QUATERNARY GEOLOGY OF THE NENANA RIVER AND ADJACENT PARTS OF THE ALASKA RANGE, ALASKA

A thesis presented

by

Clyde Adolph Wahrhaftig

to

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QUATERNARY GEOLOGY OF THE NENANA RIVER AND ADJACENT PARTS OF THE ALASKA RANGE, ALASKA*

(abstract)

by Clyde Wahrhaftig

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

The pre-Tertiary structure is a complex faulted east-trending syncline. Upper Cretaceous rocks in the center are flanked on the north by Pre-Cambrian schist and on the south by Paleosoic and Mesozoic sedimentary rocks. Middle Tertiary structures include step-like monoclines on the north, and anticlines, synclines and fault blocks within and south of the range. In general, as a result of these two periods of deformation, the formations are in broad bands parallel to the range.

Much of the Alaska Range has a dendritic north-flowing drainage superposed on the dominantly easterly bedrock trends. The north-

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*Publication authorized by the Director, U. S. Geological Survey flowing streams alternately follow narrow canyons through east-trending ridges of hard pre-Tertiary rocks and cross broad plains cut on Tertiary rocks. The plains and lowlands on Tertiary rocks 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 Long. 148°00' W. and 149°30' W. Mountains rising 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 restored present height of the surface is about 3,000 feet in the northern foothills, and 7,000 feet along the crest of the range.

Four distinct glacial advances have been recognized along the Nenana River, although deposits grouped with any single advance may represent two or more advances. During each glaciation ice advanced northward from within and south of the range to the northern foothills.

Deposits of the earliest advance include erratics, several 40 feet across, on a terrace 500 feet above the river at Browne and 1,000 feet above the river near Ferry. Near Lignite erratics occur 2,500 feet above the river. Most of the erratics are granite, apparently from near the headwater glaciers. The erratics indicate that an ancient glacier extended at least to the northern foothills and was 16 miles wide. Between this and the next glaciation the Nenana River downcut 200 feet at Browne and 700 feet at Healy, presumably in response to a northward tilting of 25 feet per mile. Tributaries destroyed much of the topography on which the erratics were deposited, producing a non-glacial topography below the upland surfaces on which they lie.

Deposits attributed to a second advance include an outwash terrace with 100 feet of gravel extending along the Nenana northward from Lignite. The terrace is 500 to 1,700 feet below the surface containing the erratics and 350 to 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 this glaciation, as it is 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 glacier probably had a terminus near Dry Creek. The height and slope of its outwash terrace indicate that between this 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 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 no small-scale glacial abrasion features are preserved. Modified lateral moraine ridges and patches of till are preserved on gentle topography. Elsewhere, glacial deposits were removed before the next glaciation. No lakes dating from this glaciation remain. The outwash terrace is about 470 feet above the Nenana near Healy and 85 feet above the river 20 miles north of Healy.

During glacial retreat a pro-glacial lake occupied the gorge between McKinley Park station and Healy, and was subsequently filled with sediments. Building of alluvial cones by tributaries from the west forced the Nenana River, flowing on lake sediments, to the east wall of part of its gorge, where it now has a superposed course in a narrow rock-cut gorge about a fourth of a mile east of the sediment-filled glacial gorge.

Glacial deposits of the fourth glaciation, the youngest major advance, 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 miles up the valleys of the Yanert Fork and Nenana. Ground moraine has well-preserved drumlinoid hills, medial moraine ridge, and many lakes. The outwash train is a set of terraces—the highest 250 feet above the river—with outwash gravel 10 to 160 feet thick. The outwash rests unconformably on eroded lake sediments between McKinley Park station and Moody. Between Moody and Healy the outwash terraces are in the gorge of the superposed Nenana. On Healy Creek, bluffs cut terraces graded to this outwash and reveal only alluvium from creek level to terrace top. This indicates that prior to this glaciation Healy Creek and the Nenana 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 through till and outwash related to the terminal moraine at Riley Creek. These suggest a wholly separate re-advance of the ice after the retreat from the terminal moraine at Riley Creek. No other river on the north side of the Alaska Range shows evidence of this advance. These deposits are explained by assuming that the retreating ice left, near Carlo, a pro-glacial lake that was subsequently drained by erosion of its drift dam. A short re-advance of the glacier pushed foreward the pro-glacial delta to form the end moraine, and a new valley train was built by the heavily loaded glacial meltwater.

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

Plate 9

A. Aerial view, looking west, of the Teklanika and Sanctuary Rivers showing superposed north-flowing drainage crossing east-trending structurally controlled ridges and valleys. Mount Wright is in center of photograph. Photo by U. S. Army Air Corps, 1941.

B. Erratic of the Browne glaciation at mile 382 on the Alaska Railroad. This granite 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 the railroad cut. The man standing on the boulder is 5 ft. 7 in. high.

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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 lower terrace.

B. Outwash of the Carlo re-advance 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.

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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 there existed 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-lying country during the glaciations; and on the north side of the Alaska Range ice tongues moving down the valleys from the range left deposits of till and outwash gravel on the valley floors. The Alaska Range, as will be shown subsequently, was undergoing uplift continuously throughout the Pleistocene; and the effect of this uplift should have been to raise the earlier deposits above the zone of erosion by the later glaciers. The north flank of the Alaska Range should therefore be a favorable place for unravelling the Pleistocene history of Alaska.

Several rivers, rising in the low country on the south side of the Alaska Range, cross the range from south to north to flow into the Tanana. Glaciers which advanced down these rivers were continuous with the Cordilleran ice sheet of southern Alaska; to a certain extent they were distributary glaciers fed by this ice sheet. The glacial history of these rivers reflected to a close degree the glacial history of the Cordilleran ice sheet as a whole. The government-operated Alaska Railroad follows one of these rivers, the Nenana, in crossing the range between Anchorage and Fairbanks. This paper is concerned with the glacial history of this river and of the parts of the range adjacent to this river, and their application to an understanding of engineering problems along the Alaska Railroad.

This paper describes in reconnaissance fashion the glacial geology of an area 78 miles long in an east-west direction and 70 miles wide in a north-south direction, that lies between Long. 147°30' W. and 150°00' W., and between Lat. 63°15' N. and 64°15' N. (see fig. 1). This area is shown on plates 1 and 2. The geology of an area 5 - 8 miles wide along the Alaska Railroad and the Nenana River between Lat. 63°25' N. and 64°15' N. (see fig. 2) is described in somewhat more detail, and is shown on plates 3, 4, 5, and 6. The glacial sequence which was worked out for this narrow strip was applied to the much larger area. The area shown on plates 3 - 6, inclusive, lies between miles 328 and 385 on the Alaska Railroad, and is approximately 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 roughly 50 miles downstream from its source at the Nenana Glacier and ending about 25 miles upstream from its confluence with the Tanana.

<u>History and methods of the investigation</u>: The attention of the Geological Survey was drawn to the Pleistocene problems of the Nenana River as a result of a request from the Alaska Railroad to investigate the causes of landslides on the railroad between McKinley Park station and Healy. These landslides had plagued the operation of the railroad almost from the time of its opening. The author had become interested

in the Pleistocene problems of this area while studying the coal deposits of the Nenana Coal Field, and accordingly was assigned to the Permafrost section of the Geological Survey's Military Geology Unit for the purpose of carrying out the investigation of the landslides.

On October 19, 1947, immediately after several severe earthquakes (St. Armand, 1948, p. 617), the railroad track at mile 351.4 on the Alaska Railroad 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 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 Clyde Wahrhaftig on October 31, 1947, and a reconnaissance of the geology in the nine-mile stretch of track between McKinley Park and Healy was made in October 31-November 2 (Black and Wahrhaftig, 1948). It was decided that a geologic reconnaissance with special reference to Pleistocene geology and engineering problems should be made along the Alaska Railroad between miles 328 and 385. This was undertaken in the summer of 1948 by Clyde Wahrhaftig and John W. James who were in the area from June 15 until August 27, and Wahrhaftig continued the work in the area until November 15, 1948. Information which had been gathered in the seasons of 1944 and 1945 (Wahrhaftig, Hickcox and Freedman, 1951) has been incorporated in the discussion of geology, where appropriate. Wahrhaftig also made re-examinations of the area, particularly the landslide localities, in 1949, 1950 and 1951. The author, assisted by

Allan V. Cox, spent several days in 1951 in mapping geology east of the Nenana River south of the Yanert Fork and west of the river near Lignite. Observations on the glacial geology of the Wood River country were made in 1950 when the author and R. A. Eckhart made a geological survey of that area, and observations on the glacial geology of the Yanert Fork and in McKinley Park were made in 1951 by the author and Allan V. Cox. In 1952, the author and J. H. Birman mapped country on lower Lignite Creek, on Moody Creek, and west of Ferry. The distribution of glacial erratics was a subject of special study.

The geology along the railroad was plotted in the field on maps and profiles supplied by the Alaska Railroad, on a scale of 1:4,800, with a contour interval of 10 feet. Geology at greater distances from the railroad was plotted on vertical and oblique aerial photographs taken by the U. S. Army and Air Corps in 1941, 1946, and 1949. The geology was transferred to topographic maps, with a contour interval of 100 feet, prepared by multiplex methods in 1950, by the Topographic Division of the Geological Survey and these maps are reproduced as Plates 3 - 6 inclusive. Wahrhaftig and James made transit traverses and plane table 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 when the terraces were made, which probably differed from its present course, can no longer be located, it was deemed sufficiently exact to use the line of the

Alaska Railroad as the average position of the river during later Pleistocene time. Plate 8 has accordingly been prepared using distances along the Alaska Railroad as ordinates, with the exception that the distance between miles 342 and 345 is doubled on the profile to allow for the arc of the river in the vicinity of Yanert Fork. The longitudinal profile of the upper terraces and glacial deposits (plate 7) was prepared from the geologic maps (plates 3 - 6).

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; A. 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 Spadem, Ted Nommsen, and Al Cass, Section Foremen; and Jerry Marshall and John Witkowski, Managers of the hotels at Healy and McKinley Park station.

GEOGRAPHIC SETTING

<u>Physiographic Divisions</u>: Most of the area shown in 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 westward and southward to Lake Clark and Lake Iliamna in southwestern Alaska, where it merges with the Aleutian mountains. The highest point in the Alaska Range, and the highest point on the North American continent, is Mount McKinley, which is 20,230 feet high, located about 35 miles S. 35° W. of the southwest corner of the area shown in plate 1. However, the number of high mountains in the Alaska Range is comparatively small. Less than 40 peaks in the whole range 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 appears low as a whole, but is dominated by four great mountain masses: the Mount Spurr-Mount Gerdine group in the extreme southwest, culminating in Mount Gerdine (12,600); the Mount McKinley group, just west of the area shown in plate 1; the Mount Hayes group, culminating in Mount Hayes, 24 miles east of the area shown in plate 1; and the mountains around Mount Kimball, 70 miles east of Mount Hayes.

The Alaska Range is crossed by several low passes and several rivers which head in the lowlands on the south side of the range and flow northward across the range to empty into the Tanana. These rivers are the White River, near the Canadian border, the Chisana and the Nabesna Rivers east of Long. 143° W., the Delta River, at Long. 146° W., and the Nenana River. Elsewhere the range is drained by rivers that rise on its flanks and flow south into the Copper or Susitna Rivers, or north and west into the Tanana and Kuskokwim. Most of these rivers are short and steep, and nearly all those rising in the higher portions of the range head in glaciers. In particular, the mountains around Mount Spurr, Mount McKinley, and Mount Hayes support enormous glaciers, some of which extend 20 or 30 miles from their source 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 in north-facing cirques at lower altitudes than in south-facing cirques.

The northern foothill belt of the Alaska Range, 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 Flats lies along the north border of the area shown in plate 1 (see fig. 3). This part of the flats is a series of coalescing alluvial fans, extending 15 - 30 miles northward from the north edge of the foothills.

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 mountain groups rise higher. The Talkeetna Mountains, the southernmost of the physiographic divisions covering the area of plate 1, are a rugged mountain upland, in which the mountains rise to altitudes of 6,000 feet.

<u>The Nenana River</u>: The Nenana River rises in the Nenana Glacier on the south side of the Alaska Range, about 30 miles east of Windy (plate 1). It flows south of west for about 47 miles, in a braided course along the Broad Pass depression, and turns abruptly northward at Windy to flow directly across the Alaska Range. At Windy the Nenana 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 ten miles of its course, to a point a few miles downstream from Carlo, the Nenana River occupies a broad U-shaped gorge with a nearly flat floor almost a mile wide and with broadly flaring walls rising to heights of 2,000 - 3,500 feet above the river. The gradient of the river in this stretch is gentle, and rapids are few. At a point a few miles north of Carlo the Nenana River enters the depression of the Yanert Fork valley. The river flows along the west side of this depression and occupies a narrow winding terraced gorge, 100-250 feet deep, cut in glacial deposits and bedrock hills that floor the Yanert Fork valley. The river is joined from the east about midway across this depression by the Yanert Fork, its largest tributary, which, rising in a large glacier 30 miles east, flows westward in a braided course to join the Nenana. 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 through a remarkable two-story canyon across a high ridge. The outer canyon is U-shaped, with a floor half a mile to three-quarters of a mile wide, and with broadly flaring walls with truncated spurs rising to heights of 2,500 feet above the canyon floor. In the downstream half of this canyon, and also for a short distance at its upstream end, the river flows in an inner gorge about 500 feet wide and with nearly vertical rock walls 200-300 feet high. Elsewhere this inner gorge broadens out 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 long across the northern foothill belt. Across these foothills it occupies a broad valley with gentle terraced walls, rising from a few hundred to 2,500 feet above the river. The entire width of the valley and its terraced walls ranges from 6 to 10 miles and individual terraces are locally more than a mile wide. North from the foothills the Nenana River enters the Tanana Flats, 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 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 over half is in the area covered in plates 3-6.

<u>Climate:</u> The climatic data for three stations representative of this area are summarized in table 2. Summit is on the Alaska Railroad at the crest of Broad Pass, and is shown on plate 1. McKinley Park station, also on the Alaska Railroad, is shown on plate 1. Its records are perhaps most typical for this region. Nenana is on the Alaska Railroad about 22 miles north of the north edge of plate 1, and its records are typical of conditions along 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.

Snow falls on the high mountains at any time of the year; it can be expected in the valleys any time after the middle of September, and lasts 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 CANYON

Summary of bedrock geology: 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 in the Alaska Range is shown on plate 1. The bedrock formations along the Nenana River, where not overlain by Pleistocene deposits, are shown on plates 3-6. In terms of age, tectonic history, and degree of consolidation they form two strongly contrasted groups: (1) an older group of rocks, ranging in age from pre-Cambrian to Cretaceous, which are well consolidated or metamorphosed. This group contains schists and gneisses, phyllite, chert, argillite, limestone, conglomerate, slate, shale and coal. Greenstone, in part intrusive and in part derived from basic lava flows, is common. (2) A group of poorly consolidated Tertiary rocks which is now confined to the northern foothill belt and lowland areas within the range, but which was once much more extensive. A major unconformity separates the two groups of rocks.

The history of the older group of rocks is very complicated, and includes several known periods of orogeny (Capps, 1940, pp. 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 of deposits borne down the rivers from those which have been 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, with 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 this region. The fault has been traced the length of the Alaska Range from a point near Mentasta Pass westward beyond Mount Foraker, and probably extends much farther in both directions. Another fault in the northern part of the main Alaska Range separates the Cantwell formation of Upper Cretaceous age on the south from Birch Creek schist of pre-Cambrian age on the north (see plate 5).

In addition to the pre-Tertiary structure there are structures imposed by the mid-Tertiary orogeny. Essentially these structures consist of an uplifted area that coincides with the higher part of the Alaska Range, and that is bordered by depressed areas on the south (Broad Pass) and north (Tanana Flats). The Tertiary deformation on the north side of the Alaska Range is a series of structural terraces and monoclines along which the Tertiary rocks are lowered 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 graben that was formed during the mid-Tertiary orogeny and that is occupied by early Tertiary rocks extends westward along the McKinley Park highway, and apparently once extended along the length of the Yanert Fork in the center of the range.

