rolled by the wind for distances ranging from several tens of feet to a few hundred feet from their source in outcrops of Birch Creek schist. In no other way could some of them have reached their present lodging place on top of and interbedded with thick turf and in the branches of low bushes growing on the dune deposit. An alternative explanation—that these fragments may have been thrown to the top of the mountain by explosions during the construction of the railroad—fails to explain an identical occurrence on the Totatlanika River (pl. 6) opposite the mouth of Daniels Creek, where no construction or excavation has been conducted. The presence of these coarse fragments in and on the dune deposit indicates very high velocities of south winds.

Deposits of windblown silt mantle slopes and tops of terraces along the Nenana River. The silt mantle is 3–8 feet thick on bluffs overlooking the river, but thins away from the river. It thickens northward from 3 feet at Healy to 8 feet at Browne, 20 miles north. Commonly the silt is in two layers: a lower layer in which the bedding has been deformed by congeliturbation into involutions, and in which the contained plant material is black; and an upper layer in which the bedding is undisturbed, and in which the contained plant material is still brown and woody. One, two, or three peat layers may be present. A prominent peat layer marks the boundary between the two types of silt. The median grain size of the upper layer of silt is about 0.15 mm, whereas the median grain size of the lower layer, which has been affected by congelifraction, is 0.015 mm (determinations by John W. James). The silt profiles on the higher and older terraces were not found to be any thicker or more complex than those on the lower terraces. The separate stratigraphic units of the silt mantle can be traced in many exposures from one terrace level to the next, the silt having been deposited upon the front slopes of the terraces as well as on their tops. (See fig. 23.) The implication is that the deposition of the present silt mantle was a late event in the history of the region, following the development of all the terraces. Consequently, the silt mantle now on the terraces is post-Carlo in age and probably of quite recent origin.

The silt is derived from two sources: silt deposited by the glacial melt water and blown off the dry river beds by strong southerly winds; and outcrops in badlands in the Tertiary rocks. Most of the silt came from the first source. Dust storms, similar to those described by Péwé (1951) along the Delta River, occur along the Nenana at the present time. Such storms were probably much more violent in the past, when the barren river flat was broader. Evidence of the rate of accumulation of silt was obtained in two places. Buried willow branches indicated a rate of accumulation of about 1 foot in 50 years along the railroad track just south of the tunnel at Moody. At Healy a metal container buried under 8 inches of silt and re-exposed at the edge of the river bluff in 1948 indicates a rate of accumulation of not less than 1 foot in 70 years, inasmuch as there is no record of white men entering this area before 1900.

Wind-polished and faceted pebbles are common in exposures of the till of the Healy glaciation west of Healy, and on the bluff in Riley Creek outwash above the railroad track about a mile south of Healy. These probably date back to the Healy and Riley Creek glaciations. Wind-sculptured erosional forms have not been observed in the badlands near the railroad. Very strong prevailing south winds have had a striking effect on the vegetation that grows on terraces from Healy northward, causing the bushes to grow in lines oriented north-south, and giving the terraces a raked or plowed appearance when seen from the air.

PERENNIALLY FROZEN GROUND

Perennially frozen ground (Taber, 1943; Black, 1950), also called permafrost (Muller, 1945, p. 3) and pergelisol (Bryan, 1946, p. 635), is common throughout the Alaska Range. Wherever deep excavations have been made it has been encountered. The only localities where its presence is doubtful are some of the very well drained terraces underlain by coarse gravel, at the base of which are large springs. Perennially frozen ground is probably not present beneath rivers and lakes.

The depth to perennially frozen ground in the Alaska Range is controlled largely by the amount of vegetation and exposure of the surface of the ground to direct sunlight. In general, perennially frozen ground is much closer to the surface on north-facing slopes than on south-facing slopes. Three types of vegetation appear to influence the depth to perennially frozen ground. The first is thick, continuous vegetation, consisting largely of mosses; it may or may not include black or white spruce. Perennially frozen ground is commonly found within 2 feet of the surface, and locally as near the surface as 1 foot. Where bare soil is present in the center of frost scars, perennially frozen ground is much deeper. The second is vegetation consisting predominantly of brush such as alder, dwarf birch (*Betula glandulosa* and hybrids), and willows; it may or may not include sparse growth close to the ground, such as annual grasses and lichens, and open stands of white spruce. Perennially frozen ground lies from 5 to 20 feet below the surface. Most moraine hillocks, most mountain slopes in the gorge between McKinley Park station and Healy, and much of the country south of McKinley Park station is characterized by this vegetation. The third type is found on slopes of bare gravel, outcrops, and talus and consists of scattered growths of lichens. Perennially frozen ground, if present, probably lies more than 20 feet below the surface, and is likely to be relict perennially frozen ground. Perennially frozen ground is reported to occur in the Suntrana mine, which is excavated beneath a south-facing slope of bare rock or talus clothed only by white spruce and aspen.

The depth to perennially frozen ground in bare scree slopes at altitudes greater than 3,500 feet is unknown.

Perennial ice in crystalline nonporous rocks, as well as in slightly pervious well-jointed rocks, such as those of the Cantwell formation, probably occurs only as thin films in joints and cracks. Likewise, in deposits consisting of coarse gravel, perennially frozen ground occurs either as "dry permafrost" (rock that is perennially below 32° F. but does not contain water) or as gravel containing interstitial ice.

In sand, silt, and clay, on the other hand, perennial ice takes the form both of lenses and veins of clear ice, and of interstitial ice. Because of the expansion of the interstitial water on freezing, the component grains of the silt and clay are commonly pried apart. They are then held together only by the ice. When the ice melts, cohesion is lost, and the resulting water acts as a support to the weight of the fine-grained material, thereby reducing frictional resistance to movement (Terzaghi, 1950, pp. 91–94). Such material slumps on slopes, and landslides and mudflows result. Thawed ground in silt and clay tends to flow from beneath heavy weights.

Ice veinlets exposed at the new pit of the Diamond coal mine during the summer of 1948 averaged ⅛ inch in thickness and were spaced ½–1 inch apart. Their strike was parallel to the contour line of the hillside, which is here parallel to the strike of the coal-bearing rocks. They dipped 30°–40° N., approximately bisecting the angle between the surface and the bedding. The rocks in which they occurred are sandstone and siltstone of the middle member of the coal-bearing formation. The hillside beneath which they were found was covered by tundra vegetation, consisting of moss, sedges, and patches and rows of willows and dwarf birch.

Perennially frozen ground exposed in 1948 in clay at the bridge at mile 351.4 on the Alaska Railroad was in the form of vertical ice veinlets one-fourth to one-half inch thick and 1–3 inches apart, oriented about normal to the direction of slope. Lenses and bodies of clear ice as much as 1 foot thick were also found in the clay at this point, and interstitial ice cemented the terraces and delta gravel. Lenses of clear ice more than 1 foot thick were found in clay at Moody in 1949.

The role of perennially frozen ground in the formation of congeliturbate has been discussed in the section on congeliturbate. Involuted silt layers—a form of congeliturbate—have been shown to occur at the base of some of the wind-blown silt deposits that mantle gravel terraces now apparently free of perennially frozen ground. They indicate that perennially frozen ground was once present in places where it is not now observed.

CLIMATIC HISTORY IMPLIED BY THE DEPOSITS

The climatic history implied by the post-Carlo deposits can be divided into four periods, as follows:

(1) A warm period during which the Riley Creek ice melted back until glaciers on many of the smaller streams, such as Revine, Moose, Louis, and Windy Creeks, and possibly the Sanctuary River, had completely disappeared. The larger glaciers were considerably smaller than they are now. This period was somewhat warmer than the present. It may correlate with the thermal maximum recognized in the United States (Matthes, 1942, p. 204–219).

(2) A period as cold as the present during which the Yanert glacier advanced to a point about 3 miles below its present terminus, rock glaciers were active, and the Nenana River and its tributaries aggraded their beds. This period dates back at least several hundred and possibly a few thousand years.

(3) A warm period during which the glaciers retreated back of their present positions, and the older rock glacier on Clear Creek was dissected.

(4) The present cold period. Historical records suggest that the peak of this period is past and that the climate is slowly becoming warmer.

DIASTROPHISM

Two of the major faults crossed by the Alaska Railroad have been active since the deposition of the Carlo outwash and retreat of the glaciers.

Alluvium resting on outwash gravel deposited by the Nenana River is exposed on the east side of the Nenana River opposite the mouth of Riley Creek. The gravel, in turn, rests on till and the upturned beds of the Cantwell formation (fig. 28). At the north end of this outcrop, the alluvial gravels are bent upward to the north. The fault contact between the Cantwell formation and Birch Creek schist is just north of the de-

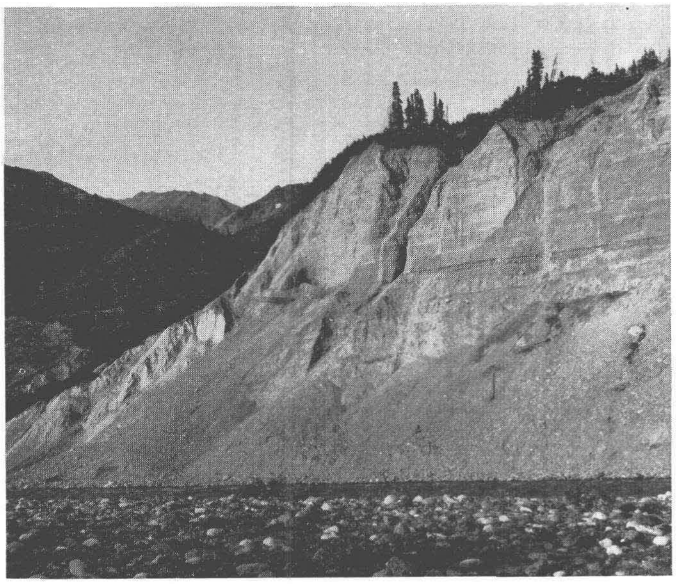

FIGURE 28.—Alluvium and outwash of the Carlo readvance deformed and offset by post-Carlo faulting on the east bank of the Nenana River opposite McKinley Park Station. Birch Creek schist to the left of the fault.

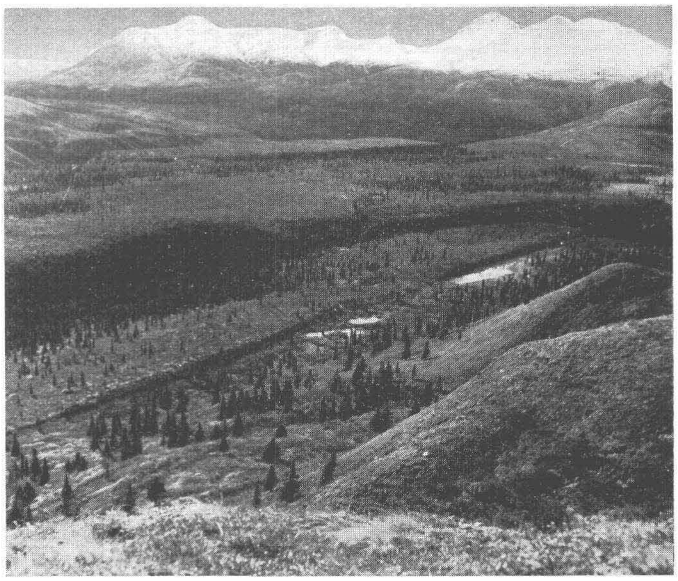

FIGURE 29.—Recent fault scarp in alluvium and terrace gravel along the fault crossing the Alaska Railroad near Windy. Looking southwest across Little Windy Creek.

formed gravel. This contact apparently extends eastward along the base of a small gulch which has dissected the alluvial fan. The original upper surface of the alluvial fan is largely preserved. The part north of the gulch is 20 feet higher than the part south of the gulch. Presumably the displacement of the alluvial-fan surface and the bending of the alluvial gravels are effects of the same cause—movement along the fault separating the Cantwell formation from the Birch Creek schist. Movement along the fault in post-Carlo time has amounted to 20 feet, the north side being the upthrown side. No evidence could be found for uplift farther west along the fault. Presumably, there was no uplift along the fault in the period between the beginning of the Healy glaciation and the end of the Carlo, for glacial deposits and terraces of the older glaciations show no noticeable displacement. A displacement of 20 feet would probably not be detected in the older deposits, for the errors of correlation of higher terraces and glacial deposits are of that order or greater.

Fault scarps displacing alluvium, outwash gravel, and Recent talus cones and alluvial fans, mark the line of the great fault that crosses the Alaska Railroad near Windy (see pl. 1). According to R. A. Eckhart (oral communication, 1951), the scarps on this fault, cutting alluvial fans in Foggy Pass, face north and are between 20 and 50 feet high. E. H. Cobb (oral communication, 1951) states that the fault scarp across the flat north of the lower course of Little Windy Creek has a height of from 6 to 15 feet (see fig. 29). Eastward, along the south-facing mountainside north of the head of Wells Creek, the fault is marked by a trench, the south wall of which is steeper than the north wall. The scarp can be traced, on aerial photographs, as far east as the Nenana glacier.

All the evidence indicates that the displacement along this fault occurred recently and that the south side went up with respect to the north side from 6 feet to more than 20 feet. The slight amount of erosion of the scarp suggests that the movement occurred not more than a few hundred years ago.

Glacial deposits on either side of the fault zone are not noticeably displaced, excepting as described above; the topography along the fault does not give any indication of much Pleistocene displacement, certainly not in the direction that the recent fault scarps indicate. It seems likely, therefore, that the revival of movement along the fault did not occur before Carlo time and probably occurred very recently.

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ENGINEERING GEOLOGY ALONG PART OF THE ALASKA RAILROAD

By Clyde Wahrhaftig and R. F. Black

ABSTRACT

The central Alaska earthquake of October 1947, triggered a landslide along the Alaska Railroad which damaged the track and disrupted traffic for several days. The management of the Alaska Railroad requested the Geological Survey to make an examination of this landslide and of other engineering problems that plagued the railroad where it crossed the Alaska Range. Investigations were conducted by the Geological Survey in the fall of 1947, in the summer of 1948, and for short periods until 1952. They included mapping of the geology along the railroad from mile 322 on the south side of the Alaska Range, to mile 385, just north of the northern foothills of the range, and detailed studies of several of the landslides. The results of these investigations are presented here. The distribution of bedrock and surficial deposits in the area mapped is shown on the geologic maps.

Bedrock along the Alaska Railroad between miles 322 and 327.5 (mileage in terms of railroad mileposts) consists of highly deformed and broken argillite, chert, and limestone. These rocks are unsuitable for riprap, but some are suitable for ballast and subgrade. They generally form stable foundations. Commercial exploitation of the limestone has been considered. Between miles 327.5 and 330 the railroad crosses massive greenstone which is suitable for riprap and ballast and forms stable foundations.

Between miles 330 and 347 the railroad crosses the Cantwell formation, which consists of conglomerate, sandstone, shale, coaly shale, and coal. The formation is intruded by sills, dikes, and irregular bodies of diabase and andesite. South of mile 336 the Cantwell formation is fairly well cemented, and has been quarried locally for riprap. North of mile 336 it is not well cemented and is not suitable for riprap. The andesite and diabase are too jointed for use as riprap, but are suitable for ballast and subgrade. Foundations in the Cantwell formation are generally stable.

From mile 347 to mile 358 the bedrock consists of Birch Creek schist, which is well-foliated quartz-sericite schist, locally containing abundant pyrite. The schist disintegrates readily by frost action, and where pyrite is abundant, decomposes to unstable detritus. Along its contact with the overlying coal-bearing formation, near mile 358, it is weathered. Because of its fissility, the Birch Creek schist does not make satisfactory riprap, subgrade, or ballast. In general foundations and embankments are stable. Locally, however, dangerous rockfall conditions exist.

North of mile 358 the bedrock formations are the poorly consolidated coal-bearing formation and Nenana gravel, both of Tertiary age. These formations provide poor foundations and are poor sources of gravel, ballast, and subgrade. They contain no material suitable for use as riprap.

For most of the distance between miles 322 and 385, the railroad is built across surficial deposits that were laid down during several glacial advances and retreats of Quaternary age. The engineering properties of each type of material are the same, regardless of the age.

Outwash gravel deposited by the Nenana River forms terraces along the river. The gravel is blue gray, clean, and well sorted, and it occurs in a matrix of coarse, clean sand. It makes excellent ballast and subgrade, and foundations built with it do not heave. The railroad follows these terraces almost continuously from Healy northward to Browne, and for short distances from Healy southward to Cantwell.

Tributaries of the Nenana have built alluvial fans across the outwash gravel. The engineering properties of the alluvium depend on its source and the size of the tributary that deposited it. North of Dry Creek (mile 361) it is similar to the Nenana gravel, from which it was derived. The alluvium of Dry Creek and Healy Creek is coarse, clean, and well washed, and is a good source of ballast and subgrade. Alluvium south of Healy, which was deposited by short steep streams, consists of fragments of Birch Creek schist and the Cantwell formation. Ballast and subgrade from it are likely to heave badly.

Varved clay and silt and associated delta gravel occur in the gorge between McKinley Park station and Healy, as high as 500 feet above the river. They were laid down in an ancient glacial lake. The clay and silt, where perennially frozen, contain ice veinlets and interstitial ice, and slump and flow when they thaw. Their outcrops are sites of many landslides.

Much of the lowland south of McKinley Park station is covered by till, which consists of boulders, pebbles, sand, and clay. This material makes poor foundations because it is likely to heave badly when it freezes, and to slump and flow when it thaws. It is a poor source of ballast and subgrade. The railroad crosses till between miles 341.5 and 346.

Other surficial deposits include wind-borne silt in thin layers, peat, congeliturbate, talus, and landslide debris. These are likely to heave badly on freezing and, therefore, should be removed before construction.

Permafrost is commonly within 2 feet of the surface under thick moss; 5–20 feet below the surface under brushland and open stands of white spruce; and, if present at all, more than 20 feet below the surface under slopes of bare gravel, coarse talus, and outcrops. Ice forms thin films and veins in joints and cracks and fills interstices in Tertiary and Quaternary rocks. Although permafrost provides a firm foundation, it is in delicate equilibrium with its surroundings and thaws when the cover of vegetation is destroyed.

Slumps and earthflows, common throughout the history of the Nenana gorge, are the result of movement of debris beneath steep slopes along sliding planes as much as a few hundred feet deep. They are marked by irregular topography, the chief features of which are an arcuate headwall scarp, a bulge at the toe, narrow ridges parallel to contour lines, open cracks and fresh scarplets, disturbed vegetation; and disorganized rock structures. They move the railroad downward and toward the river at rates from a few feet per year to a few feet per hour. They are common in banks of clay, clay-rich till, and weathered and decomposed schist. The causes are lateral erosion by the river; rain and the melting of snow and permafrost, which saturate the clay with water and render it fluid; and the weight of the material resting on the sliding plane. Suggested remedial measures are placing riprap along the river bank; reducing ground water by pumping, installing drains, and by keeping surface water from the slide; planting vegetation; and refreezing the landslides. Locally the railroad can be realined to avoid the landslides.

Rockslides and rockfalls have taken place on steep walls in Birch Creek schist, where foliation planes and drag folds dip outward. Loose blocks, which may cause serious rockfalls if they are disturbed, should be removed.

In the landslide area between miles 349.1 and 350.3 the railroad lies just below the rim of a semicircular bench about 250 feet high that projects from the west wall of the gorge. Glacial lake clay and silt form the core of the bench and crop out between miles 349.1 and 349.6 on the south side and between miles 350.0 and 350.3 on the north side. On the east side a septum of schist about 300 feet wide lies betwen the clay and the river. Outwash gravel and alluvium overlie the lake sediments. The large landslide between mile 349.1 and 349.6 has caused and is continuing to cause the track to sink, requiring filling and realinement. The headwall of the slide, marked by open cracks and scarplets, lies several feet north of the track. Surface water runs into the cracks. Remedial measures suggested are (1) conducting all surface water directly into the river via waterproof troughs, (2) draining ground water, (3) refreezing the slide, and (4) placing riprap at the toe. The slide between miles 350.0 and 350.3 can be controlled by similar measures. The wall of the gorge between miles 349.7 and 349.8, along the top of which the railroad passes, is crumbling into the river. As open joints lie on both sides of the track, a sudden rockfall that would undermine the track is possible. Realinement of the railroad a few feet farther west would avoid this danger.

At the landslide at mile 351.4, the railroad passes along the contact between delta gravel on the west and clay and silt on the east. The earthquake of Oct. 19, 1947, triggered a landslide just south of the bridge. Although the track was moved westward and piles were driven to protect it, the landslide has enlarged and is likely to affect the track. Ancient landslides at this place were stopped with the growth of permafrost. Recently the permafrost has been thawing, thus making the clay unstable and causing the landslide. Landslides may occur when frozen clay at the north abutment of the bridge thaws. Refreezing is suggested.

Between miles 352.7 and 353.6 (Moody), the railroad crosses a persistent landslide on the west wall of the canyon, where lake sediments, chiefly clay and silt, crop out. Landsliding antedates the railroad. Slumps and earthflows have required extensive realinement, rebuilding and raising of the track. Movement on the hillside extends from a point 800 feet in height above the track to the level of the river below the track. The causes are similar to those of landslides between miles 349.1 and 349.6 and at mile 351.4. Remedial measures suggested are draining surface and ground water from the slide area and refreezing the slide.

At the north end of the tunnel near Garner (mile 356.2) the railroad crosses the lower part of a large talus cone. Under the weight of debris supplied by crumbling cliffs to the north, the talus creeps and flows toward the river. No known method of control would be cheaper than periodically realining and raising the track. Large schist blocks at the heads of several steep chutes leading to the track at the north end of the tunnel occasionally break loose and descend to the track. The largest block, 100 feet on a side, is creeping at a rate of 0.2 foot per year toward a precipice, over which it will plunge to the track. The danger of rockfalls at this locality could be reduced by removing loose blocks.

At mile 357.5 the river has breached weathered and decomposed schist below the coal-bearing formation. The weathered schist moves toward the river at the rate of 2 or 3 feet per year. Spot freezing might control the movement. Realinement of the railroad around the slide will be costly.

Track heaving and settling, caused by freezing and thawing of ice in ballast beneath ties, can be controlled by use of coarse-grained nonheaving ballast, by deeper drainage ditches and additional culverts, and by chemical stabilizers and waterproofing agents.

Icings, colloquially called glaciers, form seasonally on slopes or river flood plains where circulation of surface water is impeded and where ground water emerges as springs and seeps. At times, 2 or 3 feet of ice accumulates on the tracks. It is believed that most icings between Windy and Healy could be eliminated by deepening and protecting culverts where icings occur, and by putting in culverts where drainage is impeded.

Level gravel-capped terraces of large extent near Healy and Windy are favorable industrial sites because they are free of materials likely to settle or heave on thawing.

The volumes of the reservoirs behind the dam sites on the Nenana River at miles 354, 349.8, 342, and 329 are small because of the 25-foot-per-mile river gradient and the narrow canyon. The canyon walls at the dam sites at miles 354 and 349.8 consist of jointed and foliated schist. Leakage is possible through pervious glacial sediments beneath adjacent terraces. At mile 342 a fault, probably marked by gouge, extends along the canyon. The canyon walls are made up of massive diabase and are underlain by sandstone and shale. Leakage is possible through glacial sediments northwest and southwest of the dam site at this locality. The dam site that is most favorable geologically is the one at mile 329, where the bedrock consists of massive greenstone.

INTRODUCTION

PURPOSE AND SCOPE

The Alaska Railroad, the longest railroad in Alaska, extends from tidewater at Seward on the Kenai Peninsula and at Whittier on Prince William Sound, northward via Anchorage to Fairbanks in interior Alaska (fig. 30). Since its completion in the spring of 1923, the railroad has been of great importance to the commerce of the interior of Alaska. It serves directly the two largest cities of Alaska, Anchorage and Fairbanks, and the two best-developed agricultural areas, the Matanuska and Tanana Valleys. Furthermore, the railroad serves important coalfields in the Matanuska Valley and Nenana River areas, the goldfields of the Fairbanks district, many small settlements and mining districts, and Mount McKinley National Park. The railroad is vital to the military defense of the Territory. Nevertheless, traffic has been interrupted and slowed many times by landslides, icings, and effects of frost heaving and settling. Delays of several days have occurred, and certain parts of the roadbed have been costly and difficult to maintain.

This report discusses some of the engineering problems that arise along the Alaska Railroad from mile 322 to mile 385.[1] The southern boundary of the area is 214 miles by rail north from Anchorage, and the northern boundary is 85 miles by rail south from Fairbanks. The area lies between latitude 63°25′ N. and 64°12′30″ N. and includes the middle portion of the Nenana River valley, along which the railroad traverses the Alaska Range and its northern foothill belt (fig. 31 and pls. 2–5). The geology of this area discussed in the preceding chapter has been applied to the appraisal of engineering problems presented in this report.

Because of the peculiar effects of permafrost—effects not present in temperate latitudes and about which wide-spread engineering knowledge is still lacking—the discussions of some of the problems are more detailed than normally would be necessary. Furthermore, many examples and case histories of the problems are described in order to give emphasis to the effects of permafrost and seasonal frost on construction. It is believed that these examples show the necessity of designing future roads and railroads in similar areas in Alaska to avoid such problems; if similar problems cannot be avoided, it is hoped that the suggested solutions will be helpful in combatting them.

Only that amount of information sufficient for making general engineering suggestions was gathered during this investigation. The statements that follow regarding the engineering properties of the formations are based in part only on laboratory tests of representative samples. In much greater part they are based on field observations of embankments, road cuts, river bluffs, bridge abutments and other features. It is hoped that these generalized statements will be of use to engineers and to others in laying out preliminary plans and designs; it is obvious that they cannot and should not take the place of detailed investigations, both field and laboratory, that are required before specific engineering structures are designed.

Discussion of engineering design and detailed application of geology to the problems was beyond the scope of the investigation. It is assumed that the engineer will use whatever method of correction is most practical or desirable from his viewpoint and will make whatever engineering tests of the local materials are required.

Information is also included that has direct bearing on dam sites along the middle portion of the Nenana River and on industrial sites in the Nenana coalfield. The statements are to be regarded as preliminary, as detailed investigations have not been made.

[1] Mileage given is in terms of railroad mileposts.

HISTORY AND METHODS OF INVESTIGATION

On October 19, 1947, immediately after several severe earthquakes (St. Amand, 1948, p. 617), the railroad track at mile 351.4 in the Nenana River gorge between McKinley Park station and Moody began to slump at a rate reported to average about 4 feet per day. At that time plans were being made by the U. S. Geological Survey for an engineering geologic investigation in the gorge. Col. J. P. Johnson, former general manager of the Alaska Railroad, requested that an immediate geologic investigation be made of the landslide. During the period October 31–November 2, 1947, the writers visited the slumped area and made a reconnaissance of several railroad track stability problems. A report which summarized the findings of the reconnaissance and which suggested remedial measures was prepared by R. F. Black.[2] Much more detailed investigation seemed advisable because of the complexity of the unconsolidated sediments. Consequently an investigation was made by Clyde Wahrhaftig, John W. James, and Black during the summer of 1948. This investigation was supplemented by periodic visits to the area by Wahrhaftig and Black between 1949 and late 1952. Wahrhaftig has assumed primary responsibility for the geologic and vegetation investigations. Plant collections were identified by W. S. Benninghoff and R. S. Sigafoos. Black has assumed primary responsibility for the engineering discussions and recommendations.

Detailed topographic and geologic surveys of the slides at miles 351.4, 353.0, and 357.5 were made in 1948 and supplemented by later observations. Subsurface surveys are limited to four short churn drill holes drilled at mile 351.4 by the Alaska Railroad. General descriptions of other slides and engineering recommendations are preliminary because subsurface information has not been obtained and engineering tests of the materials have not been made.

[2] Black, R. F., and Wahrhaftig, Clyde, 1948, Preliminary geologic investigation of railroad track difficulties in the Nenana River gorge, Alaska: Unpublished rept. in files of U. S. Geol. Survey.

