Glaciation of Little Cottonwood and Bells Canyons, Wasatch Mountains, Utah

By GERALD M. RICHMOND

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

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GLACIATION OF LITTLE COTTONWOOD AND BELLS CANYONS, WASATCH MOUNTAINS, UTAH

By Gerald M. Richmond

ABSTRACT

Little Cottonwood and Bells Canyons lie on the west slope of the Wasatch Mountains about 15 miles south of Salt Lake City, Utah. The glaciation of these canyons has long been of interest because the moraines at their mouths are in contact with the deposits of Lake Bonneville. The purpose of this paper is to describe the glacial and associated deposits of the canyons, to interpret their history, and to discuss their correlation with the deposits of Lake Bonneville which were studied concurrently by R. B. Morrison.

Little Cottonwood and Bells Canyon are short steep glacial gorges that rise in altitude from about 5,200 feet at their mouths to about 10,600 feet at their headward divides. The concordant profiles of interfluves projecting into Little Cottonwood Canyon suggest that at an early stage of erosion the canyon was a broad shallow upland valley. Remnants of a lower broadly U-shaped valley rim the inner steep-walled canyon.

Both the upper and the lower broad valley surfaces have been uplifted along normal faults at the west base of the range. A deposit of possible till, the oldest in the area, lies on a remnant of the lower surface north of the mouth of Little Cottonwood Canyon. A younger till of postcanyon and pre-Lake Bonneville age locally caps the divide separating Little Cottonwood and Bells Canyons. Both tills are inferred to be of middle Pleistocene age.

Deposits of two younger late Pleistocene glaciations occur on the floors of the canyons. The older of these deposits comprises two sets of large mature moraines correlated with the Bull Lake Glaciation of Wyoming. The moraines represent 2 distinct advances of the ice that reached average altitudes of 4,980 and 5,000 feet, respectively, at the mouths of the canyons and were separated by a withdrawal of the ice to the upper parts of the canyons and possibly to the cirques. The till of the moraines contains abundant deeply disintegrated boulders, and is more clayey and compact than that of the younger glaciation. A mature soil formed on these deposits during the succeeding interglaciation when the ice disappeared entirely.

Deposits of the younger late Pleistocene glaciation, correlated with the Pinedale Glaciation of Wyoming, comprise three sets of moraines. These are located in the middle and upper parts of the canyon at average altitudes of 6,570, 7,220, and 9,190 feet, respectively. They mark one maximum and two minor readvances of the ice, separated by relatively short recessions.

During the succeeding interglacial interval, the altithermal interval of Antevs (1948), the glaciers disappeared entirely and a submature soil formed on the deposits. Later, in Recent time, two sets of small moraines or rock glaciers formed in the cirques. These are correlated with the Temple Lake and historic stades of Neoglaciation (Little Ice Age of Matthes, 1939) in the Wind River Mountains of Wyoming. The older set of moraines bears an azonal soil and vegetation; the younger set bears neither soil nor vegetation.

Correlation of the glacial deposits with the deposits of Lake Bonneville was determined jointly with R. B. Morrison. The lower till of the Bull Lake Glaciation intertongues with, and is overlain by, the deposits of the first rise of Lake Bonneville (Alpine Formation of Hunt and others, 1953), which attained an altitude of about 5,100 feet. The upper till intertongues with, and is overlain by, deposits of the second rise of the lake (Bonneville Formation of Hunt and others, 1953), which formed the Bonneville shoreline (alt, 5,135 ft). The maximum of both rises seems to have shortly followed the glacial maxima. Deposits formed during the fall of the lake, during its stillstand at the Provo shoreline (alt, 4,800 ft) (Provo Formation of Hunt and others, 1953), and during its subsequent desiccation are correlated with those of the recession and disappearance of the Bull Lake glaciers.

The lower, middle, and upper tills of the Pinedale Glaciation are inferred to correlate with the deposits of three fluctuations of a post-Provo rise of the lake discovered by R. B. Morrison (1961). These attained upper limits of 4,770, 4,470, and 4,410 feet, respectively. Deglaciation accompanied the final fall and desiccation of Lake Bonneville,

Deposits of the Temple Lake and historic stades of Neoglaciation in the cirques are inferred to correlate respectively with the deposits at the Gilbert Beach alt, 4,240–4,245 ft) (Eardley and others, 1957) and the upper few feet of bottom sediments of Great Salt Lake.

INTRODUCTION

The canyon of Little Cottonwood Creek and adjacent Bells Canyon, in the Wasatch Mountains about 15 miles south of Salt Lake City, have long been famous among geologists because it was here that Gilbert (1890) first demonstrated a relation between the glacial deposits at the mouths of the canyons and Lake Bonneville.

The area drained by these two canyons covers about 30 square miles and lies between lat 40°30′ and 40°37′ 40″ N. and long 111°30′ and 111°47′30″ W. (fig. 1).

The purpose of this paper is to describe the Quaternary deposits of these canyons and to discuss their geologic history and correlation with the deposits of Lake Bonneville. The work was done concurrently with a study of the deposits of Lake Bonneville in the adjacent Draper area to the west by R. B. Morrison. Morrison and the writer together examined and mapped that part

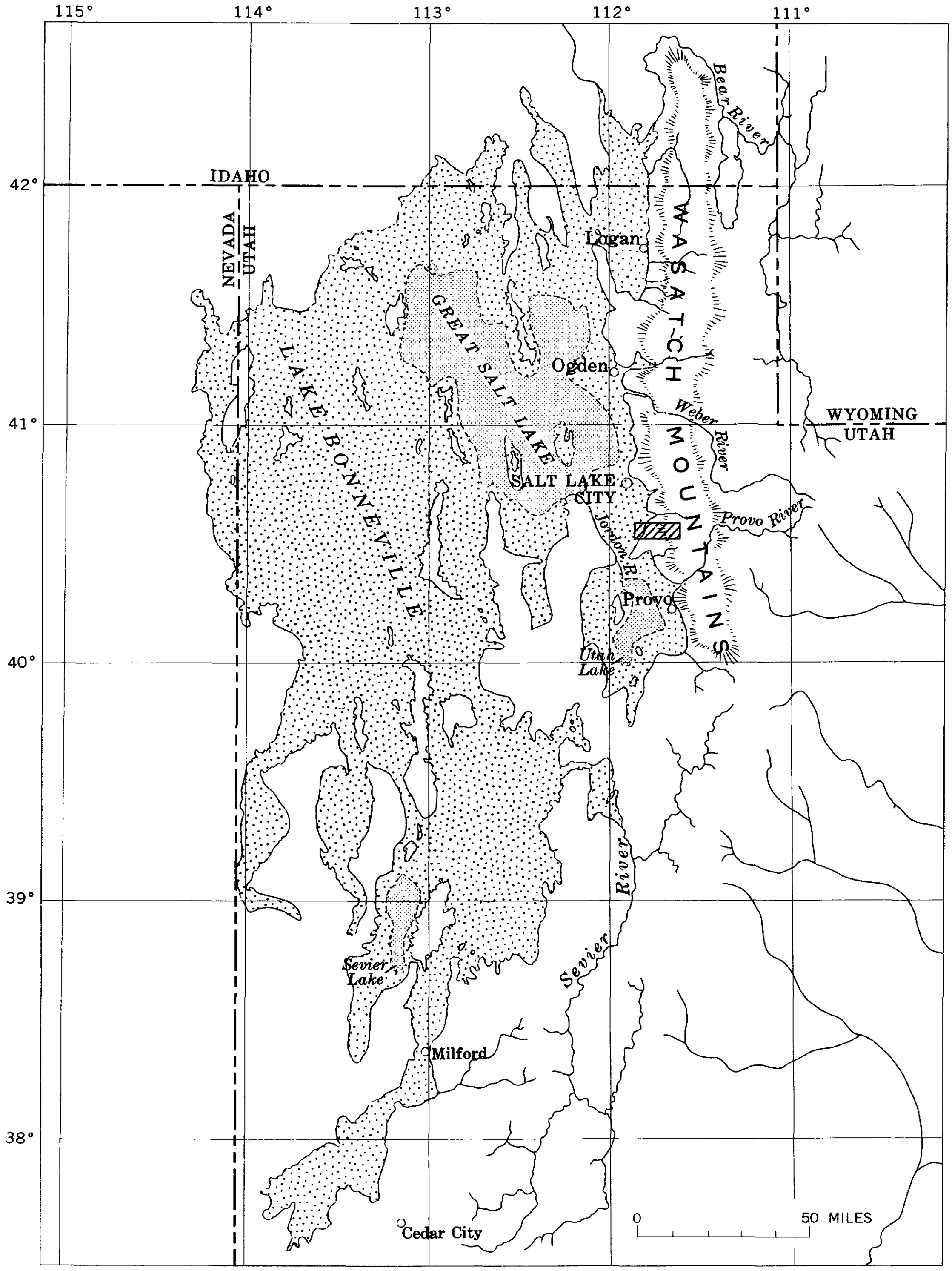

FIGURE 1.—Index map showing location of Little Cottonwood and Bells Canyons, Utah.

of the area at the mouths of Little Cottonwood and Bells Canyons where the lake and glacial deposits intertongue, and are in agreement as to their interrelations. They visited the area together first in 1950 and again briefly in 1952, and the author spent about 4 weeks during the summer of 1959 studying the glaciation in the area.

PREVIOUS WORK

Evidence of glaciation along Little Cottonwood Canyon was first recorded by Emmons (*in* Hague and Emmons, 1877, p. 353–354), who observed that moraines at the mouth of the canyon "extended as low as the ancient lake which once filled Utah basin." Subsequently, King (1878) inferred from the dual character of the deposits of Lake Bonneville that there had been two periods of glaciation separated by an episode of aridity. Gilbert (1890) described the moraines at the mouth of the canyon, but failed to find any evidence of a lakeshore cut on them. He therefore inferred that the moraines were formed while the lake level stood at the Provo shoreline after erosion of its outlet had caused it to fall from the Bonneville shoreline. Gilbert also inferred that there must have been an earlier glaciation coincident with a high stand of the lake which preceded, but attained a lower level than, the stand at the Bonneville shoreline.

In 1909, Atwood made the first, and to date the only, survey of the glaciation of the Wasatch Mountains as a whole. He observed differences in the distribution, weathering, and erosion of the moraines at the mouths of little Cottonwood and Bells Canyons that clearly proved that two advances of the ice had extended below the Bonneville shoreline at the mouths of the canyons. He called these the "earlier" and "later" epochs of glaciation and included moraines higher in the canyons as recessional deposits of the later epoch. Atwood also discovered that till of the "earlier epoch" at the mouth of Bells Canyon is overlain by lake deposits, thus substantiating Gilbert's inference that glaciation paralleled both high fluctuations of the lake.

Subsequent workers have added considerable detail to this general history. Blackwelder (1931) found deltaic deposits of the lake in the breach of Little Cottonwood Creek through the moraines of the later epoch. He therefore concluded that the prograding activity of streams flowing off the glacier prevented notching of the moraines by the high shore of the lake, which could thus have been coincidental with the glacial maximum. Antevs (1945, 1952) agreed with these general conclusions and with those of Atwood (1909).

Calkins and Butler (1943), in a discussion of the mining district in the upper part of Little Cottonwood Creek, mentioned "a terminal moraine of a late stage" at the mouth of Gad Valley. Marsell (1946) indicated that deposits of three glaciations were present on Little Cottonwood Creek, the first two of which he believed to be of pre-Bonneville age and the last of Provo age. Ives (1950) described evidence for five advances of the ice: (a) a very old glaciation, established principally on the basis of erratics; (b) a glaciation virtually equivalent to the earlier epoch of Atwood; (c) a glaciation virtually equivalent to the later epoch of Atwood, but represented by two sets of moraines; (d) an upper canyon glaciation represented by moraines at the confluence of Little Cottonwood Creek with White Pine Fork and with Gad Valley; (e) a valley-head glaciation represented by moraines 1 to 1½ miles from the cirque headwalls, which he belived were formed during the "Little Ice Age" of Matthes (1939, 1942), or less than 4,000 years ago.

Later workers (Marsell and Jones, 1955; Jones and Marsell, 1955) have provided new facts from their studies of the mouth of Little Cottonwood Canyon; for example, that the thickness of the gravelly outwash deposits just west of the moraines is as much as 1,000 feet.

Recently, Eardley, Gvosdetsky, and Marsell (1957) reviewed the evidence for multiple glaciation in the Little Cottonwood area, enlarging upon the conclusions reached by Marsell in 1946.

BEDROCK GEOLOGY

The bedrock geology of the headwaters of Little Cottonwood Creek was fully described by Calkins and Butler (1943), and a summary of a study of the entire area was published by Crittenden, Sharp, and Calkins (1952). The reader is referred to these reports for descriptions of the stratigraphic units in the area, to which occasional reference is made in this paper.

CLIMATE

The climate of Little Cottonwood and Bells Canyons ranges from semiarid at the mountain front to subarctic in parts of some of the higher cirques. Annual precipitation is in excess of 50 inches at Alta and ranges from 15 to 20 inches at the mountain front. Maximum precipitation occurs from December to April, mostly as snow. Annual snowfall at Alta is about 350 inches. The mean annual temperature is about 35°F at Alta and about 55°F at the mountain front.

Monthly average altitudes of the freezing isotherm (0°C) at Salt Lake City (alt, 4,220 ft) range from below the ground surface to about 15,000 feet (fig. 2). Readings below 8,000 feet are affected by local temperature inversion conditions, and therefore fluctuate

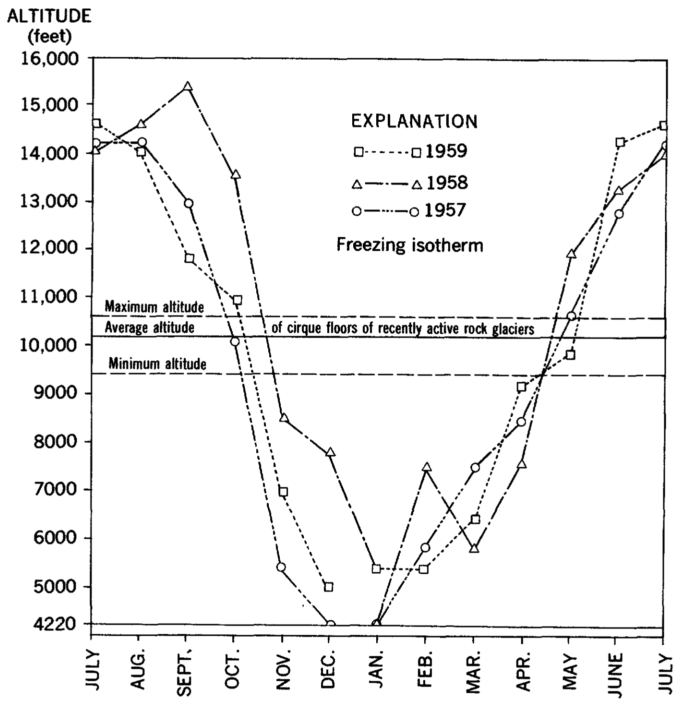

FIGURE 2.—Monthly average altitudes of freezing isotherm at 5 : 00 a.m., Salt Lake City, Utah, for years of record—1957, 1958, 1959.

widely. Of interest in its relation to glaciation in Little Cottonwood and Bells Canyons, however, is the fact that the freezing isotherm is below an altitude of 10,000 feet from about October 15 to April 15, a period of 6 months. This altitude is in close correlation with the average altitude of 10,200 feet for cirque floors occupied by rock glaciers that are known to have been active within the last 1,000 years (fig. 2).

The writer agrees with Ives (1950, p. 113) that some of these rock glaciers seem to be active at present, and that the area is marginally glacial. Ives suggested (p. 106) that an "over-all lowering of temperatures by about 10°F would re-establish glacial conditions in the summit area." This would mean lowering the freezing isotherm by about 2,000 feet, which would bring it to an altitude of about 12,000 feet in July. Lowering the freezing isotherm by 3,000 feet in July would intersect the peaks and permit the formation of ice caps on the divides. As the divides were covered by ice in only a few places at the time the late Pleistocene glaciers extended to the mouths of the canyons, the writer is inclined to believe that lowering of the freezing isotherm by only about 1,000 feet would result in the formation of small glaciers in the cirques and a marked rejuvenation of activity of the rock glaciers. This is equivalent to lowering the mean July free-air temperature only 4° or 5°F.

VEGETATION

The vegetation of Little Cottonwood and Bells Canyons has many characteristics common to that on the western slope of the middle Rocky Mountains; it also includes many aspects of the vegetation on the High Plateaus of Utah to the south.