Sedimentary rocks

The 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 (plate 1). It is the bedrock formation in the Nenana River gorge between mile 348 and mile 358 on the Alaska Railroad (plates 4, 5). The Birch Creek schist is predominately 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 easterly and dips 20°-40° southward (see plate 4). The foliation is locally very irregular and highly contorted. The schist is traversed by well-developed joints that commonly strike northward and dip close to vertical. These joints are pre-Tertiary for 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 (plate 6), 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 moderately indurated to 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 various localities in these rocks. Fossils of Devonian and Triassic age have been collected from localities separated by short distances, and in rocks which cannot be distinguished lithologically (J. M. Cobb, personal communication, 1951). Because of the complex structure, and the uncertainties regarding the age of the various rock units in this group, it is shown on the geologic maps (plates 1 and 6) as undifferentiated Paleozoic and Mesozoic rocks.

North of Bain Creek the rocks of this group are largely dark gray to purple argillite, with interbedded graywacke and stretched conglomerate. Outcrops along the railroad consist largely of chert, argillite and conglomerate. The ridge between Windy and Bain Creeks is argillite, graywacke and conglomerate with several large lenticular bodies of limestone. South of Windy Creek, and along the east side of the Nenana River from near the mouth of Windy Creek southward 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.

It has been impossible to work out the detailed structural relations within this area of sedimentary rocks. Dips are steep, and at least one fault zone of large displacement cuts the rocks. Exposures of the argillite and graywacke along the east bank of the Nenana River opposite the mouth of Windy Creek show numerous isoclinal folds and steeply dipping thrust faults deforming and breaking the rocks. Elsewhere, conglomerates have been converted to schistose-like rocks through the stretching of pebbles (Moffit 1915, p. 43).

<u>Cantwell</u> <u>formation</u>: The Cantwell formation was first described by Eldridge (1900, p. 16) with a type locality on the Nenana River (then known as Cantwell River) about 3 or 4 miles above its junction with the Yanert Fork. Since that time it has been found to extend from Big Grizzley Creek, a tributary of the Wood River, westward beyond Mount Foraker (Capps, 1927, p. 93). The Cantwell formation, where it is crossed by the Alaska Railroad, occupies a band 16 miles wide from Clear Creek (mile 330) to McKinley Park station (mile 348) (see plate 5).

The Cantwell formation consists of conglomerate, sandstone, argillite, shale, coaly shale and coal. Sandstone and conglomerate, about 60 per cent of the formation, together make up 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 total 10 to 20 per cent of the sandstone-conglomerate sections. Pebbles in the conglomerate layers average half an inch to 2 inches in diameter, but locally 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 lacking almost completely interstitial material smaller than one-half the average diameter of the pebbles. Compressive forces have moulded the pebbles in these well-sorted layers against each other, giving each pebble a crudely polyhedral shape and indenting some pebbles with others without fracturing any of the pebbles. This has reduced greatly the original porosity of the conglomerate. Sandstone in the massive beds grades from light tan to very dark grayish-brown and dark gray. It has a fairly high content of non-quartzose material, such as black chert, argillite, feldspar, etc., but is probably at least half quartz sand. Light tan sandstone is common along Riley Creek (plate 5) and along the Nenana River north of Carlo. Elsewhere throughout the outcrop area of the Cantwell formation very dark sandstone, graywacke-like in appearance, is the common type. The sandstone has been subjected to the same compressive forces as the conglomerate, and its porosity has likewise been considerably reduced.

Argillite, shale and coaly material together form zones in the Cantwell formation that are as much as 50 - 100 feet thick. Coaly material in these zones is in the form of bone and coal beds one to five feet thick, and spaced 3 - 30 feet apart. Only a few coal beds appeared to be economically minable, even under the most favorable conditions. An attempt was made to mine the coal at mile 341 on the Alaska Railroad (plate 5), but the disturbed nature of the coal and its generally poor quality caused abandonment of the mining operation (Capps, 1940, p. 114).

The Cantwell formation north of mile 336 is well consolidated but only moderately well cemented. It never forms badlands; on the other hand, its fresh outcrops are commonly fairly soft and can be scratched easily with a pick. Exposure to weather toughens the outcrops. The rocks of the Cantwell formation south of mile 336 are much better cemented and more highly indurated than those north of mile 336. They form more rugged mountains and steeper canyon walls, and are jointed into massive and resistant blocks.

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 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 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 is a zone of clayey gouge several hundred feet wide, containing "horses" of solid schist. On the south 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, with the north side down. The displacement is indicated by the offset of a diabase sill. The fact that the Nenana River followed this fault across the ridge of diabase suggests that it is marked by weakened rock, possibly a wide zone of gouge. Small faults, parallel to this fault, that are exposed in the rock walls of the gorge, have no gouge.

The Cantwell formation has been determined to be Late 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 Tangeni Creek. (See plate 4.) 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 in a recent publication of the Geological Survey (Wahrhaftig, Hickcox and Freedman, 1951). Its lithology is summarized briefly as follows: The formation is divided into three members. At Suntrana the lower member is 600 feet thick and consists of about 20 per cent subbituminous blocky-fracturing coal in beds 5-30 feet thick, 40 per cent claystone, and 40 per cent 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 over 100 feet thick in places, lies immediately beneath the base of the coal-bearing formation. Weathering in this zone, which took place prior to 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 persistent bed of brown-weathering claystone which is 80 feet thick at Suntrana. Where this claystone comes to the surface over extensive areas, landslides are common.

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 is coal in beds up to 40 feet thick. Well-sorted pebbly sandstone constitutes about two-thirds of the section. The remainder is claystone, in thin beds commonly underlying the coal beds.

The upper member of the coal-bearing formation consists of medium-grained buff-colored pebbly sandstone in layers 30 to 100 feet thick, separated by zones of clay 10 to 50 feet thick which contain thin woody coal beds. Its thickness at Suntrana is 600 feet, but it thins abruptly westward and is probably only 400 feet thick at Healy, where it crosses the railroad. At the top there 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. Under the influence of frequent freezing and thawing they disintegrate rapidly to their constituent particles, which can be handled easily by the smallest streams. Consequently, their exposures commonly take the form of gullies and badlands, and landslides are very common in the coal-bearing rocks. Because of the ease with which they are eroded, their area of outcrop is 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 strike changes to a more easterly direction and the dip decreases to about 35° N. The broad terrace south of Healy Creek and between Moody Creek and the Nenana River is apparently underlain by the lower member of the coal-bearing group in a syncline, for the white basal sandstone and conglomerate of the lower member crops out at many places around the borders of this terrace, and dips gently toward its center.

The coal-bearing formation on Lignite Creek and along the Nenana River between the mouth of Dry Creek and the mouth of Panguni Creek (pl. 4) is brought to the surface along the crest and north side of a faulted anticline. West of the river only the upper member is present at the surface; both the middle and upper members are present along Lignite Creek, and the middle member is also brought to the surface in the core of a subsidiary anticline exposed on the east side of the river opposite the mouth of Pangeni Creek. Dips in the coal-bearing formation west of the river are gentle. The beds in the vicinity of Lignite are nearly flat; they dip 10°-20° N. and W. along

Pangeni Creek. East of the river dips in the coal-bearing formation are also gentle, but the formation is deformed into an anticline exposed in the bluff opposite Pangeni Creek, and broken by the fault between Lignite and Poker Creeks which bounds this area of 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 over-lying 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, probably early Tertiary. Its exact position within the Tertiary has always been doubtful, owing to the non-diagnostic nature of the fossil remains in it, largely leaf impressions and fresh-water fishes. However, the plant remains and the weathering profile at the base indicate that the climate during deposition of the formation was much warmer than at present, and was probably comparable to the present climate of southern United States. In the Tertiary rocks of the Yakataga district on the south coast of Alaska, according to Don J. Miller (personal communication, 1951), a late Eocene warm-water marine fauna was succeeded by an early or middle Oligocene cold-water fauna, which was succeeded in turn by late Oligocene or early Miocene marine glacial deposits. It seems reasonable to assume that the same climatic change would have affected the Alaska Range, and therefore it is unlikely that the coal-bearing group is any younger than early Oligocene.

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, which was given the name Nenana gravel by Capps (1912, p. 30) 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, pp. 152-153) and by Wahrhaftig (1951, pp. 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. Pebbles are composed of schist, quartzite, sandstone, and conglomerate from the Cantwell formation, and granite and other intrusive rocks which are abundant in the Alaska Range. Interstitial material is coarse to very coarse 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 of the formation and in the upper part 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 which 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, in which the pebbles range in average size from half an inch to 2-3 inches, and pebbles larger than 4-5 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 of graywacke and conglomerate, especially, have weathered rinds as much as an inch thick, in which the graywacke is more friable and iron-stained. The core of each pebble is generally unweathered. Pebbles of certain kinds of granite and volcanic rocks are decomposed to angular sand or grus, in fresh outcrops in roadcuts and river banks as well as elsewhere. 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 run-off for erosion, and because the coarseness of its constituent particles makes them less easily removed by streams. Hence, the outcropping edge of the Nenana gravel, where underlain by the coal-bearing formation, forms hogbacks and ridges which 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 that the McKinley Park highway follows for 20 miles west of McKinley Park station.

The Nenana gravel along the Nenana River is generally parallel in attitude to the coal-bearing formation beneath it. Elsewhere, however, there are indications that an angular unconformity separates the two formations (Wahrhaftig, 1951, pp. 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., decreasing northward within a mile 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 Pangeni 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.

No fossils have been found in the Nenana gravel, and its age, therefore, is still uncertain. Capps (1940, pp. 126-128) regarded the Nenana gravel as definitely Tertiary and younger than the coal-bearing formation. The weathering rind present on most pebbles, and the brown color of the gravel contrast strongly with the prevailing unoxidized condition and gray color of the outwash and terrace gravel to be described below. Presumably, therefore, the Nenana gravel was deposited under climatic conditions much different from those prevailing in the Alaska Range today, and probably not greatly different from the climate under which the coal-bearing formation was deposited. In subsequent chapters of this paper it will be shown that a complicated history of mountain-building, partial peneplanation, and uplift followed the deposition of the Nenana gravel and preceded the earliest recorded Pleistocene glaciation. For these reasons the Nenana gravel is assigned to the Tertiary, and tentatively assigned to the Oligocene or Miocene.

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 plates 3 and 4.) It probably underlies the Nenana gravel from Slate Creek northward. 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, pp. 22-23) from its exposures in the canyon of the Totatlanika River, 15 miles east of the Nenana.

The Totatlanika schist in the areas shown in plates 3 and 4 has two types. On Slate Creek, and on Chicken and Moose Creeks, it consists of fine-grained yellow slate with scattered grains of feldspar and quartz less than 0.1 inch in diameter. In the mountains east of Browne it is a coarse-grained gneiss which consists of subhedral porphyroblasts of orthoclase as much as half an inch in average diameter and porphyroblasts of quartz as much as 0.1 inch in diameter, 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 roughly 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, but not necessarily that it had been horizontal throughout its existence.

According to Capps, (1940, pp. 106-107) the Totatlanika schist is probably Paleozoic and earlier than Middle Devonian in age.

Greenstone: A band of greenstone crosses the Alaska Railroad between miles 327.5 and 329.5. It is shown on plates 5 and 6; on plate 1, however, it has not been distinguished from the undifferentiated Paleozoic and Mesozoic rocks, with which it is grouped. It apparently makes up Panorama Mountain, as well as the Windy Peaks, and appears to extend westward to the head of Clear Creek. The greenstone is predominantly dark green, but weathered surfaces are dark brown. Where it crosses the railroad it appears to have two types. The southern half of the greenstone body consists of blocks of massive unaltered gabbro surrounded by zones of intense shearing and serpentinization. The rock is moderately closely jointed, but still massive enough to form the most rugged mountains in this part of the Alaska Range. Microscopic study of a very fresh specimen collected from talus west of the railroad showed it to consist about 55 per cent of calcic labradorite in euhedral grains 2-3 millimeters long, and 40 per cent of augite in aggregates of grains, in which individual crystals are 1/3 to 1 millimeter in average diameter. The aggregates of augite generally fill the spaces between the feldspar crystals and are moulded to their shape, giving the rock an ophitic texture. Five per cent of primary magnetite or ilmenite is present as skeleton crystals in the feldspar and augite. Locally the augite is altered to a fine-grained mass of chlorite and serpentine with some secondary quartz. Feldspar has cloudy patches which may be incipient saussuritization. A specimen of the coarse-grained type from 2 miles south of Slime Creek on the McKinley-Cantwell highway is fresh-appearing rock with ophitic texture and consists of labrodorite (An 54), augite, and ilmenite in grains between 0.2 and 2 millimeters in average diameter and with small amounts of chlorite and sericite as alteration products. This type of coarse greenstone has probably supplied most of the pebbles of the "green ophitic diorite" in the Nenana gravel (Wahrhaftig, Freedman and Hickcox, 1951, pp. 152-153, and Wahrhaftig, 1951, pp. 178-179), and pebbles and boulders of similar material in gravels of Quaternary age.

A fine-grained type 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 which 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, transporting them a short distance distance downstream, produced 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 recrystallised and altered to a mass of fine-grained oligoclase, chlorite, epidote (?), and an unidentified mineral. The phenocrysts, probably originally 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; it is presumably intrusive. The greenstone body narrows westward and has an irregular western contact with sedimentary rocks which include ferruginous slates. On the north the greenstone is in contact with the Cantwell formation. Whether it is intrusive also into 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, and 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. However, sills of gabbro similar to this greenstone are intruded into the Cantwell formation--the largest that was observed was on Young Creek, a tributary of the Wood River.

Igneous rocks in the Cantwell formation: The Cantwell formation locally contains interbedded flows and tuffs; and, 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, west of the Sanctuary River they constitute a considerable part of the formation (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 1 3/4 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 the accompanying table (table 2), which is based on a few thin sections from these rocks. The collection is not representative, but indicates chiefly the range in composition of these rocks. The most abundant intrusive rock in the Cantwell formation is diabase. This rock is dark green to black on fresh surfaces, and 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. 5). Specimens nos. 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 same 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 approximately the same stratigraphic position within the Cantwell formation, and may be part of a large sill-like intrusive (pl. 5). This sill is about 500 feet thick where it crosses the Nenana River. It may be continuous with a dike-like body that lies along the fault between the Cantwell formation and the Birch Creek schist and extends from west of McKinley Park headquarters as far east as 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 four 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, ranging in composition from andesite to rhyolite, in which the groundmass is commonly fine-grained, are common in the Cantwell formation. Sills and irregular intrusive bodies of diabase and andesite porphyry with 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 5 only on the east side of the mountain, but 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 lat. 63°37'30" N., and andesite and latite are more abundant south of it.

Igneous rocks that intrude the Birch Creek schist: Basalt dikes are common in the Birch Creek schist. They are generally vertical, strike roughly north to N. 30° W., and are 5-50 feet thick. They are spaced 1,000-2,000 feet apart on the average. The dikes were intruded along cross-joints of the Birch Creek schist, which strike N. 10° E. to

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.4). Apophyses from the body, are exposed in the railroad cut west of the river. One minor apophysis of this intrusive is a thin dike that strikes eastward and dips northward, perpendicular to the schistosity. It has been offset a few inches or 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 a white conical mountain known locally as Sugarloaf Mountain, about 8 miles south of Healy. The rhyolite body was visited by the author and R. A. Eckhart in 1950, and the following description is summarized from their report (Wahrhaftig and Eckhart, 1952, pp. 2-6).

The main body is about 3500 feet long and 2000 feet wide. It consists largely of white fine-grained rhyolite with small phenocrysts of quartz, oligoclase and biotite. The rhyolite contains an abundance of nearly spherical vesicles, each filled with a single large crystal of calcite. In places the rhyolite exhibits close platy structure. A body of basalt 700 feet wide and 2,000 feet long lies on the southwest side in nearly vertical contact with the rhyolite body. It was impossible to determine which was the younger in the short time of the examination. The basalt is similar in appearance to the basalt of the dikes. A patch of Tertiary coal-bearing formation that consists of conglomerate with pebbles of quartz and chert, and brown, slightly silicified coal is exposed at the base of the southeast corner of the rhyolite body, outside the area shown in plate 4. Its relations with the rhyolite body, and the absence of rhyolite pebbles in the conglomerate make it extremely unlikely that the coal-bearing formation is younger than the rhyolite, and it appears, therefore, that the rhyolite was extruded onto the surface 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 Sugarloaf Mountain (Wahrhaftig, 1951, p. 174), may have been derived from this rhyolite. This is the only known instance of igneous activity in the Alaska Range during the period of deposition of the Tertiary rocks.