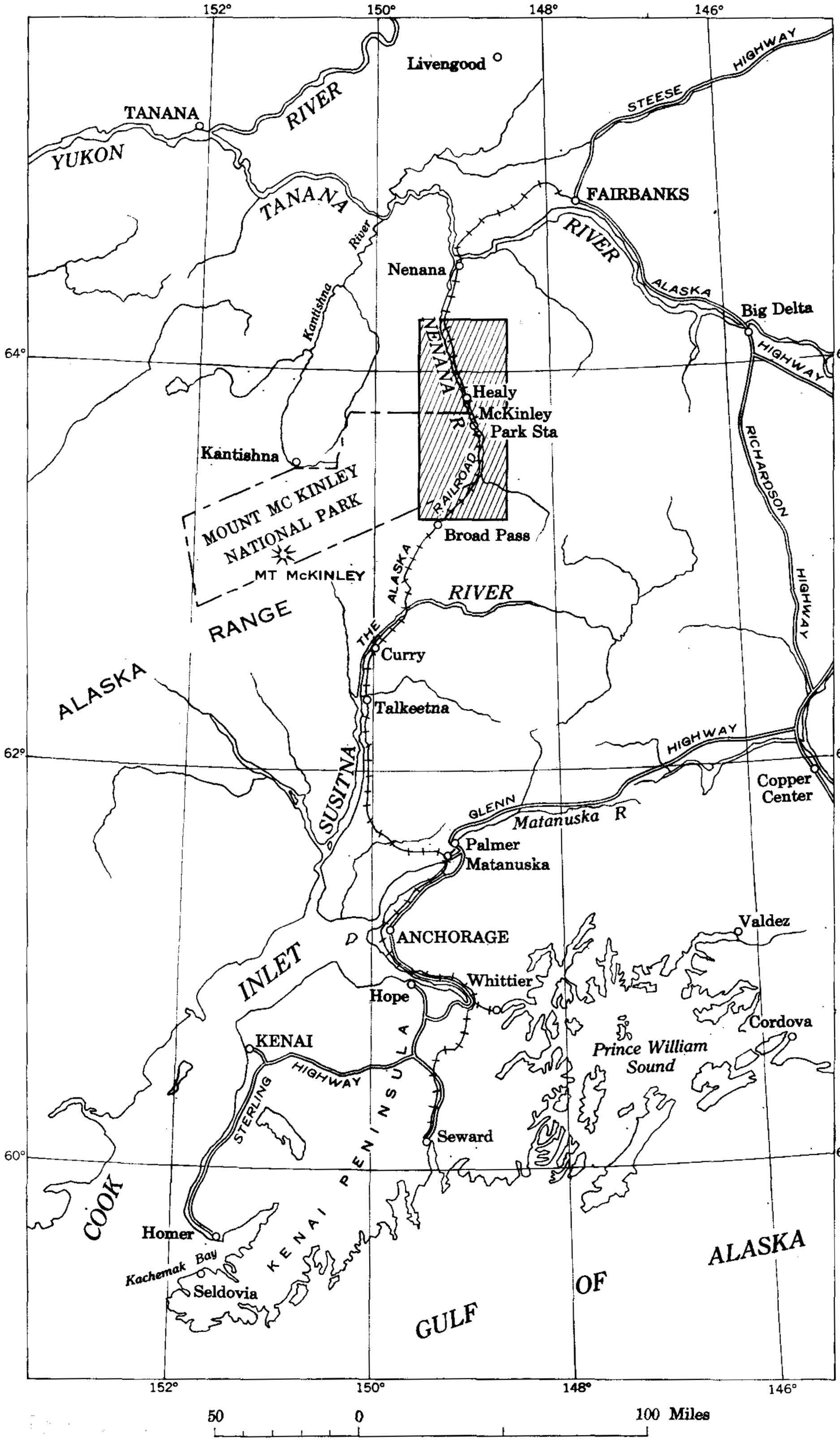

FIGURE 30.—Map of south-central Alaska, showing location of the area covered by this report.

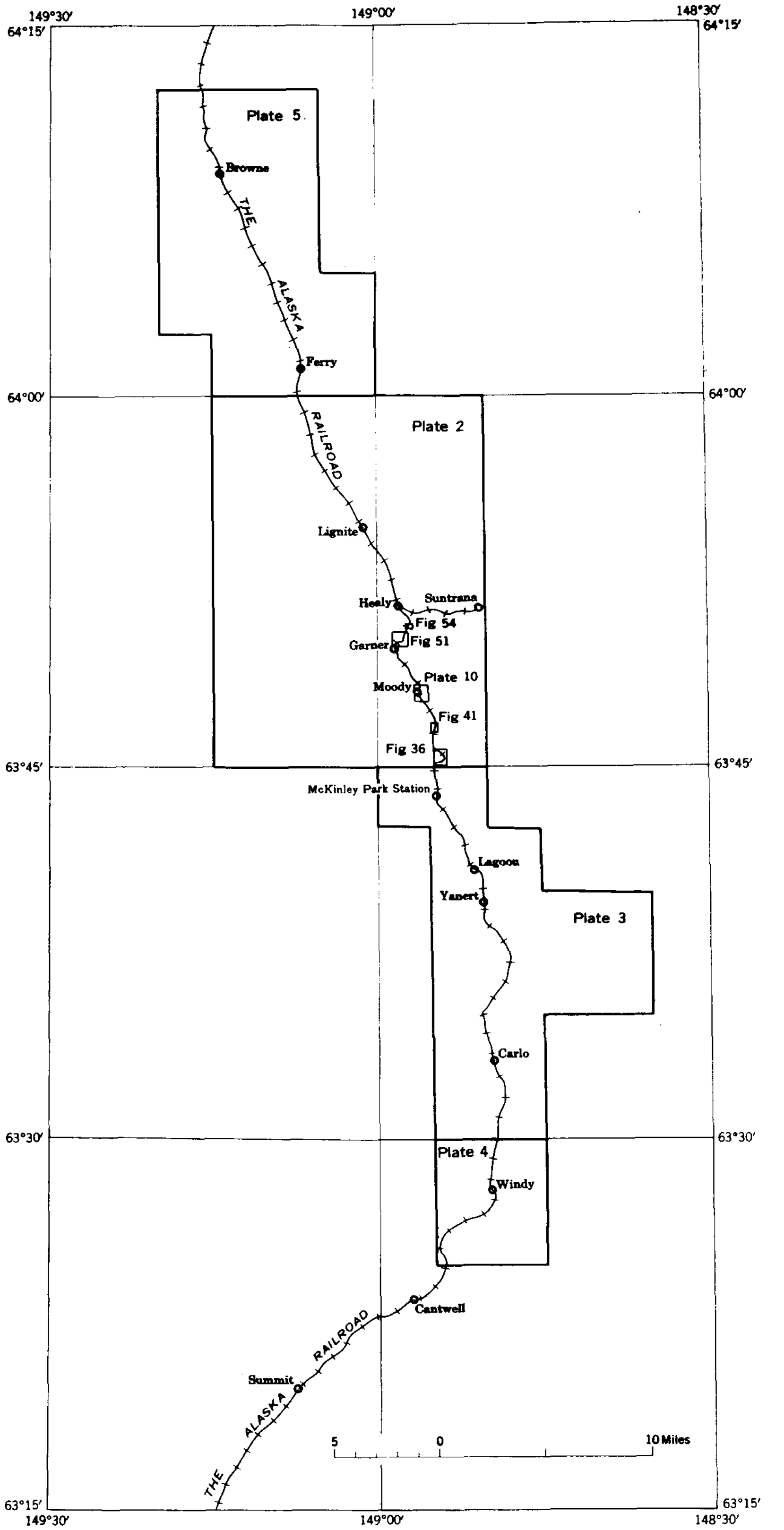

Figure 31.—Index map, showing location of areas covered by geologic maps (pls. 2–5, and 10, and figs. 36, 41, 51, and 54).

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The authors wish to acknowledge the cooperation of the management of the Alaska Railroad, which placed accommodations, transportation, and technical assistance at their disposal. They are grateful in particular for the cooperation of the following: Col. J. P. Johnson, former general manager; R. A. Sharood, former chief engineer; Irvin P. Cook, chief engineer; Charles Griffith, assistant chief engineer; Anton Anderson, engineer in charge of maintenance of way; James Morrison, resident engineer; Norval Miller and James Allen, surveyors; the late Joseph McNavish, roadmaster; Al Logsdon and Calvin Brown, roadmasters; Sven Bragstad, Frank Spadero, Ted Mommsen, and Al Cass, section foremen; and Jerry Marshall and John Witkowski, managers of the hotels at Healy and McKinley Park station.

To John W. James go special acknowledgments for his assistance in the field-mapping program.

GEOGRAPHIC SETTING

TOPOGRAPHY

The area shown on plates 2–5 lies partly in the Alaska Range, one of the dominant topographic features of Alaska, and partly in the northern foothill belt of that range. The range is extremely rugged, deeply dissected, and is crossed by several rivers. One of these, the Nenana River, which crosses the range from south to north, is followed by the Alaska Railroad.

The Nenana River rises in the Nenana Glacier on the south side of the Alaska Range, 31 air miles east of Windy. At Windy (pl. 4) it is joined from the southwest by the Jack River. From Windy to Carlo (pl. 3) the Nenana meanders in a northward-trending U-shaped valley. The valley is almost a mile wide, and it has broadly flaring walls that rise to heights of 2,000–3,500 feet above the river. The gradient of the river in this stretch is gentle, and there are few rapids. From Carlo the valley broadens northward to Yanert and the river is entrenched several tens of feet. At Yanert the river flows along the west side of the Yanert Fork depression, in a narrow, winding, terraced gorge, 100–250 feet deep, cut in glacial deposits and bedrock. The river is joined from the east about midway across this depression by the Yanert Fork, its largest tributary, and leaves the northwest corner of the Yanert Fork depression at McKinley Park station (pl. 3).

From McKinley Park station to Healy (pl. 2), a distance of 10 miles along the winding river, the Nenana flows in a remarkable two-story canyon through a high ridge. The outer canyon is U-shaped, and its floor is ½–¾ of a mile wide; the broadly flaring walls and truncated spurs rise to a height of 2,500 feet above the canyon floor. In the downstream half of this canyon, and also for a short distance at the upstream end, the river flows in an inner gorge about 500 feet wide that has nearly vertical rock walls 200–300 feet high. In the other parts of the two-story canyon the inner gorge broadens to nearly the full width of the outer gorge.

North of Healy the river follows an almost straight course N. 25° W. across the northern foothill belt. Here it flows in a broad valley having gentle, terraced walls that rise from a few hundred to 2,500 feet above the river. The valley, including its terraces, is from 6 to 10 miles wide; some terraces are locally more than a mile wide.

At mile 322, shown at the south edge of plate 4, the railroad is 2,150 feet above sea level and about 30 feet above the west bank of the Jack River. The railroad follows the west bank of the Nenana River northward to Ferry, where it crosses to the east side. At mile 385, shown at the north edge of plate 5, the railroad is 730 feet above sea level and about 15 feet above the Nenana River. Hence, the river and railroad drop about 1,420 feet in an airline distance of 55 miles.

CLIMATE

Average monthly and annual temperature and precipitation data for three stations on the Alaska Railroad are summarized in table 1. Summit is at the crest of Broad Pass, 13 miles southwest of Windy. McKinley Park station is centrally located (pl. 3). Nenana is about 29 miles north of Browne (pl. 5). The records for McKinley Park station represent conditions typical of the mountains; those for Summit represent the south side of the range; and those for Nenana represent the north side. As can be seen from the records, precipitation is considerably heavier on the south side of the range than on the north side. Average annual temperatures are about the same for all three stations, but summers are much hotter and winters are far more severe at Nenana than at the southern stations.

Snow falls on the high mountains during all months. The first snow can be expected to fall in the valleys about the middle of September (table 2). In the valleys snow remains on the ground until early May. Early summer weather is generally warm and dry, and is characterized by thunder showers of convective origin. Late summer and fall weather is characterized by periodic cyclonic storms from the south and west. Winters are generally clear for long periods of time; more clear days occur during winter than during summer. Prevailing winds are from the south, and are frequently

TABLE 1.—*Temperature and precipitation at Summit, McKinley Park station, and Nenana*

[From records of U. S. Weather Bureau (1950)]

Month	Average temperature (°F)			Total precipitation (inches)		
	Summit	McKinley Park station	Nenana	Summit	McKinley Park station	Nenana
January	4. 3	3. 0	−8. 2	1. 07	0. 86	0. 64
February	8. 9	7. 8	0. 2	1. 13	. 61	. 48
March	11. 4	12. 9	8. 8	1. 48	. 42	. 56
April	21. 6	26. 6	27. 2	. 48	. 70	. 35
May	37. 2	41. 5	46. 1	1. 08	. 85	. 70
June	49. 3	52. 6	57. 9	2. 31	1. 95	1. 31
July	52. 1	54. 7	60. 6	3. 24	2. 36	1. 91
August	48. 3	50. 7	55. 7	3. 71	2. 81	2. 54
September	40. 5	41. 9	44. 3	3. 43	1. 60	1. 21
October	25. 5	27. 1	27. 1	1. 75	1. 04	. 72
November	8. 7	11. 0	4. 3	. 88	. 68	. 49
December	1. 5	3. 2	−7. 4	1. 37	. 60	. 44
Annual	25. 9	27. 7	26. 4	21. 83	14. 58	11. 34
Number of years of record	9	26	23	9	22	15

of great intensity. Extreme temperatures are common.

Additional climatic data from McKinley Park station are summarized in table 2. Permafrost in the area probably is in equilibrium with the present climate. Microclimatic factors of exposure, vegetation, type of material, and hydrologic regime determine whether permafrost is present or absent. These, locally, are more important than the regional climate in controlling distribution, growth, and decay of permafrost.

VEGETATION

Three distinct vegetation zones can be recognized in the area covered by plates 2–5: (1) a lower zone, below altitudes of 2,500 and 3,000 feet in which white spruce (*Picea glauca*) in solid forest and parklike stands is the characteristic species; (2) a middle zone, between altitudes of 3,000 and 4,500 feet, which is characterized by tundralike vegetation; and (3) an upper zone, generally barren of vegetation. Timberline lies between altitudes of 2,500 and 3,000 feet in the Alaska Range, and is generally a few hundred feet higher on south-facing slopes than on north-facing slopes. Forest-covered areas, however, make up only a small part of the area below 2,500 feet.

Four general vegetation types appear to characterize the lower zone traversed by the railroad:

(1) Vegetation on gravel bars: gravel bars that have been recently abandoned by streams bear scattered stands of willows of several species, alder (*Alnus crispa*), vetch (*Oxytropis?*), and dwarf fireweed (*Epilobium latifolium*). Gravel bars that are more than 5 feet above stream level and are covered with a thin, discontinuous layer of silt have cottonwood (*Populus balsamifera*), alder, and *Equisetum*.

(2) Spruce forest: the entire upper surfaces of terraces 5–30 feet above the streams, a belt 100 to several hundred feet wide along the outer edge of higher terraces, and many areas having average slopes of 20 percent or more are occupied by forest dominated by white spruce (*Picea glauca*), and contain thickets of alder, scattered aspen (*Populus tremuloides*), and birch (*Betula kenaica*, *B. resinifera*, and hybirds). The surface of the ground beneath the spruce is covered with *Equisetum*, *Lycopodium*, and Labrador tea (*Ledum palustre*).

(3) Muskeg: A dense mat of vegetation, generally only 2 or 3 feet high, covers broad plains that extend across interstream divides, the back parts of the higher terraces, and gentle north-facing slopes. The characteristic plants of this mat are cottongrass (*Eriophorum* spp.), blueberry (*Vaccinium uliginosum*), *Sphagnum*, dwarf birch, and willows. Standing water in pools

TABLE 2.—*Additional climatological data for McKinley Park station*

[From records of U. S. Weather Bureau, (1943)]

Month	Temperature (°F.)				Prevailing wind direction	Precipitation (inches)			Clear days		Partly cloudy days		Cloudy days	
	Mean		Range			Greatest in 24 hrs	No. of days with .01 inch or more	Mean snowfall	No.	Percent	No.	Percent	No.	Percent
	Max	Min	Max	Min										
January	11. 7	−6. 8	47	−52	S	0. 98	5	15. 8	14. 2	45. 8	6. 7	21. 5	10. 1	32. 7
February	15. 4	−4. 0	48	−47	S	2. 02	4	13. 6	13. 3	47. 2	6. 1	21. 8	8. 8	31. 0
March	23. 1	. 7	56	−34	S	. 90	3	4. 9	13. 7	44. 0	7. 5	24. 3	9. 8	31. 7
April	37. 6	16. 3	60	−33	S	1. 90	2	3. 7	13. 8	42. 8	9. 3	30. 9	7. 9	26. 3
May	52. 0	30. 4	70	−2	S	2. 70	3	3. 0	9. 8	31. 5	11. 2	36. 1	10. 0	32. 4
June	63. 9	39. 9	89	20	S	2. 26	8	. 0	11. 1	36. 8	9. 1	30. 5	9. 8	32. 7
July	65. 8	43. 2	85	30	S	1. 50	9	. 0	10. 9	35. 2	8. 2	26. 5	11. 9	38. 3
August	62. 2	39. 9	83	24	S	2. 40	11	. 0	8. 6	27. 2	8. 9	28. 6	13. 5	43. 7
September	51. 3	32. 9	75	2	S	1. 80	9	1. 6	9. 5	31. 5	7. 2	24. 1	13. 3	44. 4
October	35. 5	18. 1	69	−23	S	1. 75	6	8. 9	11. 2	36. 0	7. 3	23. 6	12. 8	40. 4
November	20. 7	2. 8	56	−34	S	1. 54	5	10. 3	11. 8	39. 4	7. 2	23. 9	11. 0	36. 7
December	12. 7	−5. 6	52	−54	N	1. 67	4	9. 3	14. 9	48. 1	6. 0	19. 4	10. 1	32. 5
Annual	37. 7	17. 3	89	−54	S	2. 70	69	71. 1	11. 7	38. 9	7. 8	25. 9	10. 5	35. 2
Number of years of records	17–19	17–19	17–19	17–19	13–16	14–18	14–18	15–18	19–20	19–20	19–20	19–20	19–20	19–20

or trenches between cottongrass tussocks can be found in muskeg throughout the summer except in seasons of extreme drought. Muskeg supporting black spruce (*Picea mariana*) occurs as isolated patches within white spruce forest and tundralike muskeg and also forms a border zone between them.

(4) Brushland: brushland of several types occurs in the lower vegetation zone. Dense stands of aspen that attain heights of as much as 25 feet occupy well-drained south-facing slopes and some north-facing slopes. A thin ground cover of lichen (chiefly *Cladonia*) and low-bush cranberry (*Vaccinium Vitis-idaea*) occurs beneath the aspen. The presence of charred spruce logs and stumps in the most extensive aspen brushland indicates that the area was formerly covered by spruce forest.

Dense, low thickets of birch (*Betula kenaica*, *B. resinifera* and hybrids), buckbrush (*Betula glandulosa* and hybrids), felt-leaf willow (*Salix alaxensis*), and aspen (*Populus tremuloides*) grow on gently rolling areas. The abundance of charred spruce logs and stumps indicate that this vegetation also is second growth.

Dense, pure alder thickets (*Alnus crispa*) occur on steep north-facing slopes. These extend to altitudes 200–500 feet above the altitudinal limit of spruce on adjacent hillsides.

DESCRIPTION AND ENGINEERING ASPECTS OF THE BEDROCK

The bedrock formations in the vicinity of the Nenana River occupy in general east-trending bands parallel to the trend of the range and normal to the middle course of the Nenana River. They are shown on plates 2–5. Plate 9 shows a cross section of the bedrock and surficial deposits between the Alaska Railroad and the level of the Nenana River from mile 334 (Carlo) to mile 358 (Healy).

In terms of age, tectonic history, degree of consolidation, and usefulness as construction materials, the formations can be divided into two strongly contrasted groups: (1) Rocks ranging in age from pre-Cambrian to late Cretaceous that are highly metamorphosed or well consolidated, some of which are suitable for foundations, riprap, and other engineering purposes. The group contains schist and gneiss, phyllite, chert, argillite, limestone, conglomerate, slate, shale, and coal. Greenstone, in part intrusive and in part derived from basic lava flows, is common. (2) Poorly consolidated Tertiary rocks that are now confined to the northern foothill belt and lowland areas within the range, but which were once much more extensive. They have little engineering value except as a source of gravel. A major unconformity separates the two groups of rocks.

METAMORPHIC ROCKS

BIRCH CREEK SCHIST

The Birch Creek schist (Capps, 1940, p. 95–97), the oldest formation traversed by the Alaska Railroad, is in an east-trending zone 3–12 miles wide in the northern part of the Alaska Range, between mile 347 and mile 358 on the Alaska Railroad. It is pre-Cambrian in age.

The schist is composed predominantly of quartz and sericite (fine-grained mica), but locally has layers containing only quartz, or quartz and graphite. Between mile 354.5 and mile 355.5, pyrite (FeS_2) is abundant; it occurs as well-formed cubes as large as a quarter of an inch square. Foliation is well developed in the schist, and, although not uniform, generally strikes eastward and dips 20°–40° southward (pl. 2); it is locally very irregular and highly contorted. The schist is traversed by well-developed cross joints that commonly strike northward and dip almost vertically. Some are filled with basalt dikes that are overlain unconformably by Tertiary rocks.

The Birch Creek schist is inherently weak because of its ease of separation along planes of foliation, produced by tiny, oriented mica flakes, and because of its pronounced cross joints. The mica flakes are inconspicuous on surfaces that are not parallel to the foliation, but they almost cover or cover completely surfaces that are parallel to the foliation. When fresh, the mica is greenish colored. Upon weathering it turns brown or reddish colored, staining the schist. Weathering of the mica facilitates spalling along planes of foliation into small slabs and flakes bounded by cross joints. Frost action, enhanced by chemical weathering, breaks up the schist into blocks of various sizes that accumulate rapidly as talus at the base of steep slopes. Hence rockfalls are common along the railroad and below outcrops on gentle slopes.

Some of the talus accumulations have been eroded at their lower ends by the Nenana River and its tributaries, and are now unstable. They are likely to move as slumps or slides. Other talus accumulations are saturated with water and contain masses of permafrost. These also tend to move as slumps or slides under the influence of gravity and frost action.

On exposure to air and to frost action, relatively fresh schist has been broken up and largely disintegrated in 1 year (Taber, 1943a, p. 1449) to depths of 5–6 inches. Pyrite weathers readily to hydrated sulfates, with a change which causes the rock to swell, and which produces sulfuric acid that aids in the weathering process. In places where pyrite is present along the railroad, between mile 354.5 and mile 355.5, the schist is reduced to masses of debris so unstable that they flow when saturated with water. Where the schist underlies directly the Tertiary rocks, a zone of weathering, more than 100 feet thick in places and containing much clay, is found at the top of the schist. Landslides commonly occur in such zones whose slopes are steeper than 10°, and locally occur on gentler slopes.

The use of schist as riprap is undesirable because of its tendency to break up on exposure to frost action. When used as ballast, it disintegrates rapidly and is subject to frost heaving and settling. As a result, maintenance is required every year along those parts of the railroad where Birch Creek schist is used as ballast.

TOTATLANIKA SCHIST

The Totatlanika schist (Capps, 1940, p. 104–107) crops out along the railroad about 1 mile south of Slate Creek (pl. 2) and probably underlies the Nenana gravel from Slate Creek northward (pl. 5). On Slate Creek (pl. 2) and Chicken and Moose Creeks (pl. 5) the formation consists of fine-grained yellow slate; in the mountains east of Browne it consists of coarse-grained gneiss. Fossils collected by the senior author in 1955 from a locality in the Totatlanika schist about 42 miles due east of mile 366 on the Alaska Railroad were identified by Helen Duncan as *Syringopora*, probably Mississippian(?) in age (written communication May 20, 1955).

The Totatlanika schist is presumably similar to the Birch Creek schist in its geologic history. Its engineering characteristics are similar. It has not been used along the railroad largely because of its limited occurrence.

SEDIMENTARY ROCKS

UNDIFFERENTIATED PALEOZOIC AND MESOZOIC ROCKS

The undifferentiated Paleozoic and Mesozoic rocks south of Windy comprise a complex assemblage of argillite, shale, graywacke, phyllite, limestone, conglomerate, and chert. They are either moderately indurated or are metamorphosed; some are considerably metamorphosed. They are intruded by granitic rocks, greenstone, diabase, and rhyolite. The rock units in this group are not differentiated on plate 4 because of their complex structure and the uncertainties regarding their age.

North of Bain Creek (pl. 4) rocks exposed along the railroad consist largely of chert, argillite, and conglomerate. The ridge between Windy and Bain Creeks (pl. 4) is made up of argillite, graywacke, and conglomerate that contain several large lenticular bodies of limestone. From a point near the mouth of Windy Creek southward along the east side of the Nenana River to the south edge of the area shown on plate 4, bedrock consists largely of highly deformed, dark-gray to black shale, slate, and argillite, locally intruded by basic rocks and rhyolite.

Dips of beds generally are steep. At least one fault zone of large displacement cuts the rocks. Argillite and graywacke along the east bank of the Nenana River opposite the mouth of Windy Creek have been folded into numerous isoclines and cut by steeply dipping thrust faults. A few miles east of this area conglomerates have been converted to schistose rocks through the stretching of pebbles (Moffit, 1915, p. 43).

Because these rocks are highly deformed and broken, they are not suitable for riprap. The limestone, chert, and conglomerate are suitable for ballast and subgrade. Commercial exploitation of the limestone and argillaceous units for the production of cement has been considered.[3]

CANTWELL FORMATION

The Cantwell formation, of Upper Cretaceous age, is crossed by the railroad between mile 330 and mile 348. The formation consists of conglomerate, sandstone, shale, coaly shale, and coal. Sandstone and conglomerate, which make up about 60 percent of the formation, occur together as massive beds as much as 300 feet thick. The numerous conglomeratic and pebbly layers in those beds range from 1 to 10 feet in thickness and comprise 10–20 percent of the sandstone-conglomerate sections. Pebbles in the conglomerate average ½–2 inches in diameter, but locally are as much as 6 inches in diameter. Quartz and chert are the common rock types represented by the pebbles, but rhyolite, argillite, phyllite, granite, and gabbro make up significant amounts in some layers. Many of the pebble layers are extremely well sorted and do not contain interstitial material smaller than half the average diameter of the pebbles. The original porosity of the beds has been reduced greatly by compressive forces.

Claystone, shale, and coaly material form zones in the Cantwell formation that are as much as 50–100 feet thick. Coaly material in these zones includes bone and occurs in beds 1–5 feet thick and 3–30 feet apart.

The entire Cantwell formation is complexly folded and faulted. The fault zone between the Cantwell and the Birch Creek schist at McKinley Park station is several hundred feet wide and consists of clayey gouge and "horses" (large blocks) of solid schist.

[3] Moxham, R. M., West, W. S., and Nelson, A. E., 1951, Cement raw materials available to the Windy Creek area, Alaska: Unpublished rept. in files of U. S. Geol. Survey.

North of mile 336 the Cantwell formation is well consolidated but only moderately well cemented. The rock of fresh outcrops is relatively soft and can be broken up easily with a pick; the rock of weathered outcrops is more durable. Because the rocks are poorly cemented, they generally are not suitable for riprap. Rock obtained from some of the coarser textured quartz-rich beds can be used for ballast. The argillaceous and coaly material is particularly unsuitable. South of mile 336 the Cantwell formation is much better cemented and more indurated. It forms rugged mountains and steep canyon walls. Joints are widely spaced, causing the rock to separate into massive blocks on weathering. Material that is suitable for riprap has been obtained from a quarry in talus of conglomerate from the Cantwell formation at mile 331. Beds other than that supplying the talus at mile 331 probably are also suitable for riprap or ballast.

TERTIARY COAL-BEARING FORMATION

The Tertiary coal-bearing formation (Wahrhaftig, Hickox, and Freedman, 1951) crops out along the Alaska Railroad in the vicinity of Lignite and Healy (pl. 2), and on Slate and Chicken Creeks. The formation is about 1,900 feet thick at Suntrana, 4 miles east of Healy, where a complete section is exposed. Pebbly sandstone in beds 30–100 feet thick makes up about 65 percent of the formation; subbituminous coal in beds 6–40 feet thick, about 15 percent; and claystone in beds ranging in thickness from a few feet to 80 feet, the remaining 20 percent. An 80-foot-thick claystone bed about 1,300 feet below the top of the formation and a 50-foot-thick bed at the top of the formation are the loci of extensive landslides on Healy and Lignite Creeks (pl. 2).