Timberline along ridge crests is between 10,800 and 11,000 feet altitude, or just below the summits of the highest peaks. In north-facing cirques the upper limit of trees extends as low as 9,500 feet as a result of local orographic conditions, including the distribution of bare rock cliffs, rock glaciers, and talus deposits. Nowhere does wind seem to be a significant agent in its control. On the north side of Little Cottonwood Canyon, timberline parallels the contact of the quartz-monzonite stock and overlying rocks for a considerable distance. In Albion Basin, Collins Gulch, and Peruvian Gulch mining operations have extensively deforested the slopes, but the former position of timberline is readily established.

An Alpine zone is probably lacking, for areas above timberline are largely rocky slopes, and such vegetation as exists is mostly grass. Flora typical of the Alpine zone is scarce. The Hudsonian zone lies at altitudes between 11,000 and 9,500 feet, but it has a vertical extent of only 100 to 200 feet. The Canadian zone lies between an upper limit of 11,000 to 9,000 feet and a lower limit of 6,000 to 7,000 feet. The Transition zone has an upper limit of about 9,000 feet and a lower limit of about 5,000 feet. The Upper Sonoran zone lies below about 5,200 feet.

The distribution of forest types, as compiled from field observations and inspection of aerial photographs, is shown in figure 3. A spruce-fir climax lies below an upper limit that ranges from 11,000 to 9,700 feet and above a lower limit that ranges from 6,000 feet on south-facing slopes to 7,000 feet on north-facing slopes. It consists predominantly of Engelmann's spruce (*Picea engelmanni*), but includes some Alpine fir (*Abies lasiocarpa*), white fir (*Abies concolor*), whitebark pine (*Pinus albicaulis*), limber pine (*Pinus flexilis*), and, locally, Douglas-fir (*Pseudotsuga taxifolia*). Willow (*Salix spp.*), mountain alder (*Alnus tenuifolio*), and red birch (*Betula fontinalis*) are abundant along water courses and in swampy areas. Stands of quaking aspen (*Populus tremuloides*) are common throughout the lower part of the zone below altitudes that range from about 8,500 feet in Hogum Fork to 9,700 feet in Albion Basin.

A zone of ponderosa pine (*Pinus ponderosa*), which occurs both to the north and to the south along the Wasatch Mountains, is lacking in Little Cottonwood

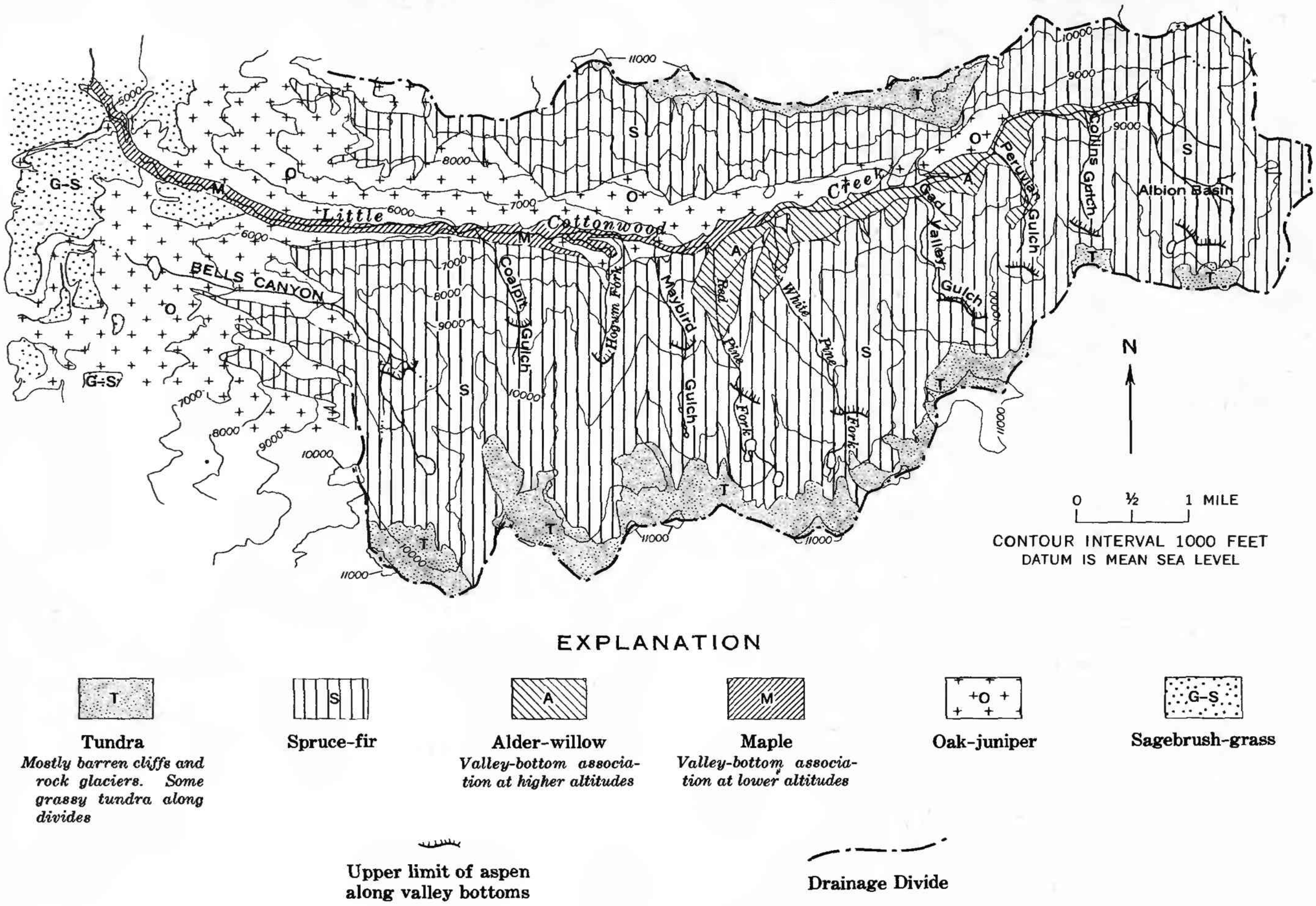

FIGURE 3.—Vegetation zones in the drainage of Little Cottonwood and Bells Canyons.

and Bells Canyon. No obvious reason for this lack was noted.

An oak climax lies between altitudes of 5,000 and 9,000 feet along the front of the mountains and also extends up Little Cottonwood Canyon along its north slope to about 9,000 feet. Gambel oak (*Quercus gambelii*) and Utah oak (*Quercus utahensis*) predominate, forming dense stands that cover large areas or scattered clumps that are separated by areas of grass and sagebrush (*Artemesia tridentata*). Rocky Mountain juniper (*Juniperus scopulorum*), Utah juniper (*Juniperus utahensis*), and one-seed juniper (*Juniperus monosperma*) occur sparsely throughout, but they are especially common in the lower part of the range. Other intermixed brush include western chokecherry (*Prunus virginiana*), mountain mahogany (*Circocarpus ledifolia*), western sarvisberry (*Amelanchier utahensis*), quininebush (*Cowania stansburiana*), and boxelder (*Acer negundo*).

The floor of Little Cottonwood Canyon upstream from an altitude of 7,500 feet is characterized by a mixed valley-bottom forest consisting mostly of quaking aspen (*Populus tremuloides*), local patches of Engelmann's spruce (*Picea engelmanni*), and scattered mountain ash (*Sorbus sitchensis*), elderberry (*Sambuscus glauca*), and various species common to the oak climax on the adjacent lower slopes of the north wall of the valley. The creek tends to be bordered by alder (*Alnus tenuifolia*), willow (*Salix spp.*), red birch (*Betula fontinalis*), and scattered blue spruce (*Picea pungens engelmanni*).

From about 7,500 feet downstream to the mouth of the canyon, the valley-botton forest consists primarily of maple (*Acer glabrum* and *A. grandidentatum*), which attains a height of 20 to 30 feet. Intermixed are oak (*Quercus gambelli* and *Q. utahensis*), western thornapple (*Crataegus douglassii*), western sarvisberry (*Amelanchier utahensis*), boxelder (*Acer negundo*), western chokecherry (*Prunus virginiana*), and scattered narrowleaf cottonwood (*Populus angustifolia*).

A sagebrush and grass climax occurs at areas within the lower part of the oak climax and at altitudes below 5,000 to 5,200 feet. Its upper limit coincides in many places with the Bonneville shoreline (5,135 ft). Secondary species within this climax are those common to the Upper Sonoran zone.

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GENERAL PHYSIOGRAPHY OF THE CANYONS

Little Cottonwood Canyon is a steep spectacularly U-shaped gorge (fig. 4). The lower sector is mostly in the quartz monzonite of the Little Cottonwood stock, and the upper sector is mostly in Precambrian and Paleozoic sedimentary rocks. The glaciated lips of tributary hanging valleys are about 600 feet above the creek along the upper sector and about 1,000 feet above the creek along the lower sector. The canyon floor rises in an easterly direction from an altitude of 5,200 feet at its mouth to 9,600 feet in Albion Basin, 11 miles upstream, a gradient of 400 feet per mile. As the divide at the head of the canyon is about 1,200 feet above the cirque floor, the overall relief along the canyon is about 5,600 feet. Bells Canyon rises 4,700 feet in 5 miles, a gradient of 940 feet per mile, and has an overall relief of 6,050 feet. The maximum relief in the area is 6,233 feet—from the mouth of Little Cottonwood Creek to Twin Peaks (alt, 11,433 ft) at the head of Gad Valley.

ASYMMETRY

As pointed out by Calkins and Butler (1943), the Wasatch Mountains are topographically asymmetric, the highest part of the range being west of the actual drainage divide. At the head of Little Cottonwood Canyon (fig. 5), peaks along the divide have an average altitude of about 10,625 feet, whereas those to the west on either side of the canyon have an average altitude of 11,150 feet (fig. 5*A*). This asymmetry, though partly due to the resistance of the Little Cottonwood stock that underlies many of the western peaks, is primarily the result of uplift of the range along normal faults along the mountain front. The asymmetry is reflected in the relief of the canyon walls, which ranges from 3,500 to 5,000 feet in the lower sector of the canyon and from 1,400 to 2,600 feet in the upper sector.

FIGURE 4.—Lower sector of Little Cottonwood Canyon showing profile of lower broad valley surface entrenched by inner U-shaped gorge.

A second obvious asymmetry is displayed by the difference in character of the tributaries on the north and south sides of Little Cottonwood Canyon as noted by Ives (1950). Tributaries from the north are short steep unglaciated gullies that head in avalanche chutes: the one heading on Dromedary Peak (fig. 5*B*) rises 3,950 feet in a total length of only 1½ miles at a gradient of 2,660 feet per mile; the one heading on Superior Peak rises 3,000 feet in a total length of only 1 mile. In contrast, tributaries from the south are long glacial gorges whose gradients become successively less steep from west to east. Hogum Fork rises 5,000 feet in 3 miles, a gradient of 1,660 feet per mile. Gad Valley Gulch rises 3,580 feet in 3½ miles, a gradient of 1,020 feet per mile.

Possible reasons for this asymmetry are the differences in moisture accumulation and in isolation between north-facing and south-facing slopes. These factors affect the headward growth of tributaries not only during glaciation but also during interglacial stream erosion. The magnitude of the asymmetry suggests that late Pleistocene glaciation has augmented differences in tributary growth that probably became apparent shortly after uplift of the range by normal faulting began. No structural or lithologic differences in the bedrock that might affect the rate of tributary growth on the two sides of the canyon have been observed.

EROSION SURFACES

Little Cottonwood Canyon comprises an inner narrow U-shaped gorge, about three-quarters of a mile wide, that is cut within a deep broadly U-shaped valley about 1¼ miles wide (fig. 5*B*). The concordant profiles of ridge crests separating the major tributaries further suggest that a still higher broad valley once occupied the present drainage of the canyon (fig. 6). The distribution of remnants of the two broad valley surfaces and a reconstruction of their long profiles are shown in figures 5*A*, *B*.

The profile of the lower broad valley lies 300 to 400 feet above Little Cottonwood Creek at the head of the canyon and about 1,000 feet above it at the mouth of the canyon (fig. 5*A*). The latter figure may indicate the amount of relative uplift of the surface by normal faulting at the mountain front. The present gradient of the profile is about 430 feet per mile. A projection of the gradient to the canyon mouth intersects a remnant of an erosion surface between 6,100 and 6,200 feet altitude along the north side of Little Cottonwood Canyon; this surface is capped by 100 feet or more of arkosic sandy bouldery gravel (pl. 1). Most of the boulders are 12 to 18 inches in diameter, but some are as much as 3 feet. They are predominantly quartzite; but

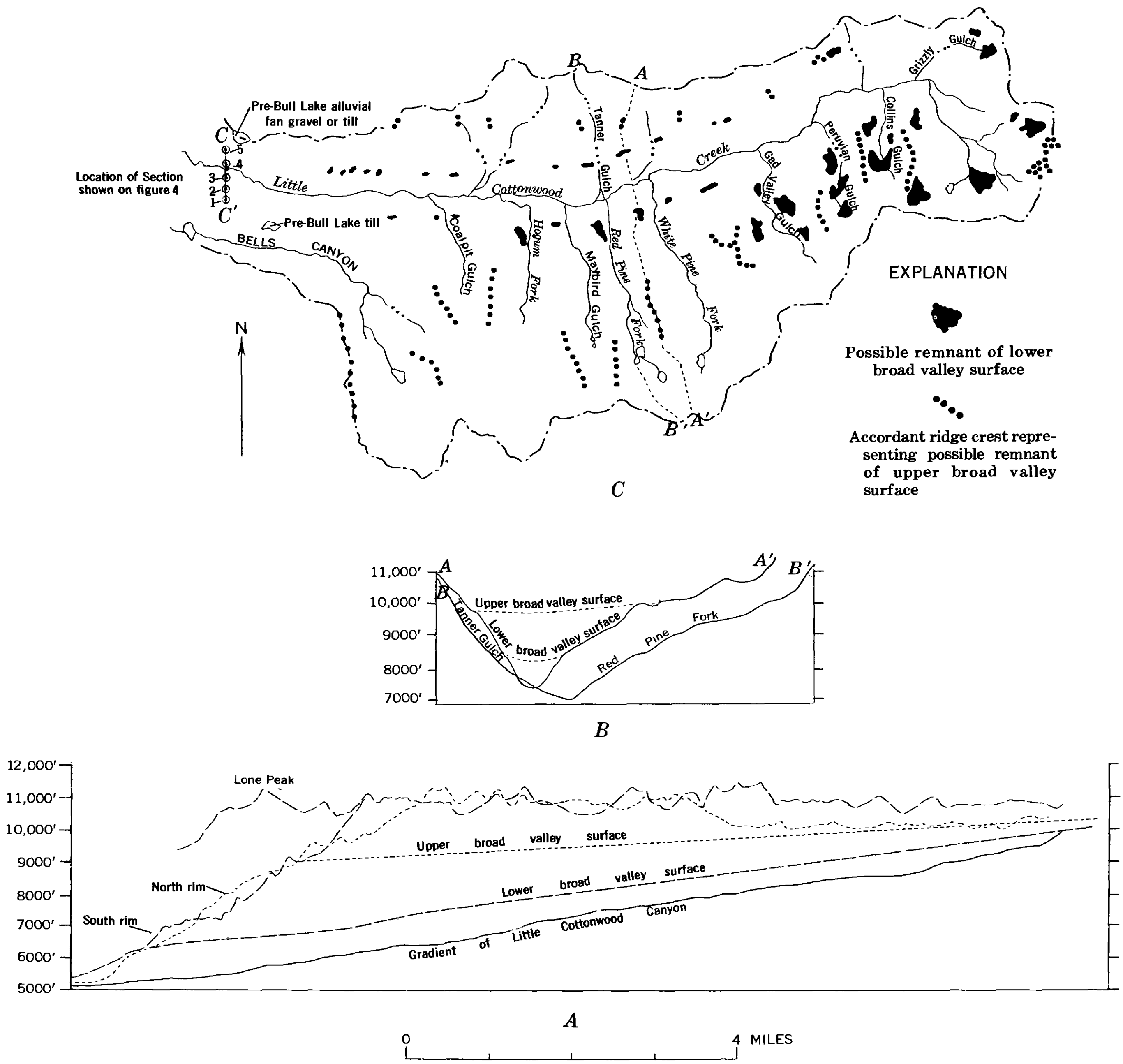

FIGURE 5.—Profiles showing asymmetry of Wasatch Mountains and of Little Cottonwood Canyon and map and profiles of upper and lower broad valley surfaces in Little Cottonwood Canyon.