The petrography of the intrusives into the Birch Creek schist is summarized in table 3.

TABLE 3 PETROGRAPHY OF INTRUSIVE ROCKS IN THE BIRCH CREEK SCHIST

Specimen Number	Percent Plag.	Comp. Plag.	Percent Augite	Percent Biotite	Percent Serpentine	Others
1	50	An60	15	1-2		Ilmenite 5%, Calcite 2%, Sphene (?) 25%.
22	50-60	An70	20-25	5-8	10-15	Ilmenite 5%.
7	2*	Oligoclase	—	1	—	Quartz 7% Groundmass = Quartz 30% Orthoclase 60%
10	30	Labradorite	—	—	?	Basaltic hbd. 10% Apatite and magnetite present.

*as phenocrysts

Specimen Number	Texture	Av. size Phenocrysts	Av. size Groundmass	Name	Locality
1	Diabasic	0.3-0.5 mm	—	Diabase	Ridge north of Gagnon Creek
22	Sub-ophitic	1 mm	—	Diabase	Between Healy and Lignite Creeks
7	Porphyritic	1 mm	0.05 mm	Rhyolite	Southeast corner of Sugarloaf Mountain
10	Seriate-porphyritic	0.5 mm	0.05-0.1 mm	Basalt	Southeast corner of Sugarloaf Mountain

SUMMARY OF THE PLEISTOCENE HISTORY

Introduction: It is desirable, at this point, to present a brief summary of the Pleistocene history, before entering into a detailed discussion of the Pleistocene deposits. This summary, presented in the following paragraphs, includes none of the supporting evidence, the description of which is left for the following sections of this paper. The purpose of this summary is manifold. In the first place, it will give the reader a general picture of the events indicated by the Pleistocene deposits and landforms. In so doing, it will give him also a frame of reference in which to relate the separate pieces of evidence as they are described in the body of the report. This should make the following sections, which are largely descriptive, both easier and more interesting to read. Finally, this summary will enable the reader to evaluate more critically the pertinence of each item of evidence and so arrive at a more sound opinion of the validity of the conclusions.

Events leading to the Pleistocene 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 grabens, structural terraces, monoclines and tilted fault blocks. At the end of the mid-Tertiary orogeny the Alaska Range stood as a belt of mountains of considerable yet variable height, bounded on the north and south by depressed 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 its later stages. Erosion quickly reduced the areas of Tertiary rock 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 of an extensive erosion surface of low relief in late Pliocene or early Pleistocene time, but presumably this period was concerned largely with the slow uplift and erosion of this part of the Alaska Range until, by the end of the Pliocene, much of the area shown in plate 2 was nearly featureless plain. 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 3,000 feet high. A few additional widely scattered monadnocks rose above the peneplain.

Late in the Pliocene or early in the Pleistocene an uplift centered south of the Alaska Range inclined the erosion surface 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 eroded by the consequent north-flowing streams. 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.

<u>The Browne glaciation</u>: 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 to the west of the Nenana River and the Mount Hayes group to the east. In the eastern group, and presumably <u>a fortiori</u> 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. 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 plate 2). 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. 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. This glacial advance, here called the Browne glaciation, on the Nenana extended farther downstream than that of any subsequent stage.

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, but much of this tilting was in a monoclinal flexure between Lignite and Ferry where the slope of the tilting was 37 feet per mile northward.

During the period of uplift between the Browne and the younger Dry Creek glaciations, 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, while in the same amount of time gullies were barely able to trench the sides of mountains supported by the hard rocks in the cores of the mid-Tertiary anticlinal uplifts. The headward growth of subsequent tributaries along easily-eroded zones, particularly at the base of the coal-bearing formation, was apparently initiated during this period. The only drainage change which appears definitely 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 by capture into a broad arc northeastward around this plain; and 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.

<u>The Dry Creek glaciation</u>: 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, the mountains bordering the Gulf of Alaska were probably being uplifted at the same time and may have been sufficiently high to catch most of the moisture from the Pacific Ocean and to decrease the amount of snow accumulation in the Alaska Range. The Dry Creek glaciation appears to have reached 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 meltwater 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 advent of the next glacial advance, the northern foothill belt had been inclined northward about 17 feet per mile. The uplift at Healy was about 500 feet. During this interglacial episode many drainage changes took place in the Alaska Range, with the result that the drainage basin of the Nenana River was enlarged at the expense of the Totatlanika River to the east. Lignite Creek extended headward along the zone of soft rocks at the base of the coal-bearing formation to capture the headwaters of Marguerite Creek. At the same time Healy Creek eroded headward along the same zone where it was brought to the surface by faulting farther south, to (pl. 1) to capture headwaters which for a short time flowed into Lignite Creek. Minor drainage changes of similar nature took place elsewhere in the Alaska Range. These involved the capture of portions of north-flowing consequent streams by short subsequent east- or west-flowing streams, so that many streams now draining the north slope of the Alaska Range consist of long northward-flowing consequent segments joined by short east- or west-flowing subsequent segments.

The 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 Alaska Range and in the ranges south of the Alaska Range, as it had done on at least two previous occasions. These glaciers advanced down the river valleys and accumulated as a great intermontane ice sheet in southern Alaska. Most of the ice of the Nenana glacier probably went southwestward down Broad Pass to coalesce with 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 contributions 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 5 miles wide. It is possible that the Healy glaciation on the Nenana River was complicated by a short period of retreat, when the ice withdrew several miles back of its point of maximum advance, and subsequently re-advanced to the former maximum position, but at a slightly lower altitude. Glaciers advanced down the Sanctuary, Teklanika, and Savage Rivers almost to the McKinley Park Highway, and down the E. Fork Toklat 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 into 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 ice of the Healy glaciation may have been interrupted by standstills or even slight advances. Eventually the ice retreated far back 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.

<u>The Riley Creek glaciation</u>: The youngest recognized ice advance is the Riley Creek. Its extent, shown on plate 2, was considerably less than the extent of ice during 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.

There is evidence which suggests that the ice advance of the Riley Creek was a double or multiple advance, like that of the Healy—separate advances being separated by short periods of minor retreat. The advance which built the terminal moraine at the mouth of Riley Creek was complex, retreating and re-advancing at least twice over a distance of several hundred yards.

Downstream from the termini of the glaciers the rivers built deposits of outwash gravel which were several hundred feet thick at the glacier fronts and which tapered downstream to a few feet thick 20-30 miles north of the glacier fronts. 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 super-glacial moraine. South of this ice the glacial meltwater built an outwash plain which abutted against the stagnant ice. That outwash plain now fronts the depression which was left by the melted-out ice. When the ice front stood at Windy, a proglacial lake apparently occupied the valley of the Nenana River for several miles north of Windy. While the lake occupied the canyon the debris from the glacier was presumably being 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 re-advanced 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 which is 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 glaciers 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 several hundred or a few thousand years ago by a short, sharp, cold period which caused a general glacial re-advance and the growth of rock glaciers. This was followed by a second period of climatic amelioration which was followed in turn by a second cold period that began a few centuries ago. This period reached its climax between 1880 and 1920, and is apparently now on the wane.

THE PRE-PLEISTOCENE EROSION SURFACE

Evidence for the erosion surface: A striking discordance exists between the drainage of the Alaska Range and its topography and underlying structure. The simple dendritic pattern of the north-flowing streams--the forks of the Toklat, the Teklanika and its tributaries, the Nenana River and Riley Creek, Totatlanika and Tatlanika Creeks--give no clue to the fact that the predominant trend of the ridges is eastward (pl. 2). Clearly these streams originated on topography or rock formations that had no similarity to the topography of the present Alaska Range. It is extremely 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 are far too feeble to have maintained themselves across rising ridges of schist and gneiss, and would quickly have been diverted, by capture, toward more vigorous streams. The upper Sushana River, some of the forks of Totatlanika Creek, and Gold King Creek, for instance, cross ridges of hard rock through deep canyons 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 (Capps, 1940, plate 3). 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 nearly undeformed late Tertiary sedimentary rocks--that this plain was subsequently inclined northward, and that a consequent drainage developed on it. It remains to be determined whether or not any remnants of the plain exist, what its original limits were, and the amount of subsequent deformation.

Many flat surfaces cap mountain tops 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. 2); the nearly flat top of the mountains through which the Teklanika and Sushana Rivers flow at about lat. 63°55' N. (pl. 2); Jumbo Dome and the mountains north and east of Jumbo Dome, around the headwaters of California and Buzzard Creeks; and the mountaintops on and around Rex Dome. Although all these flat-topped mountains truncate the structure of the underlying schist they are not necessarily remnants of the late Tertiary or early Quaternary erosion surface; in fact, most of them do not owe their origin solely to this surface.

Many smooth surfaces and areas of low relief in the Alaska Range are portions of the folded and exhumed 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 through which the Nenana River has cut its gorge between McKinley Park and Healy are remnants of that unconformity. The facets truncate at a considerable angle the schistosity in the Birch Creek schist. The slope of these facets is as steep as and in places steeper than the dip of the Tertiary beds that are exposed at the base of the hills, and the facet surfaces 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. 2).

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 thought to have a similar origin.

The Broad Pass depression, through which the railroad crosses the divide between the Pacific and Bering Sea drainages just south of the Alaska Range, is eroded out of a graben in Tertiary rocks. Patches of Tertiary rocks lie on the floor of the depression, and the walls are much dissected and modified fault-line scarps. (Wahrhaftig, 1944, p. 4).

Nenana gravel underlies the plain which is followed by the 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 Pleistocene Yanert glacier, for this glacier and the Pleistocene Nenana glacier probably existed over the same periods of time, and the much larger Nenana glacier, both above and below its confluence with the Yanert glacier, failed to carve a canyon wider than 1 mile.

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 numerous canyons with steep walls. The slope truncates steeply dipping beds in the Cantwell formation. The mountain rises high above the highest levels reached by the ice of the later glacial stages, i. e., those that have left clear marks of their presence in the topography. Although erratic boulders deposited by some of the earlier glacial stages rest on this 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, an attempt to explain this slope through processes of solifluction similar to those operating elsewhere in Alaska (Taber, 1943, pp. 1451-52; Eakin, 1916, pp. 76-78), must also explain the general absence of such slopes on mountains of similar age, at the same altitude, that are cut in similar rocks 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 the unconformity at the base of the Tertiary rocks, here deformed into an anticline.

Surfaces of similar origin are widely distributed throughout the Alaska Range, 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 (pl. 1)---are flanked by terraced lowlands underlain by Tertiary rocks which dip away from the mountains at angles approximately equal to the slope of the mountainsides. Along the crests of the anticlines and along structural terraces these surfaces should be 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. Such seems to be the case, for example, with the top of the mountain crossed by the lower Teklanika and Sushana Rivers. (See plate 1.) Small patches of basal white quartz conglomerate resting on such flat surfaces as those around Rex Dome demonstrate that these surfaces must coincide with the unconformity at the base of the coal-bearing formation.

In a few places, however, there is evidence to support the contention that some of the flat mountaintops are remnants of the late Tertiary or early Quaternary erosion surface. Mount Wright and its neighbors are the mountains for which this evidence is the strongest. In the first place, the surface on the top of these mountains makes a sharp angle with the triangular facets on the spurs along the north side of the mountain—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 top of the mountain is not part of a stripped unconformity, for it could be the unconformity 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 the top a thick layer of conglomerate made up largely of boulders of Birch Creek schist. This schist could have come only from the mountains north of the McKinley Park highway that include Mount Wright and its neighbors, for no Birch Creek schist occurs south of the highway. The layer of conglomerate containing the schist is deformed with the rest of the conglomerate, and dips 30° S. near the mouth of Savage River. The coarse pebbles of Birch Creek schist in the folded Nenana gravel several miles north of Mount Wright could have been derived only from a range of mountains along the site of Mount Wright and its neighbors, and these mountains could not have been buried by the Nenana gravel, for the layer of schist pebbles lies near the top of that formation. Furthermore, the surface on which the Savage, Sanctuary, and Teklanika Rivers were consequent must have been formed after the deformation of the Nenana gravel, and must have truncated folds and fault blocks involving the Nenana gravel. It is very likely that the flat surface that truncates the structure of the schist in Mount Wright and its neighbors is part of that surface.

<u>The nature and topography of the erosion surface:</u> It is not possible to demonstrate conclusively that the other flat mountaintops are part of the late Tertiary or early Quaternary erosion surfaces. The mountaintops of this part of the range, however, are probably not far below the level of the erosion surface, for summit levels between Long. 148°10' W. and Long. 149°30' W., are accordant between 6,500 and 7,000 feet. A reconstruction of the erosion surface, with 1,000-foot contours on its present (restored) position, is shown in figure 4. This reconstruction is based on the assumption that the top of Mount Wright is a remnant of the surface, and that the present position of the surface, if restored, would have a gentle northward slope and would just clear the tops of the mountains in this part of the Alaska Range. As figure 4 shows, the erosion surface has a present slope of about 90 feet per mile northwestward. If the gradient of this 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 Alaska Range. As will be shown in the following sections, much of this uplift took place gradually throughout the Pleistocene, during and between the successive glaciations.

Fig. 4 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 unreduced 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 Yanert Fork, 1,000-6,000 feet above the erosion surface have a moderately well-developed trellised drainage, with westward flowing rivers and glaciers. This area was likely an unreduced highland rising out of the low-lying erosion surface. It probably remained a highland because, at the time the erosion surface was being carved, the area consisted largely of hard pre-Tertiary rocks already possessing considerable relief, whereas the country to the northwest and southwest was underlain at the surface 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 and forms a drainage divide along a band of hard rocks which lies 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 the large group of high mountains rising above the erosion surface and culminating in Mount McKinley which probably had an altitude of 10,000-13,000 feet.

THE BROWNE GLACIATION

<u>Glacial deposits along the Nenana River:</u> The oldest recognized glacial deposits on the Nenana River consist of scattered boulders and blocks of granite on some of the higher mountains on either side of the Nenana River. Boulders choking the beds of small tributaries from these mountains, and in the bed of the Nenana itself, outside the limits of later glaciations, are believed to have slid or been let down to their present position from topography which was inherited from the Browne glaciation and is now completely destroyed. These occurrences of boulders are shown on fig. 5, and on plates 3, 4, and 5, and are described from south to north.

Two large boulders of granite, the largest approximately 20 feet high, rest on a mountain of sandstone of the Cantwell formation at an altitude of 3,400 feet, about one mile south of the McKinley Park headquarters (pl. 5). Granite boulders 5 - 10 feet in average diameter are found in the bed of Copeland Creek, tributary of Moody Creek (fig. 5). These boulders are found for two miles up Copeland Creek, the canyon of which appears never to have been occupied by a glacier.

Boulders of granite, gabbro, and conglomerate, from 1 foot to 10 feet in diameter, are found along Moody Creek as far upstream as a point 6½ miles southeast of its mouth. These rocks are all foreign to the drainage basin of Moody Creek. No boulders of foreign rocks were observed beyond that point, although the creek was carefully examined for another 8 miles upstream. During the field season of

1952, a record was kept of the number of foreign boulders larger than 5 feet in diameter observed along Moody Creek. The results of this record are shown as a graph, plotted along Moody Creek in figure 5. This graph shows the density of large foreign boulders along Moody Creek, plotted as the number of boulders per mile of length of the projection line which is the base of the graph. In preparing this graph, counts were kept of the number of boulders between selected points on Moody Creek. The points were then projected to the base of the graph, and the intercepts measured. The number of boulders in each intercept, divided by the intercept distance, in miles, gave the number of boulders per mile, which was plotted at the midpoint of the intercept (shown as a small circle on the graph). The points were connected by a curve, to give the graph shown along Moody Creek in figure 5.

Large boulders of granite, conglomerate, and gabbro are found along the lower 6 miles of Healy Creek and in all streams which enter Healy Creek in the lower 6 miles of its course. None are present along upper Healy Creek, or in the basins of Coal and Cripple Creeks. Granite boulders, the largest of which is 30 feet long and 15 feet high, are found as high as 3,300 feet in altitude and as far east as Suntrana, on the ridge north of Suntrana. Granite boulders choke the beds of some of the creeks draining north from this ridge into Lignite Creek.