The formation is folded into a number of anticlines and synclines and is faulted. At Healy the formation strikes about N. 60° E., dips about 60° N., and lies on the south limb of a broad syncline whose axis is about 2 miles north of Healy. The axis of a faulted anticline extends eastward from Lignite, and a subsidiary anticline is exposed on the east side of the river opposite the mouth of Pangengi Creek (pl. 2). The beds in the vicinity of Lignite are nearly flat lying; they dip 10°–20° north and west along Pangengi Creek.

No riprap is available; the formation provides poor foundations and is subject to frost heaving and landsliding. The rocks can be excavated easily with a pick; they are eroded easily by running water. The formation is a good source of commercial coal.

NENANA GRAVEL

The Nenana gravel, of Tertiary age (Wahrhaftig, Hickcox, and Freedman, 1951, p. 152–153; and Wahrhaftig, 1951, p. 176–179) is the most widespread bedrock formation along the Nenana River north of Healy. It consists largely of poorly consolidated, moderately well sorted conglomerate and sandstone. Near Healy the pebbles range in average size from 1 to 2 inches at the base of the formation to 3 or 4 inches near the top; the maximum size ranges from 4 inches at the base to 18 inches near the top. The pebbles are derived from sandstone and conglomerate in the Cantwell formation and from schist, quartzite, granite, and other intrusive rocks. Coarse- to very coarse grained dark sandstone is the interstitial material. Pebbles and sand grains commonly are coated with thin layers of iron oxide. Coarse-grained sandstone lenses, 5–10 feet thick and 50–100 feet long, are interbedded at intervals of 30–50 feet in the conglomerate. Locally, near the base and in the upper part of the formation, the Nenana gravel contains beds of claystone, 3–5 feet thick and spaced 30–50 feet apart. The total thickness of the formation that is exposed in the vicinity of Healy is 4,000 feet.

The lower part of the formation is exposed also in bluffs along the river northward from Lignite. It is composed of equal parts of coarse-grained dark sandstone and of conglomerate in which pebbles range in average size from half an inch to 3 inches; pebbles larger than 5 inches are rare. Claystone layers are more abundant northward from Lignite than in the vicinity of Healy, and fragments of carbonized wood are common in the sandstone. Between mile 384 and mile 385 on the railroad (pl. 5) a bed of lignite about 4 feet thick crops out at the crest of an anticline in the gravel.

The formation along the Nenana River has about the same attitude as the coal-bearing formation beneath it. In the vicinity of Healy the Nenana gravel strikes about N. 60°–70° E. and dips 45° N. at the south contact; within a distance of about 1 mile northward, the dip decreases to about 10° N. Just north of Poker Creek the formation is broken by the large fault that forms the south boundary of the coal-bearing formation along Lignite Creek. North of Pangengi Creek the gravel lies in a syncline that is parallel to the Nenana River. Dips are commonly gentle (10°–15°) toward the river, and beds are traceable in nearly horizontal bands in river bluffs. The axis of an anticline in the formation crosses the railroad between mile 384 and mile 385.

For the most part the Nenana gravel, although moderately well consolidated, is poorly cemented and is not usable as riprap. It supports steep cliffs, 50–100 feet high, for long periods of time. However, it is easily broken up when struck lightly by a hammer.

Its greater resistance to erosion than the underlying coal-bearing beds is attributed to its greater permeability and generally coarser texture. Rain and melting snow usually sink into it, thus reducing the amount of surface erosion. Hence, in many places where the Nenana gravel is underlain by the coal-bearing formation, the outcropping edge forms hogbacks and ridges rivaling in height nearby mountains of much harder rocks. It is a poor source of gravel because of the high proportion of fine material, high content of ferric iron, and the abundance of decomposed pebbles.

IGNEOUS ROCKS

BASALT

Basalt dikes are common in the Birch Creek schist. They are generally vertical, strike about north to N. 30° W., are 5–50 feet thick, and on the average are 1,000–2,000 feet apart. The dikes were intruded along cross joints of the schist before the deposition of the overlying Tertiary coal-bearing formation. An irregular body of greenish-gray basalt is exposed on the east bank of the Nenana River opposite mile 354.8 on the railroad; stringers of this basalt cross the river.

The basalt comprises only a small percentage of the total volume of the body of schist in which it is enclosed. Generally it is so weathered and fractured that from an engineering standpoint it is structurally little different from the schist. The irregular body of basalt on the east side of the river, at mile 354.8 on the railroad (pl. 2), is less weathered and could be used as a local source of riprap or ballast if an access road or track can be built economically to it.

RHYOLITE

Rhyolite occurs in a few places in the Cantwell formation in the immediate vicinity of the Nenana River (pls. 2 and 3). The rhyolite is too widely scattered and its volume is too small for it to be considered as a source of construction materials.

DIABASE

Diabase, in dikes, sills, and irregular bodies, is the most abundant igneous rock that intrudes the Cantwell formation (pl. 3). It makes up perhaps 20 percent by volume of the formation. The diabase is dark green to black on fresh surfaces and dark brown on weathered surfaces. It generally is too closely jointed to permit the quarrying of large blocks for riprap. Fresh diabase in the vicinity of Yanert, when crushed, might provide suitable subgrade.

ANDESITE

Andesite that intrudes the Cantwell formation crops out in many places along the Nenana River between mile 335.5 and mile 338.5. (See pl. 3.) It occurs as sills, dikes, and irregular bodies. The physical properties of the andesite are comparable to those of the diabase, discussed in the preceding paragraph, with which it is associated.

GREENSTONE

Greenstone is the name applied to the rock in a large altered gabbroic intrusive body crossed by the Alaska Railroad between mile 327.5 and mile 329.5, north of Windy (pls. 3 and 4). The rock is predominantly dark green when fresh, but weathers to dark brown. Where it is crossed by the railroad, it may be divided into two types. The southern half consists of blocks of massive unaltered gabbro surrounded by zones of intense shearing and serpentinization. It is moderately closely jointed, but still massive enough to form the most rugged mountains in this part of the Alaska Range. The northern type is fine-grained massive rock cut by irregular veins of quartz and calcite. It is broken by irregular fractures 10–40 feet apart and is locally altered to a brown earthy material. The local "badlands" south of Clear Creek were formed from glacially quarried and transported blocks of this type.

The greenstone is heavy, massive, and generally well suited for riprap. The northern, or fine-grained type, is less suitable because of veins of quartz and calcite and of decomposed areas, but is readily accessible. The southern, or coarse-grained type, is more suitable, but slightly less accessible. However, the trackage required for quarries would not exceed a few hundred yards. The greenstone, if crushed, probably would make good ballast or subgrade, but preliminary tests should be run to verify its suitability.

DESCRIPTION AND ENGINEERING PROPERTIES OF THE SURFICIAL MATERIALS

Gravel, sand, silt, clay, and peat make up widespread unconsolidated surficial deposits along the Alaska Railroad. The mappable deposits are shown on plates 2–5 and 10, and on figures 36, 41, and 54. Gravel was deposited by the Nenana River and its tributaries during several glacial advances and withdrawals that took place during the Pleistocene and have continued to the present day. Interbedded clay, silt, and sand were laid down in glacial lakes. Glaciers left deposits of unsorted debris of all sizes as till, interbedded with lenticular deposits of gravel, sand, silt, and clay. Wind picked up fine material, particularly from the bars of braided streams, and deposited it as sand dunes and a silt mantle near the Nenana River. The exposed surfaces of all rock formations, bedrock and surficial, are covered for the most part by a thin layer of material which has been stirred and moved downslope by processes which involve freezing and thawing. In general the age of the surficial deposits has no bearing on the engineering properties of the materials. Consequently, materials of different age that have similar engineering properties are described together in the following paragraphs. The history of the deposition of these formations is given on pages 22–63.

GRAVEL DEPOSITED BY THE NENANA RIVER

The Nenana River in Pleistocene and Recent time deposited outwash gravel during periods of glacial advance and reworked the deposits during periods of glacial retreat. These deposits are preserved as extensive terraces. Locally, they are overlain by other unconsolidated deposits. The deposits are shown on plates 2–5, and 10, and in figures 36, 41, 51 and 54 as outwash gravel of several glacial stages, as terrace gravel, and as stream gravel of the Nenana River. The gravel deposited by the Nenana River is shown on the plates by a pattern of large solid dots of different color depending on the age of the deposit.

The gravel is blue gray and consists of well-rounded pebbles, cobbles, boulders, and interstitial coarse to very coarse clean sand. The average size of the pebbles is 2–6 inches; however, boulders 18 inches across are common. Lenses of coarse sand are present. The gravel has high permeability and fairly high porosity. In most places it is unconsolidated. Locally, however, it is cemented by calcite or limonite into a resistant conglomerate. Dark sandstone and conglomerate from the Cantwell formation and greenstone, gabbro, and granite are the principal rocks found in the gravel south of Moody. North of Moody pebbles of Birch Creek schist are an abundant constituent, and north of Healy slightly weathered pebbles reworked from the Nenana gravel are present in the outwash gravel.

The gravel-covered terraces occupy a belt 1–4 miles wide that extends from Healy northward along the Nenana River. (See pls. 2 and 5.) Individual terraces are as much as a mile wide; most, however, are much narrower. Generally there are no more than 4 or 5 terrace levels at any point along the river; however, 14 terraces can be distinguished at Healy. The most extensive terraces lie 10–40 feet above the river, 100–160 feet above the river, and 250–400 feet above the river. On the lower terraces the gravel is 5–20 feet thick; on the intermediate terraces it is 10–50 feet thick; and on the upper terraces it is locally 160 feet. The terraces slope northward more steeply than the gradient of the river. The highest terraces have the steepest northward slope, hence the terraces tend to converge northward.

Between Healy and McKinley Park station the gravel is preserved only in patches along the walls of the canyon. (See pl. 5.) The largest terrace remnants are near Garner. Along the railroad in the vicinity of Moody, at the railroad bridge at mile 351.4, and beneath the bench above the railroad at mile 350.0, a layer of outwash gravel 10–30 feet thick rests on an erosion surface cut on clay and delta gravel; the outwash gravel is overlain by a thick layer of yellowish-brown gravel of a tributary stream. Locally the gravel in this layer is cemented by calcite.

From McKinley Park station southward to Carlo (pl. 3), outwash gravel forms a belt about 1 mile wide along the Nenana River. The most prominent terrace lies about 200 feet above the river. One or two terrace remnants are preserved at lower levels. In places the gravel extends from river level to the top of the highest terrace, but generally it is 80–160 feet thick, the lower part of the terrace consisting of till, clay, sand, or bedrock. The topography of the outwash gravel east of Lagoon is irregular and rolling and has a relief of about 40 feet. This gravel forms a pitted outwash terrace.

The present flood plain has a relief of about 5 feet. North of Healy it averages about 2,500 feet in width. Between Healy and Carlo it is about 300 feet wide, and south of Carlo it increases in width to 3,500 feet.

The Nenana River gravel in the terraces and present flood plain provides the best source of nonheaving ballast, subgrade, and concrete aggregate along the Nenana River. The gravel generally is clean, unweathered, and free from minerals likely to react in concrete. It is abundant, easily handled, and accessible to the railroad. It furnishes the best foundation for roads, railroads, airports, and building. Borrow pits at McKinley Park station and at other places along the railroad outside the area covered in this report are in Nenana River gravel. The communities of McKinley Park station, Healy, Lignite, and Ferry are on gravel terraces, as are the airstrips at Healy, Lignite, and McKinley Park station, and the railroad north of Healy.

ALLUVIUM AND TERRACE GRAVEL DEPOSITED BY TRIBUTARIES OF THE NENANA RIVER

Tributaries of the Nenana River have deposited gravel, derived from their basins, which today occurs as terrace and flood-plain deposits along these tributaries and as alluvial fan deposits resting on and interbedded with gravel deposited by the Nenana River. These deposits were laid down during many glacial stages in the Pleistocene and during the Recent. They are shown on plates 2–5, and 10, and in figures 36 and 41 as alluvium and terrace gravel deposited by tributaries of the Nenana River. They are indicated by a pattern of open circles of different colors depending on the age of the deposits. As is true of the Nenana River gravel, the age of the tributary gravel has no effect on its engineering properties; hence, in the following paragraphs, gravel deposits of different age that have similar lithology and engineering properties are described together.

Alluvial deposits resting on Nenana River gravel generally thicken toward the walls of the Nenana River valley and are thickest at the points where the tributaries which deposited them emerge from the canyon walls. The tributaries drained areas containing rocks whose lithology and engineering properties vary widely. Four main types of tributary gravel are recognized.

Between Healy and McKinley Park station the tributary gravel is yellowish brown and is composed largely of angular to subangular fragments of Birch Creek schist. The fragments range in size from a fraction of an inch to several feet and are cemented with a matrix consisting of micaceous mud derived from Birch Creek schist. This yellowish-brown tributary gravel rests on Nenana River outwash gravel at mile 350.0, at mile 351.4, and northward on the west side of the Nenana River from Sheep Creek (mile 353) to Garner. (See pl. 2.) Its thickness is not uniform. At Sheep Creek the maximum thickness is about 100 feet; at mile 351.4, the maximum thickness is 120 feet. The gravel stands in nearly vertical cliffs. The tributary gravel in the canyon between McKinley Park station and Healy is a poor source of ballast and subgrade. It provides poor foundations, because its high content of fine material promotes frost heaving and settling. It cannot be used for concrete aggregate.

Gravel of similar origin, but which is markedly different lithologically, rests on the broad terrace remnants north of Dry Creek and Healy Creek. In that area most of the tributaries drain the Nenana gravel. The deposits consist largely of pebbles of sandstone, conglomerate, greenstone, gabbro, granite, and Birch Creek schist—material which appears also in the pebbles of the outwash gravel of the Nenana River. However, many are weathered and iron stained; interstitial material in the tributary gravel is brownish coarse sand from the Nenana gravel. Because this tributary alluvium contains an abundance of weathered pebbles, it is not well suited for use as concrete aggregate. It makes fair ballast and foundations.

A third type of tributary gravel and alluvium is found south of McKinley Park station. It also is composed of material similar to that of the outwash gravel of the Nenana River. However, this material is derived directly from bedrock outcrops. The tributaries which deposited this gravel, with the exception of Riley Creek, are short and steep. Their deposits are commonly poorly sorted and subangular and contain much fine-grained material. Like the tributary terrace gravel between McKinley Park station and Healy, this gravel is commonly not suitable for use as ballast, subgrade, foundations, or concrete aggregate.

Gravel in terraces and flood plains along Dry and Healy Creeks consists largely of well-rounded boulders and cobbles of Birch Creek schist. Unlike other gravel deposits derived from the Birch Creek schist, the gravel of this deposit is well sorted, clean, and porous, and the pebbles in the gravel are those which have resisted breaking up because they are very hard and do not contain prominent planes of parting. This gravel is an excellent source of ballast and subgrade and provides good foundations. Its suitability for use as concrete aggregate is not known.

SAND

Terraces 60 feet high extend along the Alaska Railroad from Carlo 2 miles southward and appear to be composed almost entirely of dark, coarse, clean sand. The sand probably was formed by the mechanical fragmentation of bedrock. Fragments of various kinds of rocks and grains of quartz, feldspar, chert, mica, and hornblende probably make up the bulk of the sand. It has not been examined in detail, and its engineering properties are not known.

VARVED CLAY AND SILT AND ASSOCIATED DELTA GRAVEL

Interbedded silty clay, clayey silt, and some sand are exposed at many places in the gorge of the Nenana River between McKinley Park station and Healy. These deposits are generally flat lying and rhythmically bedded (varved). Where tributaries enter the Nenana River, the silt and clay interfinger with steeply dipping gravel composed largely of fragments of Birch Creek schist. These deposits occur from river level to an altitude of about 1,750 feet, 150–500 feet above the river. The flat-lying clay, silt, and sand are interpreted as deposits laid down on the floor of a lake which once occupied the gorge between McKinley Park station and Healy. The steeply dipping gravel is interpreted as comprising deltaic deposits built into this ancient lake by tributary streams. A detailed discussion of the geologic significance of these deposits is given on pages 34–36. These deposits are of paramount economic significance in that they are the loci of many of the landslides which affect the Alaska Railroad between McKinley Park station and Healy.

Clay and silt underlie the eastern part of the terrace on which McKinley Park station is located, from the Nenana River westward to a line a third of a mile east of the railroad. (See pl. 3.) Clay and silt are exposed also in bluffs on the east bank of the river about one mile north of McKinley Park station. The railroad rests on clay and silt for long stretches around the bend at mile 350.0, two miles north of McKinley Park station; at the bridge at mile 351.4; and at Moody (see pls. 6 and 10 and figs. 36 and 41). Each of these areas is a site of serious landslides. The distribution and relations of the lake deposits at each of these areas are described in detail in the sections on the individual landslides.

Clay and silt also are exposed in each of the tributary canyons that cross the terrace between Moody and Garner. The exposures are ⅛–⅔ of a mile west of the track. The exposed materials appear to be part of a body of lake sediments that extends northwestward from Moody to a point about half a mile beyond Garner and is ¼–½ mile wide. Except at their southern end, the clay and silt are separated from the railroad and the river by a body of Birch Creek schist ⅛–¼ mile wide.

Samples 1–16 (figs. 32–34) were collected at exposures of the lake sediments at miles 349.3, 349.5, 351.4, 353.2, 353.3, and 353.5. Samples 1, 2, 3, 6, 8, 10, 11, 12, 13, and 16 represent the silty clay or clayey silt facies of the original lake sediments. Samples 4, 5, and 14 represent some of the more sandy facies. Samples 7, 9, and 15 represent mixtures in flowing slides of the silt and clay and some sand and gravel. The median grain size of the silt and clay samples ranges from 0.016 to 0.0013 mm. (See table 3.) The silt and clay are well sorted to poorly sorted. Plastic limits and liquid limits are low to moderate.

Two samples of glacial-lake clay and silt were collected in 1951 by R. A. Eckhart from the bank above the track at mile 353.3; they are probably similar to sample 12. They were analyzed chemically by E. A. Nygaard and S. M. Berthold, whose report (No. IWC–

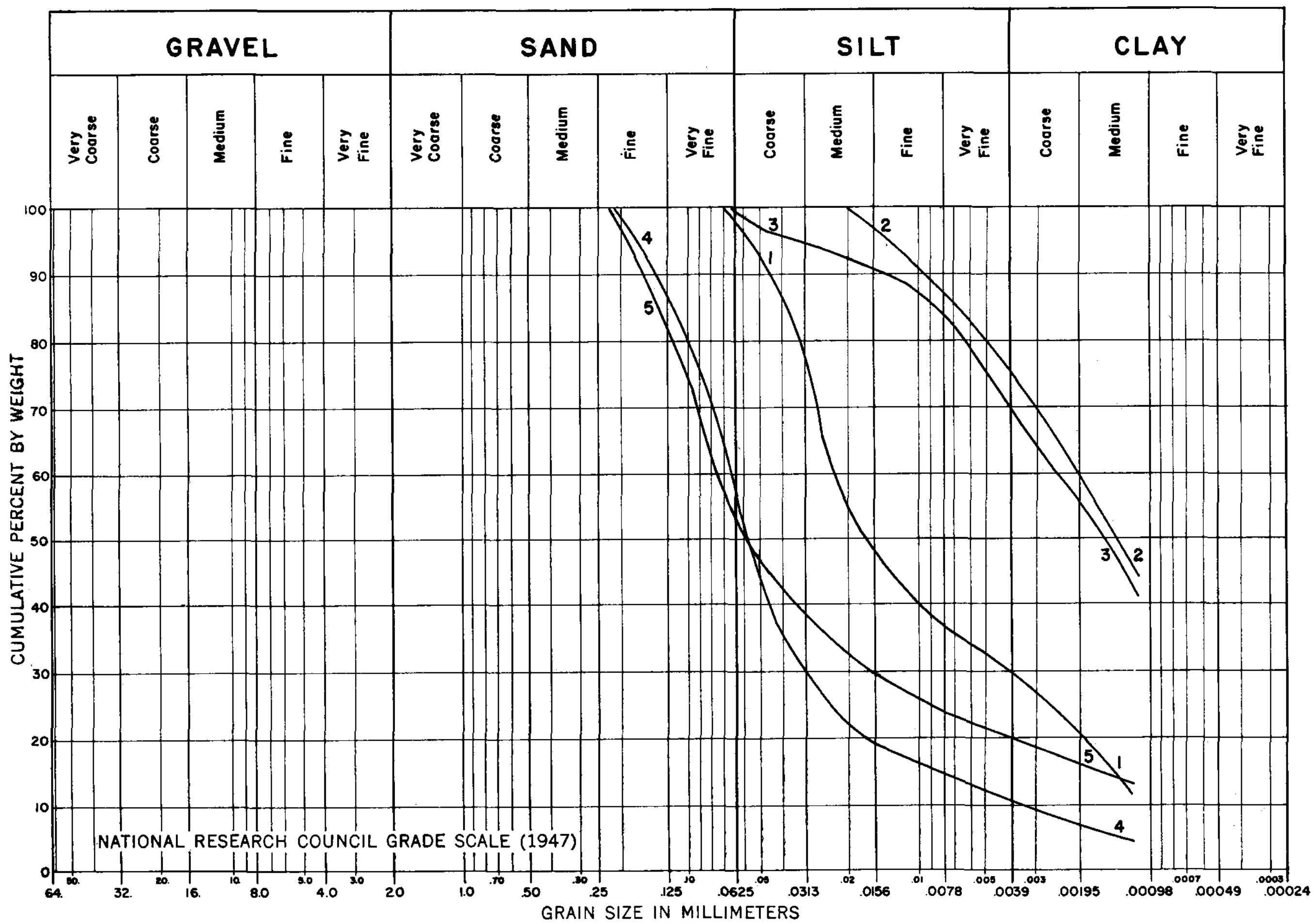

FIGURE 32.—Cumulative curves of grain-size distribution for samples 1–5 (see also table 3).

TABLE 3.—*Test data for samples of glacial-lake silt and clay*

[Samples 1-15, inclusive, analyzed August 1952 by Office of the District Engineer, Corps of Engineers, Dept. of the Army, Washington, D. C. Sample 16 analyzed by E. Dobrovolny, U. S. Geological Survey]

Sample No.	Mileage,[1] Alaska Railroad	Plasticity index	Liquid limit	Plastic limit	Specific gravity	Median grain size (mm)	Sorting coefficient $SO=\sqrt{\frac{Q_3}{Q_1}}$	National Research Council classification
1	349.3	7.2	24.8	17.6	2.64	0.016	3.48	Clayey silt.
2	349.3	16.1	45.1	29.0	2.66	.0015	>2	Silty clay.
3	349.3	26.8	44.5	17.7	2.66	.0015	>2.2	Do.
4	349.5	6.0	22.1	16.1	2.63	.058	1.86	Sandy silt plus clay.
5	349.5	4.4	20.0	15.6	2.63	.057	3.53	Sandy, clayey silt.
6	349.5	28.2	50.1	21.9	2.66	.0013	>1.7	Silty clay.
7	351.4	13.2	33.9	20.7	2.63	.0093	6.42	Clayey, sandy silt plus pebbles.
8	351.4	22.2	37.0	14.8	2.65	.0035	3.02	Silty clay.
9	351.4	16.0	33.5	17.5	2.63	.0077	5.31	Clayey, sandy silt plus pebbles.
10	353.2	16.7	32.5	15.8	2.66	.0041	2.20	Clayey silt.
11	353.2	13.4	32.4	19.0	2.66	.0027	2.8	Do.
12	353.3	22.5	41.0	18.5	2.62	.0040	2.86	Do.
13	353.5	16.8	34.9	18.1	2.65	.0022	>2	Silty clay.
14	353.5	5.4	21.5	16.1	2.65	.16	1.69	Silty sand.
15	353.5	13.7	29.2	15.5	2.63	.010	3.40	Clayey, sandy silt plus pebbles.
16[2]	353.3	29.0	----------	----------	----------	.0025	>2.2	Silty clay.

[1] Stated in mileposts on the Alaska Railroad.
[2] Centrifuge-moisture equivalent, 42 percent; field-moisture equivalent, 38 percent; shrinkage limit, 22.5 percent; shrinkage ratio, 1.60; volume change, 24.8 percent; lineal shrinkage, 7 percent; and optimum-moisture content, 22.5 percent.

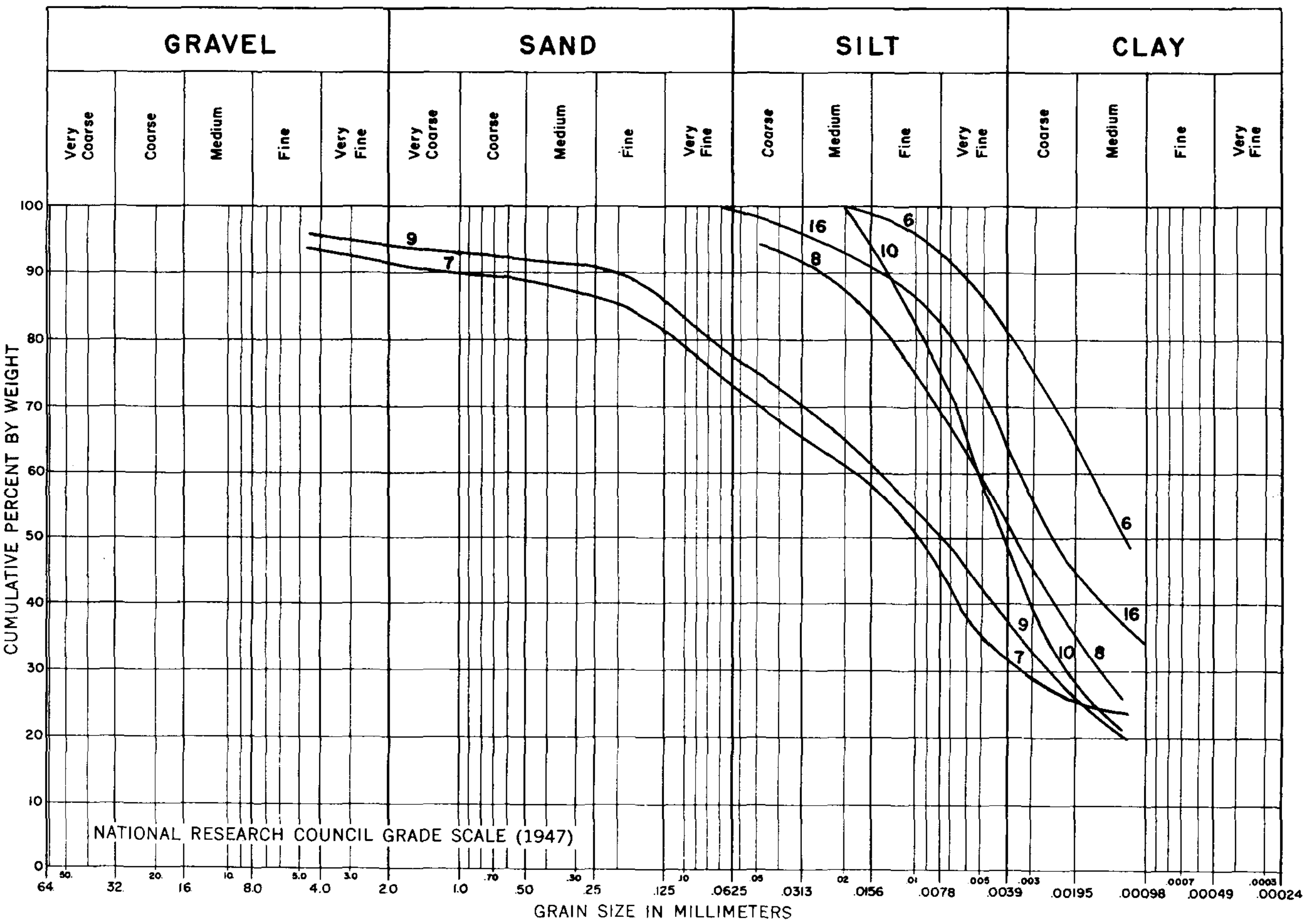

FIGURE 33.—Cumulative curves of grain-size distribution for samples 6–10 and 16 (see also table 3).