A, Long profile of Little Cottonwood Canyon showing (1) gradient of canyon, (2) projected gradient of lower broad valley surface, (3) projected gradient of upper broad valley surface, (4) profile of south rim of canyon (fine dashed line) and profile of north rim of canyon (fine dotted line) showing east-west asymmetry of Wasatch Mountains.

B, Section *A–A′*, cross profile of upper and lower broad valley surfaces along divide east of Red Pine Fork and Tanner Gulch. Section *B–B′*, cross profile of Little Cottonwood Canyon along Tanner Gulch and Red Pine Fork. Sections show north-south asymmetry of canyon.

C, Map of possible remnants of upper and lower broad valley surfaces in Little Cottonwood Canyon. Profiles *A–A′* and *B–B′* are shown in figure 5*B*; profile *C–C′* in figure 7.

quartz, quartz-muscovite gneiss, amphibolite, quartz-biotite gneiss, diabase, quartz monzonite, porphyritic quartz monzonite, and granodiorite were also observed by the writer. Some of the cobbles and boulders are well rounded, some are irregular in shape, and some are soled across their internal structure in a concave manner. Striations were noted on a few quartzite cobbles.

R. B. Morrison (written communication, 1960) interprets this deposit as an ancient alluvial fan gravel. The writer, however, agrees with Crittenden and others (1952, pl. 1) that it is a high-level till. The deposit is included in the altitude range of erratic boulders interpreted to be of glacial origin and referred to as M1 by Eardley and others (1957). Unfortunately, no conclusive evidence as to the origin of the deposit has been found.

The upper broad valley appears to have been 2 to 3 miles wide, about 700 feet deep at its head, and 2,000 feet deep at its mouth. No deposits related to it were found. Reconstruction of the long profile of the valley suggests that its present gradient is about 200 feet per mile. The profile lies about 300 feet above the lower broad valley surface in the upper sector of Little Cottonwood Canyon and about 2,500 feet above that surface at the canyon mouth. The latter figure may suggest the amount of relative uplift of the surface at the mountain front by normal faulting at the time the lower surface was being cut.

AGE OF THE EROSION SURFACES

Eardley (1944) has described two ancient erosion surfaces in the northern part of the Wasatch Mountains southeast of Ogden (fig. 1). The older, known as the Herd Mountain surface and now preserved at altitudes ranging from 8,500 to 9,100 feet, slopes gently into the upper parts of the valleys and is cut on rocks as young as Oligocene in age. The younger surface, known as the Weber Valley surface, is a dissected pediment that, in its type area, is cut primarily on soft sedimentary rocks of Cretaceous and Tertiary age. Eardley believes that the surface was cut in late Pliocene or early Pleistocene time.

Crittenden, Sharp, and Calkins (1952) suggested that the subdued topography along the crest of the Wasatch Mountains east of Salt Lake City may represent the Herd Mountain surface, and that remnants of an entrenched pediment along Emigration Canyon, east of Salt Lake City, probably represent the Weber Valley surface.

The writer found no erosion surface on the divides enclosing Little Cottonwood and Bells Canyons that he would correlate with the Herd Mountain surface. The upper broad valley surface of this report may be of late Pliocene or early Pleistocene age and, though proof is lacking, it was probably the surface on which the first glaciation of the area occurred.[1] Its relation to the Herd Mountain surface is unknown, but it was clearly related to the present drainage and was not a continuous upland plain or pediment.

The lower broad valley surface is believed by the writer to be of middle Pleistocene age and is correlated

[1] This belief is based on the fact that the oldest of three pre-Wisconsin tills in the La Sal Mountains, 200 miles to the southeast, was deposited by glaciers flowing on the older of two high-level broad valley surfaces (Richmond, 1957, 1962).

FIGURE 6.—Upper sector of Little Cottonwood Canyon showing remnants of lower broad valley surface above inner U-shaped gorge and higher accordant intertributary ridges which are believed to represent an upper broad valley surface.

with the remnants of an entrenched pediment along Emigration Canyon which Crittenden, Sharp, and Calkins (1952) correlated with the Weber Valley surface.

QUATERNARY DEPOSITS

The Quaternary deposits of Little Cottonwood and Bells Canyons include tills of at least three major Pleistocene glaciations [2] and two minor Recent regenerations of the ice. In addition, there is a variety of alluvial and colluvial deposits whose stratigraphic and geomorphic relations to the tills, to each other, to disconformities, and to soil profiles make possible their correlation with the glacial sequence.

The three Pleistocene glaciations are correlated with those of the Wind River Mountains, Wyo. (Blackwelder, 1915; Holmes and Moss, 1955) as pre-Bull Lake [3] Bull Lake, and Pinedale. Glacial deposits of the Recent Neoglaciation (Moss, 1951a) represent two stades. The deposits of the earlier or Temple Lake Stade are correlated with the Temple Lake Moraine (Hack, 1943; Moss, 1951a, b; Holmes and Moss, 1955); the deposits of the later stade, called simply the historic stade, are correlated with the cirque moraines of Moss (1951a). This terminology is applied to the deposits in the area of this report to avoid introduction of new names.

Deposits of at least one pre-Bull Lake glaciation antedate Lake Bonneville. Deposits of the Bull Lake Glaciation, which includes two stades, lie at the mouths of the canyons and stratigraphically intertongue with the deposits of Lake Bonneville in such a way that they can be correlated directly with the two high-level fluctuations of the lake. Deposits of the Pinedale Glaciation, which includes three stades, lie too far up the canyons to have direct contact with the lake deposits, and the outwash gravels are too alike and discontinuous to be traced from the moraines to the canyon mouths. On the basis of comparative weathering, however, these deposits can be correlated with a sequence of alluvial terraces that are graded to deposits of three intermediate-level fluctuations of the lake. Deposits of the Temple Lake and historic stades of the Neoglaciation are correlated indirectly with two Recent low-level fluctuations of Great Salt Lake.

TILL OF A PRE-BULL LAKE AGE

If the bouldery deposit on the remnant of the lower broad valley surface north of the mouth of Little Cottonwood Canyon, described on page D6, is till, it lies well above the upper limit of Bull Lake ice and is the oldest glacial deposit in the area.

Younger distinct till of pre-Bull Lake age occurs in the saddle along the divide between Little Cottonwood and Bells Canyons at an altitude of 6,800 to 6,900 feet (pl. 1). The till comprises two rather different deposits. One is thin and consists of boulders and cobbles in a coarse arkosic sandy matrix. Most of the boulders are derived from quartzite of Precambrian age that underlies the ridge; but some are of quartz monzonite from the Little Cottonwood stock to the east, and others are of tillite of Precambrian age, quartzite, and granodiorite of Paleozoic age from the upper part of Little Cottonwood Canyon. Several of the stones are soled or faceted, and striations are preserved on a few of the quartzite cobbles. The deposit bears no soil, and is being eroded by slope processes at present. Boulders at its surface are hard, but very few nonresistant components remain. The material extends from the saddle downslope into Bells Canyon to an altitude of 6,600 feet—the upper limit of striated surfaces and less weathered erratics of the Bull Lake Glaciation.

The other deposit of younger till of pre-Bull Lake age lies just upslope from the first on the Bells Canyon side of the saddle. It forms an abrupt ridge which appears to be a remnant of a lateral moraine from Bells Canyon. The ridge extends from an altitude of 7,000 feet to about 7,120 feet. It is 30 to 40 feet high and is composed predominantly of large boulders as much as 10 feet in diameter, some of which are soled and faceted. The entire deposit is composed of quartz monzonite from the Little Cottonwood stock, which is the only rock type upstream in Bells Canyon. Its lower limit is about 200 feet above striated ledges and erratics that mark the upper limit of Bull Lake ice.

These two deposits probably represent the same pre-Bull Lake glaciation and, on the basis of their topographic setting, seem to be of postcanyon age. The fact that morainal topography is preserved on one of them suggests that they correlate with the youngest of three tills of pre-Bull Lake age in the Rocky Mountain region (Richmond, 1957).

DISCONFORMITY BETWEEN PRE-BULL LAKE AND BULL LAKE DEPOSITS

Most of the erosion of Little Cottonwood and Bells Canyons appears to have taken place in Pleistocene time before the formation of a very strongly developed thick reddish clayey soil, called the pre-Lake Bonneville soil (Morrison 1961). Just north and south of the canyons (pl. 1), this soil is formed on pre-Lake Bonneville fan

[2] The terms "glaciation" and "stade" are used in this report in the sense recommended by the American Commission on Stratigraphic Nomenclature (1961) in lieu of the terms "stage" and "substage," respectively.

[3] The term "pre-Bull Lake" is applied here in preference to the term "Buffalo" (Blackwelder, 1915) because deposits of the "Buffalo stage" are known to represent more than one glaciation (Richmond, 1957, 1962).

gravel and is overlain by the outer moraines of Bull Lake Glaciation. It occurs at altitudes as low as 5,160 feet on the east side of the fault zone along the mountain front (pl. 1). This altitude is only 75 feet above the bedrock floor of Little Cottonwood Creek on the east side of the fault zone (fig. 7), and suggests that erosion of the canyon since soil formation has been relatively slight. Moreover, the erosion has been of only temporary character, for at least 160 feet of gravel and till lies above the bedrock floor of the canyon east of the fault zone (fig. 7), and at least 1,000 feet of gravel lies west of it (Marsell and Jones, 1955). These conditions indicate that, despite intermittent deepening of the canyon, deposition has more than kept pace with erosion resulting from uplift of the mountains since formation of the pre-Lake Bonneville soil.

DEPOSITS OF THE BULL LAKE GLACIATION

Deposits formed during the Bull Lake Glaciation in the drainage of Little Cottonwood and Bells Canyons include till, outwash gravel, and colluvium (fig. 8). These deposits locally overlap the pre-Lake Bonneville soil, and the upper limit of the till lies downslope from till of pre-Bull Lake age.

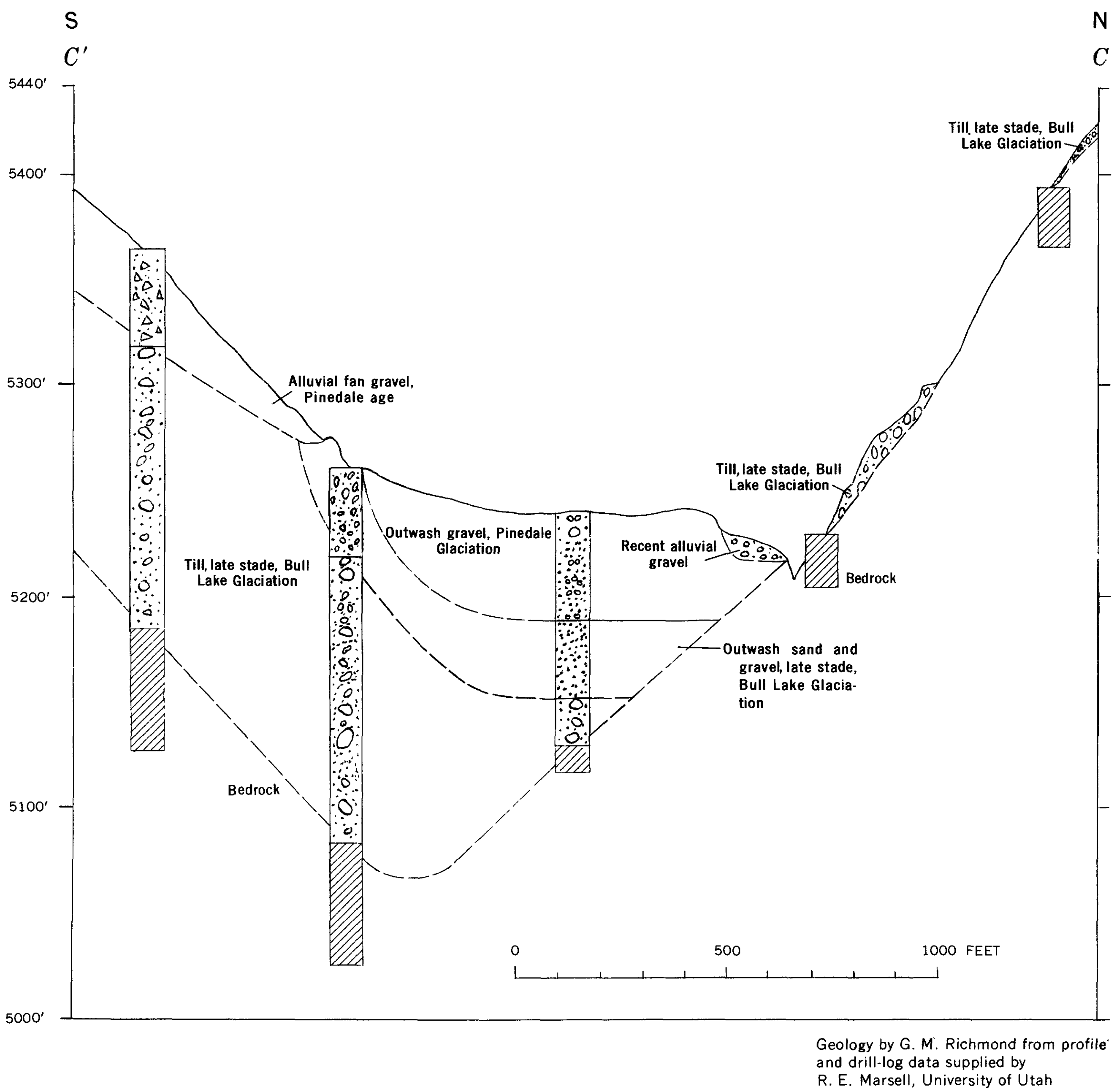

FIGURE 7.—Cross profile of the mouth of Little Cottonwood Canyon.

The deposits characteristically have a distinctive Brown Podzolic soil formed on them and are the youngest deposits to bear this soil. They commonly either are overlapped by deposits formed during the Pinedale Glaciation or are cut by channels containing such deposits. Thus, they represent a glaciation intermediate between the oldest definitely recognized in the area and the last major glaciation of the canyons.

Both the till and the outwash of the Bull Lake Glaciation include two stratigraphically distinct units—a lower unit and an upper unit. The significant unconformity separating these units and their relations to the deposits of the two high fluctuations of Lake Bonneville are such that they are considered to represent two stades of glaciation separated by an interstade of marked recession of the ice.

TILL

The glacial deposits of Bull Lake age comprise two tills—a lower till and an upper till that, respectively, underlie the outer and inner of two sets of large moraines at the mouths of the canyons. On Little Cottonwood Canyon the outer moraine extends to a lower limit of 5,040 feet altitude, the inner moraine to 5,080 feet. In Bells Canyon the outer moraine extends to an altitude of 4,920 feet, the inner moraine to 5,100 feet. Upstream, the till extends discontinuously to the headwaters of the canyon above the level of younger moraines of the Pinedale Glaciation (pl. 1).

Throughout both canyons, the till of the Bull Lake Glaciation has a compact silty sandy matrix and an abundance of angular to subangular boulders. The boulders, however, are not so numerous as they are in deposits of the Pinedale Glaciation.

CHARACTER OF THE MORAINES

LITTLE COTTONWOOD CANYON

The glacial deposits at the mouth of Little Cottonwood Canyon form an outer and an inner moraine, though the deposits of the outer moraine are mostly overlapped either by those of the inner moraine or by the sediments of Lake Bonneville. On the north wall of the canyon the outer moraine is represented by a zone of erratics and patches of till that extends to the northwest from an altitude of 5,760 to 5,480 feet, and locally overlies the pre-Bull Lake soil (figs. 9, 8*A*).

At its east end, this zone parallels, but lies above, a distinct bouldery bench representing the inner moraine, but westward it is overlapped by that bench, which extends downslope to an altitude of 5,200 feet (pl. 1).

On the south wall of the canyon are two distinct lateral moraines—an outer moraine above an inner—that extend downslope to the fault zone at the mountain front. West of the fault zone, the inner moraine is considerably higher than the outer, suggesting that some of the faulting may have occurred in the interval separating their deposition. At the mouth of the canyon, the inner moraine bifurcates into a broad complex of morainal arcs from which outwash deposits extend westward to the Bonneville shoreline at an altitude of 5,135 feet. As noted by Marsell and Jones (1955), both the moraine and its associated outwash gravels are overlapped by the lake gravels of the Bonneville Formation (Hunt and others, 1953).