Large boulders are present in great abundance along lower Lignite Creek. In 1952 a count was made of these boulders, similar to that made along Moody Creek. A similar graph was prepared showing the concentration of boulders along Lignite Creek. This graph is shown on figure 5. The concentration of boulders is greatest about 3 miles above the mouth of the creek, above which point the concentration of boulders falls off abruptly. East of a point 6 miles above the mouth of the creek there are no large boulders except for 4 large boulders of granite and gabbro, the largest 15 feet across, which are 9 miles above the mouth of Lignite Creek. (See figure 5).

Granite boulders are scattered abundantly in an east-trending band along a ridge between the east and middle forks of Dry Creek, at an altitude of 3,100 feet. (See figure 5.) A few boulders were observed in the valley of the west fork of Dry Creek, and their positions are plotted on figure 5.

Granite boulders are scattered abundantly over the surface of the ridge north of Dry Creek, as far west as a point about 6 miles west of Healy. Beyond this point the ridge is nearly free of boulders, except for a few granite erratics near the top of the 3,944 mountain on the ridge. The southwestern limit of abundant boulders on the north side of this ridge is sharply defined; it crosses the ridge approximately at the point of an abrupt change in the height of the crest of this ridge. East of this point the crest has an altitude of about 2,800 - 3,200 feet; west of this point its altitude is about 3,800 feet. (See plate 4.)

The abrupt change in crest altitude of the ridge does not reflect any change in the underlying structure. The ridge is a hogback of Nenana gravel, and the structure of the gravel along this ridge is unbroken and uniform from Dry Creek to the Savage River, the strike of the bedding nearly constant at about N. 70° - 80° E., and the dip between 30° and 45° north. No fault crosses the ridge. The crestline of the lower, eastern part of the ridge is in part at a horizon low within the Nenana gravel, and this part of the ridge is characterized by several long even-crested north-trending spurs; elsewhere this part of the ridgecrest crosses the structure transversely. The crestline of the higher, western part of the ridge is at a zone of coarse gravel high in the Nenana gravel, and the north face of the ridge is a smooth dip slope. The gravel horizon which marks the crest of the western part of the ridge crops out at the north ends of the spurs on the eastern part of the ridge. There is no change in lithology of the Nenana gravel to account for the abrupt shifting in stratigraphic position of the crestline, or for the abrupt change in the height 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 eastern part of the ridge is thought to mark an ancient valley floor of the Nenana River. The western limit of abundant boulders coincides closely with the west wall of this ancient valley.

On the east wall of the Nenana River gorge, between miles 349 and 352 on the Alaska Railroad, are four even-crested ridges, at right angles to the river, with crest altitudes of 3,000 - 3,500 feet. (See plate 4.) They give the impression of marking an ancient valley floor level or terrace on the Nenana River, and would define an open-valley stage of the gorge. This open-valley stage would probably have been the same as that recorded by the ridge-crest north of Dry Creek.

Northward from the ridge north of Dry Creek the abundant boulders litter the surface of two low parallel ridges which lie on either side of the divide at the head of Fish Creek. The eastern of the two ridges forms the drainage divide between the Nenana and Savage Rivers. Continuing northward the belt of abundant boulders coincides with the remnant of a high bench or terrace at about 2,600 feet which flanks the mountain west of Slate Creek. (See plate 4.)

West of the belt of abundant boulders, scattered boulders are found on the summit of the 3,674-foot mountain about 8 miles west of Ferry and on the ridges of Nenana gravel which extend westward from the summit of this mountain, flanking the schist core of the anticline, toward the Savage and Teklanika Rivers. (See plate 1 and figure 5.)

The mountain, 3,941 feet high, north of Lignite Creek, has many boulders scattered over its nearly flat upper surface. Most of these are granite. They are several feet to 40 feet in diameter. A few boulders are found on the ridge east of Elsie Creek. (See figure 5.)

Northward from Moose Creek and from the mountain west of Slate Creek, the valley of the Nenana River is flanked on either side by a high terrace with a relief of about 100 feet. The riser of this terrace is a steep bluff about 500 feet high. This terrace slopes northward from an altitude of 2,100 - 2,200 feet in the vicinity of

Ferry (pl. 3) to an altitude of 1,200 feet about 2 miles north of Browne (pl. 3). It is cut on Nenana gravel, the structure of which it truncates. The terrace is trenched by canyons several hundred feet deep. Large white granite boulders, similar to those mentioned above, are scattered abundantly over part of its surface, and are strewn down its slopes. (See figure 5.) At a few places deposits of sand and gravel, as much as 100 feet thick, containing these boulders, mantle the terrace. 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 plate 9-B.)

Westward, beyond the limits of this terrace, the dissected rolling upland underlain by Nenana gravel from the latitude of Ferry northward to the latitude of Browne (pl. 1 and fig. 5) has scattered boulders of granite and conglomerate as much as 20 feet across. Unlike the concentration of boulders on the terrace, which locally amounts to several hundred per square mile, the concentration of boulders west of the terrace is only one every few square miles. The boulders, however, are of the same granite as the boulders on the terrace. A similar boulder was observed on top of the 2,540-foot mountain west of lower Windy Creek, and beyond the east limit of the terrace. (See figure 5.)

A few boulders can be seen in the Nenana River, where they must have remained in the same position for a long time. One such boulder, in the middle of the Nenana River 2 miles north of Healy, is capped by a patch of turf from which is growing a tree about 20 feet tall.

The granite from all these boulders is strikingly similar petrographically to that which forms a large stock between the Yanert glacier and the Nenana glacier, and the boulders were probably derived at least in part from this stock. Presumably also, similar granite occurs elsewhere in the headwaters of the Nenana River, for granite stocks are described by Pogue (Moffit, 1915, pp. 56-58) at the headwaters of Seattle Creek and between Wells Creek and Bruskasna Creek.

These boulders were first described by Capps (1912, p. 35) who recognised them as evidence for a glacial stage older than the Wisconsin and separated from it by a considerable interval of time (Capps, 1931, p. 7). The boulders on the terrace near Browne define this glacial advance, which will be referred to in this report as the Browne glaciation.

<u>The glacial lobe defined by the glacial deposits</u>: The distribution of the glacial erratics of the Browne glaciation suggests that a great glacier advanced from the highlands around the Yanert and Nenana glaciers westward and northward down the Nenana River to 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. It had been incised by the Nenana River almost 2,000 feet below the level of

the late Pliocene or early Pleistocene 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 have been constructed on the inferred valley floor of the Nenana River during the Browne glaciation; these are shown on figure 5.

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 wall and glacier is true, the occurrence of widely scattered boulders far beyond the limits of the valley is difficult to explain. If the glacier which deposited the abundant boulders along the borders of the valley also deposited the widely scattered boulders beyond the valley, a rather curious glacial regime must be imagined to account for the formation of both types of relic till during a single glacial advance. The glacier would have had a short period of great expansion during which it carried little till, and subsequently would have retreated within the valley and there accumulated massive moraines of which the abundant erratics are the remnants. A more reasonable explanation, to the author's way of thinking, would be that the widely scattered boulders represent a glaciation earlier than the Browne glaciation, and separated from it by a long interglacial period. In an effort to determine whether or not the widely scattered boulders on the high mountain tops 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 on the Nenana River would have had a structure and thickness similar to the glaciers of the later glacial periods with similar topographic position in the Alaska Range. The thickness of ice of those later periods, as determined by well-defined ice-contact features high on the sides of valley walls, was measured at several localities on many of the rivers in the Alaska Range. These thicknesses are presented in table 4:

TABLE IV

THICKNESS OF ICE OF THE LATER GLACIATIONS ON RIVERS OF THE ALASKA RANGE

River	Distance in miles from terminus to point of measurement	Thickness in feet at point of measurement	Average downstream decrease in thickness, feet per mile
	HEALY GLACIATION		
Nenana	19	1,000	53
Wood	19	1,800	95
E. Fork 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
E. Fork 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 would have increased roughly 100 feet per mile for about 15 miles south of its terminus, and beyond that point it would have remained relatively constant. Its maximum thickness in the vicinity of Lignite was possibly no more than 1,800 feet, and 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 this table. It could, therefore, have over-ridden the 3,941 mountain at the head of Elsie Creek, as well as the 3,674 mountain southwest of Ferry and the 3,944 ridge west of Healy, and could, therefore 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 over-rode 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. The possibility that erosion subsequent to the Browne glaciation removed most of these boulders is unlikely, for the 3,674 mountain is graded to the terrace formed during Browne glaciation on the east side of the mountain, and, furthermore, such erosion, if it took place, should have delivered many boulders to the Teklanika and Totatlanika drainages, yet no foreign boulders were found on these streams or on the streams draining into them, although a careful search for the boulders was made.

There thus appears to be some evidence to suggest that the erratics here grouped under the Browne glaciation on the Nenana River are actually the product of two separate glacial advances; yet it is entirely possible that they were deposited during a single glacial advance.

Uplift of the Alaska Range since the Browne stage: The present slope of the valley floor formed by Browne glaciation between Moose Creek and Lignite is about 100 feet per mile. (See figure 5.) 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.

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 plate 2.) The source of these rocks was the granite bodies on the tributaries of the Wood River (pl. 1), and a gabbro sill in the Cantwell formation on Young Creek (pl. 1). At the time these granite and gabbro boulders were brought to their present position, therefore, it must have been possible for a glacier to move from the headwaters of the Wood River to the plateau surface around Gold King Creek. (See plate 2.) 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, and probably passed over Mystic Creek. This implies a considerable change in drainage, as well as a downcutting by the Wood River of 2,500 feet since the glacier which deposited these boulders advanced down the Wood River. This is comparable with the downcutting by the Nenana River and its tributaries beneath deposits of the Browne glaciation in the vicinity of Healy. Hence, these deposits are tentatively correlated with the Browne glaciation on the Nenana River.

Topography during the Browne glaciation: From Fig. 5 it is clear that that part of the Alaska Range which had been truncated by the erosion surface had a relief of about 2,000 feet during the Browne glaciation. The appearance during the Browne glaciation of the interior 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 with 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 wind-gaps, mentioned in the preceding section, at the head of Louis, Moose, and Riley Creeks, and the wind-gap at the head of Mystic Creek, are at an altitude at least as low as the supposed valley floors of the Browne glaciation.

Apparently not much drainage re-orientation had taken place before the Browne glaciation. By analogy with conditions in the northern foothills west of the Nenana, little drainage change would have been expected. The mountains of the Mount Hayes group probably stood 5,000 - 9,000 feet above the valley bottoms, and may have approached 10,000 - 11,000 feet in height. They were sufficiently high to have served as reservoirs of ice accumulation. The mountains of the Mount McKinley group were even higher; Mount McKinley may have been 16,000 or 17,000 feet high at this time. The mountains between the Alaska Range and the Pacific ocean probably were much lower than they now are, and may not have acted as barriers to the passage of moist winds. Hence the Browne glaciation could be more extensive in the Alaska Range than the succeeding stages, even though the mountains were not nearly so high.

THE DRY CREEK GLACIATION

Deposits of the Dry Creek glaciation 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 deposits and related deposits which are assigned to the Dry Creek glaciation lie well below the level of glacial erratics of the Browne glaciation and lie on hillsides above ice-contact 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, at an altitude of 2,400 feet, and located at approximately Lat. 63°49' N., Long. 149°05' W. (pl. 4), 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. The varved clay is flat-lying, and appears to be a remnant of a formerly more extensive 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, described in the following section, is well preserved on a broad terrace about 2 miles northeast of the varved clay deposit, at an altitude of 1,850 feet (pl. 4) and makes 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 in which the varved clay occurs is 400 feet below the lowest ridges on which boulders assigned to the Browne glaciation occur and about 700 feet below the supposed valley floor of the Browne stage 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 is very probably of a later origin than the ice advance of the Browne. The varved silts, therefore, if they were deposited in a glacially dammed lake, are younger than the ice advance of the Browne and older than the ice advance of the Healy, and were 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 about 4 miles due north of Carlo rises to an altitude of 3,700 feet. (See plate 5.) Glacial erratics are strewn over the top of this mountain. On the southwest side of this mountain, 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 River glacier of the Healy glaciation. The erratic boulders on the mountain above this moraine ridge are, therefore, deposits left by a glacier which stood at least 500 feet higher than the Healy stage glacier. They could have been deposited by the glacier which dammed Dry Creek to form the varved silt deposits.

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 1½ miles north of Carlo Triangulation station (VABM 4929 between Carlo Creek and Bovine Creek on plate 5). These deposits are about 500 feet higher than a ridge of till which was observed from the air to dam the valley just east of Carlo Triangulation station. This latter ridge is correlated with the Healy glaciation, and is regarded as marking the ice-limit of that stage. 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 positions of these deposits and their relations to the profile of the glacier they represent, and to older and younger glaciers, is shown in the longitudinal profile of the Nenana River. (See plate 7.)

<u>Outwash gravel of the Dry Creek glaciation on the Nenana River:</u> The glacial outwash deposits of the Dry Creek glaciation are believed to be represented by a prominent terrace with a thick capping of terrace gravel on either side of the Nenana River, extending from about Lignite Creek to a short distance north of Ferry. (See plates 3 and 4.) In the vicinity of Lignite, the outwash terrace of the Dry Creek glaciation has an altitude of 2,200 feet, about 450 feet above the highest of the terraces which appear to be associated with the Healy (fig. 6), 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 on the terrace are poor, but east of the Nenana River, opposite Lignite, gravel appears to be 50 - 100 feet thick. (See figure 6-b.) This gravel appears to have been deposited by the Nenana River, for it is blue-gray in color, as is the gravel of the modern 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. These latter, which form alluvial cones resting on the distal parts of the terrace, are commonly buff to brown in color, for 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.

The terrace on the west side of the river forms the flat top of the mountain just north of Tangeni Creek, 3 miles due west of Lignite. Many white granite boulders litter the top and south side of this mountain, down which they are in the process of slowly sliding into the bed of Tangeni Creek. These boulders could represent till of the Dry Creek glacier, and, if so, they would indicate the approximate northern limit of glaciation of this stage, for the terrace gravels north of this point are clearly river-deposited and must represent an outwash plain. It is more likely, however, that these boulders were not deposited by ice of the Dry Creek, but by ice of Browne glaciation, and later partly reworked by the Nenana River and its tributaries. They are preserved on the terrace at this point because they were too large to be moved any farther.

An indistinct bench that appears to be the distal edge 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. This terrace remnant—if that is what it is—would correlate with the outwash terrace of the Dry Creek glaciation.

Advance of the Dry Creek glaciation on other rivers: Climatic conditions which would 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, because of their topographic position and relations to other glacial deposits, are assigned to this glaciation have been found on the East Fork Toklat River, on Igloo Creek, Savage River, and Moose Creek (tributary to Tatlanika Creek). These deposits lie on topography which appears to be younger than that of the Browne glaciation, for, by analogy with conditions on the Nenana River, these other streams should not have eroded their valleys during the Browne glaciation as deep as the level of these glacial deposits. On the other hand, they either lie above and beyond the limits of the Healy glaciation, or occupy ancient valleys which should have been abandoned before the advent of the Healy.

Glacial deposits at two localities on the East Fork Toklat have been assigned to the Dry Creek glaciation. At an altitude of about 2,600 feet on the west bank of a tributary of the East Fork Toklat, at approximately 63°43' N., 149°53' W., (pl. 2) there is a deposit of till consisting largely of boulders of andesite and rhyolite. According to Capps (Bull. 836, pl. 4), the drainage basin of the creek on which the till occurs consists almost entirely of Birch Creek schist and Paleozoic and Mesozoic sedimentary rocks. The mountains at the headwaters of this creek are not as high as mountains in this vicinity which appear not to have supported glaciers during the Healy and Riley Creek glaciations. The volcanic rocks could have been derived from volcanic terrains on the East Fork Toklat River. The exact rock types present in the till have not been found in place where the McKinley Park highway crosses the volcanic field; however, they may crop out farther downstream.