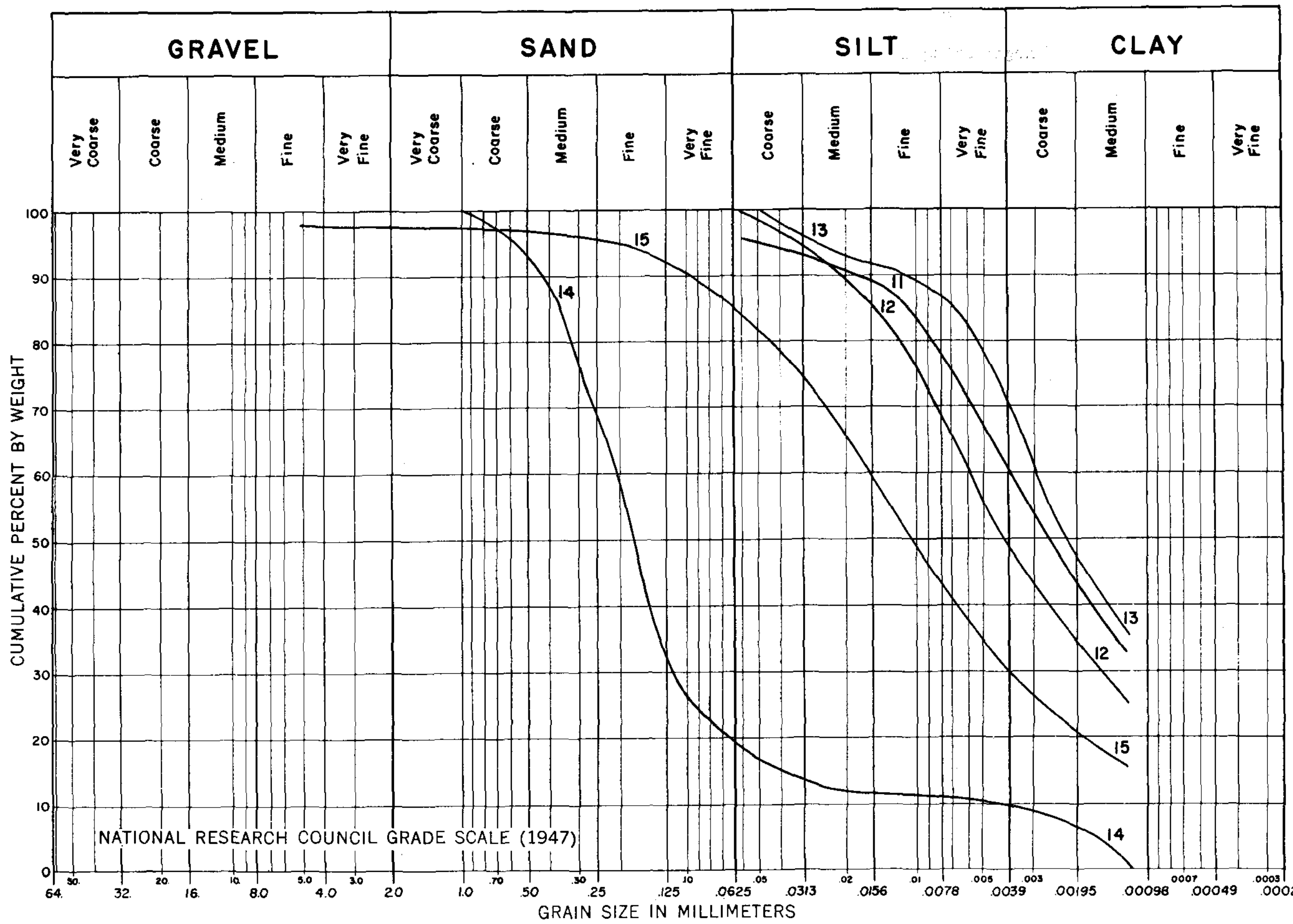

FIGURE 34.—Cumulative curves of grain-size distribution for samples 11–15 (see also table 3).

231, dated December 13, 1951) shows them to have the following composition:

	Percent
SiO	59.1
Al_2O_3	17.0
Total Fe as Fe_2O_3	6.6
MgO	2.8
CaO	2.3
Na_2O	1.2
K_2O	3.0
Ignition loss*	6.8
Total	98.8

*Includes gain due to oxidation of FeO.

These percentages are characteristic of most glacially transported and lake-deposited fine-grained sediments in many places in the world.

The glacial-lake clay and silt, as suggested by the samples and proved by experience, makes foundations subject to landsliding and to frost heaving and settling. The clay and silt absorb water readily and require little water to become plastic. Clay and silt in permafrost, when thawed, generally liberate enough water from enclosed veins of ice, irregular bodies, and interstitial cement to become supersaturated. Under such conditions the mixture flows readily.

The delta gravel is similar to the tributary outwash gravel previously described, but locally it is somewhat better sorted and slightly more porous. When dry, it makes a firm foundation. When saturated, it is subject to frost heaving and settling.

MORAINE (TILL, ERRATICS, AND ASSOCIATED DEPOSITS)

Moraine, till, and associated deposits laid down by glaciers, cover much of the lowland areas south of McKinley Park station. Till was once much more extensive north of McKinley Park station. Now only widely scattered erratic boulders, a few bodies of till preserved beneath younger deposits in the gorge between McKinley Park station and Healy, and a few large areas of till near Healy remain.

Till is a heterogeneous, poorly sorted mixture of boulders, cobbles, pebbles, sand, silt, and clay. It may possess a rude lamination or structure but lacks the perfect stratification and sorting that are characteristic of water-deposited materials. Much of the till along the Alaska Railroad consists predominately of clay and silt in which pebbles, boulders, and cobbles occur like plums in a pudding. Intimately associated with the till are irregular, discontinuous bodies of waterworked coarse gravel, sand, silt, and clay.

A large area underlain by clay-rich till lies just north of the McKinley Park highway and extends 1 mile westward from McKinley Park station. Clay-rich till forms a belt about two-thirds of a mile wide extending from the railroad bridge across Riley Creek, at McKinley Park station, southeastward to Yanert. This area has a subdued hummocky topography and contains many ponds and lakes. Gravel, sand, silt, and clay are interbedded locally with the till. Clay-rich till overlain by about 100 feet of gravel, between mile 346 and mile 347 on the railroad, is the locus of landslides. Hummocky till on which many lakes occur covers much of the lowland south of the Yanert Fork and east of the Nenana River. Till underlying the extensive gravel plain crossed by the new highway south of Yanert, is exposed in many river cuts. Till, and associated gravel and sand, forms an area of hummocky topography along the east side of the Nenana River 1–3 miles north of Carlo Creek. Till blocks the west end of the pass leading from mile 336 on the Alaska Railroad to Riley Creek. South of Carlo, till occurs only as scattered patches on bedrock.

Till covers the 1,800-foot bench from a point about 1 mile west of Healy to a point about 3 miles west of Healy (see pl. 2). The eastern half of this bench contains many dry, closed depressions, the largest of which is about 60 feet deep. Presumably the morainal material beneath this part of the bench is relatively permeable. Exposures in road cuts on the east edge of this bench reveal clay-rich till interbedded with outwash gravel. The western part of this bench has several closely spaced morainal ridges. Road cuts in these ridges expose gravel and clay-rich till.

Blocks of granite from 5 to 40 feet across occur at widely scattered localities from Healy northward to the north edge of the foothills. Blocks as much as 40 feet across are found at an altitude of 3,900 feet on mountains; they are also present on terraces and in stream valleys. These blocks are believed to be remnants of an ancient till sheet. For the most part they are remote from the railroad. Some of the blocks found close to the railroad and to potential highway routes are described in the next paragraph.

A few boulders are in Suntrana Creek; these are being moved downstream a short distance each year by mudflows. One was moved 1,000 feet by the mudflow of July 1952 and is now only a few hundred feet upstream from the railroad bridge. Boulders occur along Healy Creek as far upstream as the mouth of French Gulch. Large boulders of granite, greenstone, and conglomerate are abundant along Lignite Creek for the first 6 miles above its mouth. Several large boulders are in the bed of Dry Creek about a quarter of a mile above the railroad bridge. Others are thinly scattered over flats and hills in the headwaters of Dry Creek and Pangengi Creek. Boulders are present on both sides of the railroad track and along the Nenana River 2 miles northward from Browne. These probably slid down the bluff along the river from the terraces above. Some of these boulders are 15 feet across and it was necessary to blast through several of the boulders when the Alaska Railroad was constructed.

The properties of the till vary markedly according to its clay and silt content. Till consisting largely of clay-size fragments behaves similarly to the glacial-lake clay. Stony and relatively clay-free till makes more satisfactory foundations. However, all till, unless it has been washed free of fine material, is likely to heave badly on freezing and to slump on thawing. The erratics must be avoided or removed by blasting along rights of way.

ÆOLIAN DEPOSITS

Æolian deposits along the Alaska Railroad and the Nenana River include windblown silt and sand. The sand is confined to dunes at the heads of south-facing cliffs and "badlands." Sand dunes range from 10 to 40 feet in thickness and may extend for several hundred feet to the lee of the cliff head. Cliff-head dunes are exposed in section about a quarter of a mile northeast of Moody, about a quarter of a mile south of Garner, and on the high bluff above the railroad track about 1–1½ miles along the railroad south of Healy. The high bluff on the east side of the Nenana and the bluff on the north side of Dry Creek have many cliff-head dunes. The sand is coarse- to fine-grained and poorly consolidated. Interbedded peat and buried forest layers are common in some dunes.

Windblown silt (loess) mantles slopes and tops of terraces along the Nenana River. The silt mantle is 3–8 feet thick on bluffs overlooking the river but thins away from the river. Its thickness increases northward from 3 feet at Healy to 8 feet at Browne. Commonly the silt is in two layers. A lower layer, the bedding of which is contorted, has an average grain size of 0.015 millimeters. An upper layer, relatively undisturbed, has an average grain size of 0.15 millimeter.

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One or more thin peat layers may be interbedded with the silt.

The silt heaves and settles on repeated freezing and thawing. The bedding in the lower silt layer has been disturbed by such heaving and settling. In places the silt, saturated with water creeps or flows from beneath heavy loads or down gentle slopes. Its use as a foundation is not recommended. It can be removed easily.

PEAT

Peat has been forming in bogs along the Alaska Railroad from glacial times to the present. A few areas that are representative of peat accumulation, in particular those in which the presence of peat seriously affects the railroad or potential highways along the Nenana River, are shown on plates 2–5, inclusive. Small basins in till in the vicinity of Lagoon (pl. 3) are filled with peat from *Sphagnum*, *Carex*, and other plants. The thickness of the peat is unknown, for the ground was frozen at a depth of a little more than 1 foot. Peat mantles bog-covered hillsides on the west side of the Nenana River from Moody northwestward to the Diamond coal mine. (See pl. 2.) The bogs on the surface of the high terrace east of Browne and north of Moose Creek presumably are underlain by peat. (See pl. 5.) The thickness of the peat is unknown.

The peat is a mat of water-saturated brown-to-black vegetable material, consisting commonly of partly decayed moss, herbaceous plants, and branches of small shrubs. It commonly contains some windblown silt and in places contains frost-moved fragments of larger size. Most peat is perennially frozen below a depth of 1–2 feet.

Perennially frozen peat contains a large proportion of ice. Thawing of the peat generally results in considerable sinking of the surface; in areas where the cover of vegetation has been destroyed and where the peat has subsequently thawed, swamps and lakes have formed. Peat heaves and settles owing to repeated freezing and thawing. For these reasons it should be removed before construction is begun.

TALUS, ROCK GLACIERS, LANDSLIDE DEBRIS, AND CONGELITURBATE

Under rigorous climates in alpine areas of the sub-Arctic, geomorphic processes involving frost action and mass wasting produce unconsolidated deposits of importance to the engineer. These deposits are derived directly from bedrock by fragmentation and from unconsolidated deposits by frost modification. Debris of ancient landslides is shown only on plate 2. Talus and rock glaciers are shown only on plates 4 and 10. Talus and congeliturbate are widespread outside the areas shown on plates 4 and 10 but are not shown on the maps of those other areas. Although the external form and the lithology of the deposits vary widely, they are characterized by a general lack of sorting, and by the fact that all were derived from materials in the immediate vicinity of the deposit.

Talus is an accumulation of unsorted or poorly sorted rock waste at the base of a cliff. The fragments of talus are angular if derived by fragmentation from bedrock but are rounded if derived from gravel. Frost action commonly breaks the material out of a steep slope or cliff and gravity causes it to slide, roll, or fall. The slope of the surface of the accumulation generally exceeds 30°. The size and thickness of the talus varies considerably from place to place.

Rock glaciers are accumulations of unsorted rock waste that occupy positions in valleys similar to those of true glaciers. They are derived largely from talus and move forward from the base of talus slopes by a glacierlike movement. Their external form is similar to that of glaciers, and they show evidence of past or present downslope movement.

Landslide debris consists of all materials involved in landslides. The debris is generally unsorted, and its texture ranges from that of the material involved in earthflows, which is fine grained, to that of the fragments of rockfalls and rockslides, which is coarse grained. Landslide slump blocks are of enormous size; they commonly consist of unconsolidated or poorly consolidated material, which has been displaced and rotated by slumping.

Congeliturbate is defined by Bryan (1946, p. 640) as "a body of material disturbed by frost-action." The material consists of unconsolidated mantle which has been formed or modified by frost splitting, frost stirring, frost heaving and settling, and by downslope movements in which frost is a factor. Local sorting of fragments according to size is characteristic of many congeliturbate deposits and gives rise to stone polygons, stone stripes, involutions, and terracettes. Downslope movement of congeliturbate causes the accumulation of heterogeneous material on and at the base of slopes. Congeliturbate is characterized by wide range of size of fragments and by physical instability, particularly its susceptibility to frost action. It is commonly supersaturated. Slopes mantled by congeliturbate rarely are inclined as much as 30°. Congeliturbate deposits are widespread but generally less than 10 feet thick. The lithology of the deposits reflects that of the material from which they were derived—material directly upslope or beneath the deposits.

Talus, rock glaciers, landslide debris, and congeliturbate in most places are susceptible to frost heaving and settling and to downslope movements, either slow creep or rapid slump and earthflow. Consequently they generally make poor foundations. Coarse deposits may have formed during periods when the climate was much colder than it is at present; these are now stabilized. With care, stabilized coarse-grained deposits can be used for foundations. Because most deposits contain a relatively high proportion of fine-grained material, they make poor or, at best, fair ballast and subgrade. Locally some talus accumulations are coarse grained and are not susceptible to frost heaving. This material makes good ballast, subgrade, and riprap. Most deposits require washing and screening before they can be used for concrete aggregate.

DESCRIPTION AND ENGINEERING ASPECTS OF PERMAFROST

Permafrost or perennially frozen ground is discontinuous throughout the central part of the Alaska Range (Black, 1951, fig. 1). It is absent under large rivers and lakes and may be absent or may occur only in small isolated bodies beneath terraces of coarse-grained, well-drained gravel. All excavations to depths of several tens of feet in unconsolidated materials other than bare gravel have penetrated permafrost.

In the Alaska Range the depth to permafrost is controlled largely by the amount of vegetation, type of rock, drainage conditions, and exposure of the surface of the ground to direct sunlight. In general, permafrost is close to the surface on north-facing slopes, in fine-grained, poorly drained materials, and in areas having a dense cover of mosses. The depth to permafrost can be correlated with three types of vegetation. (1) Under thick moss, permafrost is commonly within 2 feet of the surface and locally is within 1 foot. (2) Under open stands of white spruce and brush composed predominantly of alder, dwarf birch (*Betula glandulosa* and hybrids), and willows, permafrost generally lies 5–20 feet below the surface. Most moraine hillocks, most mountain slopes in the gorge between McKinley Park station and Healy, and much of the country south of McKinley Park station is characterized by this vegetation. (3) Under slopes of bare gravel, coarse talus, and bedrock, permafrost, if present, probably lies more than 20 feet below the surface.

Perennial ice occurs as thin films or fillings in joints, cracks, and large pores in consolidated rocks of the Birch Creek schist, Totatlanika schist, and Cantwell formation. Deposits of coarse gravel may be undersaturated (contain less volume of ice than pore space); or, depending on drainage conditions, may be saturated (contain enough ice to fill all pores); or, locally, may be supersaturated (contain more than enough ice to fill all pores). When supersaturated gravel freezes, ice that forms expands the rock and separates the constituent particles. As a result, the particles are embedded in a continuous body of ice.

In poorly consolidated deposits of sand, silt, and clay, perennial ice occurs as cement, interstitial filling, and clear lenses, veins, and irregular bodies which range widely in size. In permafrost most fine-grained materials near the surface are saturated or supersaturated. Ice in clay, exposed in 1948, at the bridge at mile 351.4 on the railroad, was in vertical veinlets $\frac{1}{4}$–$\frac{1}{2}$-inch thick and 1–3 inches apart, oriented about normal to the direction of slope. Lenses and irregular bodies of clear ice as much as 1 foot in width were common (see fig. 45). The clay was supersaturated. At Moody lenses of clear ice more than 1 foot thick in clay were exposed in 1949.

Contorted bedding in the lower part of silt deposits on the terraces in the Nenana River gorge suggests that permafrost was formerly present within and beneath the silts.

Because of expansion of the interstitial water on freezing in unconsolidated materials or poorly consolidated rocks, the component grains are commonly pried apart; they are then held together only by the ice. When the ice melts, cohesion is lost, and the material slumps. If the upper surface of the underlying material is still frozen, movement takes place with ease. Slumps, earthflows, and other landslides can result. When supersaturated silt and clay have thawed, they tend to flow downslope under the influence of gravity and laterally or vertically from under the foundations of heavy structures.

The permafrost is in delicate equilibrium with its surroundings, and any disturbance of the surface during construction affects that equilibrium, generally resulting in the melting of at least the upper part of the permafrost. The thawing of permafrost of fine-grained materials results in the settling of foundations and in landsliding. Subsequent refreezing, if it should take place, produces heaving. Permafrost in the Nenana River gorge is now thawing where vegetation has been removed or destroyed by fire, where excavations have been made, where the Nenana River and its tributaries erode laterally into banks, and where the movement of surface and ground water, formerly in equilibrium with permafrost, has been altered. On the other hand, some fills in shaded areas along the track have become perennially frozen in the last 20 years.

RAILROAD-TRACK PROBLEMS

The maintenance problems encountered by the Alaska Railroad between Windy and Healy are largely the result of slumps and earthflows, rockslides and rockfalls, frost heaving and settling, and icings. The slumps and earthflows have been the most costly in both time and money.

SLUMPS AND EARTHFLOWS

The slumps and earthflows along the Alaska Railroad are the result of sliding movement of unconsolidated or poorly consolidated debris on the steep walls of the canyon of the Nenana River. The sliding planes of the slumps are commonly several tens or a few hundred feet below the surface of the ground; at their lower ends, the slumps merge into earthflows, the debris of which moves forward with a viscous fluid motion; some earthflows move large blocks of earth. Topographically, a typical slump or earthflow is marked by a niche in the canyon wall several tens or a few hundred feet above the river, and below the niche, by an outward bulge of the canyon wall toward the river. The niche is bounded by a headwall scarp. The surface of a slump, in addition to having the general form described above, commonly has many straight or arcuate ridges or steps parallel to the contour lines. An earthflow, on the other hand, has an irregular hummocky surface.

The slumps and earthflows along the Nenana River range in width from a few feet to one mile. Those which are giving the Alaska Railroad the most trouble range from 150–3,000 feet in width and 400–2,000 feet in downslope length. The ridges on them are 200–500 feet long. The largest slump along the railroad is at Moody; it extends for about three-quarters of a mile along the track from Sheep Creek almost to the Moody tunnel (pl. 10). The slump at mile 351.4, on the other hand, was only 150 feet wide and 350 feet long when it started in 1947; it is now about 350 feet wide (fig. 41).

Slumping disrupts and deforms the structure of the rock. Flat-lying beds are broken into blocks by a series of gently dipping normal faults, which are the slump planes. The beds are rotated during downslope movement so that they dip back into the hillside. The ridges and steps on the surface of a slump are nothing more than the upturned edges of these rotated slump blocks. The cross section of the landslide at mile 346.3, shown on figure 35, illustrates the manner in which the blocks are rotated backward.

Vegetation provides a striking indicator to the presence of slumps. Commonly trees on slump areas are tilted or overthrown, and the mat of vegetation covering the surface is torn and disrupted. Most spruce trees on active slumps and earthflows are inclined upslope, but some are inclined in other directions. The trunks of many spruce trees on old landslides are bent or bowed, conditions resulting from the landsliding, which tilted the trees when they were young. Following the landsliding, the tops of the trees continued to grow vertically, although the trunk remained tilted. The bends, therefore, result from periods of relatively rapid movement, and the straight portions from periods of relative stability. The time elapsed since the period of bending can be determined by study of the tree rings (Wallace, 1948, p. 178–179).

The slumps which are now active move at a rate ranging from a few feet per year to as much as a few feet per hour. Most of the slumps move very slowly for years, but this slow motion may be interrupted by periods of very rapid motion. Judging from the record of train delays cause by slumping, the most rapid motion occurs in late summer and fall, either following heavy cyclonic rainstorms or during freeze-up. The movement at the head of the slump is commonly directly downward; in the middle and toward the toe of the slump, the movement is outward toward the river as well as downward. The lower parts of some slumps are frequently seamed by a network of gaping tension cracks, caused by the flow of material at depth and under great pressure into the lower part of the slump. Minor movement may occur along these cracks when the lower part of the slump is subjected to river erosion.

As the topography and the disturbed vegetation indicate, slumping and earthflow are not new to this area. Rather, they are normal components of the process of erosion. Between miles 349.0 and 349.6, 350.0 and 350.2, at Moody (from miles 353.0 to 353.5), and at other places the railroad was constructed on existing slumps and earthflows.

The slumps and earthflows affect the railroad in several ways. Generally, the railroad crosses the middle or upper parts of the slumps. Nearly every active slump crossed by the railroad was in existence at the time the railroad was built; some were probably active at the time of construction. Where the railroad crosses the top of the slump, as from mile 349.1 to mile 349.6 (figs. 37, 38 and 39), the movement of the track is directly downward, relatively little lateral motion occurring. The depressed trackbed, locally called a sinkhole, must be continually filled. On the other hand, where the railroad crosses the lower part of a large slide, as at Moody (pl. 10, and figs. 47–50), the track is moved sideways toward the river, resulting in a series of kinks in the track, locally called doglegs. Most of the slumps produce both "sinkholes" and "doglegs." Where movement is slow, amounting to no more than a few feet a year, the slumps do not disrupt traffic; track disalinement is corrected by tamping dirt beneath the ties and straightening the track. On the other hand, sudden rapid movements of a few feet per day or hour leave the track without support or produce dangerous sags and kinks; these conditions have caused the derailment of railroad cars. A few earthflows of low viscosity lie on slopes below the railroad track; an example is the earthflow at the north end of the Moody landslide (fig. 47). These enlarge headward slowly, some of them undermining the track.

Causes.—The force that moves the slumps and earthflows as well as other landslides is the component in the direction of movement of the weight of the mass moved. In order for this force to be effective, however, a slope must exist along which movement can take place. Furthermore, this slope must be of such steepness that the component of gravitational force directed along the sliding plane is greater than the force of frictional resistance across the plane. If this slope is not steep enough, landsliding will not take place unless the frictional resistance to movement of the mass is reduced by other factors to a magnitude less than that of the component of gravitational force directed along the slope. Thus, although gravity is the force that moves slumps and earthflows, other factors (such as changes in moisture, structure, gradient) must be present to induce the movements.

The primary cause of slumps and earthflows along the railroad is the lateral erosion and downcutting of the Nenana River, which undermines and steepens the canyon walls. Steep slopes, even vertical or overhanging cliffs, can persist almost indefinitely in well-consolidated and crystalline rocks; but in the unconsolidated glacial deposits and in poorly consolidated material of the Tertiary rocks and weathered or pyritized schist, relatively gentle slopes are unstable, particularly when the underlying material is saturated with water. The ancient slump at mile 346.3 is in the cutbank of a prominent meander on the Nenana River, where the swift current had undermined the bank (pl. 3 and fig. 35). The weight of the overlying gravel caused movement to take place along planes within the clay-rich till at the base of the bluff. The slump is now apparantly stable, and the place at which the current impinges on the bank has moved some distance downstream, so that the danger to the railroad from this landslide has temporarily been averted. The headwall of the slump is only 50 feet from the railroad, however, and renewed activity of this slump would probably affect the railroad. Other landslides occasioned in large part by steepening the river banks as a result of lateral erosion have occurred between mile

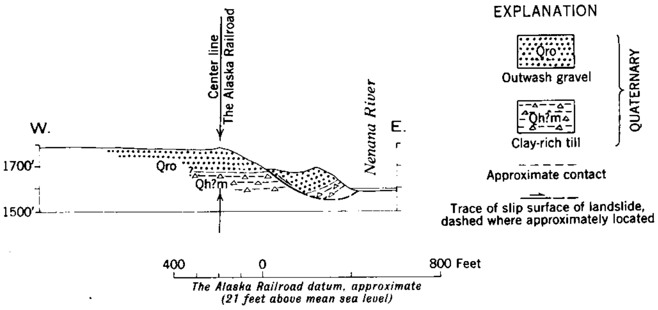

FIGURE 35.—Geologic cross section of landslide at mile 346.3, the Alaska Railroad.

349.2 and mile 349.6, (fig. 37), and at mile 356.2 and mile 357.5. All of these landslides are at the concave sides of sharp meanders in the river.

Most of the slopes in glacial-lake silt and clay, and in till, would be sliding today if it were not for the fact that much of the clay and till is perennially frozen. Ancient landslides became stabilized when permafrost formed in the sliding material, and they remained stablized as long as the permafrost was present. For instance, excavations for the south abutment of the bridge at mile 351.4, in 1948, disclosed step faults caused by ancient landslides, which are now in perennially frozen clay. The clay has remained frozen and had not moved since the railroad was constructed. At the north end of the same bridge the railroad crosses the top of an ancient landslide in clay which is now perennially frozen and stable. As long as permafrost is present the banks tend to remain stable, even in silt and clay. The melting of permafrost does two things: it destroys the bonding force of ice crystals that hold the mass of clay together, and it releases a large quantity of water which acts as a lubricant to the slide. The water has an additional effect. The pressure of the water in the pores of the rock, called pore-water pressure (Terzaghi, 1950, p. 92–93), tends to float the overlying rock. Thus the frictional resistance to landsliding, which results from the pressure of the overlying rock against the slipping surfaces, is reduced, while the component of that weight, which is directed down the slope, remains the same. Hence landslides are caused also by the increase in pore-water pressure.

Permafrost has been shown to be in very delicate equilibrium with its surroundings. One of the most important elements of the surroundings is the cover of vegetation. Along much of the railroad the cover of vegetation has been destroyed or damaged by railroad excavations and by fire. These conditions have resulted in extensive thawing of permafrost, one of the major causes of landslides in clay-rich rocks. The landslide between mile 349.2 and mile 349.6 appears to owe much of its recent activity to destruction of permafrost, for a forest of mature spruce growing on it indicates that it had been stable for a long period. Likewise, the recent landsliding at mile 351.4 and much of the landsliding at Moody (mile 353) appear to have occurred on water-saturated planes at the top of or deep within melting permafrost.

Between mile 350.6 and mile 350.9 (pl. 2) the track is laid across large talus cones of weathered schist which occupy shallow gullies between narrow sloping spurs of weathered and broken schist. The talus cones are completely covered with dense thickets of alders and willows. When the railroad was constructed the brush was not damaged, and the slope remained stable. In 1948 a new telephone line was erected a few hundred feet above the track, and a tractor trail was bulldozed along the telephone line. Slumping and sliding of surficial material onto the track soon followed. Locally, the track itself has settled. The greatest movement occurred where the largest amount of vegetation had been destroyed.

Saturation of poorly consolidated materials by melt water in the spring and by heavy rains in the summer and fall also contribute to landslide activity. The addition of water to the clay and clay-rich till lubricates and increases the weight of the material and decreases frictional resistance by buoying up the overlying rock. Cracks in the material divert the melt water and rainfall runoff to the sliding planes, where water is most effective in causing landslides.

Another factor in landslide movement is overloading of the upper part of an unstable mass with debris. The slump area at the north end of the Garner tunnel (mile 356.2, fig. 51) is in a large talus cone, which is being fed with debris from crumbling cliffs along the mountain north of the railroad. The weight of this debris causes the mass of talus to move slowly downward and outward toward the river, carrying the railroad track with it.