BELLS CANYON

The outer and inner moraines of Bull Lake Glaciation at the mouth of Bells Canyon are quite different in character. The outer end moraine forms a broad dissected arcuate mass about 100 feet high and is very mature in appearance (fig. 9). Its lower limit is at an altitude of 4,920 feet. Its slopes are relatively gentle and sparsely covered with brownish quartz-monzonite boulders. Lateral moraines form broad low ridges on both the north and south sides of the canyon, but they are not connected with the terminal moraine. The inner moraine, in contrast, forms a large ridge about 600 feet high upslope from, and in part overlapping, the outer moraine. Its slopes are steep and are covered with whitish quartz-monzonite boulders. It is relatively much less mature in appearance than the outer moraine, but is not nearly so rough and bouldery as moraines of the Pinedale Glaciation upstream. Well-developed lateral moraines rise abruptly from the terminal moraine on both sides of the canyon.

INTERPRETATION OF THE MORAINES

Atwood (1909) was the first to recognize that the moraines at the mouths of Little Cottonwood and Bells Canyons represented two advances of the ice, and concluded that the intervening interval was of interglacial character. Later, Blackwelder (1931) correlated all the moraines at the mouths of the canyons with the Bull Lake Glaciation, limiting the Pinedale Glaciation to moraines upstream in the canyons. The writer is in complete agreement with this correlation, though substantial evidence supports Atwood's conclusion that the moraines at the canyon mouths represent two advances of the ice. He differs with Atwood only as to the interpretation of the character of the climate separating these advances.

EVIDENCE FOR CORRELATION WITH THE BULL LAKE GLACIATION

Correlation of the till in Little Cottonwood and Bells Canyons with the till of the Bull Lake Glaciation in the Wind River Mountains, Wyo. (Blackwelder, 1915), is based primarily on the similarity of their stratigraphic positions. That is, both tills overlie thick red-

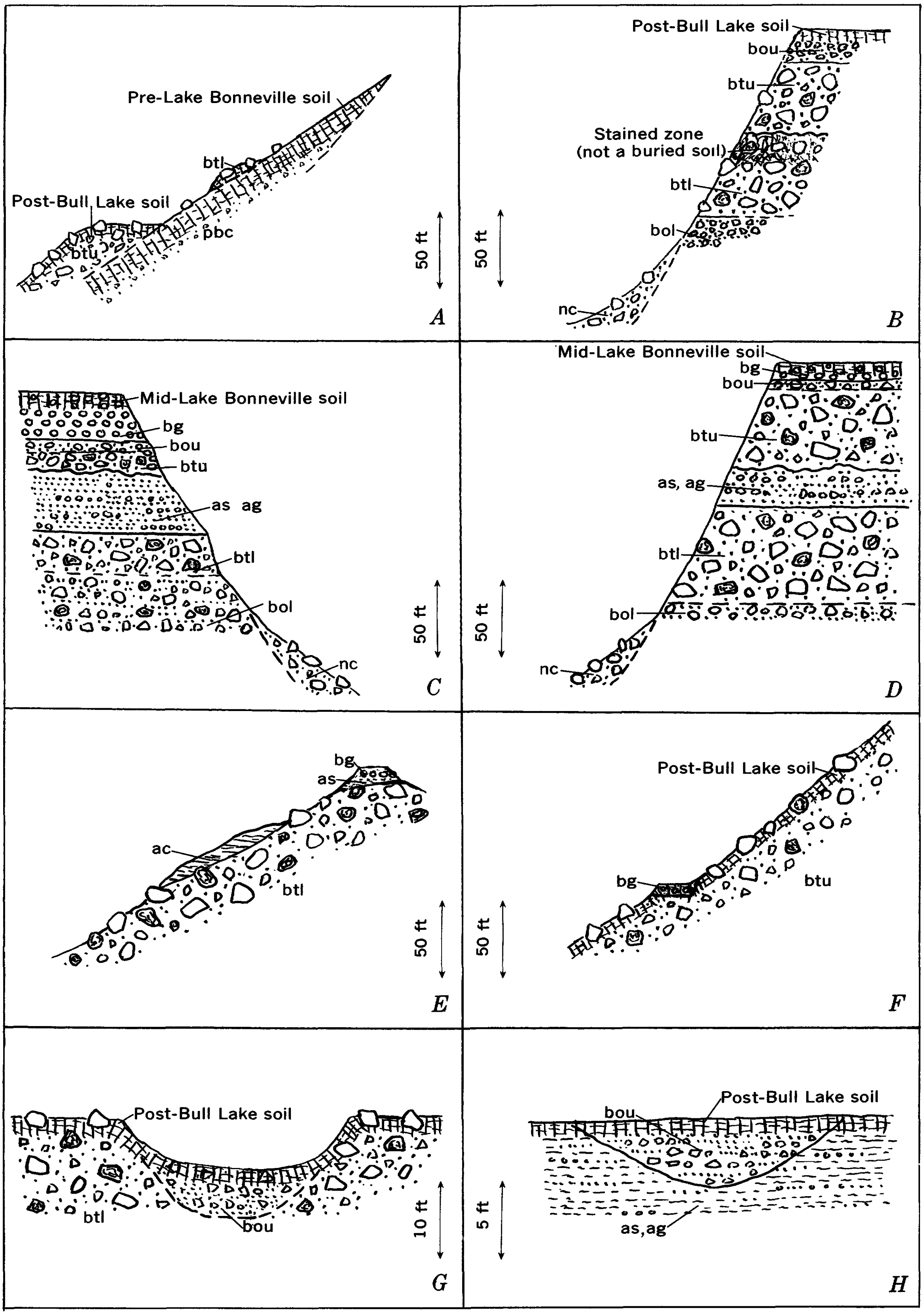
Pre-Lake Bonneville soil
btl
Post-Bull Lake soil
btu
pbc
50 ft
A
Post-Bull Lake soil
bou
btu
Stained zone
(not a buried soil)
btl
bol
nc
50 ft
B
Mid-Lake Bonneville soil
bg
bou
btu
as ag
btl
bol
nc
50 ft
C
Mid-Lake Bonneville soil
bg
bou
btu
as, ag
btl
bol
nc
50 ft
D
bg
as
ac
btl
50 ft
E
Post-Bull Lake soil
bg
btu
50 ft
F
Post-Bull Lake soil
btl
bou
10 ft
G
Post-Bull Lake soil
bou
as,ag
5 ft
H

FIGURE 8

dish clayey soils on deposits associated with older glaciations, and both underlie deposits of the last major canyon glaciation.

Surface features and form:

1. The terminal moraines are large and bulky.
2. The terminal moraines are thoroughly breached by axial streams.
3. Lateral moraines are deeply notched by tributary streams.
4. The slopes of the moraines have a mature appearance.
5. Kettles are nearly filled with colluvium and tend to be breached by erosion.
6. Surface boulders are numerous, but less abundant than on moraines of the Pinedale Glaciation.
7. Many boulders on the surface of the moraines are cracked, broken apart, or exfoliated.
8. Many boulders on the surface are stained or decayed to depths greater than half an inch.
9. Limestone fragments tend to display evidence of solution.
10. Some boulders show evidence of wind erosion.

Internal character and soil:

1. The till is moderately compact.
2. The till is moderately bouldery and has an arkosic matrix containing noticeable amounts of silt and clay.
3. The till above the level of the Bonneville shoreline contains scattered deeply disintegrated boulders throughout its full thickness.
4. The soil developed on the till has a mature zonal profile.

Ice scour features and cirque development:

1. Very few areas of striations or polish are preserved.
2. Grooves and roches moutonnées are preserved, but they tend to be extensively fractured or exfoliated.
3. Cirques not occupied by ice since Bull Lake Glaciation have a ragged appearance, are gullied along fractures, and are thickly mantled with inactive talus that is mostly covered by soil and vegetation.

RELATIONS OF THE MORAINES TO THE LAKE DEPOSITS AND THE INTRA-BULL LAKE DISCONFORMITY

LITTLE COTTONWOOD CANYON

The relations of the outer and inner moraines (lower and upper tills) of the Bull Lake Glaciation to the deposits of Lake Bonneville at the mouth of Little Cottonwood Canyon are best displayed along the high scarp that trends northeast along the south side of the terraced plain of Little Cottonwood Creek about a mile west of the mountain front (fig. 10). Here, an exposure in which the two tills are interbedded with lake sediments was shown to R. B. Morrison and the writer in 1950 by Prof. Ray E. Marsell, of the University of Utah. The following section was measured by the writer in August 1959. The nomenclature applied to the lake deposits is that of Hunt, Varnes, and Thomas (1953).

Section of interbedded tills, outwash, deposits and lake sediments in SE¼SW¼ sec. 2, T. 3 S., R. 1 E.

[Altitude, top of section, 5,130 ft]

	Thickness (feet)	*Depth (feet)*
Bonneville Formation: Well-rounded, evenly bedded, loose, pebble to cobble lake gravel in a sandy matrix. Mainly quartz monzonite; some limestone, dolomite, quartzite, red sandstone, tillite, and granodiorite	20	0–20
Gradational contact.		
Upper outwash gravel—Bull Lake Glaciation: Subround to subangular, locally soled and faceted pebble to cobble in bedded arkosic sandy matrix. Almost wholly quartz monzonite; a little greenish quartzite and limestone. A few rotted cobbles. Thickness variable	3±	20–23

FIGURE 8

DIAGRAMMATIC SKETCHES OF SOME STRATIGRAPHIC RELATIONS OF DEPOSITS OF THE BULL LAKE GLACIATION.

A, Lower (*btl*) and upper (*btu*) tills of Bull Lake Glaciation, on which post-Bull Lake soil is developed, overlying a pre-Bull Lake soil developed on pre-Lake Bonneville (pre-Bull Lake) colluvium (*pbc*), at an altitude of about 5,600 feet on the slopes north of the mouth of Little Cottonwood Creek.

B, Upper outwash gravel (*bou*) and upper till (*btu*) of Bull Lake Glaciation disconformably overlying lower till (*btl*) and lower outwash gravel (*bol*) of Bull Lake Glaciation along east wall of post-Bull Lake graben crossing mouth of canyon of Little Cottonwood Creek (SE¼SE¼ sec. 1, T. 3 S., R. 1 E.). Zone of brownish staining in upper part of lower till is not a soil. Lower part of section covered by colluvium (*nc*).

C, Section along high northeastward-trending scarp about a mile northwest of mouth of canyon of Little Cottonwood Creek (SE¼SW¼ sec. 2, T. 3 S, R. 1 E) showing lake gravel of Bonneville Formation (*bg*) (2d rise of Lake Bonneville, overlying upper outwash gravel (*bou*) and upper till (*btu*) of Bull Lake Glaciation. These deposits, in turn, disconformably overlie lake sand and gravel of Alpine Formation (*as, ag*) (1st rise of Lake Bonneville) which rests on lower till (*btl*) and lower outwash gravel (*bol*) of Bull Lake Glaciation. Colluvium (*nc*) covers base of section.

D, Section on east side of Little Cottonwood Creek along its trench through the moraines at the mountan front (SE¼SE¼ sec. 2, T. 3 S, R. 1 E.) showing lake gravel of Bonneville Formation (*bg*) overlying upper outwash gravel (*bou*) and upper tille (*btu*) of Bull Lake Glaciation. These deposits disconformably overlie gravelly lake sand of Alpine Formation (*as, ag*) which rests on lower till (*btl*) and lower outwash gravel (*bol*) of Bull Lake Glaciation. Colluvium (*nc*) covers base of section.

E, Diagrammatic section of exposures east of Dimple Dell Road (NW¼NE¼ sec. 14, T. 3 S, R. 1 E.) showing exhumed moraine of lower till of Bull Lake Glaciation (*btl*) overlain by patches of gravelly lake sand (*as*) and clay (*ac*) of Alpine Formation (1st rise of Lake Bonneville). This, in turn is locally capped by beach gravel of Bonneville Formation (*bg*) (2d rise of Lake Bonneville).

F, Frontal slope of inner moraine (upper till) of Bull Lake Glaciation (*btu*) at mouth of Bells Canyon (SW¼NE¼ sec. 14, T. 3 S., R. 1 E.) showing bench cut at Bonneville shoreline (alt. 5,135 ft) on which rests beach gravel of Bonneville Formation (*bg*). Post-Bull Lake soil is developed across both deposits.

G, Lower till of Bull Lake Glaciation (*btl*) dissected by gully which is partly filled by upper outwash gravel (*bou*) of Bull Lake Glaciation (NW¼NE¼ sec. 14, T. 3 S, R. 1 E). Post-Bull Lake soil is developed across both deposits.

H, Lake sand and gravel of Alpine Formation (*as, ag*) cut by channel filled with upper outwash gravel of Bull Lake Glaciation (*bou*). Post-Bull Lake soil is developed across both deposits.

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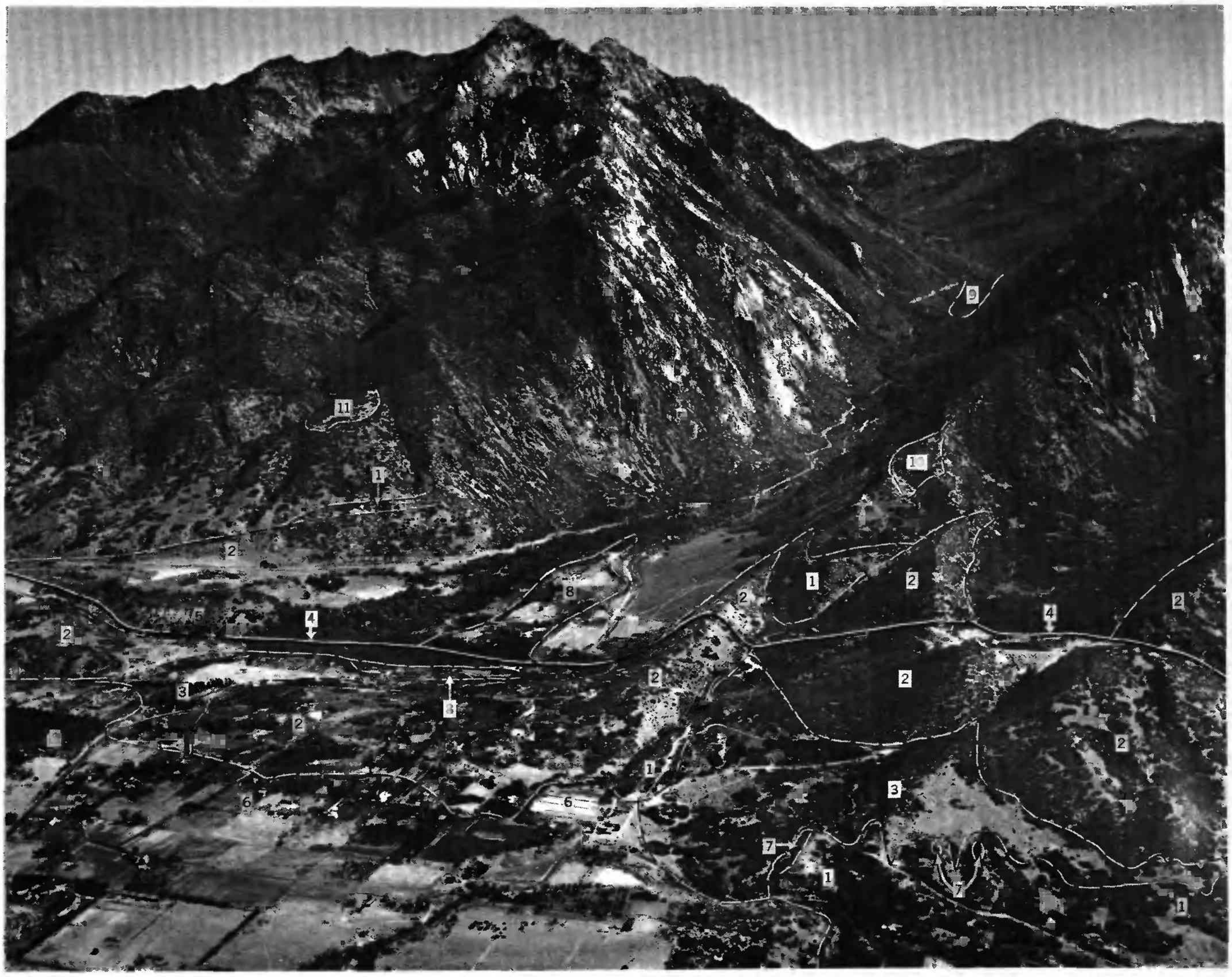

FIGURE 9.—View of moraines and lake flats at mouths of Little Cottonwood and Bells Canyons. Aerial photograph by A. E. Granger.

1. Outer moraine of Bull Lake Glaciation.
2. Inner moraine of Bull Lake Glaciation.
3. Outwash plain from inner moraine of Bull Lake Glaciation.
4. Post-Bull Lake fault scarp.
5. Exposure in fault scarp where upper till of Bull Lake Glaciation overlies lower till of Bull Lake Glaciation.
6. Plain underlain by lake gravel of Bonneville Formation.
7. Remnant of Alpine Formation overlying crest of outer moraine of Bull Lake Glaciation and capped by gravel of Bonneville Formation.
8. Terrace underlain by gravel that extends basinward to Provo shoreline.
9. Outer moraine of Pinedale Glaciation.
10. Till of younger pre-Bull Lake Glaciation.
11. Till or alluvial fan gravel of older pre-Bull Lake Glaciation.