If the till was brought to its present position by a glacier advancing down the East Fork Toklat River, the surface over which the glacier advanced must have been largely destroyed inasmuch as the canyon of the East Fork Toklat for at least 3 miles south of this point is a narrow V-shaped gorge with interlocking spurs several hundred feet high. Above the inner canyon is a broad canyon, with straight flaring walls and a floor about a quarter of a mile wide, which could have been occupied by a glacier, although this canyon, also, is far narrower than the broadly U-shaped valley of the East Fork Toklat, which ends abruptly downstream about 5 miles south of this till deposit. It would appear, therefore, that the glacier which deposited this till, if it advanced down the East Fork Toklat, is of considerable antiquity, and that uplift and erosion to the amount of several hundred feet have occurred since its advance. Evidence which is presented in the following sections indicates that two separate glacial advances have taken place on the East Fork Toklat since the deposition of this till. These younger ice advances 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 Toklat, and presumably the valley floor of the East Fork Toklat during the Browne glaciation would have been far higher above the present river level. The till deposit at this locality is, therefore, correlated with the Dry Creek glaciation on the Nenana River, although it must be remembered that the evidence for this ice advance is still tentative; the geology at the head of this river was studied only in reconnaissance fashion by Capps and Brooks, and the absence of volcanic rocks in the basin of this tributary must be demonstrated before it can be certain that the volcanics could have come only from the basin of the East Fork Toklat.

The top of the 4,900-foot mountain about 3 miles S. 20° E. of Sable Mountain in McKinley Park is littered with large boulders of limestone and of a clastic breccia which consists of limestone pebbles in a matrix of well-cemented graywacke. Some of these boulders are more than ten feet long. They are not found in the Nenana gravel which makes up this mountain, and they must have been brought to their present position by glaciers advancing down the East Fork Toklat from mountains to the south, where these rock types are present. These boulders are 1,500 feet above the bed of the East Fork 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 Healy glaciation. 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 1¼ miles north, as evidence of a glacial advance which, in height, probable extent, and antiquity, resembles the Dry Creek ice advance on the Nenana, and is therefore correlated with that glaciation.

A field of boulders, about 50 per cent Birch Creek schist and the remainder granite, gabbro, conglomerate and basalt, lies about half a mile north of the McKinley Park highway and 3 miles east along the highway from 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 brought to their present position only by glaciers advancing out of the mountains to the south, for the terrain on which they 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, for the extension of the Sanctuary glacier to this point would require a considerable ice-sheet in the valley followed by the McKinley Park highway. One would suppose that this ice-field would send a lobe down the Sanctuary Canyon north of the highway; yet, there is no evidence of glacial erosion in this canyon, which is a narrow V-shaped gorge 2,000 feet deep with 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 be 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 a following section. It seems likely that the U-shaped gorge of the Savage River south of the Park Highway, was formed during Healy glaciation. This deposit of boulders is probably beyond the terminus of the Healy ice, for all topographic evidence of the terminal moraine of the Healy has been destroyed. The glacial advance which deposited the erratic boulders of this field is tentatively assigned to the Dry Creek glaciation.

Boulders of Birch Creek schist, the largest of which is 8 feet on a side, are strewn over the flat saddle (alt. 4,000 ft.) 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, and has since been diverted by headward capture toward Tatlanika Creek. The stream bed is now several hundred feet below the boulder field. This boulder deposit is tentatively correlated with the Dry Creek glaciation, although it is possible also that it was made during the Browne glaciation.

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

<u>Uplift and erosion during the interval between the Browne and Dry Creek glaciations:</u> Comparison of contours on the restored valley of the Nenana River during the Browne glacial advance (fig. 5) with the profile of the Dry Creek outwash terrace (pl. 7) shows that the Nenana River of the Browne glaciation has a slope of about 25 feet more per mile between Lignite and Browne than has the outwash terrace of the Dry Creek glaciation. (See table 5.)

TABLE V

DIFFERENCES IN HEIGHT OF NENANA RIVER PROFILES OF BROWNE AND DRY CREEK GLACIATIONS

Locality	Distance from Browne	Ht. Browne glaciation	Ht. Dry Creek glaciation	Difference
Browne	0	1,300	1,100	200
Ferry	10	2,000	1,650	350
Lignite	18	2,850	2,200	650
Healy	22	3,200	ca. 2,500	700

The greatest amount of divergence in slope is between Ferry and Lignite, where the difference in slope amounts to 37 feet per mile. This 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, approximately 8 miles wide, along the north side of the range. Presumably this monoclinal belt extends eastward to pass just north of the high plateau around Gold King Creek, where deposits of the Browne glaciation indicate a valley floor 2,000 feet above the present river level. The monoclinal flexture probably trends southwestward from the Nenana River toward the Kantishna Hills.

The uplift in the interval between the Browne and Dry Creek glaciations was accompanied by extensive erosion by non-glacial agencies, including chiefly mass-wasting processes and stream erosion. The surface over which the Browne glaciers had advanced was dissected by streams eroding chiefly along belts of soft Tertiary rocks, and the original surface of the Browne glaciation in the vicinity of Lignite Creek is now preserved only on high mountain-tops. 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 destruction of the mountains. These pediments in turn are graded to the Dry Creek outwash terrace, and to younger terraces along the Nenana River. Non-glacial 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 this interval. During the Browne glaciation, the Wood River drained northward through the pass at the head of Mystic Creek to flow approximately along the present course of Bonnifield or Gold King Creek. 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 to flow a few miles east of its original course.

THE HEALY GLACIATION

Glacial deposits on the Nenana River: The Healy glaciation, with a type locality consisting of terminal moraine deposits near Healy, follows the Dry Creek. No deposits have been found which require the interpolation of a separate glacial advance between these two glaciations. The deposits of the Healy glaciation are much more abundant and much better preserved than the deposits of earlier glaciations.

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. The terminal moraine of which they are thought to be a part, was deposited by a piedmont lobe of the Nenana River glacier during the Healy glaciation.

An exposure in a roadcut in the south end of the outermost of these ridges shows rudely stratified, coarse, clean gravel consisting of boulders of gabbro, conglomerate, and granite. The granite is disintegrated. Pebbles in the gravel average 3 inches in size. Boulders up to 3 feet across are present. The surface of the ridge is mantled with a layer of mixed silt and pebbles about 2 feet thick. Presumably this surface layer is congeliturbate, as a result of the mixing by intensive frost action of an upper layer of pebbles with windblown silt deposited on the ridge. Road cuts in other ridges are largely in till.

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 latest glacial advance 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 deep, irregular, closed depressions. These depressions are mostly dry, and the largest is over 50 feet deep. Large boulders of conglomerate, the largest nearly 10 feet across, are on the terrace surface.

On the east side of the Nenana River, near Lat. 63°50' N., a terrace 1,800-1,900 feet in altitude extends between the River and Moody Creek (pl. 4). This terrace is shown on Figure 14 as Terrace XIV east of the river. The upper surface of this terrace has many hillocks and undrained depressions. The material that caps this terrace appears, from poor exposures, to be largely gravel. This may be a pitted kame terrace deposited along the margin of the terminal lobe of the Nenana River glacier at the maximum advance of the Healy glaciation.

Glacial till is exposed on the north wall of the canyon at mile 355.1 on the Alaska Railroad (pl. 4)(about three-quarters of a mile south of Garner). The till rests on Birch Creek schist and lies against the east wall of an ancient gorge of the Nenana River, now filled with blue clay. 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. 5, and fig. 10). 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. 5), 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, etc., 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 exposure 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, these 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 ice maximum of the Healy advance 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. 5) 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 melting away of the Healy ice, or during a short re-advance of the ice.

Till remnants of the Healy glaciation south of McKinley Park station consist 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 along the southwest side of the mountain between Riley Creek and the Nenana River about 3-4 miles north of Carlo. (See plate 5.) The top of this ridge has an altitude ranging from 3,175 feet at the south end to about 3,000 feet at the north end, two 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. This 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 which has been preserved on the relatively flat shoulder of the mountain.

Prof. Kirtley F. Mather, Troy L. Péwé, and the writer, on an airplane flight in 1951, observed what appeared to be a moraine-like ridge, with greatly subdued morainal topography, blocking the mouth of a small canyon draining eastward into Revine Creek from Carlo Triangulation station (pl. 5), and causing the stream that formerly flowed eastward into Revine Creek to flow 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 plate 7.)

<u>Landforms of the Healy glaciation on the Nenana River:</u> Landforms of the Healy glaciation on 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 which have evidently been planed away by the glacial ice of the Healy and, possibly also, of the Dry Creek glaciation; however, no glacial grooves or rounded <u>roches moutonees</u>

are preserved. The triangular facets of the spurs facing the river are rough and hummocky in detail. 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 possess distinct horizontal grooves and benches parallel to the river, and the lower slopes of spurs are gently rounded. The absence of minor glacial landforms could be attributed to the greater susceptibility of the Birch Creek schist toward 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 the canyon of the Delta River, 80 miles east, both of which were occupied by glaciers of the last advance (Troy L. Pewe, personal communication, 1951), contain excellently preserved glacial grooves on the canyon walls and have well-rounded <u>roches moutonees</u> on the walls and floors of the canyons. Both these 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 (*i.e.*, the Healy glaciation) is much older than the latest ice advance in this region.

<u>Lake deposits of the Healy glaciation on the Nenana River</u>: After the retreat of the ice of the Healy glacial stage, the Nenana River gorge

was occupied by a lake--Glacial Lake Moody--about one-third of a mile wide, and at least 9 miles long, from Riley Creek northward beyond Garner. The surface of this lake stood at an altitude of about 1,750 feet, and it was completely filled with clay and gravel before the river began to cut down its outlet. Between Riley Creek and Moody the lake coincided closely with the present canyon of the Nenana River. North of Moody, however, the lake was one-eighth of a mile to half a mile west of the present Nenana River, which flows in a narrow rock-cut gorge that was made after the lake was filled with sediments. The lake deposits are largely blue-gray and yellowish-gray, horizontally varved, silty clay; but each stream flowing into the lake built a delta of coarse sand and gravel. Some of these deltas are exposed in cross-section along the Alaska Railroad, and others are undoubtedly buried beneath younger deposits. The exposures of the lake deposits are described in detail in the following paragraphs.

The northernmost exposure of clay is in the forks of the creek half a mile west of Garner (pl. 4), in frost-polygons on a hillside up to 1,750 feet in altitude. Clay is exposed on both banks of the canyon that the Alaska Railroad crosses at mile 355.0, 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, outcrops indicate an irregular mass of till and gravel, which is the deposit of till at this locality mentioned on page 84. The clay in this canyon is found from the level of the canyon floor (1,470 feet) to about 1,670 feet altitude on the canyon walls. It is overlain on the north side of the canyon by gravel consisting entirely of Birch Creek schist about 50-70 feet thick. The upper surface of this gravel bank is 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. This gravel deposit and the slope across it are apparently an alluvial fan built by this canyon across the upper surface of the clay, and later partly dissected. The exposures of clay are very poor, as extensive slumping of the wall of the canyon tends to obscure 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. 4) (about 1½ miles south of Garner and half a mile north of Moody) and extend along the canyon wall from one-eighth of a mile to half a 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 in figure 7.

From about mile 353, just south of Moody (pl. 4), to mile 353.5, north of Moody, the Alaska Railroad is laid across 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 it is flat-lying and varved. Poor exposures of the clay along the railroad track near Moody also indicate its varved character. 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 from the railroad track is a bank of gravel 165 feet high, rising to about 280 feet above the river. A cross section of this bank is shown in figure 8-a. For about 50 feet above the railroad track (up to an altitude of 1,540 feet) the gravel bank is well-bedded, coarse gravel consisting almost entirely of boulders of Birch Creek schist. The bedding dips 35°-40° toward the river. (See plate 10-B.) These are apparently foreset beds of a delta built by Sheep Creek into Glacial Lake Moody. Resting on the foreset delta beds with a channeled unconformity is a 35- to 40-foot layer of coarse blue-gray gravel, consisting of boulders of conglomerate, coarse dark sandstone, andesite, gabbro, and granite, derived from the Cantwell formation and other rock bodies many miles upstream on the Nenana River. This gravel is exactly similar 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 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. As will be shown in the following section, the layer of blue-gray gravel is the outwash gravel of the later Riley Creek glaciation, resting unconformably on partially 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 plate 4.) (See figure 8-b.) Here, horizontally bedded, varved, blue and gray glacial clay, exposed along the railroad and between the railroad and the river interfingers westward with coarse gravel that consists almost entirely of Birch Creek schist, and dips 20°-25° toward the river. The gravel is the foreset part of a delta built by this creek into Glacial Lake Moody. 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 in the bridge foundations on this creek in 1948, disclosed that the clay extends to a depth of as much as 100 feet below the railroad track, 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. 4), and a small body of clay was exposed on the north bank of the creek just west of the bridge during construction of the new trestle in 1948. Gravel dipping 15° toward the river makes 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 situation here is a repetition of the situations 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. 4), 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 apparently was cut largely on varved clay of Glacial Lake Moody, which 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 surface of the bench is an almost perfectly preserved alluvial cone deposited by the creek at mile 350.3. The alluvial gravels, which consist almost entirely of Birch Creek schist, rest on a thin layer of blue-gray gravel deposited by the Nenana River, which rests in turn on the glacial lake clay and the septum of schist east of the clay. Geologic conditions beneath this bench are illustrated in figure 9, 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 plate 5.) The relations at this place are indicated in figure 10. The terrace east of the railroad and about half a mile north of McKinley Park station is underlain by clay, on which is resting 100 feet of blue-gray gravel 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 outlet had been northeastward over a ledge of Birch Creek schist, probably just south of the tunnel at Garner. Had the lake outlet been north over the terminal moraine at Dry Creek, the lake would have been drained by erosion of its unconsolidated dam before it was completely filled with clay and silt. The deposition of alluvium by canyons at miles 354 and 355 was sufficiently rapid to keep the Nenana River forced against the east bank of its canyon between Moody and Garner; no comparable tributaries enter the Nenana River from the east in this three-mile stretch. Consequently, when down-cutting was resumed on filling of the lake and retreat of the glaciers, the river was superposed on the east bedrock wall of the glacial gorge, and carved a narrow post-glacial gorge subsequent to the Healy glaciation.

Outwash gravel of the Healy glaciation along the Nenana River: Outwash of the Healy glaciation forms a layer of gravel, resting on bedrock terraces, that extend downstream along the Nenana River from Garner northward. Locally the gravel is as much as 180 feet thick, and the upper surface of the outwash plain near the glacier terminus at Healy is 400-500 feet above the present river level. The outwash terraces are complex including at least 3 and possibly 5 different terrace levels formed by the Nenana River during the advance and retreat of the Healy ice.

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 Dry Creek to Pangeni Creek. (See plates 4, 7, 8.) Its topographic position along Dry Creek suggests strongly that it is the outwash plain of the terminal moraine of the Healy glacier, and it is so considered here. This terrace continues northward as a bench along the hillside from Pangeni Creek almost to Ferry, at which place it is about 260 feet above the river. Northward from Ferry (pl. 3) the Healy outwash plain is probably one of a complex series of terraces along the west side of the river, and stands about 250 feet above the river opposite Ferry and 100 feet above the river opposite Browne. The thickness of gravel on this bench is unknown, but it is probably between 50 and 100 feet.

The Healy outwash terrace 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 on the west side of the river, 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 Sangoni Creek, is 160 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 of the river, and the two terraces could easily have been formed during the same episode of filling and cutting despite the disparity in slope and altitude.

A terrace about 60 feet lower than the terrace on which the Healy moraine rests, beginning about half a mile north of the road west of Healy and having a slope of nearly 100 feet per mile (Terrace XIII of fig. 14), is thought to have been cut during the period of erosion that followed the retreat of Healy ice. A terrace correlated with this terrace, 1 mile due south of Healy (fig. 14), with a surface altitude of 1,680 feet, and underlain by about 150 feet of terrace gravel, is also believed to have been cut during the retreat of Healy ice; although the gravel may have been deposited by the pro-glacial stream during the advance of the ice, and may have been over-ridden by ice. Gravel banks, with altitudes up to 1,800 feet, 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 over-ridden by ice.

Terraces capped with alluvium as much as 50 feet thick, graded to the terraces of the Healy glaciation on the Nenana River, can be traced up Healy and Lignite Creeks and their tributaries. (See figure 17.) These terraces are about 500 feet above the present creek beds. Use is made of these terraces in a subsequent part of this section in dating stream-capture east of the Nenana River.