Overloading of unstable masses can also be done artificially. At some places along the railroad, debris which accumulated in ditches along the uphill side of the track was removed and dumped across the track, or, in an effort to move the track back into the hill from a dangerous landslide, the debris excavated from the uphill side of the track was dumped on top of the landslide. The enlargement of the landslide at mile 351.4 during the summer of 1948 was caused by such overloading.

A special set of circumstances has caused landslides in several places in the gorge where normally they would not be expected. For about a quarter of a mile north and south of mile 350.0 and from miles 353.5 to 356 the river flows in a narrow gorge cut in Birch Creek schist. The west wall of this gorge is a narrow septum of schist, in places less than 1,000 feet wide at the base, west of which lie glacial-lake clay and silt that fill an ancient glacial valley of the Nenana River. Where the lateral erosion of the river has breached the septum of schist, the clay, unstable on the steep slopes of the narrow canyon, slumps and flows toward the river. One such landslide is beginning at mile 349.95 (fig. 35), and another is expected to move toward the track at mile 354.5 (pl. 2). Similar conditions have caused the large landslide at mile 357.5 (pl. 2 and figs. 54–56), where the river, eroding the outer bank of a large meander, has approached the contact between the Birch Creek schist and the coal-bearing formation, and has breached the zone of weathered schist below this contact. As a result, the great weight of terrace gravel at the top of the bluff has forced the poorly consolidated and deeply weathered schist to flow outward toward the river. Erosion by the river has not contributed to the movement of this landslide since the railroad was built, for cribbing at the riverbank in the center of the slide is undisturbed.

Possible remedial measures.—Measures that are adopted to arrest landslide movement should control one or more of the factors which facilitate that movement. As was pointed out in the discussion of slumps and earthflows, these factors are: (1) lateral erosion of the Nenana River; (2) steepness of slopes; (3) melting of permafrost; (4) presence of water in sliding areas; (5) incompetent nature of the sliding material; and (6) overloading of the upper parts of the landslides. Consideration should be given to the possibility of avoiding the landslides altogether, by placing the railroad, highway, or other structure where landslide danger does not exist.

Some of these factors cannot be controlled artificially and some can be controlled only at great expense. For example, it probably is impractical to reduce the slopes of the Nenana gorge to gradients of 10° or less, merely to control the landslides. Moving the track between mile 349 and mile 358 to the east side of the Nenana River in order to avoid the slides in that area would be very expensive and would involve crossing at least one currently inactive slide on the east side of the river. Relocation of the roadbed either above or below its present position on the west side would not avoid the slide areas, as some slides now affect mountain slopes from river level to a height of 900 feet. However, relocation of the track away from sliding material and on bedrock or gravel, as was done at mile 348.6 and from mile 352.7 to mile 353.0 is feasible locally and probably is more economical than are methods of control of the slumps and earthflows.

The lateral erosion of the Nenana River between mile 349.2 and mile 349.6 and at other places where it is a factor in slumping and earthflow can be controlled by placing riprap along the river bank. Riprap of shaped blocks of conglomerate obtained from a quarry in talus from the Cantwell formation at mile 331 was placed along the river bank beneath the north end of the Garner tunnel at mile 356.2 Although it receives the full force of the river at a sharp bend of more than 90°, it has not moved since it was installed in 1920. At many of the landslides, however, the lateral erosion of the river is not now a factor. At mile 356.2 and at mile 357.5, for instance, riprap or cribbing at the base of the slide has not been disturbed by the river, yet the sliding continues. The initial rupture of the landslide at mile 351.4 was halfway up the slope. Although control of the river will stop the movement of some of the slides, it will not stop the movement of others.

The major factor in slumping and earthflow is water, derived from runoff, rainfall or the melting of permafrost. The amount of surface water reaching the slide can be greatly reduced by constructing channels, flumes, and galleries that conduct the water directly to the river. Willows, cottonwoods and other such plants which consume large amounts of ground water, if planted on the surface of the slide and of the surrounding area, will keep much of the rainwater and melt water from reaching the sliding surfaces. Plants are useful in controlling landslides in two other ways: their mat of roots binds together the soil at the surface, and their vegetation provides an insulating cover through which the outflow of heat during winter is greater than the inflow of heat during summer; ice, being a better conductor of heat than water, the frozen vegetation of winter conducts heat outward from the ground more rapidly than the wet vegetation of summer conducts it inward (Muller, 1947, p. 53). Hence plants protect permafrost where it exists and promote its development where it does not exist.

If the surface drainage across landslides cannot be effectively controlled, it may be advisable to freeze the slides; in other words, to create artificial permafrost. Permafrost can probably be induced locally by reducing the amount of ground-water infiltration, by encouraging or planting vegetation, by removing snow in early winter, or by covering the surface of the slide with coarse gravel. At Fairbanks, permafrost has formed recently in coarse-grained drag-line tailings, and on slip-off slopes of rivers (Péwé, oral communication, March 9, 1952).

Where permafrost has largely been destroyed in some of the slumps and earthflows that are entirely in clay, it probably will be necessary to refreeze parts of the clay artificially to stop movement. Rapid movements which occur on the upper surface of permafrost (that is, the surface between the perennially frozen ground and the thawed ground, or the surface zone of annual freezing and thawing) could be eliminated by freezing the sliding material permanently, that is, by raising the top of the permafrost to within 1 or 2 feet of the surface. On the other hand, sliding that is taking place on planes within or beneath the permafrost cannot be stopped in this way. In such places it may be necessary to drill holes through the frozen sediments and to drive well points into the underlying clay for the circulation of refrigerants beneath the permafrost. The base of the permafrost can then be frozen to a depth well below the base level of the slides or frozen so irregularly that sliding is impossible. If refrigeration is done in winter, the refrigerant (for example, kerosene, diesel oil, or an aqueous solution) could be cooled in surface radiators and circulated during periods of subfreezing weather; the need for expensive cooling equipment would thus be eliminated. Portable pumping units could service several areas. Freezing would have two favorable effects: it would fix the water that is now providing both the lubricant and the buoyant pressure that induce the slumps and earthflows; and it would change poorly consolidated, unstable claystone into claystone that is well cemented by ice. Thus, as a result of freezing, material that is now slumping would be able to stand indefinitely at angles considerably greater than the angle of repose of loose debris.

Some of the techniques used at Grand Coulee dam and described by Gordon (1937) could be adopted. Presumably well points for the refrigerants would be driven in late fall at wider spacing than was used at Grand Coulee dam. A rule of thumb for spacing well points could probably be based on the depth of seasonal freezing. Like natural seasonal freezing, refrigeration by this technique is effected by conduction only, assuming that no flowing water is present in the formation. If the distances between well points are appropriately chosen, it should be possible to freeze most of the landslide in a single season. The successful application of a rule of thumb based on the depth of seasonal freezing requires that the material which is to be frozen be homogeneous. Where the material varies with depth, either in thermal conductivity or in water content, marked differences in the rate of heat flow and freezing can be expected. Therefore, in order to space the holes properly, the moisture content would have to be determined, probably by test drilling. Once the well points were installed and the landslide area frozen, little expense would be incurred in circulating a refrigerant for a short time each winter and thereby maintaining permafrost.

The mathematics involved in relating the linear conduction of heat in a semi-infinite solid (the type of heat flow involved in natural seasonal freezing) to conduction along radii of a cylinder (the type of heat-flow involved in the use of well points) is beyond the scope of this paper.

Rathjens (1951, p. 41) has described a similar method that maintained the heat balance of permafrost in the material on which an oil derrick rested, even though the temperature of drilling mud in the well was 110° F. The temperature at which the slide material freezes will be lower than that at which water freezes, and the temperature at which the clay freezes may be several degrees lower (Johnson, 1952, p. 9–13). The bearing strength of the frozen sediments varies markedly according to the temperature, moisture content, and other factors (Kersten, 1951; Muller, 1947, p. 24–45), but it is sufficient to produce good foundations for the track.

Electro-osmotic and vacuum techniques, described by Terzhaghi and Peck (1948, p. 337–340), also tend to dry out and strengthen the material of the landslides.

The fifth factor, overloading of the upper parts of the landslides, can, of course, be effectively controlled where the overloading has been done artificially. Waste should be dumped only where the debris will not affect the stability of the slopes. Overloading of landslides due to the natural accumulation of debris is difficult and perhaps impossible to control.

ROCKSLIDES AND ROCKFALLS

Several rockslides and rockfalls occur in Birch Creek schist in the Nenana River gorge between McKinley Park station and Healy. Where rockfalls occur, foliation in the schist commonly dips toward the gorge or fold axes plunge toward the river. Along these planes and lines of weakness the schist is attacked quickly by frost action and by chemical weathering. Blocks of schist are worked loose and slide outward toward the river along the foliation or fold axes. During fall freezeup and periods of heavy rain during the spring and summer, the surface layers of entire mountains may creep or slide downslope. Such movement is taking place on the slope west of mile 353. At other places many tons of rubble have cascaded onto the tracks from the steeper rock walls. Such rockslides and rockfalls are of frequent occurrence on steep, blocky bedrock slopes at many places in the world (Sharpe, 1939). Permafrost is not generally a factor.

Suggestions for control.—Probably the most economical and practicable method of controlling rockslides and rockfalls along railroads is to remove the material threatening to fall on the track. In places, however, tunnels or protective sheds probably can be installed at less expense than the cost of removing potential rockslides and rockfalls. Ditches along the track should be widened and deepened to intercept as much debris as possible.

FROST HEAVING AND SETTLING

Heaving of the roadbed in winter is caused by growth of seasonal ice in fine-grained material at the bottom of or underlying the ballast, and settling in the spring is caused by thaw of the ice. Movements generally are less than an inch. Locally, however, hydrostatic pressure may cause larger movements. Heaving and settling have caused fewer traffic delays than landslides, but they have necessitated considerable maintenance. "Pumping" of fine-grained ballast from under the ties has been the major factor contributing to an overall settling of the rails of as much as a foot or more in some places. Where differential heaving or settling of the track is occurring, trains must reduce their speeds.

Locally, permafrost provides an impervious zone that prevents normal ground-water drainage and consequently promotes frost heaving and settling. In most places along the railroad, however, the depth to permafrost is so great that its effect on seasonal frost heaving is negligible. Hence, the problems generally are similar to those that exist elsewhere in north temperate zones.

Suggestions for control.—Methods of control of seasonal heaving and settling in the Nenana gorge are suggested in order of general preference, as follows: (1) Improvement of drainage by digging deeper ditches and building additional culverts, (2) use of chemical stabilizers and waterproofing agents to reduce capillary action and prevent seasonal freezing from drawing water into the subgrade of the track, and (3) replacement of the present ballast with nonheaving coarse-grained ballast.

ICINGS BETWEEN CARLO AND HEALY

Icings are deposits of seasonal ice on slopes or river flood plains. They are formed when water derived from surface and subsurface sources freezes [4] (Eager and Pryor, 1954; Muller, 1947, p. 76–82; and Taber, 1943b, p. 250). In Alaska they are called "glaciers." The only icings examined by the authors were along the railroad between Carlo and Healy. They were seen during periods of relative inactivity and were not studied in detail.

[4] Ghiglione, A. F., 1951, Problems of icing on roads and airfields: Paper presented before Am. Soc. Civil Eng., Oct. 23, 1951.

Along the railroad, icings are common in three sets of geologic and topographic conditions. The first set of conditions involves the presence of thick layers of coarse pervious gravel. Icings form where water emerges at the base of the gravel. The second set of conditions involves shallow depressions that drain extensive swampy areas or slopes of muskeg. The railroad crosses these depressions on fills through which water is normally conducted by culverts. In winter, ice forming in the culverts impedes and finally blocks the flow of water. The third set of conditions involves muskeg on open hillsides. Water trickles through the vegetation of the muskeg without forming distinct channels or watercourses. Where the railroad crosses such sloping muskeg, the water is collected in ditches on the uphill side of the track and is conducted to the downhill side through culverts. In winter, ice accumulates in the culverts and ditches. This ice is fed by water trickling through the muskeg—water that is kept above the freezing temperature by the insulating effect of the saturated vegetation. In all three of these sets of conditions the water in the pools and slow-moving streams freezes to its bed—that is, from the bottom up rather than from the top down. By this process accumulations of ice several feet thick may form for distances of a few hundred feet uphill from the railroad. In a few places the track may be covered by ice a few feet deep. Where this occurs, ice must be chipped from the track continuously during part of the winter in order to keep traffic moving.

Suggestions for control.—Many methods for control of icings have been developed over the years in Alaska and Siberia [5] (Eager and Pryor, 1945; and Muller, 1947, p. 109–123). Each icing presents individual problems depending on local conditions, and no one method is always best. However, in the Nenana River gorge south of Healy most icings along the railroad probably could be eliminated by deepening and protecting existing culverts where icings occur, and by putting in other culverts where the drainage is impeded. Slopes are adequate for good drainage, and runoff need be protected from freezing only long enough to get it across the track.

At Ferry (see pl. 5) a serious icing on the railroad has been successfully controlled at little cost through the use of a boiler; the boiler is connected to a steam pipe, which passes through the culvert. The boiler has to be operated only a few times each winter to keep the culvert open. (T. L. Péwé, oral communication, 1954.)

[5] Ghiglione, A. F., 1951, ibid.

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INDIVIDUAL LANDSLIDES BETWEEN MILES 349.1 AND 350.3

The landslides described in the following sections have been studied in comparative detail. They serve as examples of the slumps, earthflows, rockslides, and rockfalls which have hindered the operation of the railroad and which are common throughout this part of Alaksa. The remedial measures which the authors believe would successfully control each landslide are described. Remedial measures which have been tried or suggested, but which the authors believe will not permanently control the landslides, and the reasons for such belief, are also described.

Between mile 349.1 and mile 350.3 a bench about 250 feet high projects from the west wall of the Nenana River gorge and reduces the flood plain of the river from its normal width of about three-eighths of a mile to a width of about 250 feet (fig. 36). This bench is half a mile long and is semicircular in groundplan. Its upper surface slopes 7°–10° toward the river. The railroad, which is nearly 200 feet above the river and about 50–100 feet below the brow of the bench, follows the west wall of the inner gorge made by this bench and describes an arc about half a mile across at the base, convex toward the east (fig. 36). Throughout this great curve, from the bridge at mile 349.1 to the bridge at mile 350.3, the railroad has been subject to landslides since it was first constructed.

Geology.—This bench preserves a short segment of the ancient, clay-filled glacial gorge of the Nenana River. Along the south side of the bench, from mile 349.1 to mile 349.5, and on the north side, from mile 350.0 to mile 350.2, glacial-lake clay and silt are exposed on the canyon wall from river level to about the level of the railroad track. The clay and silt are soft and plastic when wet and absorb a large amount of water. Samples 1, 2, 3, and 6 (figs. 32 and 33) are of typical mixtures of the clay and silt. In the walls of the tributary canyon at mile 350.3, the clay and silt interfinger with delta gravel dipping about 20° toward the river, and presumably the northwest part of the bench is underlain by a buried delta built by this tributary into the lake. Elsewhere, however, sand and gravel are minor constituents of the lake sediments. Along the east side of the bench the clay is separated from the river by a septum of Birch Creek schist about 300 feet wide at the top and probably no more than 700 feet wide at the base.

The clay is overlain by a layer of blue-gray outwash gravel that was deposited by the Nenana River when the ice front stood at Riley Creek, about 2 miles south of this bench. The gravel is well exposed in the railroad cut on the south side of the bench, and also in

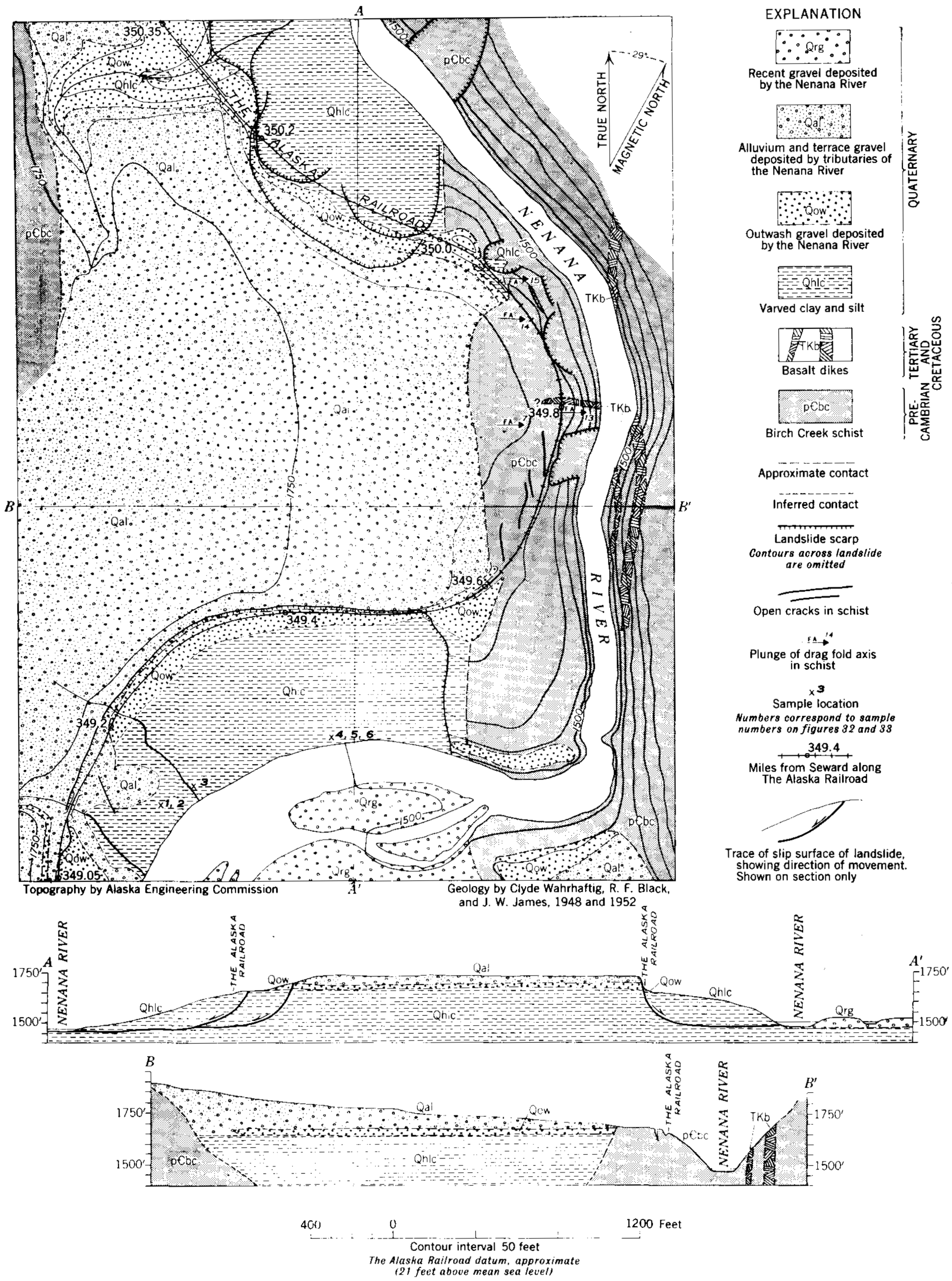

FIGURE 36.—Geologic map and cross sections of landslides between mile 349.1 and mile 350.3, the Alaska Railroad.

the railroad cut just south of the bridge at mile 350.3, where it rests on the delta gravel. Many springs emerge from the hillside along the contact of the permeable outwash gravel and the underlying impervious glacial-lake sediments. Resting on top of the outwash gravel is a deposit of yellowish-brown gravel deposited as an alluvial fan by a tributary stream from the west—the stream which now passes beneath the bridge at mile 350.3. About two-thirds of this gravel consists of fragments of Birch Creek schist and one-third of silty mud. In many places it absorbs much water and becomes plastic or fluid. Along the contact between the yellowish-brown alluvial gravel and the blue-gray outwash gravel, the latter is partly cemented with calcite to a thickness of 1–4 feet, particularly along the south side of the bench. This hard, calcite-cemented layer of gravel is very difficult to excavate.

The septum of Birch Creek schist along the east side of the bench is broken by north-trending vertical joints. Some of the north-trending joints and one east-trending joint are filled with basalt dikes, 10–50 feet thick. The dikes are slightly altered along their borders, and the schist near the dikes is pyritized and when weathered is easily eroded. Fold axes and crenulations in the foliation of the septum of Birch Creek schist plunge eastward toward the river at angles of 7–15°.

The gorge east of the bench is probably less than 10,000 years old, and its walls have not yet stabilized. The west wall is slowly crumbling into the river, and eventually the septum of schist will be destroyed and the west bank of the river will consist largely of clay. The schist septum has already been breached at its north end, near mile 349.95.

The construction of the alluvial cone on the outwash gravel by the tributary from the west was the cause of the diversion of the river and of the preservation of the glacial-lake sediments. The building of the cone forced the river to the east side of the glacial gorge. As conditions of aggradation were succeeded by conditions of degradation, the river carved a channel in the schist that makes up the east wall of the gorge. The course of this superposed gorge was controlled partly by the presence of basalt dikes, which provided zones of altered rock along which the river could erode easily.

These geologic conditions have led to the extensive landslides along this segment of the track. Landslides occur wherever the bank of the gorge is formed by silt and clay. Indeed, it is likely that slump and earthflow is the normal manner of erosion of the glacial-lake sediments, and the manner by which they have always been delivered to the Nenana River. Along the east bank of the bench, where the bench faces the narrow gorge, the crumbling walls of the gorge are producing dangerous rockfall conditions.

BETWEEN MILES 349.1 AND 349.6

The exposure of glacial-lake clay on the wall of the canyon between mile 349.1 and mile 349.6 is marked by a large slump, which was in existence long before the railroad was built. The railroad was constructed across the upper part of this slump (fig. 37). Evidence of movement several decades ago is indicated by abrupt bends in the trunks of spruce trees below the railroad track. Most trees are tilted 5°–10° or more toward the hill—an indication that individual slumps have rotated backward.

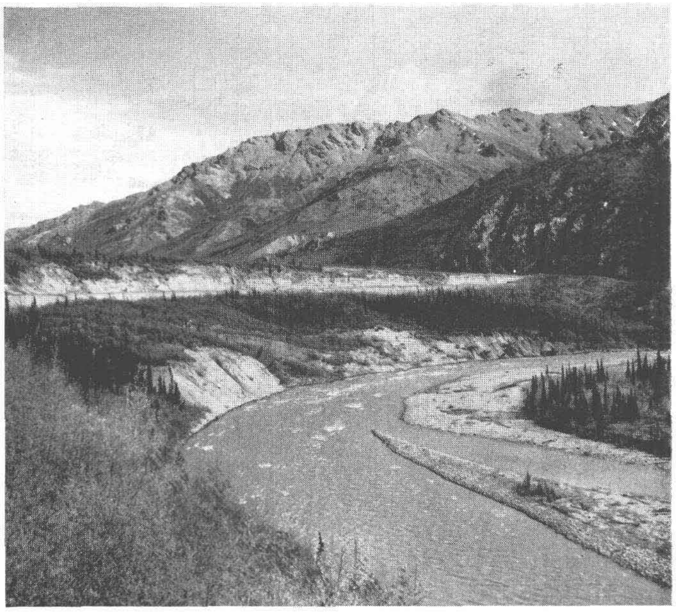

FIGURE 37.—View northward from mile 348.8 on the Alaska Railroad, showing the landslide between mile 349.1 and 349.6, June 17, 1952.

The railroad began to sink across the slump a few years after construction. Additional fill beneath the track was required almost every year to maintain a reasonable grade across the slump. By 1945 the track was sinking so rapidly that it was difficult to maintain the grade, and a new grade was cut on the uphill side of the track. Before the railroad could be realigned, however, great crescentic cracks opened in the new cut, and the south side of the cut began to sink (fig. 38). By 1947 the track bed had dropped as much as 6 feet along some of the new cracks, and it was becoming increasingly difficult to keep traffic moving across what had now become a very steep dip or "sinkhole". In the summer of 1948 when the track was 15–20 feet below the original grade it was again moved, this time to a position 75 feet north. Shortly after the realignment was completed, fresh cracks appeared along the foot of the slope above the grade between mile 349.30 and mile 349.45. Between mile 349.45 and mile 349.60 these cracks passed into the middle of the grade and for a short distance ran between the rails. In 1949 and 1950 the track was again moved northward into the hill. However, by 1952 the new track had been raised as much as 2 feet across several local "sinkholes" (fig. 39) in order to maintain the grade and was still sinking. Debris from the new cut was spread out south of the track.

FIGURE 38.—View westward from mile 349.5 on the Alaska Railroad, showing a landslide scarp in an excavation for a new railroad track, November 3, 1947. The track at the left was abandoned in 1949.

FIGURE 39.—Passenger train crossing "sinkhole" in track at mile 349.5 on the Alaska Railroad, June 17, 1952. An abandoned grade line is on the left. The cross marks the place from which the photograph shown as figure 38 was taken.

In 1950 piles were driven along the downhill side of part of the track at the east end of the slide in an attempt to arrest the sinking of the railroad. They were reported to have penetrated easily their full length of 35 feet. By June 1952, these piles and the debris in which they were located had sunk as much as 6 feet, with no appreciable tilting.

In June 1952, crescentic cracks that mark the headwalls of coalescing slumps were traceable about 20–50 feet north of the track between mile 349.1 and mile 349.6. In some places the cracks appeared in the ditches adjacent to the track, but in most places they were part way up the embankment to the north. Most of the cracks were fresh, which indicates that movement took place during the spring of 1952; a few appeared to have formed during the preceding fall. Movement along the newest cracks amounted to only a few inches; however, fresh cracks and slump headwalls as much as 6 feet high were seen in the woods below the track at mile 349.2 and mile 349.3. In 1948 this forest had been undisturbed, but later, surface runoff from north of the track was diverted into the area. In June 1952 most of the water disappeared into cracks at the head of a slump on the north side of the track at mile 349.25. The remainder was conveyed by a short culvert under the track and disappeared into the cracks in the forest immediately below the fill.

It seems reasonably certain that surface water entering the ground at the track has melted the permafrost completely under parts of the landslide. The present extent of permafrost is not known. Presumably permafrost formerly underlay the entire area, but probably is now patchy and underlies only a part of the forest at shallow depth. After breaching the protective body of permafrost the water developed sufficiently high pore-water pressure to cause the glacial lake sediments along the river to bulge and flow outward under hydrostatic pressure. The overlying gravels and isolated patches of permafrost are also sliding outward and downward over the plastic mass. Deep slumps are developing headward from the thawed area as the Nenana River removes the toe of the landslide. The vertical headwalls and predominately vertical movements at the head of the slide indicate that the base of the slide is near river level.

It is clear that the sinking of the track at this point has not been controlled by realinement. Moving the track farther into the hillside would increase the curvature of the track, which is already excessive, and would not solve the problem. Stabilization of the track in this area probably will be difficult to accomplish, but bypassing the landslide will be more difficult. A cut through the bench from mile 349.0 to mile 350.3 would be more than 100 feet deep and half a mile long. The grade would be increased from its present average of about 0.8 percent to about 1.3 percent. Slumps and earthflows probably would be a common occurrence along the walls of the cut, as natural slopes in the lake sediments are generally stable only if they are of less than 10°.

Piles, to be effective in holding up the track, would have to be about 200 feet long and capable of with-holding tremendous shearing pressures. Shorter piles would rest in the slide material. A retaining wall at the toe of the slide would have inadequate foundations to withstand the lateral thrust. Thus, stabilization appears to be the most satisfactory method of arresting movement. The most immediate and economical step in stabilization is to conduct surface water in waterproof culverts completely across the area of the slide and into the Nenana River. Culverts which do not conduct the water directly to the Nenana River, but which lead it only to a lower part of the landslide, are likely to do more harm than good. Where the infiltration of surface water cannot be stopped, a second step can be taken to control the landslide—the establishment of well points, tunnels, and galleries to drain ground water from within the slide, and of lined culverts to conduct it directly to the river. If these relatively inexpensive drainage methods fail to arrest the slumping, consideration should be given to artificial refreezing of the slides. A program of artificial refreezing, to be effective, must serve to create an irregular contact between frozen and unfrozen ground, thus eliminating the smooth sliding surfaces which probably exist at present beneath this landslide. This objective could best be achieved by distributing refrigerants from well points. Most of the well points probably could be driven, but some would have to be placed in drilled holes. If surface water were prevented from entering the ground, the creation of frozen columns of clay spaced 50 feet apart might, by the withdrawal of water from the surrounding clay to form ice veinlets in the columns, lower the ground-water table to below the critical level. Vegetation should be planted on bare areas in order to protect the natural permafrost. Once movements have been retarded, riprap should be used along the toe of the slide to prevent further lateral cutting by the Nenana River and subsequent steepening of the slope.