Section of interbedded tills, outwash, deposits and lake sediments in SE¼SW¼ sec. 2, T. 3 S., R. 1 E.—Continued

[Altitude, top of section, 5,130 ft]

	Thickness (feet)	*Depth (feet)*
Gradational contact.		
Upper till—Bull Lake Glaciation: Large angular to subangular, locally soled and faceted blocks, as much as 6 ft in diameter, in a nonbedded unsorted arkosic silt sand and angular gravel matrix. Almost wholly quartz monzonite. Some rotted cobbles	12	35
Disconformity.		
Alpine Formation: Medium- to fine-grained well-bedded well-sorted lake sand and local silt layers, buff in upper part, gray in lower part. Gravelly lenses in lower part. Mainly quartz monzonite; some limestone, dolomite, and quartzite	25	60
Abrupt contact.		
Lower till—Bull Lake Glaciation: Large angular to subangular blocks and boulders, as much as 12 ft in diameter, in nonbedded unsorted clayey silty sand and subangular gravel matrix. Almost wholly quartz monzonite. Some rotted cobbles	15	75
Gradational contact.		
Lower outwash—Bull Lake Glaciation: subangular to subround cobbles and coarse gravel in clean arkosic sandy matrix. Irregularly bedded and poorly sorted. Some rotted cobbles	20+	95
Base not exposed.		

The above section, shown diagrammatically in figure 8*C*, demonstrates that glacial deposits of two advances of the ice are separated and overlain by lake sediments, and the altitude of the section (5,130 ft) indicates that the lake was near its maximum during both episodes of overlap. Apparently some recession of the ice had taken place before overlap of the glacial deposits by the lake, for the outwash gravels occur beneath the lake beds rather than interspersed in them. The succession of deposits can be observed in gullies along the scarp to the west where first the upper till and then the lower grade into outwash cobble gravel. In the same interval the lake beds maintain a relatively uniform character. Farther west, the upper and lower outwash gravels lens out, and about a third of a mile west of the measured section the scarp is underlain by the two only lake units—the upper disconformably above the lower.

At none of these localities does the nature of the disconformity suggest that the interval was of interglacial character. Nor is there anything in the character of either the lake or the glacial deposits above or below the disconformity that suggests interglacial conditions. Rather, the downslope extent of the disconformity, as determined by Gilbert (1890), Bissell (1952) and Morrison (1961), indicates that a lake about 100 feet deep persisted through the interval. This, in turn, suggests that the glaciers probably receded markedly, but that they did not disappear from the mountains.

East of the measured section, the six units can be traced into the narrows of Little Cottonwood Creek where the following section, shown diagrammatically in figure 8*D*, was measured by R. B. Morrison about 1100 feet south of the Murray City Power Plant.

FIGURE 10.—Trench of Little Cottonwood Canyon (C) through moraine of upper till of Bull Lake Glaciation (camera pointed west). Moraine is cut by bench along Bonneville shoreline (dashed line) and overlapped by lake gravels of Bonneville Formation, which are faulted along dotted line. Section at which lower and upper tills of Bull Lake Glaciation interfinger with lake beds of Alpine and Bonneville Formations is at arrow. Lower terraces (t) along Little Cottonwood Creek at right are underlain by outwash and alluvial gravel of Pinedale Glaciation.

Section of interbedded tills, outwash deposits, and lake sediments along Little Cottonwood Creek in SE¼SE¼ sec. 2, T. 3 S., R. 1 E.

[Altitude, top of section 5,140 ft]

	Thickness (feet)
Lake gravel of Bonneville Formation	7.5
Bull Lake Glaciation:	
Upper outwash gravel	1.5
Upper till	32.0
Abrupt disconformity.	
Lake gravel of Alpine Formation	15.0
Bull Lake Glaciation:	
Lower till	38.0
Lower outwash gravel	6.0

A short distance upstream, the gravel of the Alpine Formation lenses out, leaving the upper and lower tills in juxtaposition but separated by a disconformity. The disconformity cannot be distinguished along the bluffs of the creek to the south, owing to a cover of colluvium, but it can be observed discontinuously in the east wall of the post-Bull Lake graben (fig. 8*B*). At the north end of this structure, outwash and thin lenses of lake sediment again separate the two tills.

Along the wall of the graben, the upper several feet of the lower till below the disconformity is more brown in color than the lower part, which is gray, as is the upper till. Atwood (1909) interpreted this color change as a weathering phenomenon and considered it a criterion for distinguishing the two tills as deposits of separate glaciations. A thin coating of iron oxide on the grains of the matrix, probably deposited by ground water moving along the base of the upper till, is responsible for the brown color. The colored zone bears none of the characteristics common to soil profiles and does not seem to this writer to signify interglacial climatic conditions.

BELLS CANYON

The stratigraphic relations of the inner and outer moraines of Bull Lake Glaciation to the deposits of Lake Bonneville at the mouth of the Bells Canyon clearly support Atwood's observations (1909) that the moraines represent separate advances of the ice. West of the road leading south from the village of Granite, the till of the outer moraine extends under a sequence of flat- and even-bedded gravelly sands and clays of the Alpine Formation, which was deposited during the first rise of Lake Bonneville. Erosional remnants of these sediments lie against the front of the moraine and cap its highest parts (fig. 8*E*). Outwash from the inner moraine extends along channels which transect both the outer moraine (lower till; fig. 8*G*) and deposits of the Alpine Formation (fig. 8*H*). Along the headwaters of Dry Creek these outwash deposits extend continuously from the inner moraine to a level about 60 feet below the top of the Alpine Formation, thus indicating that the valley of Dry Creek was first cut in the interval separating deposition of the two moraines.

Gravel deposits of the Bonneville Formation at the Bonneville shoreline overlap the Alpine Formation both north of Dry Creek and along the crest of the outer moraine (pl. 1). They also cap a distinct wave-cut bench which notches the lower western slope of the inner moraine (fig. 8*F*). These relations demonstrate that, as on Little Cottonwood Creek, the sequence of events was: deposition of the outer moraine, deposition of the Alpine Formation, erosion, deposition of the inner moraine, and deposition of the Bonneville Formation at the Bonneville shoreline.

The nature of the interval separating deposition of the two moraines was interpreted by Atwood (1909) to be of interglacial character. He noted that the outer moraine was much more mature in appearance than the inner and, further, that it contained many more rotted boulders than the inner. He also noted that it passed beneath the deposits of Lake Bonneville, but did not observe that the Bonneville shoreline is cut on the inner moraine. Thus, he concluded (p. 81) that

> the disintegration of these older drift deposits (outer moraine) is so much greater than the disintegration of the later deposits (inner moraine) that the time which elapsed after they were deposited and before they were covered by the lake waters must have been many times longer than the time which has elapsed since the last retreat of the ice.

Restudy of the deposits suggests an alternate conclusion. The outer moraine, comprising the lower till of the Bull Lake Glaciation of this report, is certainly of very mature appearance. This, however, does not appear to be simply a matter of surface weathering. Indeed, the fact that deposits of the Alpine Formation lie against the front of the moraine, and locally cap it, suggests that the mature appearance is due primarily to the action of waves during the first rise of the lake to the thick mantle of lake deposits and to partial exhumation from beneath that mantle. Furthermore, this has happened twice, for the moraine was submerged for a second time during the subsequent rise to the Bonneville shoreline, as indicated by the presence of thin but distinctive gravels of the Bonneville Formation along its crest. The brownish color of the boulders on the moraine is also probably due to burial and exhumation.

The unusual weathering of the boulders in the till of the outer moraine may also be due to special circumstances. Certainly a great many of the boulders in the frontal sector of the moraine are deeply disintegrated, but some are not; and in the lateral moraines the proportion of weathered boulders seems to this author to be no greater than in the till of the inner moraine. The difference in the frontal sector might be due in part to the effects of successive submergence and emergence, and possibly also in part to the effects of the subsurface drainage of Bells Canyon through the till under a variety of climatic conditions. The writer believes, however, that most of the deeply weathered boulders were derived from deeply weathered deposits of pre-Bull Lake age, either glacial or alluvial, such as have been described at the mouths of canyons to the south (Hunt and others, 1953), and were probably present at the mouth of Bells Canyon before the Bull Lake Glaciation.

Thus, though Atwood's conclusion (1909) that the moraines represent separate advances of the ice can be substantiated, it seems more likely that the climate separating their deposition was of interstadial character, with ice persisting in the mountains, rather than that of a long interglaciation.

TILL OF BULL LAKE AGE UPSTREAM FROM THE END MORAINES

Till of Bull Lake age occurs along the walls of Little Cottonwood Canyon between the end moraines of the Bull Lake Glaciation and those of the next younger glaciation, the Pinedale. The deposits have a relatively smooth topography, and the many boulders at the surface are more pitted, stained, and fractured than those on the younger moraines. Some of the boulders are as much as 30 feet long. The deposits bear the same kind of mature zonal Brown Podzolic soil as that on the end moraines above the level of the Bonneville shoreline at the mouth of the canyon. This soil contrasts markedly with the immature Brown Podzolic soil on deposits of Pinedale age at the same altitude. The till is overlapped in places by talus of Pinedale age (fig. 11*A*), some of which forms large cones of compound origin in the lower part of the canyon. Exposures along the north wall locally show that talus of Pinedale age, bearing a post-Pinedale soil, overlies talus bearing a soil like that on till of the Bull Lake Glaciation.

Upstream from the moraines of the Pinedale Glaciation, till of the Bull Lake Glaciation occurs on the south side of the canyon above the upper limits of till of the Pinedale Glaciation. These deposits contrast with till of the Pinedale Glaciation in the degree of weathering of their boulders and in the character of the soil developed on them. The subangular to subround soled or faceted shape of the boulders differentiates them from talus, and in some places the lithology of the boulders shows that they are derived from upcanyon rather than from the local valley wall. In places, they are overlapped by talus of Pinedale age (fig. 11*B*).

Numerous erratics and small patches of till of the Bull Lake Glaciation occur north of Alta and in Grizzly Gulch (pl. 1). A large lateral moraine of the Pinedale Glaciation crosses the mouth of the gulch, and only two small bodies of Pinedale ice occurred at its head. The ice-scoured bedrock knobs and ledges that floor the greater part of the drainage of the gulch are therefore the product of Bull Lake Glaciation. These are much fractured—in places so much so that they are covered by a veneer of coarse angular rubble. The erratic boulders of the Bull Lake Glaciation also tend to be cracked or split apart.

Very few remnants of till of the Bull Lake Glaciation were found upstream from the terminal moraines at the mouth of Bells Canyon. Along the northern wall a zone of sparse erratics and patches of till, most of which are too small to show on the map (pl. 1), lies on or between weathered and fractured ice-scoured rock ledges that mark the upper limit of the Bull Lake glaciers.

OTHER DEPOSITS FORMED DURING THE BULL LAKE GLACIATION

OUTWASH GRAVEL

Outwash gravel formed during the Bull Lake Glaciation occurs at the mouths of both Little Cottonwood and Bells Canyons, where its relations to the lower and upper tills of Bull Lake Glaciation have been discussed. The deposits consist mostly of coarse subround to subangular cobbles and gravel in an arkosic sandy matrix. They are crudely bedded and poorly sorted, and abrupt changes in texture are common. Boulders are abundant where the deposits are closely associated with the lower till. Lithologically, the outwash is predominantly quartz monzonite, but at the mouth of Little Cottonwood Canyon it also contains a variety of limestone, dolomite, and quartzite and small amounts of granodiorite, dark argillite, amphibolite, quartz-mica schist, and a tillite of Precambrian age.

Outwash associated with the lower till extends for about a mile in all directions west of the mouth of Little Cottonwood Canyon. It occurs as lenses in the lower till, as a layer both on and beneath the lower till, and as a sheet of gravel interfingering with, and extending beyond, the outer limits of the lower till. Below an altitude of 5,080 feet the outwash lies beneath lake sediments of the Alpine Formation, and, where it is thin, it is locally mapped with that unit. In this position it bears no soil. Above an altitude of 5,080 feet the outwash is known from only one locality—on the south side of the mouth of Bells Canyon, where it fills a channel stemming from the outer moraine (lower till) and bears a mature Brown Podzolic soil like that on deposits of the lower till above the level of the Bonneville shoreline.

COLLUVIUM

Colluvial deposits formed during the Bull Lake Glaciation are much more abundant than shown on plate 1, but no effort was made to study them, except along the divide east of Albion Basin where their prominence attracted attention.

Along the trail to Lake Catherine, the north-facing slopes on the east side of Albion Basin, beyond the limits of Pinedale glaciers, are mantled by several feet of brownish massive to crudely bedded silty colluvium which rests on arkosic stony till of the Bull Lake Glaciation. Large boulders of granodiorite in the till, some of which are 10 feet in diameter, project through the colluvial mantle.

To the south, where the slopes are underlain by quartzite or sandstone, the colluvium is a buff sand; where they are underlain by limestone, it is a reddish-brown silt. The deposits are compact and locally attain a thickness of 20 feet, as can be observed along gullies that dissect them. Their lower 5 to 10 feet is commonly rubble of local derivation. The colluvium is interpreted as primarily of slope wash and solifluction origin. A soil much like that found on till of the Bull Lake Glaciation is formed on it, but tends to be more sandy or clayey according to the character of the colluvium. Both the soil and the underlying colluvium have been extensively stripped on steeper slopes, but in saddles where the slope flattens they are disconformably overlain by a loose colluvium of Pinedale and Recent age.

POST-BULL LAKE SOIL

A stratigraphically distinct soil, here informally called the post-Bull Lake soil, may be defined as that distinctive and strongly developed zonal soil occurring above the upper limits of the Bonneville Formation on deposits of the late stade of Bull Lake Glaciation, and on deposits of the early stade not covered by those of the late stade. The soil also probably occurs on deposits formed during pre-Bull Lake glaciations, but was not so recognized. It does not occur on deposits of the Pinedale Glaciation that, however, overlie it in places. These conditions suggest that although the soil may have undergone some development throughout post-Bull Lake time, it had acquired its dominant megascopic characteristics before the onset of the Pinedale Glaciation.

Throughout the drainage of Little Cottonwood and Bells Canyons between altitudes of 5,135 and 9,600 feet—the highest point at which it was observed—the soil has a mature Brown Podzolic profile that varies but little in character.

The A horizon, not preserved in buried profiles, ranges in thickness from 3 to 15 inches. It is dark gray (10*YR* 4/1–4/2), structureless, and consists of loose nonsticky nonplastic stony sandy silt loam.[4] The pH is about 6.0, except in mineralized areas where it may be as low as 5.

The contact between the A and B horizons is commonly abrupt to clear. In many places the B horizon contains numerous krotovinas (burrow fillings), and locally it is thoroughly mixed with material from the A horizon. Elsewhere, it has been extensively stripped, and the A horizon rests on the lower part of the B horizon or on the C horizon. Under such conditions the A horizon is probably of considerably younger origin and possibly of post-Pinedale age.

Where the B horizon appears to be fully preserved, it is 40 to 50 inches thick and consists of two parts. The upper part, or B_2 horizon, is 18 to 24 inches thick. It is strong brown (7.5*YR* 5/6) to brown (7.5*YR* 5/4) when dry, and has a moderate to strong medium to coarse angular blocky structure. It is slightly sticky slightly plastic friable hard, stony sandy loam. The reaction is medium acid. The boundary between the upper and lower parts is diffuse.

The lower part, or B_3 horizon, is 24 to 36 inches thick, and is pale brown (10*YR* 6/3) to light yellowish brown (10*YR* 5/4–6/4). It is a structureless nonsticky nonplastic sandy loam that is friable and hard. The pH tends to range from about 6 to 7. The boundary between the B and C horizons is diffuse.

The C horizon, or parent material, is commonly light brownish gray to pale yellow (2.5*Y* 7/4), and consists of structureless compact stony sandy loam. The pH is about 7.

In mineralized areas the soil profile and included rock fragments generally have a rusty stain. Profiles on alluvial gravels tend to be somewhat more reddish than on other materials. In a few places near the mouth of Bells Canyon a zone of calcium carbonate occurs 12 to 18 feet below the surface of the inner moraine of Bull Lake Glaciation. The carbonate forms streaks and lenses in the till, in which it coats the rock fragments, especially the undersides, and weakly cements the matrix. It was probably deposited from ground water moving through the till, and is not a part of the overlying soil profile.