Glacial deposits of the Healy glaciation on other rivers: Glacial deposits and landforms in other river valleys of the Alaska Range, 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 Healy glaciation on the Nenana River. (See plate 2.) These deposits have been observed on the Wood, the Sanctuary, and East Fork Toklat Rivers. Glaciated valleys that are thought to have been carved, in part, during Healy glaciation, are present at the headwaters of Last Chance Creek and Savage River.

The deposits on the Wood River are best preserved in the valley of Mystic Creek. (See plate 2.) The flat at 3,500-3,800 feet altitude, 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 forks of Mystic Creek. Similar till is found at about 3,600 feet at the headwaters of Coal Creek. (See plate 2.) Apparently the ice which brought these boulders to this position did not extend any farther west, up Mystic Creek valley, and was no higher than about 3,900 feet. These boulders were brought to their present position from a body of granodiorite on the west side of the Wood River about halfway between Copper Creek and Cody Creek. The deposits 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, and probably were left by the Healy ice advance.

A very low arcuate ridge on the flat on the east side of the Wood River at an altitude of 1,400 feet, near Lat. 64°11' N., Long. 147°30' W. (pl. 2), was identified on aerial photographs as possibly the terminal moraine of the Healy glacier which deposited the boulders in the valley of Mystic Creek. This ridge has not been visited on the ground, nor has it been inspected from the air. If this is the terminal moraine of the glacier, it has been almost completely buried by outwash of a younger stage, for the present ridge is no more than 20 or 30 feet high.

The Healy glacial deposits on the Sanctuary River (pl. 2) consist of scattered giant boulders of graywacke, greenstone, conglomerate, and gabbro, as much as several feet in diameter littering 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. This 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. These boulders are therefore probably remnants of a lateral moraine of a glacier of the Healy advance which may have advanced down the Sanctuary River as far as the McKinley Park highway.

The only place on the East Fork Toklat where Healy till has been examined is in the pass at the head of Igloo Creek and about 4 miles southeast of Sable Mountain. (See plate 2.) Ridges of till lie on either side of the broad valley at the head of Igloo Creek from the 4,500-foot pass at the head of the creek 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 against the sides of the valley of Igloo Creek is well-defined, and they appear to be lateral and terminal moraines defining a glacial lobe that extended down Igloo Creek for 2 miles north of the pass. They were probably deposited by an advance of the small glacier that occupies the valley in line with the upper part of Igloo Creek and which lies south of the pass; yet, the most recent ice advance down this valley appears to have gone down the canyon which turns sharply westward to join the ice of the East Fork 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 Toklat still drained northward, before Igloo Creek was beheaded. They probably resulted from Healy glaciation.

No glacial deposits correlated with the Healy 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-shaped form of these valleys is, therefore, attributed to ice-scour during Healy glaciation, and the morainal deposits of the Healy advance were presumably removed during the interval between Healy and Riley Creek glaciations.

Examples of these valleys are: The valley of the East Fork Toklat River for 6 miles north of the McKinley Park highway; the valley of the Savage River south of the McKinley Park highway (pl. 2); the valley of Last Chance Creek south of its junction with Moose Creek; and the headwater valleys of Cody and Healy Creeks (although these latter may be explained in part as having been formed by the removal of Tertiary rocks along extensions of the Healy Creek syncline). All 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.

<u>Uplift and erosion between the Dry Creek and Healy glaciations:</u> 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 the glaciers had their maximum extent. In

comparing these terraces it is assumed that the profile of the river at the time of the earlier ice advances would have been essentially the same as the profile of the river during the later ice advances, and 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 that a river affected by continuing uplift and climatic variation with repeated glaciation over so much of its length is ever in equilibrium. Perhaps, instead, the terraces may represent stages in the adjustment the stream made to an uplift which had already ceased by late Tertiary time. A careful consideration of the evidence in the Nenana River valley leads to the conclusion that this latter is not the case, but that the river was essentially in equilibrium throughout most of its history. The Nenana appears to have aggraded its bed in response to slight glacial advances and to have re-excavated the gravel during inter-glacial periods. All the periglacial streams on the north slope of the Alaska Range have done likewise. The sensitive response of the stream profiles to climatic variation suggests that most of the streams in this area must have been very nearly graded during most of the Pleistocene. Otherwise a change in climate would not have altered the regimen of the streams so strikingly. One must assume, therefore, that during some part, at least, of each glaciation, the river had a graded course, and it is very likely that its course from Healy northward was always graded, or nearly so. Had the river 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.

On the other hand, the tremendous effect glacial advances have had on the profile of the 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 ice advance, or whether, instead, the greater height of the older outwash terraces merely reflects the greater extent of these older glaciers. However, the terminus of the Dry Creek glacier was only 3 to 5 miles downstream from the terminus of the Healy glacier, and only 15 miles downstream from the terminus of the Riley Creek glacier. The ice terminus of the Riley Creek 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 Dry Creek glacier, the Dry Creek outwash terrace should be only very little higher than the Healy outwash terrace, and only one-fourth higher than the Riley Creek outwash terrace. 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 Dry Creek outwash terrace at Ferry is over twice as high as the Healy terrace, and 4 times as high as the Riley Creek terrace. The great difference in the heights of the outwash terraces is probably due, therefore, to deformation, and not merely to climatic fluctuations.

At Lignite the outwash terrace of the Dry Creek is 450 feet higher than the Healy outwash plain. (See plate 7.) Eight miles north of Lignite, the terrace of the Dry Creek is 350 feet higher than the Healy outwash plain. Near Browne station, 10 miles farther north, the Dry Creek outwash plain can hardly be 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 can have 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 surface of the two glaciers, as nearly as can be determined, appear to have been parallel (pl. 7), and it is likely there was no tilting of that part of the Alaska Range south of Healy, but rather bodily uplift. Comparable amounts of uplift in the Alaska Range near the East Fork Toklat are indicated by the differences between the altitude 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, Tatlanika, and Wood Rivers 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 tributaries 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 to reach the Tanana Flats. By the latter part of the Dry Creek and Healy interglacial, the Nenana had deepened its bed, in response to the uplift, sufficiently that the tributaries of the Nenana, eroding headward along bands of soft Tertiary rocks, were able to capture some of the headwaters 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. 2) during Dry Creek glaciation, for the slope of sediments graded to the Dry Creek outwash terrace 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 and suggest a drainage to the north. Pediments north of Lignite Creek graded to the Healy terrace, on the other hand, slope gently southward, away from this pass, indicating that the capture of the headwaters of Marguerite Creek by Lignite Creek had taken place before the Healy advance.

Shortly after Lignite Creek captured the headwaters of

Marguerite Creek, Healy Creek, eroding headward on a band of soft Tertiary rocks, captured a large portion of the headwaters of Lignite Creek. The pass between Healy Creek and Lignite Creek, about $1\frac{1}{4}$ miles north of the mouth of Coal Creek (pl. 2), is floored with coarse gravel consisting largely of Birch Creek schist, but containing boulders of basalt which are also in the gravels of Coal Creek. The terraces at the level of this pass around the junction of Sanderson and Lignite Creeks are graded to terraces which are lower than the pass between Lignite and Marguerite Creeks. The pass is about 100 feet above terraces on Healy Creek which 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 mostly of pebbles of Birch Creek schist. Presumably before the Healy advance, Healy Creek and Moody Creek flowed north 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 and their diversion causing them to flow into the Nenana River at Healy. The drainage diversions during the Dry Creek and Healy glaciations are indicated on figure 11.

<u>Summary of the history of the Healy glaciation</u>: The Healy glaciers advanced over a topography similar to that existing in the Alaska Range

today. Main streams have deepened their channels since the retreat of Healy ice no more than 300 feet, if that much. Although the grosser landscape features produced by the Healy ice have been preserved, deposits of the Healy glacier have been preserved only in favorable localities. Consequently, the events of the Healy glaciation can be reconstructed only with uncertainty.

Ice advanced down the Nenana River to Healy, down the Wood River to the Tanana Flats, and down the East Fork Toklat to about 6 miles north of the McKinley Park highway. Ice also filled the valleys of the Savage, Sanctuary, and Teklanika Rivers for about 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 the Healy glaciation had two separate ice advances, with an intervening period during which the ice retreated an unknown distance from the maximum terminus. This period of retreat was very much shorter than the interglacial periods before or after the Healy. During this period of retreat the glacial meltwater removed the earlier terminal moraine and lowered the level of the outwash plain nearly 100 feet, but did not remove all the outwash deposits. The second ice advance returned the glacier front to its original position, but without the tremendous burden of debris for the river to carry away, which was originally responsible for the thick outwash plain of the first advance. After the complex terminal moraine of the second ice advance was deposited, the glacier retreated, leaving Glacial Lake Moody, a lake about 400 feet deep occupying the canyon of the Nenana River from Garner to McKinley Park station.

Glacial Lake Moody drained northeastward over a bedrock lip near Garner. The lake was completely filled with sediments and the Nenana River built an outwash plain across the sediments. The river, which had formerly been unable to erode the bedrock lip because of lack of abrasive tools and which had probably cascaded down a bedrock slope near Healy, began to erode the bedrock barrier vigorously once it was carrying coarse gravel past that spot. At the same time, canyons emerging from the west side of the glacial gorge were building alluvial fans across the lake deposits and the outwash plain. No comparable canyons emerged from the east side of the canyon, and the river, as a consequence, was forced to flow against the east wall of its outwash plain. As down-cutting progressed, the river was superposed on the east bedrock wall of the gorge from Moody northward to Garner, and for a short distance near mile 350. Elsewhere it was able to erode its channel in the lake deposits of Glacial Lake Moody.

Ice-caps 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 from the Alaska Range. Evidence to support this contention is presented in the section on gravel deposits of the Riley Creek glaciation. 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 between these two glaciations.

THE RILEY CREEK GLACIATION

Deposits of the Riley Creek glaciation on the Nenana River: The Riley Creek was probably the latest extensive glaciation of the Alaska Range. The morainal deposits of this stage are much better preserved than the deposits of any earlier stage. The existing deposits are so well preserved, and their dissection is so slight, that it is likely that the missing portions of the lateral moraines either were never deposited or were removed during the melting down of the glacier ice, by having their support on the glacier side removed. 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 moraine areas. The remarkable freshness of the topographic features serves to make them easily identifiable and set 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 70-150 feet high is preserved as an irregular ridge extending along the south bank of Riley Creek for about three-quarters of a mile. This large gravel ridge 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 railroad cut through this moraine reveals an excellent exposure in which the structure of the terminal moraine is well displayed. A photograph of this cut is shown in plate 12-a, and a sketch of the geology exposed is shown in figure 12.

Immediately south of this 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. The 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) The glacier re-advanced, shoving the already deposited gravel and till forward into a recumbent isoclinal 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. (5) Till on the lake sediments was probably deposited from grounded icebergs. At this time, the ice for about 500 feet behind the front of the glacier was thickly covered with 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, with its disappearance, outwash gravel built an interior flat (Tarr and Martin, 1914, pp. 209-211) behind the ridge of till-covered ice back of the moraine. Much later, when the till-covered ice finally melted away, it left a depression between the moraine and the interior flat.

The lateral moraines of the Riley Creek glaciation are well preserved as irregular hummocky benches, or as smooth even-crested ridges extending for miles along the sides of the valley of Yanert Fork and its tributaries, and along the canyon of the Nenana River, except where slopes are too steep for it to be preserved. Lateral moraine deposits are rare along the west side of the Nenana River. However, the low pass, with an altitude of 2,450 feet, between the Nenana River and Riley Creek (pl. 5), about 3 miles north of Carlo, was apparently occupied by ice of the Riley Creek glaciation. Irregular arcuate moraines block the northwest end of this pass, and 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 facing the river at the southeast end of this plain, about 200 feet high, 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 approximately 50 feet deep. These are apparently kettle-holes that resulted from the melting-out of ice buried by the gravel of the plain. This plain is probably a kame terrace deposited by the lateral meltwater of the Nenana River glacier in a depression formed by the melting away of a small distributary lobe of ice between the moraine 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 of the canyon form a bench that rises gradually from 2,900 feet in altitude at the pass to about 3,400 feet in altitude on the mountain-side west of Carlo (pl. 5), 3 miles south. A small amount of this till is preserved on the north side of Clear Creek (pl. 5), and 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. 2), a prominent bench with 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 2 have been drawn to follow this bench.

The lateral moraine along the south side of Yanert Fork valley, west of Revine Creek (pl. 5), is a prominent even-topped gravel bench, at about 2,700 feet, paralleled on its uphill side by a depression about 50 feet deep. Lateral moraines extend for three miles up Revine Creek and can be clearly recognized on the topographic map of Healy C-4 quadrangle. (See plate 5.) The walls of the canyon of this creek, farther upstream, are apparently too steep to support continuous moraine deposits, or else are the areas from which these deposits were derived.

An arcuate ridge extends northeastward from the lateral moraine on the south side of Yanert Fork Valley near the point where it crosses the 148°46' meridian, and forms in plan a large bow convex toward the Yanert Fork. (See plate 5.) It ends near the Yanert Fork about 2 miles (airline) above the mouth of that stream. This ridge appears to be an interlobate moraine deposited between the Nenana and

Yanert glaciers, where they expanded in the great valley of the Yanert Fork to form coalescing lobes.

Ground moraine and pitted outwash covers 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 rising above the till, and a narrow band of river-deposited gravel in terraces and floodplains along each river. The ground moraine has an irregular hummock-and-hollow topography. In some areas of ground moraine the undrained depressions are dry most of the year, or have very small marshy areas at their very bottoms. Other depressions are occupied by deep lakes. The areas in which all depressions are either dry or lake-filled are extensive, and probably are areas in which the moraine is either porous or impervious. The porous moraine presumably consists largely of sand and gravel from which most of the clay-size particles have been removed by melt-water. It may consist largely of outwash gravel which was deposited over ice, and may owe its hummocky topography to melting out of irregular bodies of ice beneath it. The impervious moraine probably consists largely of clayey till with or without small bodies of lake-deposited clay and gravel.

Several drumlin-like hills in the ground moraine of the Nenana River 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 in figure 13. As can be seen from the sketches, most of the ground-moraine hills on the floor of the Nenana Canyon have cores of stream-deposited gravel or lake silt, with a thin and, in part, discontinuous veneer of till. The structure of these hills suggests a complex series of retreats and re-advances at the lower end of the Nenana River glacier during Riley Creek glaciation; for the lake deposits and outwash gravels, which include masses of till and probably rest on till, have presumably been rounded by later advances of the ice after the proglacial deposits were laid down.

Erosional landforms of glacial origin of the Riley Creek glaciation: 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, of which this canyon is one, are common in the fretted upland around the Nenana River near Carlo. Clear Creek, Slime Creek, Carlo Creek, Revine Creek, and many other streams flow in these gorges, and their headwall cirques 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, which originated at a much later date, as will be indicated in the next section.

Roches moutonees 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, with numerous couloirs. The erosion of this mountain may have taken place after the retreat of the ice, but it was probably sculptured in part before the Riley Creek ice advance, and subsequently protected by a veneer of talus fragments and till caught in the concave side of the glacial bend.

Lake deposits: Glacial lake deposits of the Riley Creek advance are not common in the valley of the Nenana River. A morainal hill about one and one-half miles south of Lagoon station on the Alaska Railroad, consists largely of deformed clay. (See figure 13-a.) Along the river bank, below the railroad at mile 338 (about 4 miles north of Carlo), there is exposed about 40 feet of varved, slightly calcareous, silt and clay, overlain by about 25 feet of terrace gravel. This clay is exposed for about 1 mile along the river bank, and landslide topography on the opposite river bank suggests that it is also present on the east side of the river. This clay is believed to have been deposited in a lake left by retreating ice of the Riley Creek glaciation.

Outwash gravel on 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 maximum stand at Riley Creek, forms terraces 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 extending 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 from the Yanert Lakes and Riley Creek lobes. Presumably the greater portion of the lateral drainage on the west side of the Nenana glacier drained through the canyon of 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 above the present river level. At mile 350.3 the thickness of gravel appears to be at least 110 feet, and the base is within 70 feet of 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. 8), 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. 4 and 8), and 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 for 1 mile north of Garner.