BETWEEN MILES 349.7 AND 349.8

The west wall of the gorge, between the river and the railroad (fig. 36), has been retreating westward for the last two decades. Large blocks of schist have separated from the wall along north-trending vertical joints and have moved outward toward the river along crenulations and drag folds in the schist which plunge eastward 5°–15°. Rockfalls and rockslides have been the result of this movement.

The westward retreat of the canyon wall is now endangering the railroad. Several pits, 7–20 feet east of the track, lie along a northward-trending vertical joint that has widened considerably since 1948. The pit nearest the track began to open in 1948, and in 1952 it was at least 20 feet deep and 2–3 feet wide. Four northward-trending trenches on the west side of the track also mark open joints in the Birch Creek schist. These trenches are 150–200 feet long, 1–10 feet deep and 1–10 feet wide. They are partly filled with loess to a depth of 4 feet, contain numerous ponds, and in places are overgrown with willows and alders.

AT MILE 349.95

At mile 349.95 about 100 feet of the track rests on clay and silt where landsliding into the gorge has breached a protective wall of schist (see fig. 36). The thickness of fine-grained sediments that lie directly under the track is not known but may be as much as 100 feet. Clay and silt from the high bench southwest of the track are moving slowly northeastward into the gorge through the narrow gap. Movement is most rapid at depth. On November 2, 1947, the headwall crack of a slump, 1 inch wide and about 100 feet long, was 4 feet from the track. In June 1952, the slump was only 1 foot from the track. Activity seems to have been slight, but a "sinkhole" has formed in the track bed.

The culvert that drains the ditch on the southwest side of the track is not deep enough to carry off all the water that accumulates in the ditch. Water is conveyed in the culvert only one-quarter of the way down the slope. Below the end of the culvert it is allowed to sink into the slide area. Continued slow settling is to be expected until the clay is dried out. Complete diversion of surface water is necessary for stabilization. As long as surface water is allowed to seep into the slump, realinement of the track will only postpone further movement of the track. If present movement of the slump is allowed to continue for several years, bridging or artificial freezing may be required to save the track.

BETWEEN MILES 350.0 AND 350.3

The slumps and earthflows between mile 350.0 and 350.3 are similar to those between mile 349.1 and mile 349.6 (see fig. 36). The lake sediments that underlie the area crop out in the west wall of the canyon from river level to the level of the track. Here, as between mile 349.1 and mile 349.6, trees are tilted 5°–10° toward the hill, and abrupt bends in the trunks of the spruce trees indicate that movement took place several decades ago. It is reported that movement was particularly rapid at mile 350.1 and mile 350.3 during the early years of the railroad. Little movement occurred in 1947. Activity in the slump, particularly in the northwestern part, began again in 1948 and has continued to the present time. Fill on the northeast side of the track at mile 350.3 settled as much as 15 feet

FIGURE 40.—View northwestward from mile 350.2, the Alaska Railroad, showing the landslide at mile 350.3, June 17, 1952.

from 1950 to 1952 (fig. 40). Along the track itself, settling of 2 feet per year has required frequent addition of fill beneath the rails to maintain grade. On the lower part of the slump, supersaturated clay and silt flow on a slope of less than 10°. Slumping and flowing can be expected to continue unless remedial measures, similar to those recommended for the slide between mile 349.1 and mile 349.6, are taken.

LANDSLIDE BETWEEN MILES 351.2 AND 351.5

Geology.—Another persistent landslide occurs between mile 351.2 and mile 351.5, where the railroad passes across the toe of a glacial delta, whose gravels interfinger with lake clay and silt (figs. 41 and 42). Unusually accurate data on the geology of this landslide area have been obtained through the study of material exposed in excavations that were made in connection with the construction of a new bridge across the tributary canyon at mile 351.4.

The Birch Creek schist that makes up the bedrock between mile 351.2 and mile 351.5 generally is covered with gravel and lake sediments to a level about 200 feet above the track, but is exposed at track level south of mile 351.25 and in the gorge about 400 feet west of the track at mile 351.4 (see fig. 41). The surface of the bedrock slopes 25° or 30° E., toward the river, and lies more than 200 feet below the track at the bridge across the tributary canyon. The schist is cut by vertical joints that strike parallel to the river and are spaced from a few inches to several feet apart. Drag folds and crenulations in the foliation plunge 15° toward the river.

Fine-grained lake sediments similar to those between mile 349.1 and mile 350.3 crop out between the river and the track from a point about 300 feet south of the bridge northward to a point beyond the area shown in figure 41. The fine-grained lake sediments consist predominately of clay and silt, but locally contain sand and gravel. Samples 7, 8, and 9 (fig. 33) consist of mixtures of the sliding material. For the most part the sediments are covered with a dense mat of vegetation. Locally they are covered with a thin veneer of gravel which has slid or rolled down the hillside and partly incorporated the clay and silt.

The fine-grained lake sediments are underlain by and interfinger westward with delta gravel that was deposited in the ancient glacial lake by the tributary at mile 351.4. Drill-hole data and exposures along the track and in the canyon at mile 351.4 (figs. 41 and 42, section *B–B′*) show that the zone of interfingering is irregular but that it coincides roughly with the present position of the railroad. The delta gravel is exposed along the west bank of the railroad south of mile 351.4, and on the south bank of the canyon of the tributary for a distance of about 300 feet westward from the track (fig. 43). The delta gravel is in layers that dip 20°–25° toward the river. It is composed almost entirely of angular pebbles and cobbles of Birch Creek schist.

Overlying the delta gravel is a layer 10–25 feet thick of clean blue-gray outwash gravel of the Nenana River. This gravel contains well-rounded boulders and pebbles of conglomerate, greenstone, and other rocks. About 100 feet of yellowish-brown alluvium deposited by the tributary at mile 351.4 overlies the outwash gravel. Bedding in this uppermost gravel dips 7°–10° toward the river, parallel to the upper surface of the bench.

Permafrost.—Permafrost is generally present in the lake sediments and in the overlying gravel. Its depth and thickness vary from place to place, depending on exposure and vegetation. At the south end of the bridge, permafrost in clay and gravel lies 10–15 feet below the surface (fig. 44). At the north end of the bridge, excavators struck permafrost in clay at a depth of 6 feet. West of the track and south of the bridge excavators dug through 15–20 feet of frozen blue clay and into unfrozen yellow clay. A hole that was churn-drilled just south of the bridge passed through unfrozen clay at a depth of 32–45 feet, whereas the rest of the material through which the hole passed seemed to be frozen. The hole just north of the bridge was drilled in frozen clay and gravel to a depth of 100 feet and in unfrozen gravel containing flowing ground water between depths of 100 and 110 feet. This body of permafrost is the thickest that has been penetrated

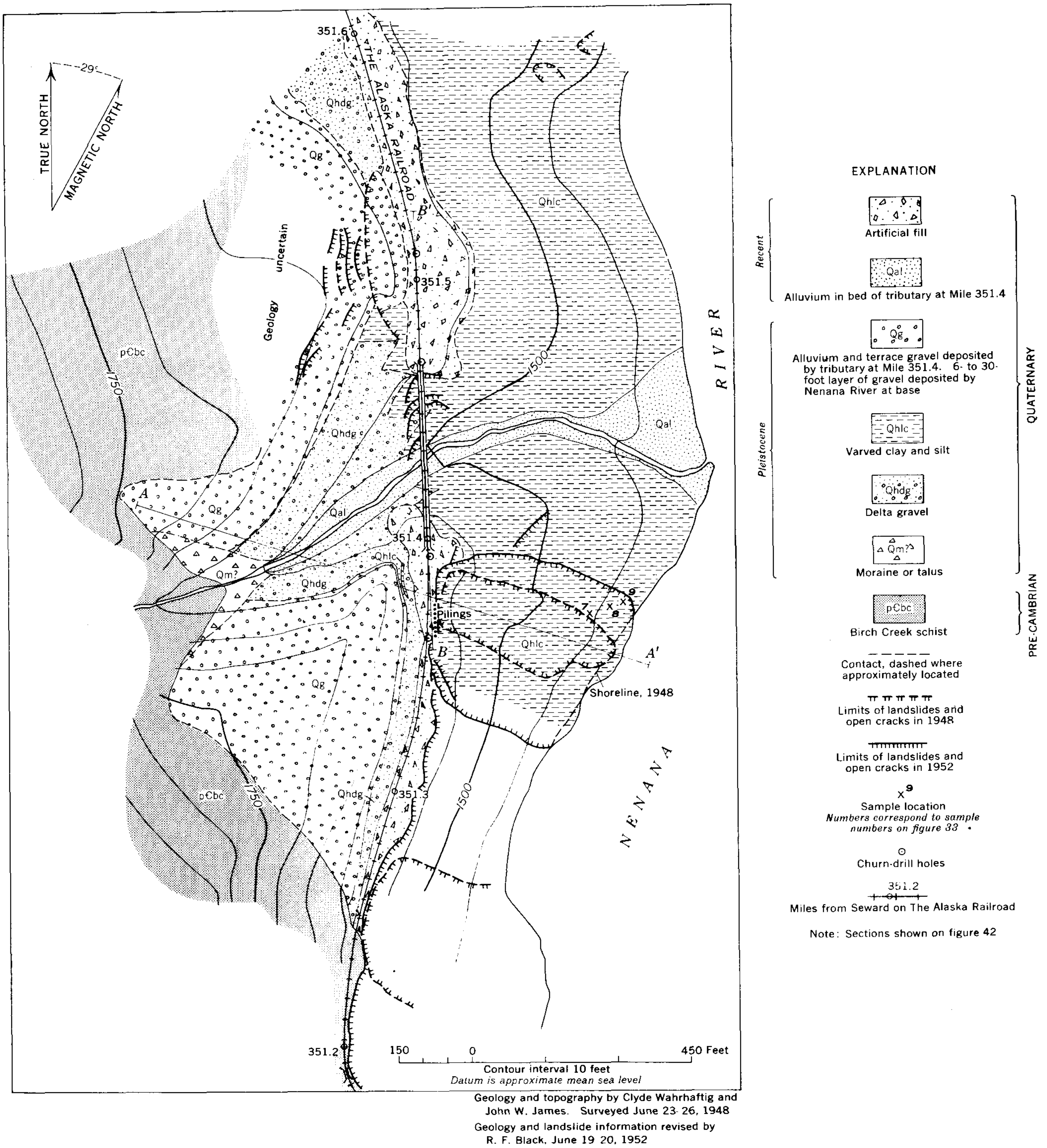

FIGURE 41.—Geologic map of landslide between mile 351.2 and mile 351.5 on the Alaska Railroad.

in the area; however, the permafrost may be considerably thicker at other localities.

The perennially frozen clay and silt contain ice in the form of nearly vertical veinlets, ½–4 inches thick and 3–12 inches apart, which strike approximately north. Horizontal seams of ice are present along bedding planes. Clear ice masses are estimated to make up 20–25 percent of the frozen clay, and ice also cements individual particles. The total amount of contained water is thus much greater than the plastic limit of the

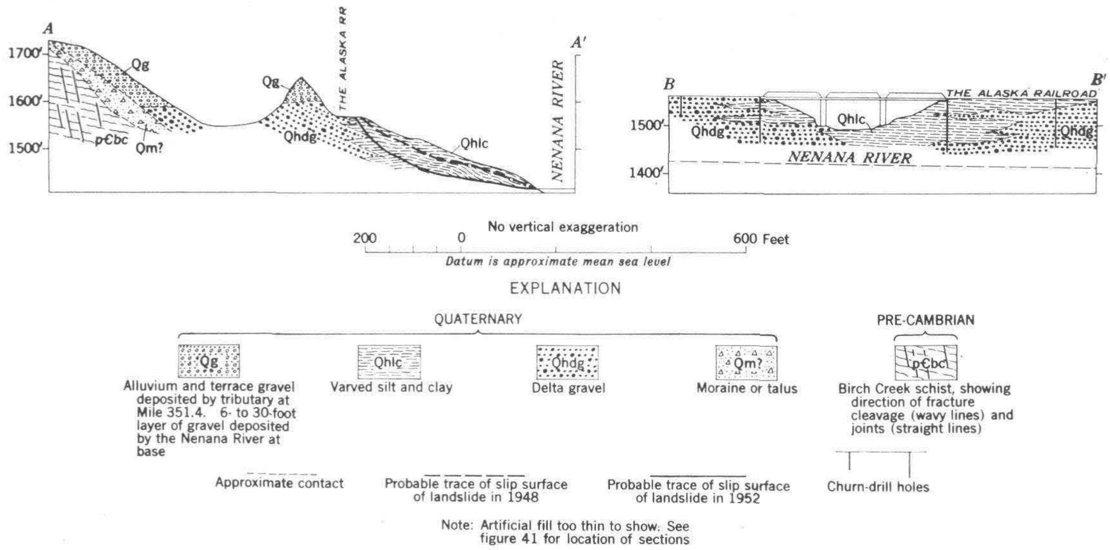

FIGURE 42.—Geologic cross sections of landslide between mile 351.2 and 351.5 on the Alaska Railroad.

sediments (see table 3), as defined by the American Society for Testing Materials (1950, p. 7). Perennially frozen gravel contains ice which fills interstices between pebbles and cements them together. The frozen gravel must be blasted or thawed before it can be removed. The clean gravel does not settle or flow as it thaws.

Landslide activity.—The landslide of October 19, 1947, the investigation of which revealed the need for this study of engineering geology along the Alaska Railroad, occurred at mile 351.4, immediately after a severe earthquake. Before 1947 several hundred feet of the track had been settling slowly for many years. Grade was maintained by adding fill each year. However, immediately after the earthquake of October 19, 1947, about 150 feet of track south of the bridge began sinking at a rate of 3 feet per hour (St. Amand, 1948, p. 617). Most of the slumping ceased on about October 30, but on about September 20, 1948, service was again disrupted by a very rapid slump (fig. 45). By September 25, movement had almost ceased. The track was realined about 30 feet westward after thousands of tons of gravel were removed from the hill and spread over the slump. Later that year 28 piles, centered about 3 feet apart, were driven along the river side of the railroad and anchored with wire cables

FIGURE 43.—View southward from the north abutment of the bridge at mile 351.4 on the Alaska Railroad, showing foreset delta gravel overlain by outwash and terrace gravel. The excavation beside the trestle is in interbedded clay, silt, and gravel. Note slumps into the excavation. September 24, 1948.

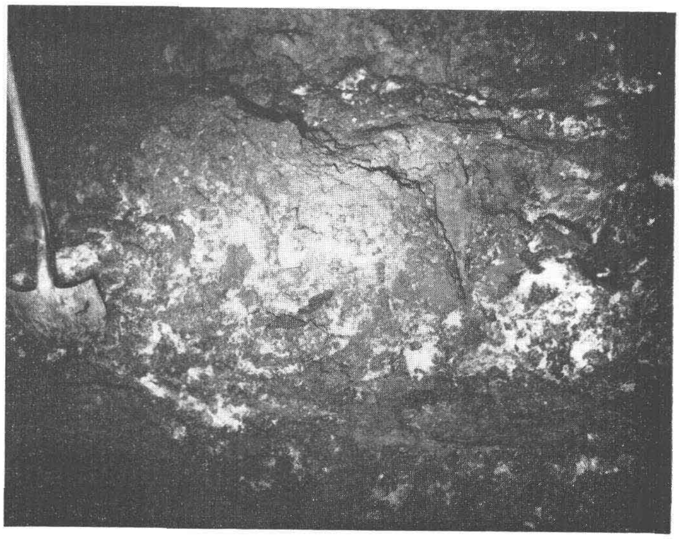

FIGURE 44.—Clear ice in perpetually frozen clay, silt, and gravel at mile 351.4 on the Alaska Railroad, June 22, 1948.

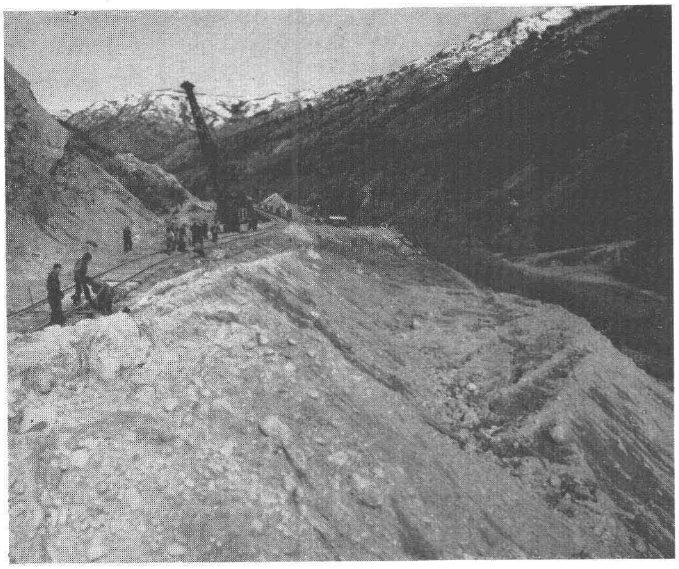

FIGURE 45.—Realining the track at mile 351.4 on the Alaska Railroad immediately after slumping, September 24, 1948.

to other piles that were steam-jetted into place on the opposite side of the track. The track has been relatively stable since, but slumping still occurs farther downslope (see fig. 46).

The landslide of October 19, 1947, initially broke out about halfway down the slope between the tracks and the river. Above that point the ground sank; below it a tongue of material spilled from the hillside to the river. The initial slide area extended from a point about 50 feet south of the bridge southward along the railroad for 150 feet. By 1952 the sliding area had more than doubled in width. The most active area extended from the bridge to a point 350 feet south. Other less active slumps in fill form a continuous sliding belt extending to mile 351.2 (fig. 41).

Judging from the size of the blocks that were rotated, the thickness of the slide originally was less than 40 feet. Presumably, movement was on or near the top of the permafrost. In 1952, rotated blocks were considerably larger, indicating that movement was going on at depths of as much as 100 feet. Earthflows had moved outward from the toe of the slide at least 30 feet into the river. Exposed portions of vertical headwalls of some individual blocks were more than 20 feet high; the greatest downward vertical movement took place adjacent to and just north of the piles at the head of the slump (see fig. 46). In June 1952, cracks appeared on the uphill side of the piles, and subsequent slumping exposed segments of the piles 5 or 6 feet long.

The slumps to the south were not affecting the track in 1952, although the headwall of the slump about 700 feet south of the bridge was at the edge of the ties.

The north pier and north abutment of the bridge at mile 351.4 rest on clay. When excavations for the new bridge were made in 1948, it was discovered that wooden foundations of the piers of the old trestle had been bent and broken, apparently by slow creep of the clay. Small slumps from the clay and from fill on the top of the clay were pressing against the concrete base of the north pier of the bridge in 1952. On June 15, 1952, water was running from these slumps onto the concrete footing. Water was running out from under the southeast corner of the pier also, probably weakening the foundation. A vertical crack 1 millimeter wide was present in the southeast concrete support of the

FIGURE 46.—Upper part of slumps, showing partly exposed piling at mile 351.4 on the Alaska Railroad. View is southwestward from a point a few feet east of the south abutment of the bridge. June 15, 1952.

north pier. The slumps that were observed in 1952 probably are not large enough to move the bridge support, but slumps that are large enough to do so may occur.

Landslides are present for a distance of 400 feet along the west side of the track north of the bridge. Some are in schist and some are in gravel that rests on clay. Blocks of schist 100–200 feet west of the track are broken along joints and have moved eastward along grooves that were formed by drag folds. Movements of 1–4 feet are indicated by trenches and small headwall escarpments. Movements of from several inches to a few feet since 1948 are recorded in fresh headwall escarpments. During realignment of the track in 1949 much slump material was removed and dumped on the east side.

Landsliding appears to have occurred in this area before the present body of permafrost was formed. The north abutment of the bridge is in an ancient stabilized landslide block of frozen clay and silt. Contorted bedding and step-faults produced by ancient landslides in excavations in frozen clay and silt were exposed at the south abutment of the bridge. The movement of these ancient landslides presumably ceased when the area became perennially frozen. It seems reasonably certain that the renewed landslide activity in the vicinity of mile 351.4 is the result of the melting of permafrost, which occurred after railroad construction was begun. Melt water supersaturated the clay and silt and built up high pore-water pressure. Movement took place on the top of permafrost and possibly on thawed zones within it.

Possible remedial measures.—Effective methods for combatting this landslide will include those by which pore-water pressure is reduced and the sliding material is strengthened. Improved drainage will be only partly effective, because much of the water facilitating the movement is being derived from melting permafrost. Freezing the slide area, or part of it, is considered to be the most effective remedial measure. Growth of permafrost possibly can be induced by planting insulating vegetation. However, the seriousness of the slide makes necessary the use of a more rapid method. A method employing a refrigerant that is cooled by winter air temperature and pumped through well points might be practical and might also be the least expensive. The clay and silt that are partly buried by gravel backfill at the north pier and abutment of the bridge should also be frozen to prevent a slump under the pier. In addition to freezing the critical slide areas, lined culverts should be installed to drain surface water away from other parts of the landslide.

Realinement of the track west of its present position would require the removal of thousands of cubic yards of frozen gravel. If a retaining wall were built at the toe of the slide it would have to be capable of withstanding a thrust of several tons per square foot, and would have to rest on water-saturated clay and silt. Piling, to be effective, would have to be driven more than 100 feet, well into permafrost. Steam jetting, which would be required to penetrate the frozen ground, would in all likelihood initiate further sliding. None of these last methods is likely to control the slide permanently, and all are more expensive than the suggested methods of drainage and refrigeration.

LANDSLIDE AT MOODY

Geology.—From mile 352.7 to mile 353.6 the railroad passes over a body of lake sediments similar to those between miles 349.2 and 350.3 and between miles 351.2 and 351.5. From Sheep Creek (mile 352.8) to Moody (mile 353.3) the railroad trends about N. 40° W. and is about 100 feet above the river and about 150 feet below the brow of a narrow bench at the base of the high mountain that forms the west wall of the Nenana gorge (pl. 10). At Moody the railroad trends about N. 45° E as it swings in a broad arc that follows the contour of the west wall of the canyon. At this point, the bench that is about 250 feet above the river widens abruptly to about half a mile, and the railroad and the river enter a narrow steep-walled gorge which extends about 5 miles northward to Healy. At Moody the river leaves the ancient glacial gorge, which it occupies with but one short interruption from McKinley Park Station to Moody, and enters a narrow canyon that is superposed in the rock making up the east bedrock wall of the gorge. The northward continuation of the ancient glacial gorge, now filled with lake sediments, lies underneath the broad bench on the west side of the Nenana gorge between Moody and Garner. The cause of the superposition of the Nenana River was the deposition of alluvial cones by tributary streams emerging from the west side of the sediment-filled gorge, which forced the river against the east wall of the gorge. No comparable tributaries exist on the east side of the canyon between Moody and Healy to offset this effect.

The west wall of the gorge from Sheep Creek to mile 353.6 consists of lake sediments from river level to a height of 150 feet. Outwash gravel, alluvium, and talus, whose total thickness is 100–150 feet (pl. 10) overlie the lake sediments. Horizontally bedded blue-gray clay and silt (samples 10–13, figs. 33 and 34), make up most of the lake deposits. A lens of silty sand (sample 14, fig. 34) at mile 353.5 is shown separately on plate 10. A delta built by Sheep Creek into the ancient glacial lake in which the silt and clay accumulated extends northward from Sheep Creek to about mile 353.0 (see pl. 10). This delta gravel consists almost entirely of coarse pebbles and boulders of Birch Creek schist and is remarkably clean. The dip of the foreset beds of the delta is about 38° E. The contact of the delta gravel on the west and clay and silt on the east lies about 50 feet east of the railroad track from Sheep Creek to mile 353.0, and is marked by the headwall scarps of an active landslide (see pl. 10). A small patch of till that lies beneath the gravel, and that was deposited by the glacier which occupied this gorge just before the lake was formed, is exposed on the north wall of Sheep Creek, about 300 feet west of the railroad.

A 40-foot layer of coarse clean blue-gray outwash gravel deposited by the Nenana River overlies the lake deposits west of the railroad track. This layer abuts against the west bedrock wall of the ancient gorge, 300–700 feet west of the railroad between Sheep Creek and Moody. The layer of blue-gray gravel probably abuts against a buried bank of clay not far north of the bluff between mile 353.3 and mile 353.5, for clay is exposed to an altitude of 1,700 feet in the canyon half a mile north of Moody (see pl. 2). A younger deposit of outwash gravel of the Nenana River lies on the terrace about 20 feet above the railroad between mile 353.5 and mile 353.6.

One hundred feet of yellowish-brown alluvium that was deposited by Sheep Creek overlies the blue-gray outwash gravel west of the track between Sheep Creek and mile 353.0. Similar gravel north of the track between mile 353.3 and mile 353.6 (pl. 10) was deposited by the stream which now flows in the canyon half a mile north of Moody (pl. 2). The material that overlies the blue-gray gravel in the bluff west of the railroad between the two alluvial fans is partly talus and partly congeliturbate. It consists of large and small blocks of Birch Creek schist, some as much as 30 feet across, in a matrix of brown micaceous dirt. It is unsorted and has no bedding.

Permafrost.—Permafrost is probably present throughout most of the area, but its extent and thickness are not known. Clay banks at Moody, and the alder-covered slope below the railroad track at mile 353.0, were probed with a soil auger to a depth of 3–4 feet in July 1948. No permafrost was found. The earthflow at mile 353.5 (fig. 47) was probed with a soil auger to a depth of 7 feet in October 1948, but no permafrost was found. The dip and displacement of the landslide cracks at the head of this earthflow suggested that permafrost was at least 10 feet below the surface. The presence of a dense mat of moss on the high sloping bench west of Moody suggests that permafrost under the bench is probably within 3 feet of the surface. In

FIGURE 47.—Earthflow at north end of Moody landslide area at mile 353.6, September 24, 1948.

1948, cribbing and fill which was replaced beneath the track on the shaded hillside at the north end of the tunnel at mile 353.7 was found to be perennially frozen. The development of permafrost in this material must have taken place after 1920 when this cribbing was constructed. In 1945, clay at a depth of about 30 feet was solidly frozen for a distance of 300 feet along the track near mile 353.0, where thawed clay was excavated and the roadbed was backfilled with gravel.

Although no drilling has been done to test the landslide at Moody, the slip plane, at least in part, is believed to be at the base of the permafrost. Sven Bragstad, section foreman, reported in 1948 that in 1945 Joseph McNavish, roadmaster, descended into a headwall crack west of the track at mile 353.0. This crack penetrated permafrost and running water could be heard at the bottom. Although no records are available to indicate whether or not permafrost is thawing in the Moody landslide area, it seems likely that it is doing so, at least locally, as a result of disturbance of thermal equilibrium through deforestation, excavations, and changes in the hydrologic regime.

Landslide activity.—The railroad at Moody was built across an ancient landslide with an irregular hummocky surface and crescent-shaped headwall scars (fig. 48). Low, asymetrical ridges on the surface of the slide, parallel to the contour, are parts of rotated landslide blocks. From Sheep Creek to mile 353.0 the track was originally built across a steep bank of clay along the river. When this bank slid into the river, a wooden trestle, also anchored in clay, was built across the slide.