[4] The terminology used in describing soils in this report is that of the Department of Agriculture, Soil Survey Manual, 1951.

DEPOSITS OF THE PINEDALE GLACIATION

Deposits formed during Pinedale Glaciation in the drainage of Little Cottonwood and Bells Canyons include till, rock glaciers, outwash gravel, alluvial-fan gravel, talus, protalus, and landslides (fig. 11). These deposits lie upstream or upslope from, and locally overlap, or are entrenched within, those formed during the Bull Lake glaciation. In places, they overlie the distinctive post-Bull Lake soil on deposits of the Bull Lake Glaciation; thus, they represent a distinct and separate glaciation. The deposits characteristically bear an immature Brown Podzolic soil, and locally are either overlapped by younger deposits of the Neoglaciation or are cut by channels containing such deposits.

TILL

The glacial deposits of Pinedale age comprise three tills—a lower, a middle, and an upper. These form three sets of end moraines, whose relations to each other and to outwash deposits indicate that they represent three stades of glaciation—a maximum advance of the ice followed by two recessional stands or minor readvances. These units include the recessional moraines of Atwood's "later epoch" of glaciation (1909), but not the outermost moraine of that epoch. They also include the Yellow Pine Fork and Gad Valley Moraines of Ives (1950) and the M4 moraine of Eardley and others (1957).

EVIDENCE FOR CORRELATION WITH THE PINEDALE GLACIATION

Moraines upstream from those at the mouth of Little Cottonwood Canyon were first correlated with the Pinedale Glaciation by Blackwelder (1931). This correlation is based primarily on the similarity between the stratigraphic positions of the deposits here and of those at the type locality in the Wind River Mountains, Wyo.—that is, both lie stratigraphically above deposits of the Bull Lake Glaciation, bear a relatively immature zonal soil, and lie stratigraphically below small cirque moraines that bear only a relatively thin azonal soil. This correlation is supported by the following similarities to the type deposits in the Wind River Mountains.

Surface features and form:

1. The end moraines are relatively small.
2. The end moraines are dissected but only a few are breached by axial streams.
3. Lateral moraines are only slightly dissected by tributary streams.
4. The slopes of the moraines are irregular and youthful in appearance.
5. Kettles are not breached and some contain water seasonally.
6. Boulders are very abundant at the surface of the moraines.
7. Most boulders are fresh; few are fractured or exfoliated.
8. Few boulders at the surface are stained or decayed to depths greater than a quarter of an inch.
9. Limestone fragments display almost no evidence of solution.
10. Boulders show very little evidence of wind scour.

Internal character and soil:

1. The till is loose, sandy, and very bouldery.
2. The till contains relatively few deeply disintegrated boulders.
3. Many boulders are soled and faceted, and some are striated.
4. The soil developed on the till has an immature zonal profile.

Ice-scour features and cirque development:

1. Striations are well preserved, as are also polish, grooving, and roches moutonnées.
2. Cirques not occupied by younger ice have abrupt steeply cliffed headwalls and moderate to large accumulations of stable vegetation-covered talus.

EVIDENCE FOR THREE STADES OF THE PINEDALE GLACIATION

Three sets of moraines, locally associated with small outwash plains, constitute the main evidence that Pinedale Glaciation in the drainage of Little Cottonwood and Bells Canyons included three stades (pl. 1). The tills of these moraines, called, for convenience, the lower, middle, and upper tills of Pinedale Glaciation, are much alike, bear the same kind of soil, and have similar surficial and internal characteristics. No evidence that one was separated from the other by more than a relatively brief interstade was noted, though the outer moraines, in places, are slightly more dissected than the inner moraines.

PINEDALE GLACIATION ALONG LITTLE COTTONWOOD CANYON

The Pinedale glacial deposits in Little Cottonwood Canyon are more complex than those in Bells Canyon because of the relations of moraines formed in the tributary valleys to those on the axial stream.

The lower till forms an outer end moraine on the canyon floor between Maybird Gulch and Hogum Fork at an altitude of 6,600 feet (pl. 1; table 1). The moraine was formed by a mass of ice representing the coalescence of glaciers from Maybird Gulch and other tributaries to the east with ice flowing from the headwaters of Little Cottonwood Creek. The moraine abuts another arcuate morainal crest that marks the outer limits of the correlative glacier on Hogum Fork. The two deposits are, in fact, juxtaposed to form a single sharp steep-sloped double-crested ridge, whose crests separate toward their respective sources upslope along the south wall of the canyon. The ridge as a whole is about 100 feet high and is thickly forested. The western sector of the moraine on Hogum Fork has been removed by erosion. The northern arc of the moraine in Little Cottonwood Canyon is preserved as a distinct ridge.

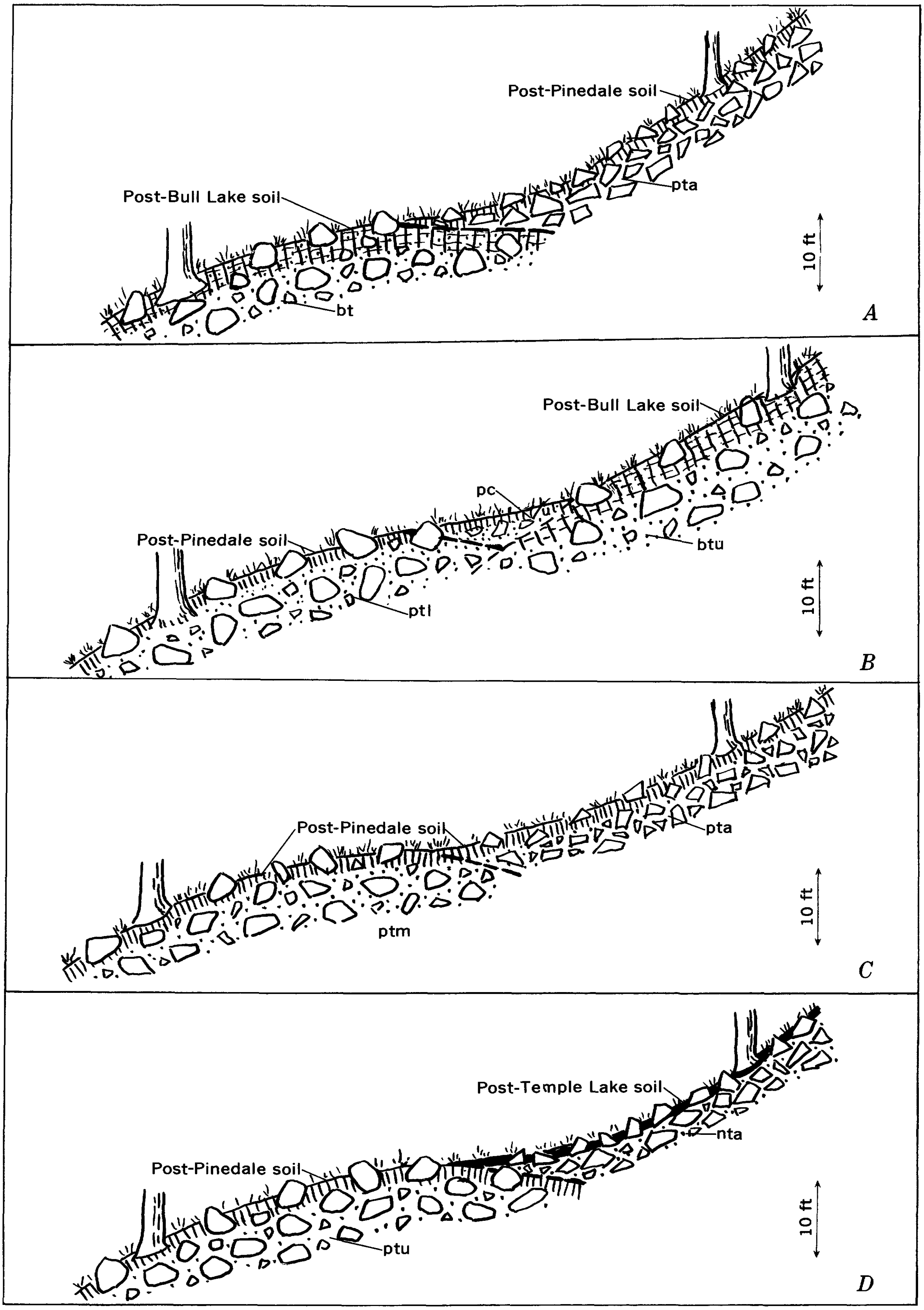
Post-Pinedale soil
Post-Bull Lake soil
pta
bt
10 ft
A
Post-Bull Lake soil
pc
Post-Pinedale soil
btu
ptl
10 ft
B
Post-Pinedale soil
pta
ptm
10 ft
C
Post-Temple Lake soil
nta
Post-Pinedale soil
ptu
10 ft
D

FIGURE 11

TABLE 1.—*Altitudes, in feet, of end moraines and rock glaciers of successive late Pleistocene glaciations and stades in Little Cottonwood and Bells Canyons*

[*Indicates informal stratigraphic name. rg, rock glacier; em, end moraine]

Time-stratigraphic unit	Climate-stratigraphic unit		Little Cottonwood Canyon	Collins Gulch	Peruvian Gulch	Gad Valley Gulch	White Pine Fork	Red Pine Fork	Maybird Gulch	Hogum Fork	Coalpit Gulch	Bells Canyon	Average altitude (feet)
Recent	Neoglaciation	*Historic stade	10,040 rg 9,880 rg	-----------	-----------	10,180 rg	10,200 rg 10,150 rg	10,240 rg	10,160 rg	9,780 rg 9,480 rg	-----------	10,640 rg 10,240 rg 9,800 rg 9,680 rg 9,560 rg 9,300 rg	9,950 rg
		Temple Lake Stade	9,800 rg 9,760 em 9,740 em	9,920 em	-----------	10,120 em 10,120 em 9,920 em	10,080 rg 10,040 rg 9,850 rg 9,440 rg 9,400 rg	10,300 rg 10,120 rg 10,120 rg 10,040 rg	10,030 rg	9,860 rg 9,840 rg 9,800 rg 9,680 rg 9,500 rg 9,300 em	9,240 rg	10,160 rg 10,080 rg 9,920 em 9,600 rg 9,250 rg 9,160 em	9,800 em, rg 9,770 em 9,820 rg
*Upper Pleistocene	Pinedale Glaciation	*Late stade	9,640 em	9,840 em 9,700 em	9,720 em	9,220 em	9,400 em 9,400 em 9,220 em	9,620 em	9,840 em	8,680 em	8,700 em	6,560 em	9,195 em
		*Middle stade	←	—7,760 em—	—	→	7,240 em	6,970 em	8,400 em	8,400 em	8,200 em	5,720 em	7,220 em
		*Early stade	←	—	—	6,600 em	—	—	→	6,560 em	7,450 em	5,680 em	6,570 em
	Bull Lake Glaciation	*Late stade	←	—	—	5,080 em	—	—	—	—	→	5,100 em	5,090 em
		*Early stade	←	—	—	5,040 em	—	—	—	—	→	4,920 em	4,980 em

The till derived from Hogum Fork in all of quartz monzonite and contains numerous large angular boulders, some more than 20 feet in diameter. The till derived from Little Cottonwood Creek is also very bouldery, but more of the boulders are subangular to subround. Though the boulders are mostly quartz monzonite, many cobbles and smaller sized fragments are quartzite, limestone, dolomite, and tillite. The matrix of the till in both moraines is mostly coarse arkosic sand.

Upstream along Little Cottonwood Canyon, the lower till of Pinedale Glaciation occurs along the south wall of the canyon above lateral moraines of the middle till. It extends well up into Maybird Gulch and along the sides of the lower sectors of Red Pine Fork and White Pine Fork. Northeast of Alta, it lies along the north slope of the valley above a lateral moraine of the middle till and extends up into the lower part of Grizzly Gulch.

The middle till of Pinedale Glaciation forms two end moraines, at altitudes of 6,970 and 7,240 feet, respectively, along Little Cottonwood Canyon and just below the mouths of Red Pine Fork and White Pine Fork—the sources of the glaciers that formed the moraines (pl. 1; table 1).

A third end moraine formed by the middle till lies at an altitude of 7,760 feet just below the confluence of Little Cottonwood Creek and Gad Valley Gulch—the sources of the glacier that formed it. This is the Gad Valley Moraine of Ives (1950) and the M4 moraine of Eardley and others (1957). It is a broad irregular bulky deposit whose lateral ridges rise 600 feet in a distance of only half a mile upstream from the terminus. Ice-scoured bedrock knobs project through the deposit locally, and a small outwash plain borders its lower margin on the south side of the creek. Alluvial-fan gravel of Recent age overlaps its northern margin.

FIGURE 11

DIAGRAMMATIC SKETCHES OF SOME STRATIGRAPHIC RELATIONS OF DEPOSITS OF THE PINEDALE GLACIATION

A, Talus of Pinedale age (*pta*), on which the post-Pinedale soil is developed overlapping the post-Bull Lake soil on till of the Bull Lake Glaciation (*bt*) on south slope of Grizzly Gulch.

B, Upper till of the Bull Lake Glaciation (*btu*), on which the post-Bull Lake soil is developed, overlapped by the lower till of the Pinedale Glaciation (*ptl*) on which the post-Pinedale soil is developed. Contact covered by colluvium (*pc*) of Pinedale age. Location is north slope of Little Cottonwood Creek opposite Hogum Fork.

C. Middle till of the Pinedale Glaciation (*ptm*) on the east side the head of Collins Gulch overlapped by talus of Pinedale age (*pta*). The post-Pinedale soil is developed across both deposits.

D, Upper till of the Pinedale Glaciation (*ptu*), on which the post-Pinedale soil is developed, overlapped by inactive talus of Recent age (*nta*) on which the post-Temple Lake soil is developed at the head of Peruvian Gulch.

The middle till extends upstream along Little Cottonwood Canyon well into Albion Basin. Locally, for example east of Alta, it encloses small areas of outwash gravel or lacustrine deposits. At the mouths of most tributaries the middle till is either overlapped or entrenched by alluvial-far gravel of Recent age; in Albion Basin it is overlapped by a rockfall-avalanche type of landslide deposit composed mostly of large angular blocks of blue limestone derived from the cliff at the head of the basin. This landslide, whose terminus is about a mile from its source, was noted by Calkins and Butler (1943). It must have formed between deposition of the middle and upper tills of Pinedale Glaciation, for it, in turn, is overlapped by the terminal moraine of the upper till that lies at an altitude of about 9,640 feet about half a mile from the cirque headwall.

The moraine, formed by the upper till, is composed of several subsidiary ridges. It is a broad arcuate mass that has a steep front locally cut by outwash channels. The till consists of angular to subangular cobbles and boulders of limestone, dolomite, and quartzite in a sandy silt matrix. The deposit heads in the central cirque of Albion Basin where it is overlapped by moraines and a rock glacier of the Temple Lake Stade of Neoglaciation and by a protalus rampart formed during the historic stade. Neither the east nor the west cirque of Albion Basin contains moraines of the upper till of Pinedale Glaciation.

COLLINS GULCH

Collins Gulch, first tributary west of Albion Basin, hangs about 500 feet above Little Cottonwood Creek. It is floored with the middle till of Pinedale Glaciation that extends upslope from the end moraine at the mouth of Gad Valley Gulch. The till is composed mainly of limestone and quartzite. A rock step, about 200 feet high, lies across the valley floor at an altitude of about 9,400 feet. At the head of the valley the bedrock lip of the cirque, at an altitude of 9,850 feet, is overlapped by a forested bouldery end moraine of the upper till. The profile of the post-Pinedale soil on the till is well exposed in roadcuts through the moraine; and contrasts markedly with the profile of the soil on a small blocky moraine of the Temple Lake Stade of Neoglaciation just upslope (fig. 12). Along the west side of the basin another blocky moraine of the upper till is overlapped by talus of Recent age at the foot of the cirque.

PERUVIAN GULCH

Peruvian Gulch hangs about 600 feet above Little Cottonwood Creek, and its stream has cut about 40 feet into bedrock along the hanging slope. The lower sector of the gulch is floored by the middle till of Pinedale Glaciation that extends upslope from the moraine at the mouth of Gad Valley Gulch. The till on the east side of the valley is mostly of limestone; that on the west side is mostly of quartzite and tillite of Precambrian age. A rock step 350 feet high extends across the valley at an altitude of 9,200 feet, and much of the upper basin is underlain by bare rock. A large end moraine at an altitude of 9,720 feet marks the outer limit of the upper till of Pinedale Glaciation. The moraine is mostly of angular to subangular blocks of quartzite in a sandy matrix, and bears the same soil profile as that on nearby areas of the middle till. Stable talus of Recent age lies above the moraine along the base of the cirque headwall. Northwest of the moraine a vegetation-covered protalus rampart bears the same soil and is believed to be of the same age as the moraine. No deposits of the Neoglaciation were noted.