The flight of terraces at Healy is probably one of the most complex terrace flights anywhere. (See plate 11.) Fourteen terraces which have been identified between the Healy glacial moraine and the river are shown in plan and section in figure 14, numbered consecutively, with Roman numerals, from river level upward. Most of the terraces are preserved on both sides of the Nenana River at Healy, 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. They represent, rather, extensive plains formed by the river during pauses in downcutting after the maximum advance of the Riley Creek glaciation. The Healy terminal moraine rests on terrace XIV. Terraces XIII and XIV 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 figure 14.) 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 VII or terrace VIII at Healy. Above these terraces are four terraces, each 15-30 feet above the other, which appear to be much closer in altitude, geographic position, and relative preservation, to the Riley Creek terraces below them than to the Healy terraces above them. These terraces are tentatively correlated with the Riley Creek outwash, although 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 steep than at the present time. It could certainly have been dammed for a short time by an excess of alluvium being brought down Moody, Healy, and Dry Creeks; or it is possible that a still higher and farther advance of the Riley Creek glacier, the terminal moraine of which is not preserved, may have brought the glacier to a point 3 or 4 miles north of Riley Creek, a distance sufficient to give a grade parallel to the present river gradient, yet coinciding in altitude with terrace XII at Healy. An alternative 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 a nearly plane, rock-cut bench overlain by 5 to 50 feet of river-deposited gravel. Judging from exposures on the banks of the Nenana River, the gravel capping each terrace maintains its thickness fairly uniformly from the terrace face to the back of the terrace, and at the back lies against a bedrock slope which is continuous with the terrace front of the next higher terrace. (See figures 14 and 15 and plate 13-a.) For the Nenana River to have formed all these terraces during a single episode of cut-and-fill, would require that, during the stage of removal of the gravel (downcutting after aggradation), the river remove the excess thickness of gravel over the lower bench exactly up to the burried base of bedrock in the upper bench, at least at every locality 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 during or immediately after the terrace was cut, and that each terrace represents a short pause in the retreat of the Riley Creek glacier, or even a short re-advance. In all, seven terraces at Healy (terraces VI to XII) are assigned to the Riley Creek glaciation, not including the Carlo re-advance described below. Four terraces at Lignite and three at Ferry are assigned to this glaciation. (See plate 8.)

Alluvium deposited by the tributary streams of the Nenana River: Terraces graded to the terraces of the Riley Creek glaciation on the Nenana are well developed along the tribuatries of the Nenana River, in particular on Healy and Lignite Creeks. Those along Healy Creek are especially prominent. Terrace X has been traced up Healy Creek for about 14 miles. Where Healy Creek flows across the coal-bearing formation, this terrace is a gravel-veneered, rock-cut bench, similar to the terraces at Healy. (See figure 17.) Above the coal field, however, the terrace of the Riley Creek glaciation consists of gravel deposited by Healy Creek, from modern creek level to the level of the terrace. The gradient of the terrace and of Healy Creek are parallel, and the gravel exposed in the terrace is about as coarse as the gravel in the modern stream bed. Therefore, it is likely that Healy Creek once flowed in a canyon along its present course before the terraces were cut, and that it aggraded its valley with debris provided by increased solifluction to a new slope, parallel to the old one, and meeting the Nenana at the level of the Riley Creek terrace. The stream at its maximum altitude cut a new bench across the coal-bearing deposits, and the terraces below this bench on Healy Creek and on Coal Creek (figure 17) 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 forms deposits of yellowish-brown gravel consisting almost entirely of pebbles and fragments of Birch Creek schist resting on a layer of blue-gray gravel deposited by the Nenana River. Such deposits, already described in the section on the lake deposits of Healy glaciation, are found at miles 349-350, 351.4, 353 (Moody) on the Alaska Railroad (figs. 7, 8, and 9), and in the canyons crossed by the railroad at miles 354 and 355. Truncated remnants of alluvial cones deposited by two streams entering the Nenana River opposite mile 351 are shown in plate 12-b.

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 Healy (fig. 16), where a flat-lying layer of blue-gray gravel deposited by the Nenana River resting on steeply dipping Nenana gravel is overlain by about 50 feet of brown gravel identical in appearance to Nenana gravel, but dipping about 7° toward the river. The brown gravel was apparently a group of coalescing alluvial fans built by the small torrents eroding the bluff east of the river, and extending out across the river bed when the Nenana River stood as high as terraces X and V.

Deposits of the Riley Creek glaciation 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 other rivers.

The most striking evidence of Riley Creek glaciation on the Wood River (pl. 2) is the remarkable U-shaped canyon of the river from its source to the edge of the mountains. It is true, of course, that most of the sculpture of this canyon was accomplished by earlier glaciations, but the evidence on the Birch Creek schist walls of the canyon, in the form of glacial grooves and scratches and remarkably smooth roches moutonees, which indicates recent occupancy by ice, is impressive. On the east side of the river, northward from 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, is the lateral and, in part, terminal moraine of the Wood River glacier of the Riley Creek ice. The terminus of this glacier at its maximum extent probably stood at 64°07' north latitude, at an altitude of 1,800 feet. The surface of the glacier stood at 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. It was thus nearly 1,500 feet thick for much of its length.

Glacial till, made conspicuous by its content of large white granodiorite boulders, forms a thick lateral moraine on both sides of Kansas Creek (pl. 2) for about 3 miles below the present terminus of the glacier, down to an altitude of 3,600 feet. Similar till, consisting of conspicuous light-gray granodiorite boulders resting on the brown canyon walls of Virginia Creek (pl. 2), extends down that creek to its junction with the Wood River, and indicates that the two glaciers coalesced. Judging from till deposits, the Riley Creek glaciers on Neevy Peak (pl. 2) were not more than half a mile longer than they are now, and the glaciers at the head of Copper Creek (pl. 2) were about a quarter of a mile longer than at present.

The valley of the Sanctuary River (pl. 2) is nearly completely blocked, about 2 miles south of the McKinley Park highway, by a U-shaped area of hummocky topography rising about 75 feet above the surrounding plains and containing many ponds. This U-shaped area is clearly shown on Healy C-5 quadrangle. It was recognized by S. R. Capps (1932, p. 290 and pl. 4) to be the terminal moraine of the glacier which advanced down the Sanctuary River. The excellently preserved U-shaped gorge of the Sanctuary River in the mountains south of the terminal moraine is approximately 1½-2 miles wide. The freshness of topographic expression of glacial origin, both on the moraine and in 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.

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

The terminal moraine of the Riley Creek glaciation on the East Fork Toklat (pl. 2) 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 with 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 southward from an altitude of 3,200 feet at its north end to an altitude of 4,200 feet in four miles.

Several branches of the East Fork Toklat join just south of the McKinley Park highway bridge. (See plate 2.) 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 to 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 Toklat 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 have come from a belt of limestone about 6 miles south of their present position, and were presumably borne here 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 out beyond the edge of the hills during the Riley Creek glaciation.

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

The "terminal moraine" of this younger advance is an area of irregular hummocks and hollows, roughly crescent-shaped, extending on the east side of the Nenana River for about 3 miles north of Carlo Creek. (See plate 5.) Some of the hollows are nearly 100 feet deep. Most of these hollows are undrained depressions. Exposures in new road-cuts being made during the summer of 1951, indicated that the till in the north part of this moraine area consists chiefly of large and small subrounded boulders and pebbles, with interstitial sand and relatively little 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 built from river level up to the surface of the plain. A tongue of this plain lies between the moraine and the Nenana River, extending northward from Carlo Creek. On the west side of the river, from Carlo 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-top and pass of the Riley Creek glaciation to the northwest. 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, approximately a mile wide. The gravel beneath this plain is 100-150 feet thick, and rests on bedrock, till, or well-bedded fine sand (possibly lake deposits). The base of the gravel in all exposures appears to be a level surface, presumably cut by the stream which deposited the gravel. In the cutbank of a meander about half a mile downstream from the new highway bridge at Yanert, a bluff exposes about 100 feet of this gravel resting on 100 feet of till presumably from Riley Creek glaciation. (See plate 13-b.)

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 up to the height of the terrace, about 150 feet above the river. The map relations of this gravel body suggest that it occupies part of a valley cut by the Nenana River in Riley Creek till. At the south end of this terrace are large steep-walled closed dry depressions. These depressions are obviously pits left from the melting of stagnant ice blocks. One of these pits lies partly in the triangular terrace and partly in the higher moraine area of the Riley Creek moraine. This pit 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. Terraces lower than the Riley Creek terraces can be found at several localities in the Nenana River canyon between McKinley Park station and Healy. The broad terrace a few feet lower than the railroad track at Garner is probably the largest such remnant.

Terraces III, IV, and V, at Healy, are tentatively assigned to the fluviatile deposits of the Carlo re-advance.

Terraces correlated with these terraces are locally developed at several places on Healy Creek and its tributaries. No such terraces have been recognized to date on the Yanert Fork. Well-defined glacial deposits, similar to the Carlo "terminal moraine", are likewise absent on the Yanert Fork; although a steeply sloping lateral moraine ridge intersects the river about 15 miles above its junction with the Nenana River, and about 15 miles downstream from the present terminus of the Yanert glacier. This lateral moraine ridge may represent a re-advance of ice, but it could equally well represent simply a short pause in the melting-back of Riley Creek glaciers.

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 from the mouth of Clear Creek to Carlo, from which steep mountain walls rise abruptly, 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 may have dammed a lake which extended for a few miles up the Nenana. The lake was drained before it was completely filled with lake sediments, and before the glacier retreated so far that sand could not be deposited on the lake floor.

The glacial and fluviatile deposits that are shown on the map (pls. 3, 4, 5, and 6) as Carlo deposits, indicate unequivocally the following events:

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

(2) After the southward retreat to or beyond Carlo, the Nenana River was able to excavate a canyon nearly 50 miles long through the Riley Creek morainal deposits and through the outwash train extending northward from these deposits. This 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 this canyon, the river filled it with gravel to the level of the Carlo outwash plain--a thickness of 250 feet at a point three miles north of Carlo. At the same time, the glacier deposited the body of till here called the Carlo moraine.

(4) The glacier retreated, 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 by melting away of the ice to a position near the present glacier front. During this retreat the river would erode the deposits of the Riley Creek outwash terrace, always maintaining a gradient sufficient to move the material supplied to it by the ever-retreating ice-front; and when the ice front stood near the present terminus of the Nenana glacier, the river would be flowing at approximately its present level, as it must have done north of Carlo in order to cut the canyon. Following this retreat of the ice, there would be a re-advance of about 50 miles to the position of the Carlo terminal moraine, with the river filling the canyon with outwash gravel of a separate Carlo glaciation. This explanation of the relationships of the Carlo till and outwash assumes that the glacier and its meltwater river system always tend to a condition of equilibrium in which the glacial meltwater would deposit outwash gravel until it established a slope steep enough to remove all the debris supplied to it; and that during the advance and retreat of the glacier, barring accidents, and interruptions in the course of the river, a series of graded profiles, essentially parallel to one another but converging downstream, will be created in turn by the river; and the height of each profile will be determined by the position of the glacier front and by the amount and coarseness of gravel supplied to the melt-water river (Mackin, 1948, pp. 475-477). This would be the most likely explanation of the events indicated by the Carlo deposits if all the rivers of the Alaska Range showed deposits similarly situated on their courses, and if lateral moraine deposits equivalent to the Carlo moraine were present on all rivers. Glacial deposits which could be correlated with the Carlo deposits have not been found on any other river on the north side of the Alaska Range, although the East Fork Toklat, Sanctuary, Wood, and lower Delta Rivers (Pewe, personal communication, 1951) were carefully searched for them; therefore, another explanation for the Carlo deposits must be found.

If, on melting back from the canyon between Windy and Yanert, the Nenana River glacier of the Riley Creek glaciation left a pro-glacial lake, the river draining that lake would no longer have to be graded to the position of the glacier front; for the coarse debris of the glacier would be deposited in the lake, and the river draining the lake would be clear. The meltwater river would tend to erode the gravel deposits downstream from the lake by rolling and bouncing pebbles along the river bed without replenishing its gravel bedload from upstream sources. It is necessary to assume that this erosion would be 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 pro-glacial 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 melted back southward, beyond Yanert station, and the glacier front may have retreated to Windy before re-advance began. The advancing glacier would have incorporated in its lower part much of the delta gravel which would have been built into the lake in front of it, and would have carried this gravel foreward as the mass of porous bouldery till which choked the canyon of the Nenana River north of Carlo Creek. The lake having been drained, the meltwater Nenana River would aggrade its bed with gravel, forming the Carlo outwash deposits. Upon the subsequent melting-back of the glacier from the position of the Carlo till, another lake occupied 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 for a few miles north of 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 re-advance during the general retreat of the Riley Creek glacial ice.

Summary of the history of the Riley Creek glaciation: 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 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 except in details. 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 in plate 2.

With the general cooling of climate, ice advanced down the Nenana River, and eventually reached a position near McKinley Park station. This ice advance may have involved many reversals in the direction of movement of the ice front, including short episodes when the ice-front was stationary, and then retreated, only to advance beyond its former position. At the same time that the ice was advancing down the Nenana River, ice advanced down the Yanert Fork and Riley Creek to coalesce with lobes of the Nenana River glacier. Most of the ice accumulating in the headwaters of the Nenana River probably moved southwestward down Broad Pass into the Susitna basin; however, sufficient ice flowed down the Nenana River to reach a position near McKinley Park station.

Ice advanced down the Wood River to the edge of the mountains, and down the Sanctuary to within 2 miles of McKinley Park highway. Ice advanced down the Teklanika 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 excess length 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 glaciers in the Alaska Range. This is also apparent when the depression of the regional orographic snowline (determined from the position of cirques), is considered. In the latitude of Windy, the regional snowline appears to have lowered approximately 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 could have been only more severe than at the present time under conditions of glaciation in southern Alaska. This indicates that snowfall and cloudiness, rather than mean temperature or winter extremes, are major, and possibly predominant factors in producing glaciation 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. The fluctuation of the glacier front probably took the form of repeated short, rapid advances, followed by gradual wasting away of the ice. Certainly 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 such an advance of the Black Rapids glacier (1942, pp. 146-157) and Tarr and Martin reported similar advances of the Yakutat Bay glaciers (1914, pp. 168-197), and of the Childs glacier (1914, pp. 400-409), and Columbia glacier (1914, pp. 261-282). The cause of the fluctuations of the Nenana glacier of the Riley Creek advance is not necessarily similar to any of the causes--chiefly earthquake-induced avalanches--attributed by Moffit and Tarr and Martin (1914, pp. 168-197) to the glacial advances 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 left were filled with outwash gravel. Continued melting of the ice left irregular moraine deposits over much of the lowland country at the junction of the Yanert Fork and the Nenana. South of Yanert, the glacier left a lake. This lake was quickly drained, as it was dammed solely by glacial debris and outwash. A re-advance of the glacier brought the ice-front northward to Carlo, and caused the river to aggrade its bed. After this short advance, the glacier again melted back, leaving a short-lived lake between Carlo and Windy.

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

DEPOSITS AND LANDFORMS YOUNGER THAN THE CARLO DEPOSITS

Terraces: Some of the terraces along the Nenana River are much lower in height than the terraces assigned to the Carlo re-advance. They have been separately distinguished on plates 5, 6, and 7, from the mouth of Dry Creek southward. Northward from Dry Creek, the terraces assigned to the Carlo re-advance are so close in height to the younger terraces that it was difficult to distinguish them. These terraces, like most of the higher terraces, are in pairs that match across the river; that is, the same terrace can be recognized on both sides of the Nenana. They occur only as interrupted remnants, and have been removed where the river erodes steep banks, or where the river flows in narrow rock-walled gorges. Dry Creek and some other tributaries of the Nenana have recently built alluvial cones which bury the terraces. Because of their low and variable height, correlation of these terraces is difficult, if not impossible.

At Healy, where the terraces on the Nenana River are most fully developed, two terraces lie below the lowest terrace assigned to the general period of the Carlo re-advance. Terrace I stands 10 feet above the floodplain, and consists entirely of river gravel. (See figure 14). Terrace II stands 28 feet above the floodplain; 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 floodplain. (See figure 14.)

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 with a thin layer of 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 re-advance. 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 to be correlated with the low terraces along the Nenana River near Healy.