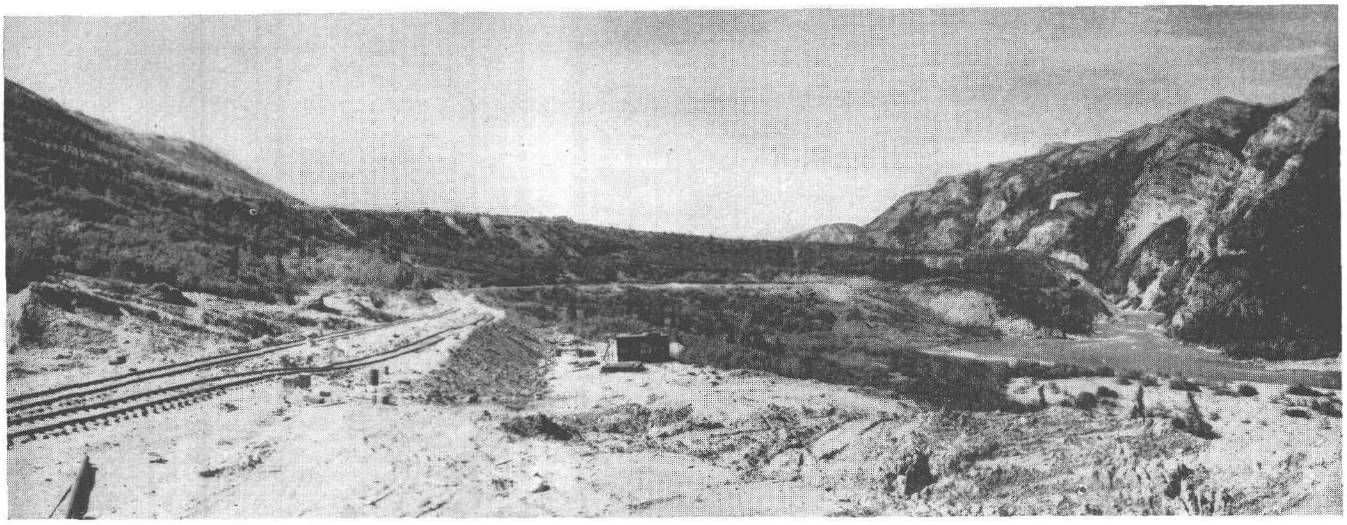

FIGURE 48.—View northward from mile 353.0 on the Alaska Railroad, showing the Moody landslide area. The building in the foreground is on an abandoned railroad grade. The Moody section house is in the background at the bend of the track. Tension cracks in the right foreground are in clay and silt and are produced by upward welling of sediments from below. The Nenana River enters its superposed course between Moody and Healy to the right of the railroad tunnel in the background. The bench between the tunnel and the Moody section house is capped by tributary terrace gravel. June 22, 1948.

In 1940 the trestle gave way. The track was moved westward to its present position on clay-free delta gravel in successive stages after several hundred thousand cubic yards of gravel had been excavated from the cliff. The clay along the river continues to slide, and the area between the track and the river (pl. 10), about 300 feet wide, consists of rotated landslide blocks separated by fresh scarps and cracks. The track, where it rests on gravel, has not moved for several years.

The most rapid movement of the roadbed in recent years has taken place between mile 353.0 and Moody (mile 353.3). The landslide there is divisible into three belts that are moving in part independently. A lower belt from 1,400 to 1,480 feet in altitude has moved considerably in the past but shows little sign of movement at present. An intermediate belt from 1,480 to 1,600 feet in altitude has moved actively since 1948 and had moved considerably before then. An upper belt from 1,600 to 2,300 feet in altitude began significant movement in 1947. In July 1948 the center line of an abandoned portion of the track, about 50 feet east of the main line and on the east edge of the intermediate belt, was 30 feet below the original grade at mile 353.15. Ties in this abandoned portion had rotated so that the west end was a few inches lower than the east end. At that time the main line was about 10 feet below grade at the lowest point of the "sinkhole" and had moved several feet east of its original position. By the fall of 1948 several "doglegs" appeared in the track, evidence of more eastward movement during the summer.

Movement of the track since 1948 is reported by Mr. Bragstad to have averaged about 4 feet horizontally and about 1½ feet vertically per year. In June 1952 numerous active scarps were seen between mile 353.0 and mile 353.2 from the track uphill to the top of the bench, at an altitude of 1,700 feet. The central part of a north-trending line of stakes, which James Morrison, surveyor for the Alaska Railroad, had placed between 100 and 200 feet west of the track, moved more than 7 feet eastward in the 9-month period, from October 1947 to July 1948. (See pl. 10.) The stakes were not relocated in 1952. The telephone line (fig. 49), which crosses the upper part of the intermediate slide belt, has been offset as much as 35 feet in the period from 1947 to 1952, indicating a maximum average downslope movement of 7 feet per year.

An upper line of stakes was placed by Morrison between 600 and 700 feet west of the track, in the upper belt of the landslide (see pl. 10). Maximum movement on this line in the period from October 1947 to July 1948 was 8.5 feet. These stakes also were not relocated in 1952. The surface of the upper part of the slide in 1948 and in 1952 was seamed with fresh cracks, some as much as 2 feet wide. The lower end of this belt is a barren bluff from which blocks of schist frequently roll down upon the upper edge of the intermediate belt of the slide.

Fresh cracks in the bedrock at the top of the steep mountain slope (fig. 50) that rises 800 feet above the track were observed by Mr. Bragstad and the late Mr. McNavish in the summer of 1947. Additional cracks were seen by the authors in 1948 and in 1952.

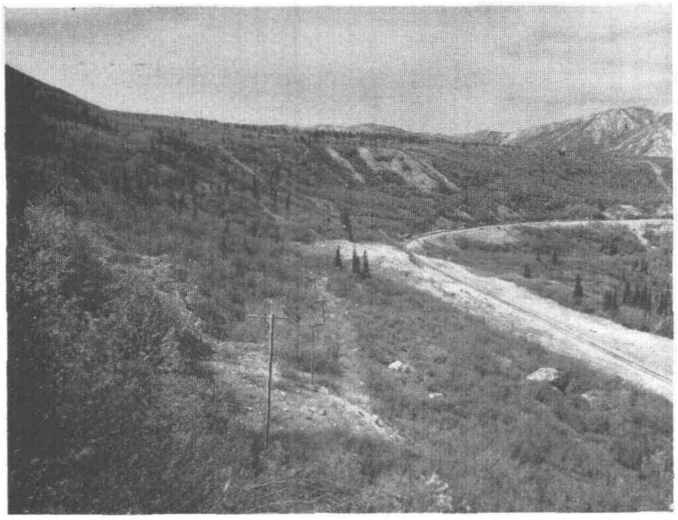

FIGURE 49.—Displaced telephone line on the Moody landslide; view is to the north. Maximum displacement is 35 feet, from 1947 to June 19, 1952.

The schist on this ridge is broken into large blocks, some of which are sliding southward from the crest of the ridge toward Sheep Creek and others eastward toward the railroad.

Between Moody (mile 353.3) and mile 353.5 the railroad crosses a part of the landslide that was active before 1945, but which gave little trouble between 1945 and 1949. In September 1937, the track across this part of the slide sank 30 feet in 15 days. Before 1945 this part of the slide was not covered with vegetation. Except for its east end, which is still barren, this area is now covered with a dense growth of alders and willows.

At the northeast end of the Moody slide, at mile 353.5, a very active earthflow in glacial-lake clay and silt (sample 15, figs. 34 and 47) enlarged headward toward the track and undermined the track in 1949. To protect the track, 34 wooden piles were driven on the south side of the track and anchored, by steel cables running under the track, to 12 piles on the north side. The track has not settled since the piling was emplaced. In June 1952 cracks were present in the fill between the railroad and the south line of piling, and one crack was seen 60 feet north and about 20 feet above the track. Slumping seems imminent.

Surface water that drains the upper slopes runs into the head scarps of many slump blocks. Water stands in sag ponds in several places on the intermediate belt of the landslide, and a small temporary reservoir was built in 1947 on the slide at mile 353.2 to provide domestic water for a construction crew. Several springs emerge within the slide area, and several intermittent streams cross the slides.

Possible remedial measures.—The recommendations for the control of the landslide between mile 352.7 and mile 353.5 are in general similar to those for the landslides between miles 349.1 and 349.6, between miles 350.0 and 350.3, and between mile 351.2 and mile 351.5. Probably realinement of the track would be too costly to be practical. Piles and concrete retaining walls are short term expedients only. The best remedies presumably involve drying or refreezing of the slide. All but one of the flumes that were constructed to facilitate removal of surface water now carry the water only to the lower side of the track. These should be extended to the river and many more should be constructed. The ponds saturate the landslide material and should be drained. Water from springs should be conveyed from the slide area by flumes. Lined ditches across the upper slope are necessary to divert surface water.

In order to stop movement which is taking place at considerable depth, in part at least at the base of permafrost, it will be necessary to intercept ground water or to freeze the clay or gravel from the tops of those layers to bedrock or to a level below that of the river. Drain pipes or freezing pipes could be driven, steam-jetted, or placed in drilled wells. To avoid the possibility of shearing the casings containing the freezing points before stabilization is accomplished, they could be installed from the periphery of the slide inward. It would be very desirable to start freezing the slide immediately after each point has been put in place.

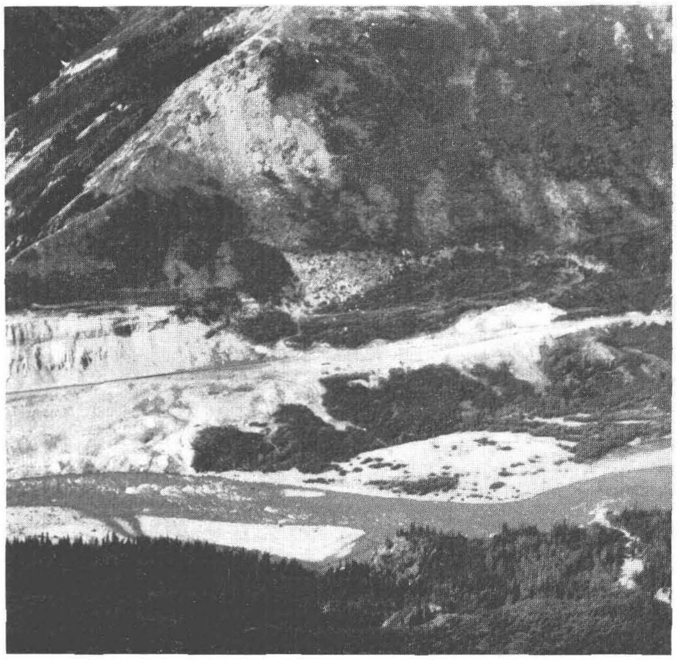

FIGURE 50.—Air view of the Moody landslide area, from a point above the east wall of the Nenana gorge.

LANDSLIDE BETWEEN MILES 356.2 AND 356.6

At mile 356.2 the railroad passes through a tunnel beneath a hill (fig. 51), composed of Birch Creek schist, that rises about 500 feet above the track. Foliation in the schist strikes eastward and dips gently northward; crenulations plunge gently eastward. Part of the southeast side of this hill has been moved by a great landslide. (The head scarp and other pronounced scarps of the landslide are shown on figure 51.) The eastern part of the landslide consists of a great mass of talus that sulmps toward the river. The talus is fed by rockfalls and rockslides from cliffs on the west side of the slump. The railroad crosses the landslide for a distance of 1,000 feet northeastward from the tunnel.

The slope of the eastern part of the slide from the track to the crest of the hill is considerably less than the angle of repose for the blocky talus that lies on it. The cliff at the head of this part of the slide is seamed by open joints as much as 20 feet wide that extend to unknown depths. Blocks of schist 100 feet or more on a side have parted from the bedrock along these joints and are sliding outward onto the talus or are sinking

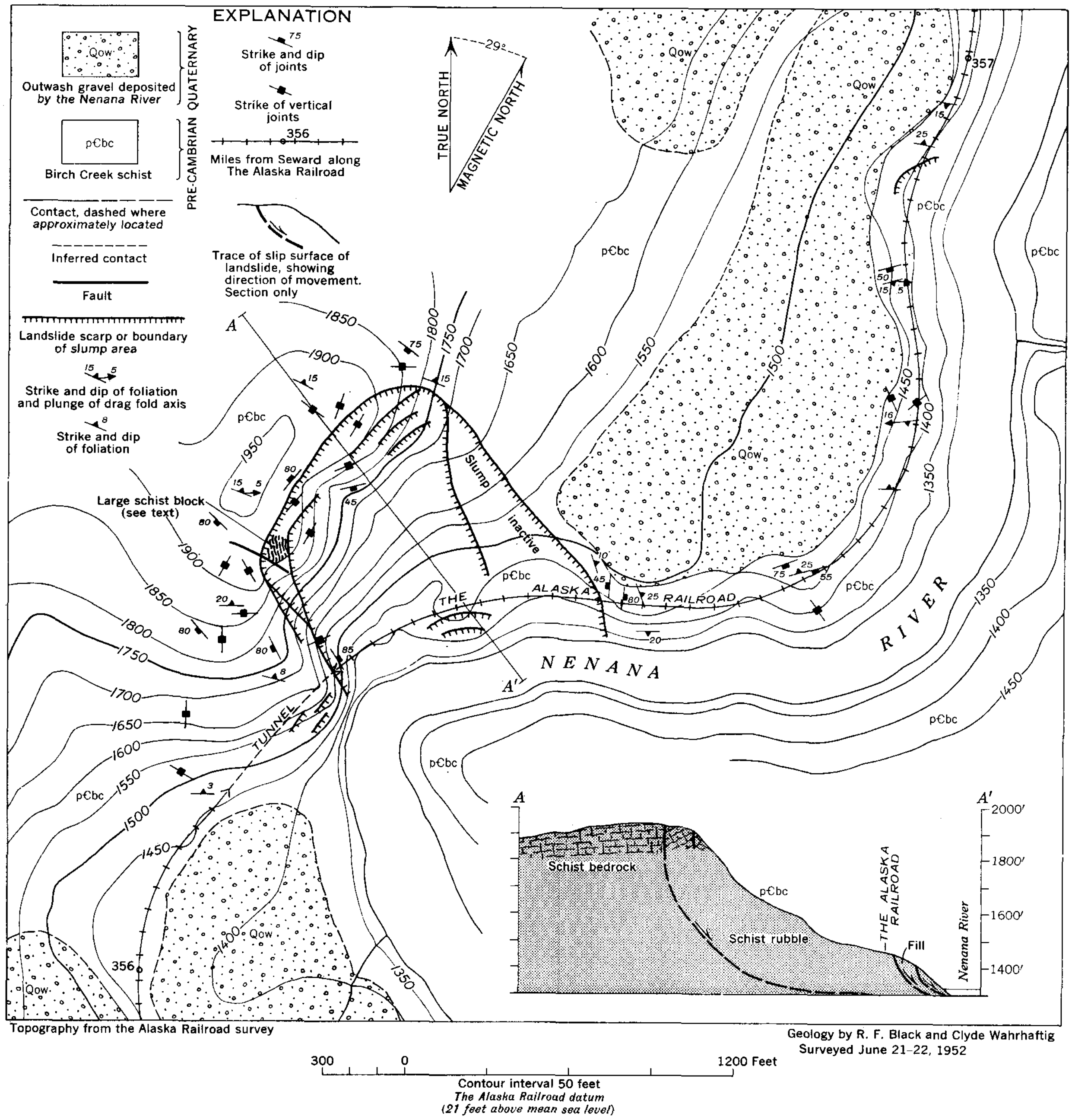

FIGURE 51.—Geologic sketch map and cross section of landslide between mile 356.3 and mile 356.6, the Alaska Railroad.

FIGURE 52.—Tunnel and broken cliff of Birch Creek schist at Garner landslide area at mile 356.2 on the Alaska Railroad. Arrow indicates broken block of schist approximately 100 by 60 by 100 feet in dimension. June 22, 1952.

vertically with the slump. The north border is characterized by pits, overhangs, and open joints.

The great weight of the broken rock at the head of the landslide forces the talus in the lower part to move downward and outward (fig. 51) toward the river. The river erodes the toe of the slide as fast as it advances. The track has moved with the slump at the rate of 2–4 feet per year for many years. No adequate method of controlling track movement is known that would be less expensive than periodic adjustment of the track.

Along the southwest margin of the landslide a cliff rises several hundred feet above the northeast portal of the tunnel. It has slopes of 50°–90° and overhanging ledges are common. Several chutes having gradients of 50° extend from the top of the cliff to the track. Blocks of bedrock are separated by open joints and open seams along planes of foliation at the heads of these chutes. One block 100 feet long, 60 feet wide, and at least 100 feet high (fig. 52) is separated by an open joint 17 feet wide (fig. 53). The position of the block is indicated on figure 51. Measurements of the width of this crack were made about once a year in the period from 1948 to 1952 and show that the crack is enlarging at the rate of about 0.2 foot per year. According to Mr. Bragstad, the width of the crack doubled in the period from 1938 to 1948. Blocks of schist have been falling from this cliff onto the track for many years. Rockfalls delayed trains from several hours to several days on October 5, 1939, August 24, 1946, August 16, 1948, and August 20, 1950. The last rockfall buried 150 feet of the track to a depth of 30 feet.

LANDSILDE BETWEEN MILES 357.3 AND 257.7

Geology.—Between mile 357 and mile 358, between 1 and 2 miles south of Healy (pl. 2), the river and the railroad make a sharp curve convex to the north, and then, east of this curve, a much sharper curve convex to the east. At the north end of the second curve the river and railroad emerge from the narrow rock-walled gorge which they follow for nearly 5 miles to the south, and enter a broad, terraced valley, the floor of which is nearly half a mile wide. In the area of these two curves the gorge is about 220 feet deep and is incised in a broad terrace. The south bank of the river in the western curve is marked by a flight of terraces, whose presence indicates that the river has been migrating laterally into its north bank during the time it has been cutting the narrow gorge. On the north bank of the river in this same bend is a sloping hummocky bench, about 120 feet above river level and about 50 feet above track level. As will be shown subsequently, this bench is a complex slump block of a landslide which affects the railroad at this point. The landslide area is shown in figures 54 and 55; cross sections through it are shown in figure 56. Throughout the two curves the railroad is about 70 feet above the river.

The bedrock through this part of the gorge is mostly Birch Creek schist; the west wall of the gorge as much

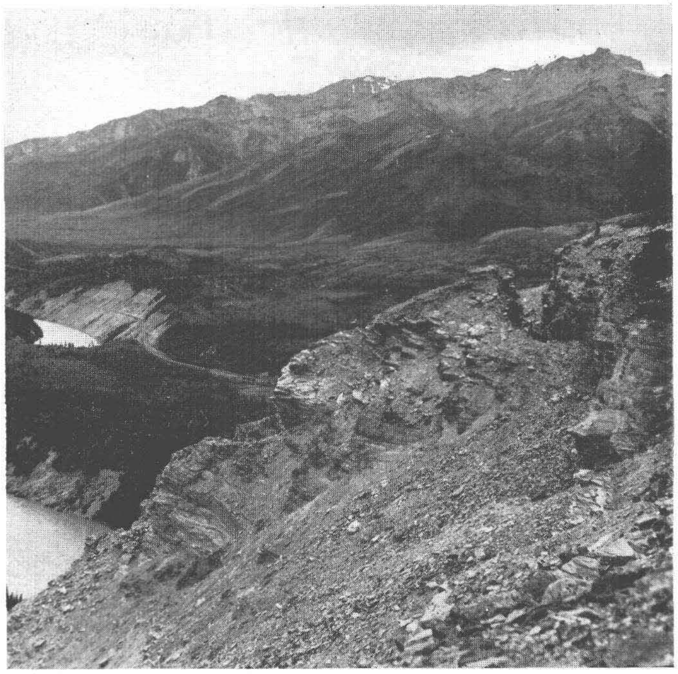

FIGURE 53.—Open joints behind schist block at Garner landslide area at mile 356.2 on the Alaska Railroad. July 18, 1948.

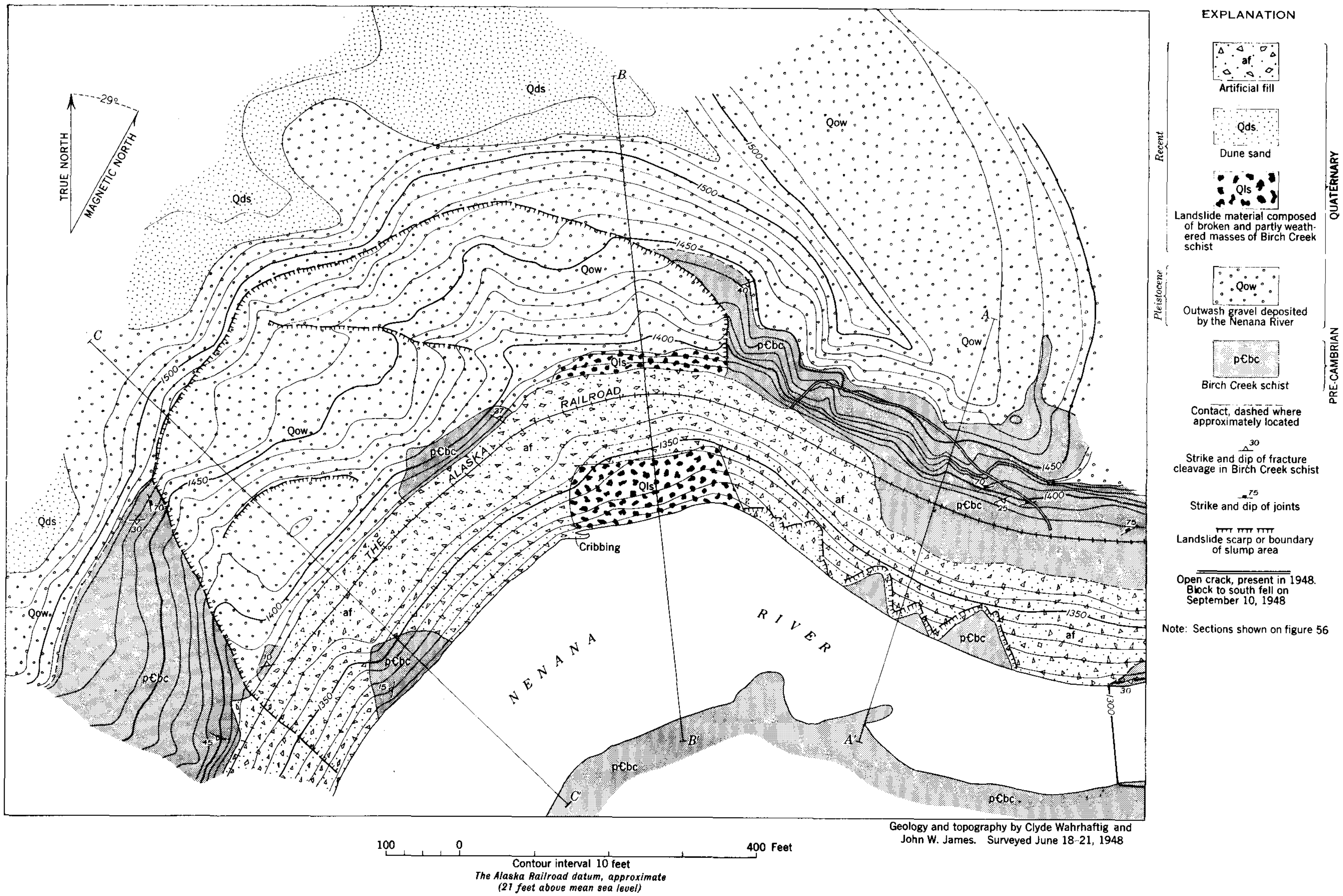

FIGURE 54.—Geologic map of landslide between miles 357.3 and 357.7 on the Alaska Railroad.

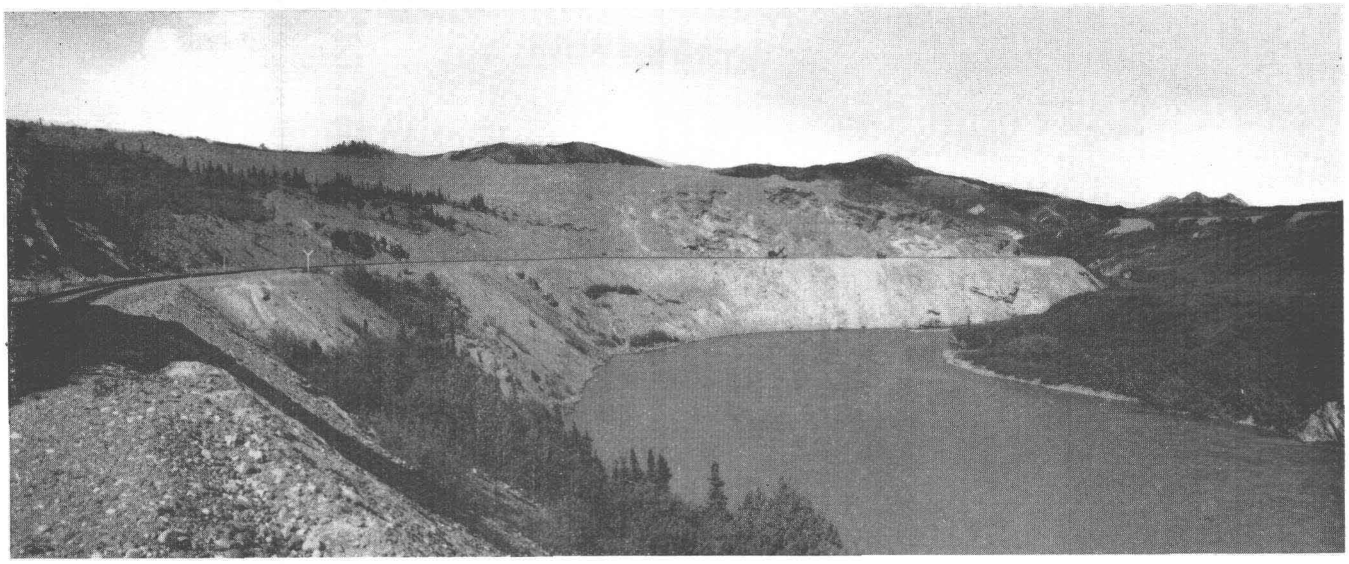

FIGURE 55.—View northward to landslide area between mile 357.3 and 357.7 on the Alaska Railroad. June 22, 1952.

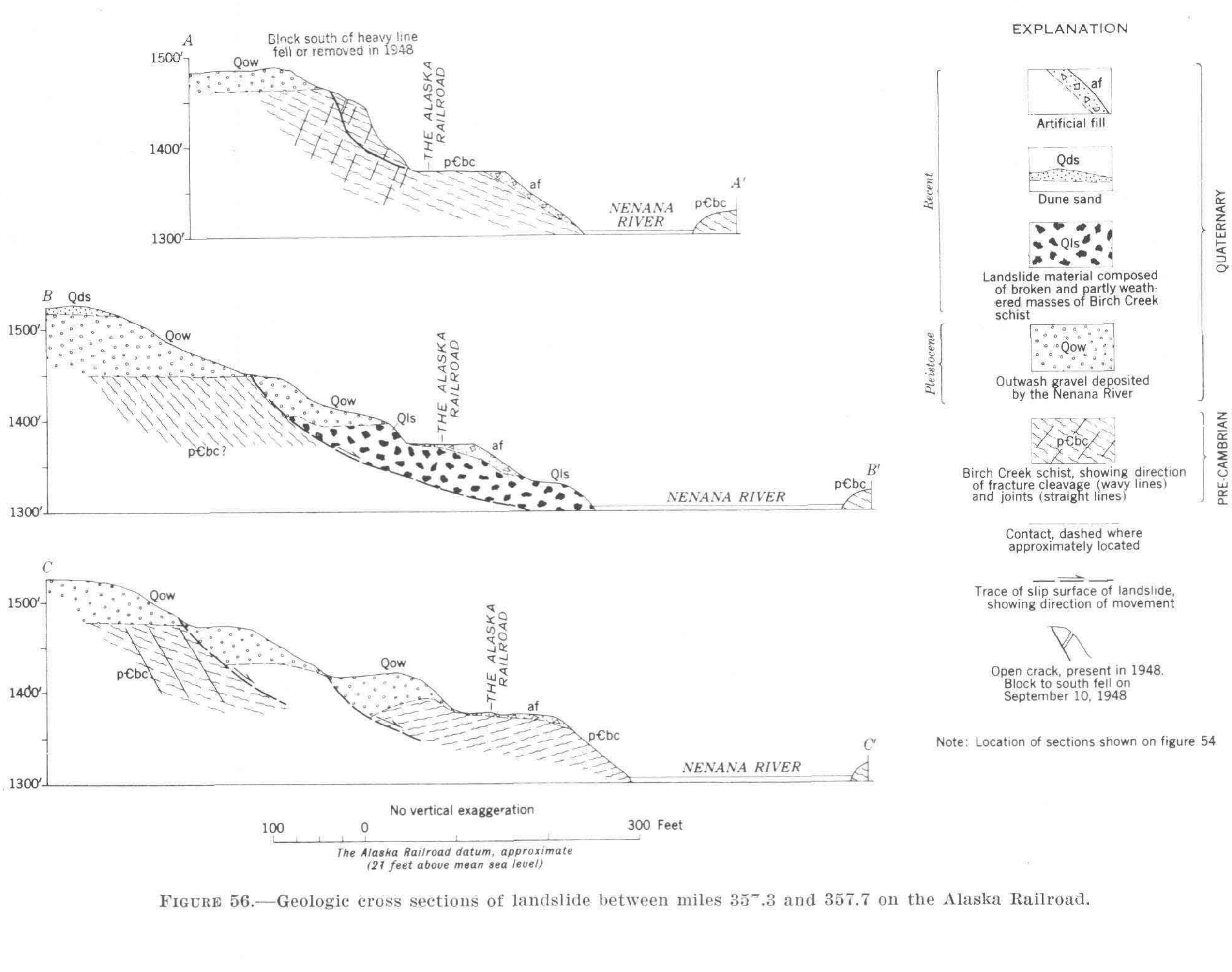

FIGURE 56.—Geologic cross sections of landslide between miles 357.3 and 357.7 on the Alaska Railroad.

as 180 feet above the river is schist (see fig. 54). Foliation in the schist strikes approximately N. 70° E. and dips 25°–40° S. Joints strike N. 70° W. and dip 70° N. Generally the schist in the gorge is firm and unweathered. This part of the gorge is very close, however, to the depositional contact at the base of the Tertiary coal-bearing formation. This contact crosses the railroad near the north end of the eastern curve (pl. 2), and probably lies only 600 feet north of the railroad in the western curve, where it is buried by 50–80 feet of outwash gravel. The contact north of the railroad probably dips about 30° N.