GAD VALLEY GULCH

Gad Valley Gulch hangs about 500 feet above Little Cottonwood Creek. The hanging slope, however, is much less steep than that of other tributary valleys and is, for the most part, till covered. The south lateral ridge of the large end moraine of the middle till of Pinedale Glaciation in Little Cottonwood Canyon extends up this slope into the west side of Gad Valley Gulch. The central sector of the gulch is largely underlain by ice-scoured rock, mantled locally by thin patches of till. A rock step nearly 300 feet high lies across the floor of the valley at an altitude of 8,400 feet; another rock step about 150 feet high occurs at 8,800 feet. The upper sector of the gulch is a broad compound basin. The western part of this basin is floored by till composed largely of quartz monzonite. The eastern part is underlain mostly by cliffs of quartzite of Precambrian age. A large end moraine of the upper till of Pinedale Glaciation lies across a bedrock cliff at 9,600 feet altitude and terminates along the eastward-trending sector of the creek at an altitude of 9,240 feet. The lateral ridges of this moraine are 40 to 60 feet high. Upslope, it is overridden by very coarse blocky moraines and talus flows of the Temple Lake Stade of Neoglaciation and by a single talus flow associated with the historic stade. These deposits are all predominantly of quartz monzonite.

At the head of the basin, in the cirque west of Twin Peaks, is a rock glacier of the historic stade of Neoglaciation composed almost wholly of dark-brown argillite of Precambrian age. The two cirques east of Twin Peaks contain small moraines of the Temple Lake Stade. The more easterly moraine is composed of quartzite and argillite; the more westerly, of quartzite and quartz monzonite.

FIGURE 12.—Small spruce-covered end moraine of the Temple Lake Stade of Neoglaciation overlapping larger moraine of upper till of the Pinedale Glaciation at head of Collins Gulch.

WHITE PINE FORK

The lower till of the Pinedale Glaciation in White Pine Fork is coextensive with that along Little Cottonwood Canyon. The middle till forms a thick mantle over the lower sector of the valley of White Pine Fork and extends across the hanging slope, which is only about 400 feet high, into Little Cottonwood Canyon. Here it forms an end moraine whose lower limit, at the upper end of Tanners Flat Campground, is at an altitude of 7,240 feet. This is the Yellow Pine Fork Moraine of Ives (1950). The till in White Pine Fork and on its hanging wall is composed of subround to subangular glacially soled and faceted boulders of quartz monzonite in an arkosic sandy matrix. The till of the end moraine, however, consists of large angular blocks of quartz monzonite without interstitial fine debris. The two tills grade abruptly into one another without noticeable break in the lobate form of the moraine. Obviously, the large angular blocks in the terminal zone of the deposit have not been subject to glacial scour, yet they are clearly part of the glacial deposit. In the writer's opinion, the blocks represent debris deposited on the surface of the ice by rockfall from nearby cliffs. The fact that such blocks do not occur in the till on the hanging slope of White Pine Fork suggests that they fell onto the ice, possibly across snowbanks, from the north wall of Little Cottonwood Canyon, and were moved by the ice only enough to form the lobate mass that is the end moraine.

The central sector of White Pine Fork is floored by a thick mantle of the middle till. A large peat bog lies on the floor and lower western slope of the valley at an altitude of about 8,550 feet. The peat is intimately interlayered with masses of fallen logs, the whole forming a gyttja about 5 feet thick, which rests on gravel.

A till-covered rock step, 200 feet high, lies across the valley at an altitude of 8,200 feet; two other rock steps, each also about 200 feet high, occur at altitudes of 8,700 and 9,000 feet, respectively.

Three end moraines of the upper till mark the locus of three separate ice masses in the broad complex cirque basin at the head of the valley. One extends across the lip of the cirque on the east side of the basin and terminates at 9,400 feet in altitude. Its upper margin is overlapped by a talus flow formed during the Temple Lake Stade of Neoglaciation. A second end moraine, derived from two cirques southeast and south of White Pine Lake, terminates along White Pine Fork at an altitude of 9,220 feet. It is overlapped upslope by several rock glaciers and a moraine of the Temple Lake Stade of Neoglaciation, which are, in turn, locally overlapped by rock glaciers formed during the historic stade in the cirque south of White Pine Lake (fig. 13). A third moraine, at an altitude of 9,400 feet, stems from a small cirque, on the west side of the basin, that is separated from the main drainage by a high rock ridge. Along the cirque headwall the moraine is overlapped by blocky talus flows of Temple Lake age. All three of these moraines bear the post-Pinedale soil, which is much more strongly developed than the soil on the overlapping deposits formed during the Temple Lake Stade. The till of all three moraines consists mostly of angular to subangular boulders of quartz monzonite.

RED PINE FORK

Deposits of the Pinedale Glaciation on Red Pine Fork parallel those on White Pine Fork. The lower till is coextensive with that along Little Cottonwood Canyon; the middle till extends across the hanging lip of Red Pine Fork and forms a separate end moraine at the lower end of Tanners Flat Campground along Little Cottonwood Canyon at an altitude of 6,970 feet. The margin of the moraine lies along the north wall of the canyon 60 feet above Little Cottonwood Creek. The till is entirely of quartz monzonite and is very blocky—some blocks are as much as 20 feet in diameter. A small bouldery outwash plain extends downstream from the toe of the moraine, and an alluvial fan of Pinedale age extends along its northern side. It is transected by fan gravels of Recent age.

The valley of Red Pine Fork hangs more than 500 feet above Little Cottonwood Creek. Bedrock is exposed along the stream on the hanging slope and for nearly a mile upstream; elsewhere, the floor of the valley is thickly mantled by the middle till. The slope

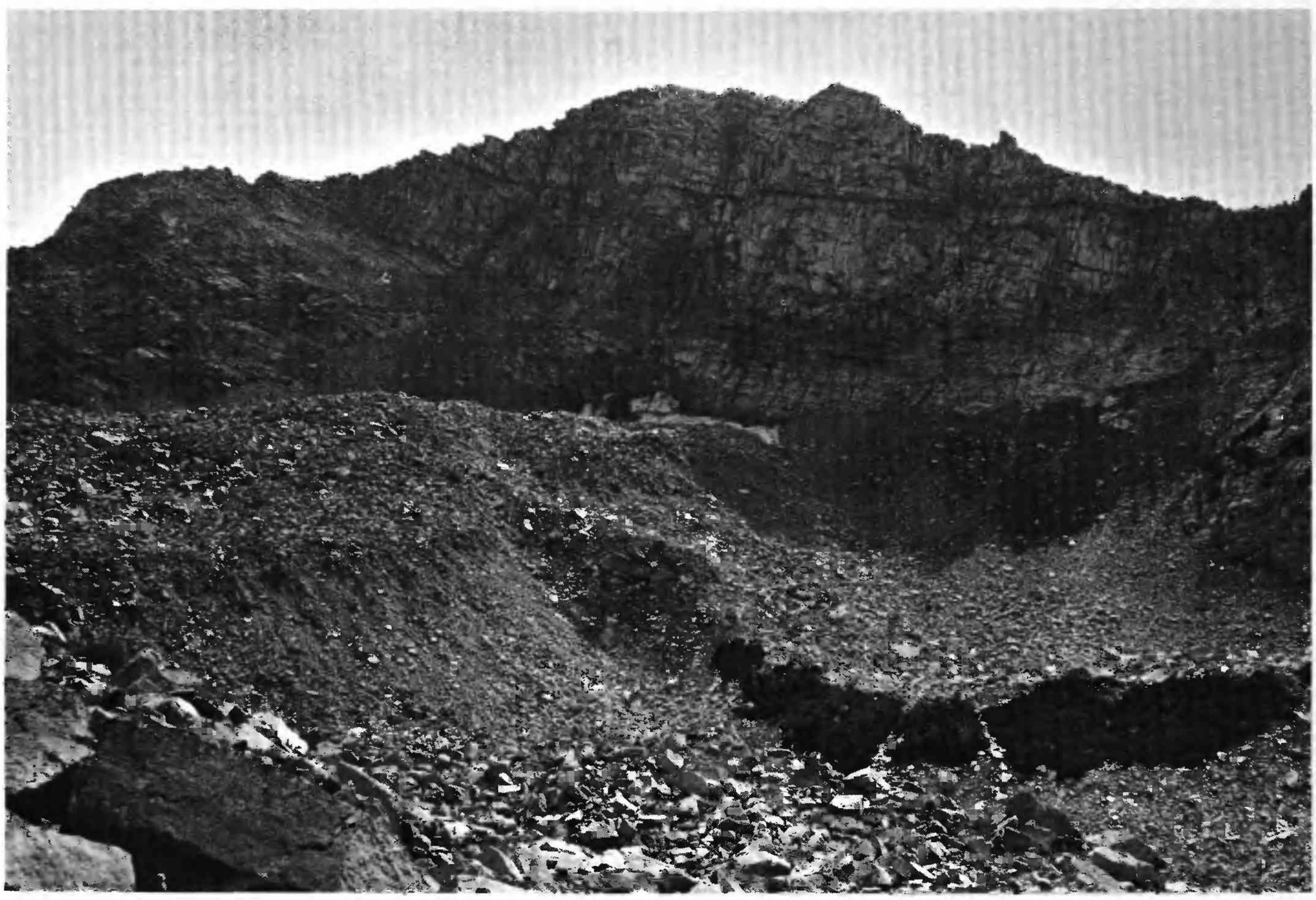

FIGURE 13.—End moraine of the Temple Lake Stade of Neoglaciation covered by scrub spruce and overlapped by rock glacier of the historic stade at head of White Pine Fork.

of the valley is uniformly steep, and is broken by only one bedrock step, about 100 feet high, below Red Pine Lake. A large moraine of the upper till, composed mostly of angular blocks of quartz monzonite, terminates at the south shore of Red Pine Lake. Bedrock knobs are exposed in the ground moraine upslope from the lake. Along the cirque headwall, the deposit is overlapped by two rock glaciers of the Temple Lake Stade of Neoglaciation.

MAYBIRD GULCH

The lower till of Pinedale Glaciation extends from the terminal moraine in Little Cottonwood Canyon, opposite the mouth of Hogum Fork, up the steep 800-foot-high hanging slope of Maybird Gulch into its central sector. An end moraine of the middle till lies at an altitude of 8,400 feet, where it extends across a partly exposed bedrock step. A second steeper rock step breaks the valley floor at 9,400 feet altitude. The till overlaps the ridge to the east, showing that the glacier in Maybird Gulch merged along the divide with the glacier along Red Pine Fork. In the upper basin, a rock glacier correlative with the upper till extends across the valley from a source on the west side of the canyon. It has a steep snout, in front of which low ridges of blocks enclose two shallow ponds. Upstream from the rock glacier, at an altitude of 9,840 feet, rises the steep blocky front of a moraine of the upper till (fig. 14). Despite its apparent blockiness, the deposit locally contains fine-grained intersititial debris that, where exposed at the surface, bears a typical post-Pinedale soil. The abrupt headward slope of the moraine is overlapped by a large rock glacier of the Temple Lake Stade of Neoglaciation that has very prominent arcuate ridges and furrows. The upper half of this deposit has been reactivated to form an inner rock glacier characteristic of the historic stade (fig. 16*E*).

HOGUM FORK

The lower till of Pinedale Glaciation along the canyon of Hogum Fork forms a moraine below the mouth of that canyon on the floor of Little Cottonwood Canyon (p. D19). This moraine abuts against, but can be distinguished from, a correlative moraine derived from Little Cottonwood Canyon. The till extends up the 800-foot-high, predominantly bedrock, hanging slope of Hogum Fork and along the east side of the canyon above for about a mile. The west side of the canyon is underlain by ice-scoured bedrock. At an altitude of 8,400 feet the abrupt front of a moraine of the middle till lies across the canyon. This deposit is composed of large angular blocks of quartz monzonite with just enough interstitial fine debris to support a forest vegetation. Upstream, at an altitude of 8,680 feet, the deposit is overridden by an end moraine of the upper till, which is composed almost wholly of huge angular blocks—some 30 to 40 feet across—and lacks interstitial fine debris over large areas of its surface. The ground moraine upstream from this end moraine is of similar blocky debris, and forms long ridges and furrows that appear to represent flow lines parallel to the axis of the valley. The deposit extends headward into large steep walled cirques that hang 500 to 600 feet above the upper sector of the valley.

In the eastern cirque, the upper till is overridden by a large rock glacier of the Temple Lake Stade of Neoglaciation, which is also composed of huge blocks. Its headward sector was reactivated to form a younger rock glacier during the historic stade. Below the south and west cirques, the upper till is overridden by a single large blocky morainal tongue of the Temple Lake Stade above which, at the heads of both cirques, are rock glaciers of the historic stade. The unstable and cascading block fronts of these rock glaciers suggest that they may yet be active.

COALPIT GULCH

The lower sector of Coalpit Gulch was not glaciated in Pinedale time, though it was occupied by ice during the Bull Lake Glaciation. A very narrow streamcut chute, notched within the bedrock valley wall, rises steeply for 600 feet from an alluvial cone built out over the canyon of Little Cottonwood Creek. The chute is only about 15 to 20 feet wide in places, but it opens headward into the central sector of the canyon, where a blocky morainal lobe at an altitude of 7,450 feet marks the outer limit of the lower till of Pinedale Glaciation. A second morainal front, believed to mark the lower limit of the middle till, lies at 8,200 feet altitude. The upper till forms a third irregularly lobate mass at 8,760 feet altitude, below a 200-foot-high cliff that breaks the canyon floor. Above the cliff is a broad steeply sloping rock glacier of Temple Lake age.

BELLS CANYON

Moraines of the Pinedale Glaciation extended to lower altitudes in Bells Canyon than in Little Cottonwood Canyon. No terminal moraine of the lower till is preserved, but very bouldery lateral moraines extend from both sides of the canyon onto the floor at an altitude of 5,680 feet. These lie just east of the boundary fault at the mountain front and within the much larger lateral moraines of the Bull Lake Glaciation. The till is composed of fresh boulders of quartz monzonite in an arkosic sandy matrix. The soil on the till is much thinner and less well developed than the soil on adjacent deposits of Bull Lake age, but is like the soil on till of the Pinedale Glaciation along Little Cotton-

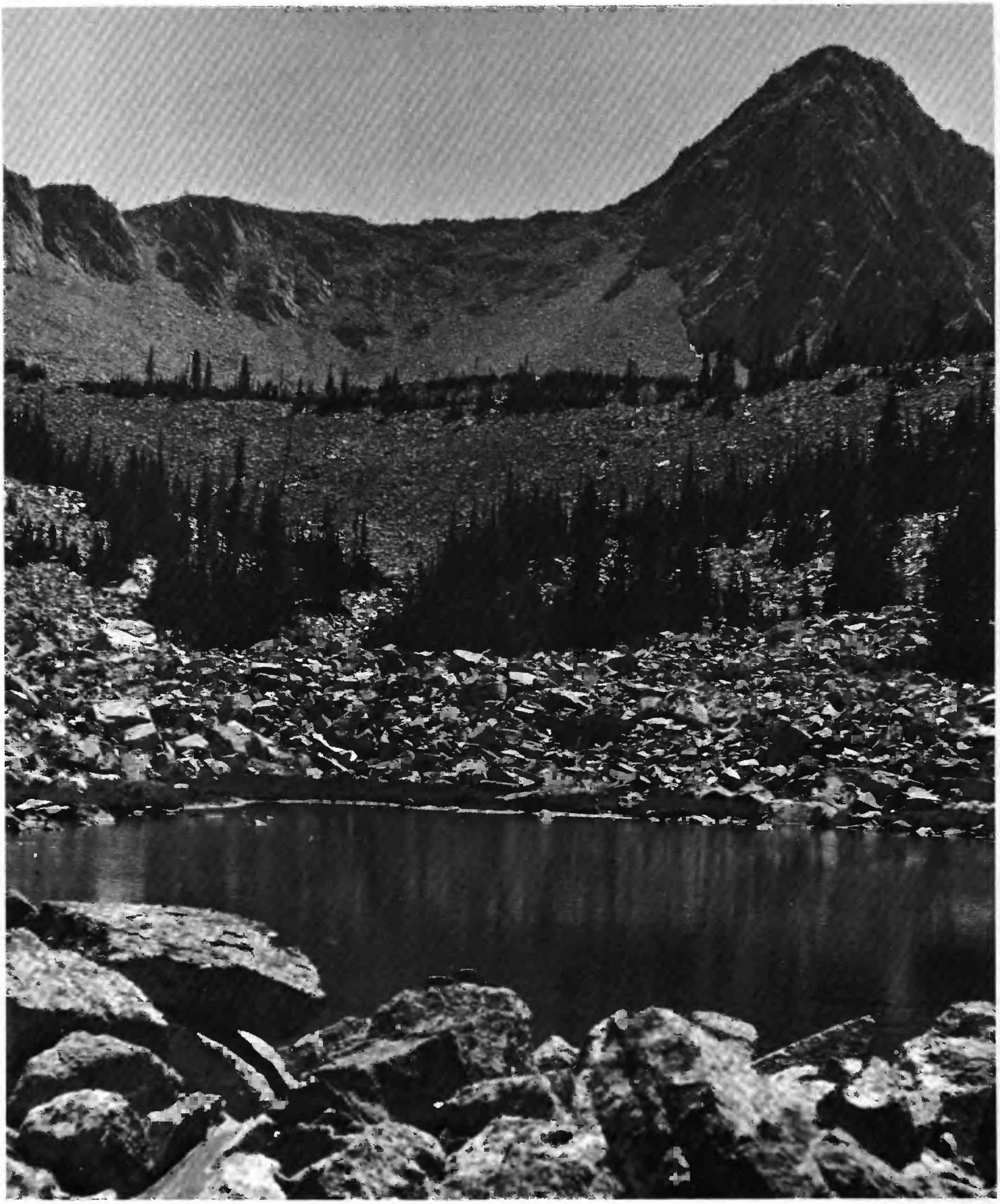

FIGURE 14.—Steep front of blocky end moraine of upper till of the Pinedale Glaciation from rock glacier of same age along Maybird Gulch.

wood Canyon. The lack of a terminal moraine seems to be due in part to erosion and in part to burial by outwash from a moraine of the middle till that extends across the canyon floor at an altitude of 5,720 feet. Upstream, the middle till covers the floor of the canyon for more than a mile to a point where it steepens abruptly over a series of bedrock cliffs and ledges. A broad lateral moraine of the upper till hangs across these ledges on the south side of the canyon and terminates in a narrow snout at an altitude of 6,560 feet (fig. 15). The many boulders on the surface appear excessively numerous because they are whitish. The soil on the deposit is like that on other moraines of the Pinedale Glaciation.