Terraces 5 to 20 feet above stream level are present on most of the tributaries of the Nenana River, and also on many other streams in the Alaska Range. At many localities, especially on Healy Creek and Lignite Creek, these are rock-cut benches with a thin veneer of stream gravel. More commonly, however, they appear to consist entirely of gravel, from stream level to terrace-top. Similar low terraces have been observed on many other rivers, both glacial and periglacial, in this part of the Alaska Range. Their ubiquitousness, and their nearly uniform height, far below the lowest terraces of the Riley Creek glaciation, make it 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 a climatic rather than a structural origin for these terraces. Along with other features, to be described subsequently, they are regarded as evidence of recent, minor cold periods that occurred after the thermal maximum which followed the retreat of the Riley Creek ice.

Talus: There are large or small amounts of talus 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 mantled by a thin layer of talus which is presumably an accumulation of rock fragments that rolled or slid to the slopes. Slopes less steep are covered with congeliturbate which will be described in the following section. Large deposits of coarse blocky talus have accumulated below cliffs and cirque head-walls 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, and 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 upward-facing surfaces of the boulders are completely covered with lichen. Boulders in the quarry face, however, have no lichens growing on them; 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 are no longer present at this locality, which is unlikely, or that the period required for lichens to establish themselves is so long that there has been no appreciable lichen cover since the quarry was abandoned.

Talus deposits of considerable thickness are present locally along the canyon between McKinley Park station and Healy. At the north end of the tunnel at Garner, blocks of schist breaking away from the mountain of Birch Creek schist northwest of the railroad track, form a great talus deposit, which overloads the talus cone extending to the river, causing it to move slowly out toward the river.

<u>Congeliturbate</u>: Congeliturbate, defined by Bryan (1946, p. 640), as "a body of material disturbed by frost-action", forms an almost continuous mantle over all the land surface of this part of the Alaska Range, except where actual outcrops of other formations are present. The mantle of this material is rarely more than a few feet thick. Because of the great extent and thin nature of this material, it is not mapped separately on plates 4, 5, 6, and 7, except for deposits 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 (Anderson, 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. This is provided in arctic regions by the layer of pergelisol (Bryan, 1946, p. 640), or perennially frozen ground (Taber, 1943), which is present nearly everywhere from the crest of the Alaska Range northward (Black, 1950, p. 249).

Congeliturbate of solifluction origin can be recognized by extensive evidence that soil moved down slopes gentler than the angle of repose. 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 rock varies slightly in color from place to place, slopes have a streaked appearance—streaks and bands of different colored rock extending downslope from each outcrop. Such streaked topography is the most striking 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 containing appreciable amounts of peat and wind-borne material. They consist exclusively, however, 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 congeliturbate.

Congeliturbate on level surfaces can be recognized in cross-section by typical structures in the soil: in soils with wide range of grain size (from boulders or pebbles to fine sand, silt, and clay), congeliturbation effects a sorting of the soil into rings or polygonal networks of stones surrounding clay-rich centers of level ground, and causes the formation of alternate stripes of stones and finer soil on sloping ground (cf. Washburn, 1950, p. 89). Where the coarse particles in the soil are rare or absent the effect of congeliturbation is still recognizable in the presence of frost-scars, peat-rings, and allied forms (Hopkins and Sigafoos, 1951), and, in cross-section, in the shape of involutions of differently colored bands in the soil (Schafer, 1949, pp. 156-165). Even where there are no exposures, congeliturbate may be recognized by the development of a special micro-topography which consists of mounds or hummocks 6 inches to 3 feet high and a few feet to 10 feet across on level ground, or 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 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 around 5,500 feet altitude, 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 "free-swimming" 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 broken at only a few localities--by landslides, badlands, outcrops, or frost-scars (Hopkins and Sigafoos, 1951, pp. 65-70)--and congeliturbation, although locally effective at the present time, is not generally active over the entire surface.

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 Alaska 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 by either a layer of fine-grained material (clay or clay-rich till) or 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, they moved downward and outward toward the river, creating a series of assymetrical ridges at successively lower altitudes from the railroad track toward the river. This landslide occurred because the Nenana River eroded the base of a bluff, about 150 feet high, that consisted of 65 feet of clay-rich till overlain by 85 feet of outwash gravel. The till flowed out toward the river, undermining the gravel and dragging blocks of gravel with it, and causing their originally horizontal upper surfaces to rotate away from the river. The landslide is now stable.

Landslides in the Tertiary coal-bearing formation are common along the walls of the canyons of Lignite Creek and its tributaries. (See plate 4.) The landslides start where ground water is concentrated along the tops of impervious beds which slope gently toward the creek or its tributaries.

Ancient landslides, now completely inactive, have occurred along the bluff between the Healy outwash terrace and the Riley Creek terrace from Dry Creek northward to the road west of Lignite. These landslide deposits were recognized from their topographic expression, which 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 clay horizon, either till, pro-glacial lake deposits, or a clay-rich zone within the Tertiary rocks. The clay flowed out from beneath the gravel, letting it settle as irregular blocks.

Detritus slides and mud-runs generally flow into a stream, which re-deposits thick debris as alluvium, or removes it altogether. Small mud-runs on hillsides are quickly overgrown with vegetation, and their recognition is difficult. No ancient examples of such landslides were recognized, although it is believed that many badland areas resulted from the exposure of Tertiary rocks to active erosion after the integument of vegetation was removed by a detritus slide.

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 commonly 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 declevities 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 both arcuate ridges convex downstream, and straight ridges parallel to the direction of flow.

Rock glaciers occupy the headwater cirques of Clear Creek, Slime Creek, Carlo Creek, and Revine Creek—all tributaries to 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. The deposits of rubble, composed of andesite blocks, surrounding Jumbo Dome (Wahrhaftig, 1949) are regarded as ancient rock glacier deposits.

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 Yanert glacier.

Exposures of the interior portions of rock glaciers are rare; loose, angular debris from the top and sides quickly slides into any exposure that is made. An exposure of the side of an active rock glacier, which is 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 mostly large blocks of granite. Similar relations between the interior and surface of rock glaciers 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 a now-inactive rock glacier on Jumbo Dome (Wahrhaftig, 1949) shows that the material of the interior of the rock glacier is of much finer grain size, and has a much larger proportion of fine material, than that on the surface.

Preliminary results of measurements, now in progress, of the movement of a rock glacier at the head of Clear Creek, show that this rock glacier is moving foreward at a rate of about 2½ feet per year along the medial axis, decreasing to 1-1½ feet per year along the sides.

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.

According to Richmond (1952) rock glaciers of the La Sal Mountains, Colorado, have cores of till and other features of glacial origin. He believes that they are "residual from small glacial re-advances, 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 glacier-like 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.

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 cooling of the climate. The rock glacier for which a recent origin is most clear is at the head of Clear Creek. Here, the 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 slopes which face down-valley as well as toward the valley walls on either side, 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. The upper part of the mound is buried by the active rock glacier, but from its appearance and exposures along the walls of the gulches that dissect it, it is evident that it is an ancient rock glacier, completely stabilized and overgrown, and later dissected by tributaries of Clear Creek. The sides of the active rock glacier are free of turf, and turf on its upper surface, where present, 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 two miles downstream from the present terminus of the Yanert glacier. (See plate 2.) 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 blocks of similar granite. These hills form a double arc convex downstream across the river, and are continuous upstream along the walls of Yanert Valley as two low ridges of till about 200 feet apart but merging locally. These rise to 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 glacial valley. The forest covering the terminal moraine is a dense growth of mature spruce. This forest continues upstream for about a mile, where it grades into a forest of cottonwood and willow which extends almost up to the base of the glacier. At about the point where the two forests grade into each other, about one mile below the glacier terminus, another moraine crosses the river. On the mountainsides around the terminus of the glacier, this moraine is a thin sheet of till. The glacier itself abuts against the till-covered slopes, which are overgrown by alders and low tundra, with an abrupt contact between moraine-covered ice and vegetation-covered till.

Recent till, covering stagnant ice, was observed a few tens of feet downslope from the glaciers on Reevy Peak. Till, recently deposited by glaciers and now separated from the glacier by narrow outwash plains, is present around glaciers at the head of Copper Creek, Virginia Creek, and Kansas Creek. This till passes downslope into rock glaciers.

Glaciers: There are no active glaciers in the area immediately adjacent to the Alaska Railroad through the Alaska Range; although the Nenana River, Yanert Fork, Sanctuary River, Teklanika River, East Fork Toklat, Wood River, and many of their tributaries, head in glaciers. (See plate 2.) Less than one-twentieth of the area that was ice-covered during the height of the Riley Creek ice advance is ice-covered today. Existing glaciers range in length from half a mile to 20 miles; the longest and largest is the Yanert glacier, which heads in Mount Deborah, 12,540 feet high, just east of the area shown in plate 2. 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, pp. 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 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, 1933, pp. 898-903).

The glaciers of this part of the Alaska Range show evidence for similar recent advance and retreat, although, as will be shown in a following paragraph, the combined evidence of all the recent deposits, glacial and otherwise, suggests a somewhat more complicated climatic history for Alaska than that outlined by Cooper. Presumably the vegetation against which the moraine-covered ice of the Yanert glacier is in sharp contact, took a considerable time to establish itself and completely cover the one-mile moraine. The sharp contact with this mature tundra implies either a long period of stand-still 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 the smooth surface of the white ice of the glacier. Similar conditions were observed by Tarr and Martin (1914) on stagnant glaciers of the Yakutat Bay region. The Yanert glacier presented a similar appearance in 1913, as photographs taken then (Moffit, 1913, pls. 4 and 5) attest. 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 in active movement during 1941, but had been dormant in 1913 and was dormant in 1950 and 1951.

Tarr and Martin (1914) have shown that rapidly advancing glaciers have deeply crevassed surfaces, whereas glaciers which are stagnant or in which ice is moving forward only slowly have relatively smooth surfaces. The remarkable smoothness of the surface of the Yanert glacier for at least 8 miles above its terminus, when examined in 1951, and its freedom from crevasses (shown by the large meltwater streams flowing on its surface), indicate that the lower part of the glacier was not advancing for several years prior to 1951.

The small glaciers on Keevy Peak and around the Wood River also show signs of recent retreat. On nearly all these glaciers, the areas of visible ice are smaller than the glaciers shown on topographic maps made in 1910 (Capps, 1910, 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 pro-glacial or super-glacial lake. The large, nearly circular glacier at the head of Virginia Creek was bordered by a band of bare till and bedrock two hundred feet wide. Beyond the band of bare rock, the till and granite were covered with lichens and have 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 frozen ground was encountered at a depth of a little more than one 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 plate 4.) The bogs on the surface of the high terrace east of Browne and north of Ferry are presumably underlain by peat. (See plate 3.) The thickness of this peat is unknown. Layers of peat a fraction of an inch to more than a foot thick, are interbedded with the silt which mantles many of the terraces. Woody plant remains are found in the peat, along with remains of vascular plants. Where the peat is in two layers, the lower layer is black and involuted, and the upper layer is brown and only slightly disturbed by frost action. This relationship of two peat layers 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 dune and loess layers, are common along the Nenana River and in adjacent parts of the Alaska Range. These deposits 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 cliff-heads 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 the Nenana coal field, 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 erosion or railroad cuts, the dunes show one, two, or three peat and forest layers.

Cliff-head dunes with interbedded forest layers are exposed in section along the railroad about a quarter of a mile northeast of Moody (pl. 4), about half a mile south of Garner (at the south end of the siding), 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.

A dune deposit at the top of the mountain above the Garner tunnel (pl. 4) contains platy fragments of schist half an inch thick and as much as 4 inches in long diameter. These have been blown, rolled, or ricocheted by the wind for a distance of several tens of feet, or 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 inter-bedded with thick turf and in the branches of low bushes. An alternative explanation that these fragments may have been thrown up to the top of the mountain by explosions during the construction of the railroad, fails to explain an exactly similar occurrence on the Totatlanika River (pl. 2), opposite the mouth of Daniels Creek, where no construction or excavation has been conducted. The presence of these coarse fragments indicates very high velocities of south winds.

Deposits of wind-blown silt mantle slopes and tops of terraces along the Nenana River. The silt mantle is 3 to 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 silt is about 0.15mm., whereas the median grain size of the lower silt, 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 plate 13.) The implication is that the period of 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: (1) silt deposited by the glacial meltwater and blown off the dry river beds by strong southerly winds; and (2) badland outcrops in the Tertiary rocks. The first-mentioned source is quantitatively the most important. Dust storms, similar to those described by Pewe (1951) on the Delta River, occur on the Nenana at the present time, and 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 one foot in 50 years, of the silt mantle bordering 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 indicates a rate of accumulation of not less than one foot in sixty years.

Wind-polished and facetted 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 one mile south of Healy. 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, and has been reported from all localities where deep excavations have been made. The only localities where its presence is doubtful are some of the very well-drained terraces underlain by coarse gravel, from the base of which great springs emerge. 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 vegetation cover and exposure to direct sunlight. In general, it 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: (1) Thick, continuous vegetation, consisting largely of mosses, with or without black or white spruce. Perennially frozen ground is commonly found within two feet of the surface, locally as close to the surface as one foot. Where bare soil is present in the center of frost-scars, perennially frozen ground is much deeper. (2) Vegetation consisting predominantly of brush: alder, dwarf birch (Betula nana), willows, with or without sparse growth close to the ground consisting of annual grasses and lichens, and with or without 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. (3) Slopes of bare gravel, outcrops, and talus, with or without scattered growth of lichens. Perennially frozen ground, if present, probably lies more than 20 feet below the surface, and is likely to be "fossil" perennially frozen ground. Perennially frozen ground is reported from 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 non-porous rocks, as well as in slightly pervious well-jointed rocks like the Cantwell formation, probably occurs only as thin films in joints and cracks. Likewise, in deposits consisting of coarse gravel, perennially frozen ground is either "dry permafrost" (rock perennially below 32° F. but without water) or gravel containing interstitial ice only.

In sand, silt, and clay, on the other hand, perennially frozen ground takes the form of clear lenses and veins of ice, as well as solidly frozen silt and clay. Commonly, because of the expansion of the interstitial water on freezing, the component grains of the rock are pried apart, so that in perennially frozen ground in fine-grained sediments, the only binding force is the cohesion and adfreezing strength of ice. When the ice melts, the cement 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 points of support of heavy weights.

Ice veinlets exposed at the new pit, Diamond coal mine, during the summer of 1948, averaged one-eighth of an inch in thickness and were spaced half an inch to one inch apart. Their strike was parallel to the contour line of the hillside, which is here parallel to 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 of moss and sedges, with 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, a quarter of an inch to half an inch thick, and one to three inches apart, oriented approximately normal to the direction of slope. Lenses and bodies of clear ice up to a foot thick were also found in the clay at this point, and interstitial ice cemented the terrace and delta gravel. Lenses of clear ice more than one foot thick were found in clay at Moody in 1949.

The involuted silts at the base of the silt deposits on terraces, show that the former presence of permafrost beneath or in the lower layer of these silts, aided congeliturbation to the extent of notably deforming the soil.

Climatic history implied by the post-Carlo deposits: The climatic and geologic history implied by the post-Carlo deposits involves the following events:

(1) Melting of the Riley Creek glaciers, 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 now are.

(2) A period somewhat warmer than the present. This may correlate with the thermal maximum recognized in the United States (Moss, 1951, pp. 82-83).

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

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

(5) The present cold period. Historical records suggest that the peak of the present cold period is past and that, at the moment, the climate is slowly becoming warmer.

Post-Carlo 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.

The exposure on the east side of the Nenana River opposite the mouth of Riley Creek consists of alluvium resting on outwash gravel deposited by the Nenana River. The gravel in turn rests on till and the upturned beds of the Cantwell formation (pl. 14). 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 deformed 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. The 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 this 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 which crosses the Alaska Railroad near Windy. (See plate 1.) According to R.A. Eckhart (personal 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 (personal 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 plate 14-b.) 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 appears, in aerial photographs, as far east as the Nenana glacier.

All the evidence points to recent displacement along this fault, in which 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 is recent, and very likely no more than a few hundred years old.

Glacial deposits on either side of the fault zone are not noticeably displaced, other than the displacement described above;

the topography along the fault does not give any indication of Pleistocene displacement of any magnitude, certainly not from movements in the direction that the recent fault scarps indicate. It seems likely, therefore, that the revival of movement along this fault does not date back beyond the age of the Carlo deposits, and is probably much later.

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