The broad terrace east of the river is probably underlain by the coal-bearing formation in a shallow syncline. Before erosion had reduced the land to the level of the broad terrace, the two bodies of coal-bearing formation were connected over the site of the canyon by an anticline in the coal-bearing rocks. The base of the coal-bearing rocks at the crest of the anticline could have been no more than a few hundred feet above the level of the terrace.

Immediately below the depositional contact elsewhere in the Alaska Range the Birch Creek schist is commonly weathered partly to clay. This weathering took place during the early Tertiary, when the climate was much warmer than at present. Along Healy Creek, about 4 miles to the east, the schist is weathered partly to sticky clay from the contact to a point more than 100 feet below the contact (Wahrhaftig, Hickcox, and Freedman, 1951, p. 148). Presumably the zone of weathered schist is present along the buried contact north of this area.

The upper part of the canyon wall consists of clean coarse-grained blue-gray outwash gravel, 30–60 feet thick, which was deposited by the Nenana River. Northward from the top of the bluff the gravel forms a terrace that is covered in part with sand dunes as much as 20 feet high (fig. 54).

Landslide activity.—"Sinkholes" have caused considerable trouble along the stretch of track between mile 357.3 and mile 357.6, which is on the convex side of the western of the two bends of the river (figs. 54 and 56). The "sinkholes" result from a landslide on the outer side of the curve in the river. The material exposed at the toe of the landslide between the railroad and the river is broken and weathered Birch Creek schist. For a distance of about 200 feet along the east edge of the landslide, where the movement is most active, the schist is reduced to a mass of small blocks and much sericite paste. In the southwestern part of the landslide the blocks are much larger, as much as 100 feet on a side; rotation of these blocks is indicated by the erratic strikes and dips of the foliation in the schist. The downward and outward movement of the schist has caused an arcuate block of outwash gravel 800 feet long and 300 feet wide to be lowered as much as 90 feet below the base of the outwash gravel on the terrace behind it. This material has slumped and settled irregularly over the slumped blocks of Birch Creek schist beneath it (fig. 56), thus forming the sloping hummocky bench above the railroad track at this place.

During 1948, landslide movement consisted of downward sinking of the material on which the track rests and outward bulging of the slope below the track. Slumping along the track was confined to an area 200 feet wide at mile 357.5—the northeast part of the landslide, where the rock consists of badly broken fragments of weathered and discolored schist. Cribbing, which had been set along the base of the bank a number of years before, was undisturbed. Presumably, river erosion of the toe of the slide is not causing the slumping at present.

It is believed that this landslide occurred as the result of lateral migration of the Nenana River into its northwest bank. The river breached the wall of unweathered schist separating it from the mass of weathered schist, which was then forced to move into the river as an earthflow by the great weight of material that rested on it. If this interpretation is correct, expensive measures will be required to control sliding of the great mass of weak material that lies beneath the terrace to the north of the track (fig. 56).

Possible remedial measures.—Realinement of the railroad by cutting or tunnelling directly through the terrace would be difficult and expensive. A cut would have to be nearly 200 feet deep, and its walls would consist of about 100 feet of weathered schist "clay" and of sand and clay of the coal-bearing formation, overlain by 70 feet of coarse gravel. Landsliding would occur frequently along the walls of the cut. A tunnel would require lining throughout its length. A massive retaining wall at the base of the slide would be very expensive and would control the slide only temporarily. On the other hand, spot freezing of the slide might control the movement.

INDUSTRIAL SITES

The resources of coal, clay, and limestone of the Nenana River area[6] (Wahrhaftig, Hickcox, and Freedman, 1951; and Cobb, 1951), and the favorable position of the area with respect to transportation, make an evaluation of potential industrial sites advisable. Suit-

[6] Moxham, R. M., West, W. S., and Nelson, A. E., 1951, Cement raw materials available to the Windy Creek area, Alaska; Unpublished rept. in files of U. S. Geol. Survey.

able locations for factories are scarce in interior Alaska, where most of the level ground is underlain by fine-grained sediments containing much perennial ice. The cost of construction in such areas commonly is prohibitive. If careful tests and evaluations of the rock units and thermal regime are not made before structures are designed, destructive settling usually results. The following considerations have been given to the selection of sites to be used for industrial purposes: (1) The site should embrace at least a quarter of a square mile of level ground. (2) It should be reasonably accessible to the Alaska Railroad. (3) The foundation material should be free of permafrost, or it should be unaffected by thawing of permafrost.

In general, the only suitable industrial sites in the Nenana River area are the gravel-capped terraces on either side of the river. The terrace gravel should be overlain by no more than 4 feet of silt or solifluction debris and should be at least 20 feet thick. If the gravel is thinner, it should rest on suitable bedrock. Test drilling should precede final selection of an industrial site.

NEAR WINDY

Two areas near Windy are regarded as favorable for industrial sites. One is on the alluvial fan of Bain Creek at Windy, which is underlain by medium- to fine-grained gravel composed of argillite and graywacke (pl. 4). This is overlain by 1–3 feet of moss and silt and is perennially frozen. A more favorable site is on the broad terrace north of the Alaska Railroad where the tracks cross Windy Creek. It is apparently underlain by a thick layer of well-washed gravel and may be free of permafrost. Between this terrace and the limestone hill about 2,000 feet to the north is a lower area covered by peat. Industrial structures should be built in areas in which peat does not occur, if possible, because of the high percentage of ice in the permafrost that underlies the peat.

NEAR HEALY

The most suitable industrial sites near Healy are those on terraces capped by 20–40 feet of gravel that was deposited by the Nenana River (pl. 2). Of these sites the most suitable is on a set of terraces, totalling 1½ miles in width and 2 miles in length, just west of Healy. Individual terraces are ¼–½ mile wide, 2 miles long, and 10–20 feet high. This set of terraces is bounded on the west by the next higher group of terraces, along the base of which is a belt of solifluction material and muskeg. Industrial construction could probably be extended into the belt of solifluction material and muskeg if that ground were prepared properly for it. This site is about 80–100 feet above the railroad track at Healy.

Other industrial sites are on the terraces at Healy and along the river below Healy. The site on the railroad terrace at Healy is 200–400 feet wide. However, it is already occupied by switchyards and other installations of the Alaska Railroad. The terrace below the railroad is about 15 feet above the river, 400–800 feet wide, and 4,000 feet long. It could be reached by a branch of the Suntrana spur track.

A broad gravel-covered terrace at an altitude of 1,600 feet, south of Healy Creek and east of the Nenana River, is probably suitable for an industrial site, provided it is not underlain by minable coal, and provided the gravel cover on the terrace is of sufficient thickness. This terrace is about 4,000 feet wide and 10,000 feet long. Access to the terrace could be had by a steel bridge across the canyon at mile 357 on the Alaska Railroad.

West of Lignite (mile 363) is a terrace about 1–1½ miles wide, about 4 miles long, and about 150 feet above the railroad (pl. 2). It is underlain throughout by 20–50 feet of dry gravel, resting on the Nenana gravel and upper part of the coal-bearing formation. It is probably the most suitable industrial site in the Nenana coalfield. The terraces at the railroad level in the vicinity of Lignite, are about a quarter of a mile wide. However, they are covered for the most part by extensive muskeg and swamps and probably by a much thinner layer of gravel than that on the higher terrace. Similar terraces occur between Ferry and Browne (pl. 5).

DAM SITES

In general the Nenana River is not favorable for power installations. The river heads in glaciers and carries great quantities of glacial silt during the season of flood, May 1 to September 15. During the remainder of the year, when the water is clear, the discharge is small. The gradient of the river is steep, averaging about 25 feet per mile. Consequently, the length of a reservoir would be relatively short for any given height of a dam. The canyon is narrow throughout, and no reservoir could be more than 1½ miles wide at the widest point; consequently, the storage capacity of the reservoirs would be small.

Sufficient data are available to permit an appraisal of four dam sites between Healy and Windy. Most of the dam-site foundations are in permafrost, and special precautions are required in the event dams are built on them (Huttle, 1948; Lewin, 1948a and 1948b).

During the summer of 1950, the Water Resources Division of the Geological Survey inaugurated streamflow measurements on the Nenana River.

FROM MILE 354 TO MILE 356

The only part of the canyon between Moody and Healy that is topographically suitable for dam sites lies between mile 354 and mile 356. The most favorable locality here is at about mile 354.3. A dam about 230 feet high and 750 feet wide at the top would impound a lake 3 miles long and as much as half a mile wide. The reservoir would cover an area of 2.5 square miles, and its storage capacity would be about 100,000 acre feet. The building of such a dam would require realinement of at least 9 miles of track.

The canyon walls at mile 354.3 are in Birch Creek schist, slightly impregnated with pyrite. Although this schist is considerably stronger than that 1 mile farther north, it is not strong enough to provide adequate foundation for a dam. Lying along the west side of the canyon is a half-buried ridge of schist, about 1,500 feet wide (fig. 57), beyond which lies a preglacial gorge 2,000–2,500 feet wide, filled with glacial-lake sediments (see p. 83–86 and fig. 57). The sediments consist largely of silt and clay. Sand and gravel were deposited along the shores of the ancient lake. Some leakage through the sediments in a segment of the gorge about two-thirds of a mile long that lies between the tributary canyons crossed by the railroad at mile 354 and mile 355.2 would probably occur until the clay sealed off the openings.

AT MILE 349.8

A dam 180 feet high and 500 feet wide at the top at mile 349.8 would impound a reservoir 5 miles long and as much as 1¼ miles wide. It would have an area of about 2.5 square miles and a storage capacity of about 67,000 acre feet. Construction of such a dam at this point would not require realinement of the track.

Geologically, this dam site is very unfavorable (fig. 36). The schist in the canyon is weak structurally and is sliding into the river. It is likely that the schist is broken by numerous throughgoing fractures. Several partly altered basalt dikes in the east wall of the canyon follow north-trending vertical joints. The body of schist that forms the west wall of the canyon is only 600–800 feet wide at the base and only 300 feet wide at the top. West of this schist lies a segment, about 0.6 mile long, of an ancient glacial valley that is filled largely with glacial-lake sediments that consist mostly of clay and silt (fig. 36). The creek at mile 350.3 had built into this ancient lake a delta, the pervious gravels of which are exposed in the south canyon wall of the creek, just west of the railroad bridge. It is possible that the delta gravels from this creek extend beneath the west side of the bench and crop out on the river bank at mile 349.1. If so, leakage through it would be considerable. Moreover, the glacial history of the Nenana River gorge indicates that an ancient channel may exist in the clay beneath the bench. If this ancient channel does exist, it is probably as deep as the present channel of the river and is filled with porous glacial gravels.

AT MILE 342.0

The river at mile 342.0 passes through a narrow gorge in diabase. A dam 200 feet high and 1,000 feet long at its crest would impound a lake about 6 miles long and as much as three-quarters of a mile wide. The reservoir would have an area of about 2.5 square miles and a storage capacity of about 80,000 acre feet. The Alaska Railroad would have to be realined for a distance of 1–1½ miles if such a dam were built.

The west abutment of the dam would be in a diabase sill about 250 feet thick. (See fig. 58.) The east

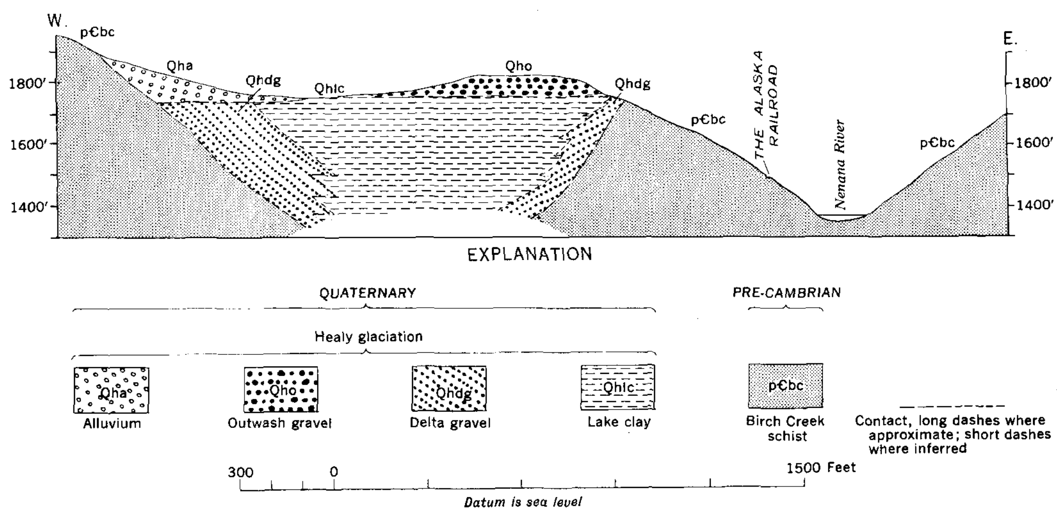

FIGURE 57.—Geologic cross section of dam site at mile 354.3, the Alaska Railroad.

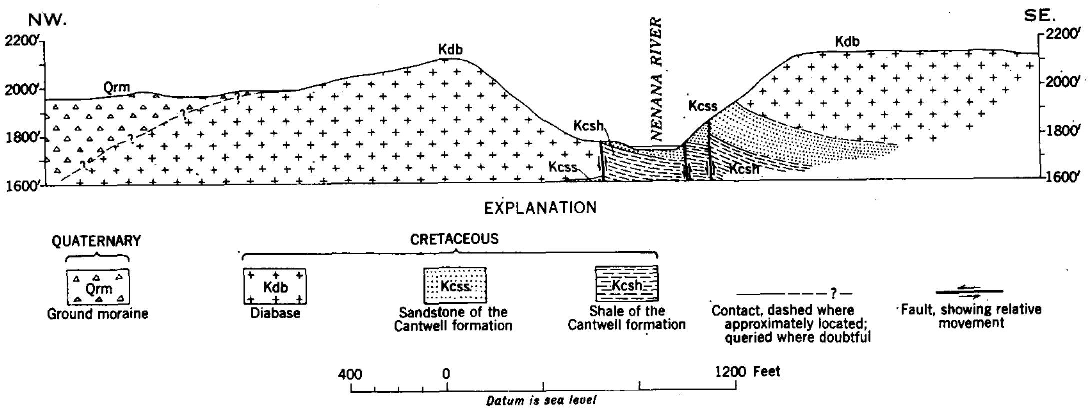

FIGURE 58.—Geologic cross section of damsite at mile 342.0, the Alaska Railroad.

abutment would be in a 100-foot bed of partly metamorphosed sandstone, overlain by diabase. The sandstone and diabase strike approximately northwest and dip about 20° NE. A fault having a displacement of about 300 feet passes down the center of the gorge and has apparently controlled the course of the Nenana River through this ridge. The fact that the river follows this fault through the gorge suggests that the fault may have a wide clay-gouge zone. Other faults of small displacement, exposed on the east wall of the gorge, show no gouge. The faults are not now active.

Between the diabase hills of the damsite and the railroad, the confining walls of the reservoir would consist of glacial deposits. It is entirely possible that a subglacial or interglacial stream channel, filled with coarse, pervious river gravels, occurs beneath the reservoir site and extends from the reservoir site to the Nenana River at mile 346. Other interglacial channels may exist on the south side of the east abument of the dam.

AT MILE 329.0

Near mile 329.0, a dam 3,000 feet long and 100 feet high would impound a reservoir having an area of about 6½ square miles and a storage capacity of about 250,000 acre feet. The station at Windy would be flooded by this reservoir. About 10 miles of railroad would have to be realined. A dam 4,000 feet long and 200 feet high would impound a lake having an area of about 14 square miles and a storage capacity of about 1,000,000 acre feet. Both Windy and the community of Cantwell would be flooded, and about 14 miles of railroad would have to be realined. The foundation rock at this point is greenstone. In general, the rock is massive and coarsely crystalline, but it may be serpentinized locally and may also contain many shear zones. Calcite veinlets are common.

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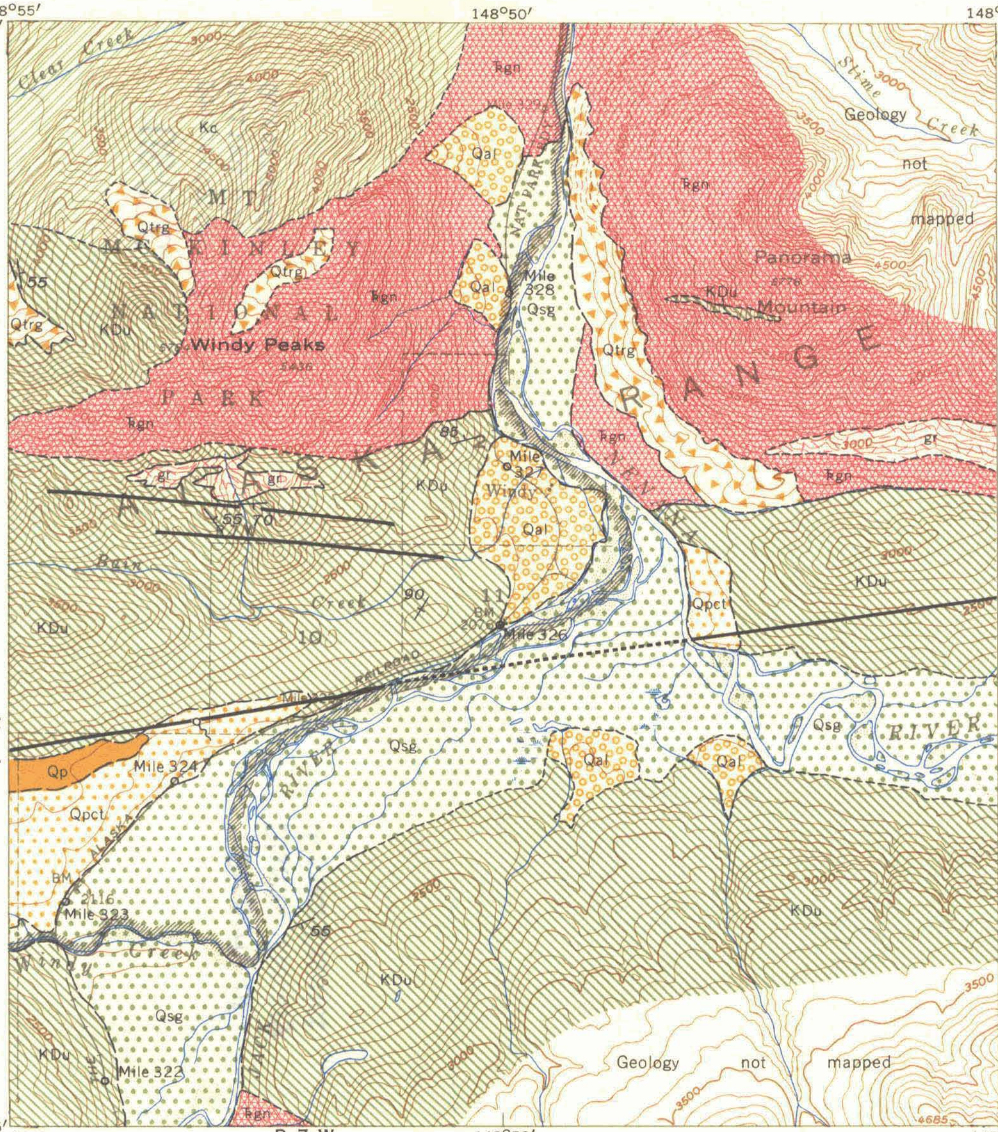


Base from U. S. Geological Survey map of Healy B-4 (1951) quadrangle

Geology by Clyde Wahrhaftig and R. E. Fellows, assisted by John W. James, Allen V. Cox, and J. H. Birman, 1948–1952

EXPLANATION

UNCONSOLIDATED SEDIMENTARY DEPOSITS

QUATERNARY — *Recent*

- Qal — Alluvial fan deposits
- Qp — Peat
- Qsg — Stream gravel — *Deposits in modern stream beds*
- Qtrg — Talus and rock glaciers
- Qpct — Terrace gravel — *Deposited by the Nenana River and its tributaries after the Carlo readvance*

SEDIMENTARY ROCKS

- Kc — Cantwell formation (CRETACEOUS)

UNCONFORMITY

- KDu — Undifferentiated sedimentary rocks of Devonian to Cretaceous age (DEVONIAN TO CRETACEOUS)

IGNEOUS ROCKS

MESOZOIC

- gr — Granite
- Rgn — Intrusive greenstone (TRIASSIC(?))

Contact — *Dashed where approximately located*

Fault — *Dotted where concealed*

Mineral spring

Inferred contact — *Includes contacts mapped from topographic expression only*

55 — Strike and dip of beds

Mile 322 — Railroad milepost

90 — Strike of vertical beds

INTERIOR-GEOLOGICAL SURVEY, WASHINGTON, D. C.
MR 5984

29°
TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 1951

GEOLOGIC MAP OF PART OF HEALY B-4 QUADRANGLE, ALASKA, SHOWING QUATERNARY DEPOSITS ALONG THE NENANA RIVER

Scale 1:63,360

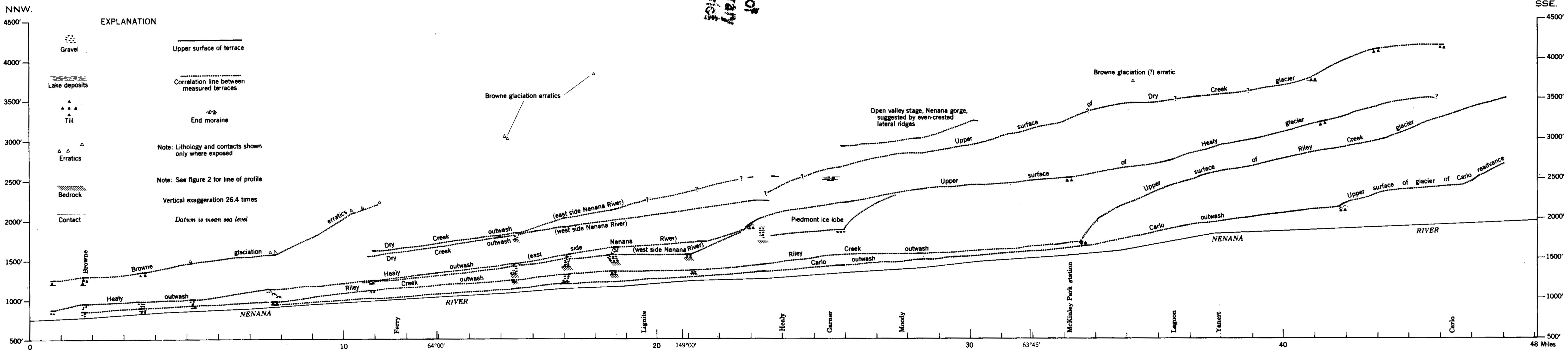
1 0 5 Miles

3000 0 21000 Feet

Contour interval 100 feet
Areas not surveyed in detail indicated by broken lines
Datum is mean sea level

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PROFESSIONAL PAPER 293 PLATE 7



GENERALIZED PROJECTED PROFILE OF TERRACES AND GLACIAL DEPOSITS ALONG THE NENANA RIVER, ALASKA

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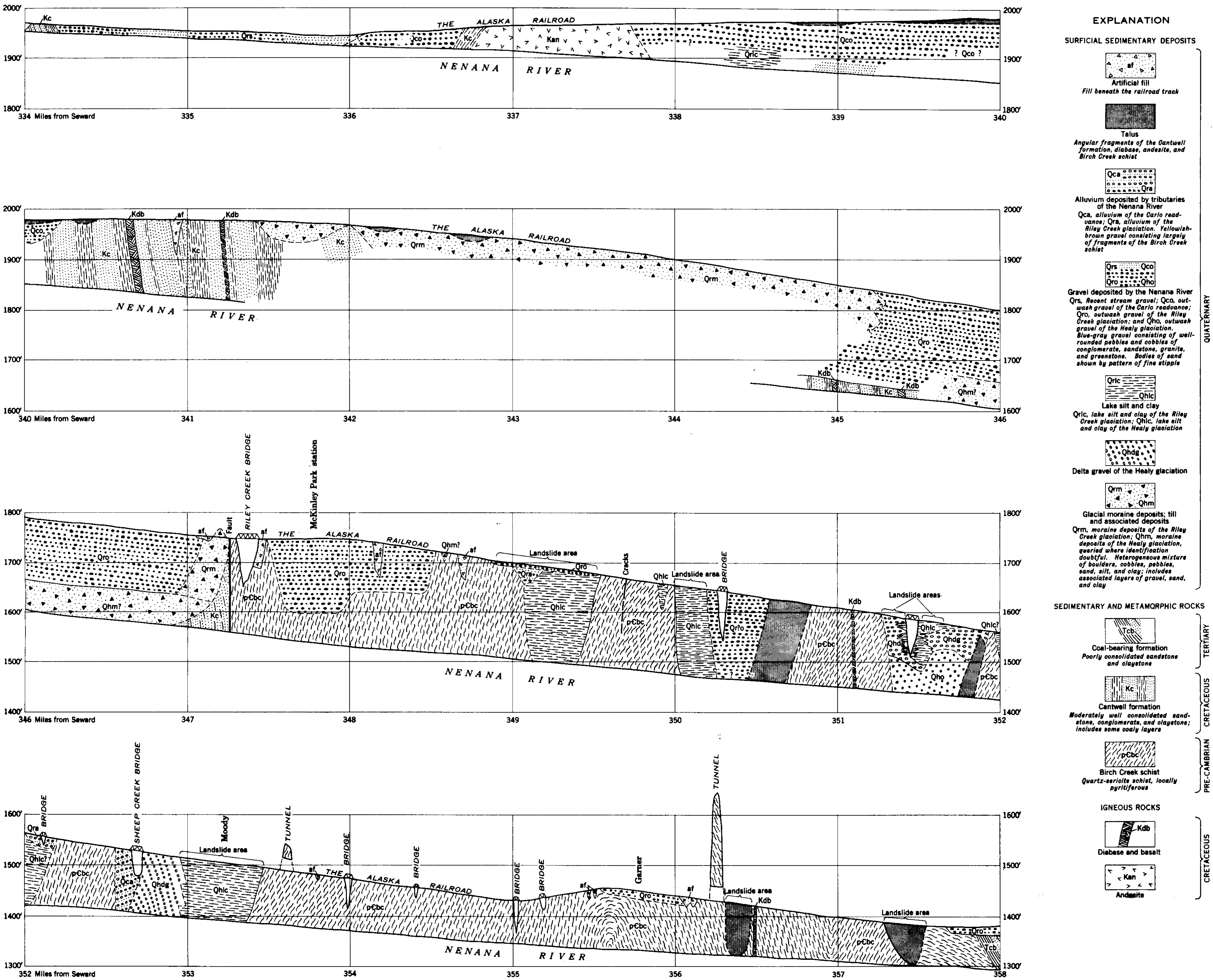

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GEOLOGIC SECTION ALONG THE ALASKA RAILROAD
BETWEEN MILE 334 AND MILE 358, ALASKA