The upper till occurs discontinuously between areas of bedrock on the canyon floor, well into the upper sector of Bells Canyon. In the cirque northeast of Lone Peak, the till is overlapped by a large lobate rock glacier of the Temple Lake Stade of Neoglaciation, above which a rock glacier of the historic stade lies at the foot of the cirque headwall. Two similar pairs of rock glaciers lie in the shelter of north-facing cliffs in the large cirque to the northeast which also drains into Bells Canyon.

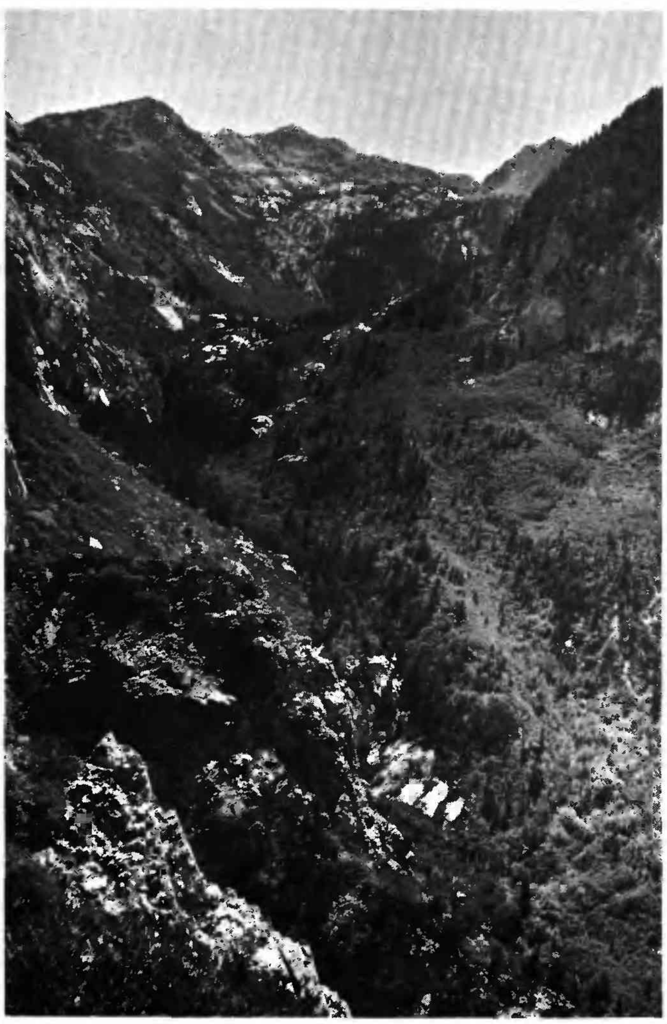

FIGURE 15.—End moraine of upper till of the Pinedale Glaciation overlying rock ledges along Bells Canyon.

OTHER DEPOSITS FORMED DURING PINEDALE GLACIATION

OUTWASH GRAVEL

Outwash gravel, formed during Pinedale Glaciation, occurs for the most part as low terraces along Little Cottonwood Canyon. The most prominent deposits are at the following localities along the creek: upstream from a rock lip west of Alta, along the outer edge of the moraine of the middle till near the confluence of Gad Valley Gulch, upstream from and along the lower margin of the moraine of the middle till at the confluence of White Pine Fork, and along the lower margin of the moraine of the middle till at the confluence of Red Pine Fork (pl. 1). Other deposits occur at the mouth of Little Cottonwood Canyon east of the graben and below the outer margin of the moraine of the middle till near the mouth of Bells Canyon. Most of these deposits appear to be stratigraphically associated with the middle till—though some may be younger—and those along the lower part of Little Cottonwood Canyon may correlate with the lower till. All are mapped as a single unit.

The outwash deposits, except those in Bells Canyon, are cut by channels containing remnants of younger terrace deposits 10 to 20 feet above the stream. The outwash consists of subround to round, poorly sorted, and irregularly bedded boulders, cobbles, and gravel in an arkosic sandy matrix. Some boulders have a maximum diameter of about 3 feet, but those between 6 and 18 inches, together with cobbles, make up the bulk of the deposits. Most of the boulders are quartz monzonite, except in the upper part of the canyon where they are mostly quartzite, limestone, and granodiorite. All the deposits bear the same soil profile as that on moraines of the Pinedale Glaciation.

ALLUVIAL FAN GRAVEL

Along the lower sector of Little Cottonwood Canyon near Wasatch Resort (pl. 1), several large coalescing alluvial fans lie on the south side of the canyon. Others occur on the north side of the canyon just upstream from the terminal moraine of the lower till of of Pinedale Glaciation. These deposits locally overlie or grade into outwash of Pinedale age; they bear the same soil profile as that on the moraines of Pinedale age, and are entrenched by gullies containing alluvial-fan gravel of Recent age. Thus, they are presumed to have formed during the Pinedale Glaciation. Most of the deposits are composed of angular to subangular boulders, cobbles, and gravel of quartz monzonite in a bedded arkosic sandy matrix. Boulders in the deposits along the lower sector of the canyon are as much as 20 feet in diameter; they were brought to their present position by flash floods and avalanches in the deeply notched gullies in the cliffs above them.

TALUS AND PROTALUS

In many places in the drainage of both Little Cottonwood and Bells Canyons, there are deposits of talus which appear to be of Pinedale age. Some grade into outwash or alluvial-fan deposits of Pinedale age; others overlap one of the three tills of the Pinedale Glaciation. Most are heavily forested, and all bear the same soil profile as that on till of Pinedale age (fig. 11*C*). Many are overlapped by talus of Recent age, or they have block rubble deposits of Recent age formed in them (fig. 11*D*). All are inactive at present, and many are deeply dissected by gullies.

The deposits are composed of locally derived angular rock debris that varies greatly in texture, depending on its source. Debris composed of quartz monzonite tends to be the coarsest, in places containing huge blocks 20 to 30 feet across. Most of the deposits are soil covered and support a heavy forest.

A single protalus rampart of probable Pinedale age was noted. It occurs along the west side of the large cirque at the head of Peruvian Gulch downslope from inactive grass-covered talus of Recent age which bears a thin azonal soil (fig. 16*B*). The protalus, which consists mostly of blocks of quartzite, forms a steep ridge or rampart about 20 feet high. It is forested and bears an immature Brown Podzolic soil profile like than on an adjacent end moraine of the upper till the Pinedale Glaciation.

ROCK GLACIERS

A few rock glaciers of Pinedale age occur in the drainage of Little Cottonwood Canyon—one just below the moraine of the middle till in Maybird Gulch has been mentioned previously. It is composed of angular blocks of quartz monzonite, and the arcuate ridges and furrows in it are so oriented as to indicate a source from the cliffs to the west. The terminal zone of the deposit encloses two kettlelike shallow ponds, suggesting that this part of the deposit may have been composed of relatively clean ice. The rock glacier is locally forested, and in these areas it has a soil like that on the adjacent moraine of the upper till of the Pinedale Glaciation, which abuts it to the south. It is overridden by talus flows correlative with the Temple Lake Stade of Neoglaciation.

Two other lobate blocky partly forested rock glaciers occur in a small tributary to Little Cottonwood Creek between Gad Valley Gulch and White Pine Fork. They have abrupt terminal snouts and are characterized by arcuate ridges and furrows. Till-like material, which locally supports a soil like that on moraines of the Pinedale Glaciation, underlies their blocky surfaces in places. Inasmuch as the deposits lie upstream from moraines of the lower till and are overlapped by Recent talus, they are probably correlative with the middle and upper tills of the Pinedale Glaciation.

LANDSLIDES

Landslides are uncommon in the drainage of Little Cottonwood and Bells Canyons except in the form of avalanche debris. These deposits, in this report, are included with either talus or alluvial fans, with both of which they are intimately associated. One large rockfall-avalanche type of landslide, described by Calkins and Butler (1943), occurs in Albion Basin. It is of interest because it overlies the middle till of the Pinedale Glaciation and is overlain by the upper till. Its age is thus bracketed as younger than the middle stade of the Pinedale Glaciation but older than the maximum advance of the late stade.

The deposit is about three-quarters of a mile long and about 300 yards wide. Its toe is about a mile from the cirque headwall to the south. It is composed of very angular blocks, in contrast to the subangular, soled, and faceted blocks in the adjacent till. All the blocks are composed of dark-blue-gray limestone, which forms the upper part of the cirque headwall. The matrix is fine-grained debris, in places almost dustlike, and is also entirely of limestone. Some of the blocks, especially near the toe, are more than 20 feet in diameter. The deposit has a relatively gentle slope, and does not appear to be more than about 20 feet thick. As pointed out by Calkins and Butler (1943, p. 50), "the slide was probably in the main the result of a single immense rockfall from a glacially oversteepened cliff."

POST-PINEDALE SOIL

A stratigraphically distinct soil, here called informally the post-Pinedale soil, may be defined as that immature zonal soil formed on deposits of the Pinedale Glaciation and locally on older deposits. It was not observed on deposits of the Neoglaciation, which, in fact, locally overlie it. These conditions suggest that, although the soil has in places been undergoing some degree of development throughout post-Pinedale time, it acquired its dominant megascopic characteristics before the onset of Neoglaciation.

Between altitudes of 5,135 and 10,400 feet, the highest point at which it was observed, the post-Pinedale soil is an immature Brown Podzolic soil whose characteristics vary only slightly regardless of the texture or lithology of the deposits on which it is formed.

The A horizon is commonly 2 to 12 inches thick, dark gray (10*YR* 4/1) to dark grayish brown (10*YR* 4/2) nonsticky, nonplastic, loose, and soft. The pH is commonly about 6, except in mineralized areas where it may be lower. The boundary between the A and underlying B horizons is gradual.

The B horizon, where fully preserved, is 24 to 30 inches thick, yellowish brown (10*YR* 5/4) to light yellowish brown (10*YR* 5/3), nonsticky, nonplastic, very friable, and soft. Its pH is commonly about 6. In many places it is penetrated by krotovinas from the overlying A horizon and is locally completely mixed with material from that horizon. The boundary between the B and underlying C horizons is diffuse.

The C horizon is commonly light brownish gray (10*YR* 6/2) to pale yellow (2.5*YR* 7/4) and consists of structureless loose sandy material having a pH of about 7.

DEPOSITS OF THE TEMPLE LAKE AND HISTORIC STADES OF NEOGLACIATION

Deposits formed during the Temple Lake and historic stades of Neoglaciation include till, rock glaciers, alluvial gravel, talus, protalus, talus flows, block rubble, frost rubble, and colluvial mantle formed by creep solifluction and slopewash. These deposits either rest on bedrock or overlap or lie in gullies cut into deposits of the Pinedale or older glaciations. They have a thin azonal or very weakly zonal soil formed on them that contrasts markedly with the immature Brown Podzolic soil formed on deposits of Pinedale age, which in places they overlie. Thus, they represent a depositional sequence that is separated from that of the Pinedale by a widespread disconformity and weathering.

TILL

Nine distinct moraines of the Temple Lake Stade occur in the drainage of Little Cottonwood Creek and Bells Canyons, but none of the historic stade were observed. The nearest moraine of the historic stade known to the writer is that below the former small glacier on Mount Timpanogos, 15 miles to the south of this area.

Moraines of the Temple Lake Stade occur in cirques at the heads of all the major tributaries of Little Cottonwood Canyon from Gad Valley Gulch eastward, except Peruvian Gulch, which has not been glaciated since Pinedale time. All these tributaries are underlain by sedimentary rocks, mainly quartzite and limestone. Farther west, in the area underlain by quartz monzonite, large rock glaciers of the Temple Lake Stade occur in nearly all cirques, but moraines were found only in Hogum Fork and in the northern tributary of Bells Canyon. This distribution of moraines and rock glaciers is probably largely due to differences in the abundance and spacing of fractures in the bedrock and to consequent differences in amounts of debris contributed to the ice.

The altitude of the 9 moraines ranges from 9,160 feet to 10,120 feet (table 1) and averages 9,770 feet. The overlapping or upstream relations of most of the deposits to the upper till of the Pinedale Glaciation has been described above in the discussion of Pinedale Glaciation of each tributary.

From Gad Valley Gulch east, the till in the moraines consists typically of angular to subangular blocks in an unsorted matrix of smaller rock fragments, sand, and silt. Only a few of the blocks are soled, faceted, or striated. The material is more sandy where derived from quartzite and more silty where derived from limestone. West of Gad Valley Gulch, the till consists mostly of large blocks, which, in Hogum Fork, are as much as 30 feet in diameter. Interstitial sandy material is scanty, but it occurs in depressions at the crest and front of morainal ridges.

All the moraines are much fresher in appearance than those of Pinedale age. They are characterized by steep fronts, abrupt crests, and well-preserved knobs and depressions. Except where very blocky, the deposits support a scrub spruce and tundra vegetation and bear a thin azonal soil.

ROCK GLACIERS

As pointed out by Ives (1950), rock glaciers occur in nearly all the major cirques tributary of Little Cottonwood and Bells Canyons. West of Gad Valley Gulch, most cirques contain two rock glaciers—an outer one representing the Temple Lake Stade and an inner one representing the historic stade. In Gad Valley Gulch and tributaries to the east, a rock glacier of the historic stade commonly overlaps, or lies upslope from, a moraine of the Temple Lake Stade.

Twenty rock glaciers of Temple Lake age were observed. They range in altitude from 9,250 to 10,300 feet and average 8,903 feet (table 1). The deposits form lobate tongues of rock debris, and in most places entrench or overlap the upper till of Pinedale Glaciation. They commonly consist of a surface layer of large angular blocks beneath which is blocky till-like material that extends to the surface locally. On deposits in the eastern part of the area the blocks are mostly 1 to 6 feet in diameter, but locally they are as much as 10 feet. In the western part, where the deposits consist entirely of quartz monzonite, the blocks are mostly 4 to 10 feet in diameter, but some are as much as 30 feet.

Most deposits have steep, but stable, frontal slopes, some of which are as much as 100 feet high. A few have low fronts only a few feet high. The surface of the deposits above the frontal slope may be merely a featureless, uniform jumble of blocks. In many deposits, however, the terminal zone is characterized by arcuate transverse ridges and furrows and by local enclosed depressions; the medial zone is characterized by longitudinal ridges and furrows and by local oblique subparallel crevasselike furrows along the margin. The headward zone of many deposits has been reactivated during the historic stade to form an inner rock glacier, but where not so reactivated, it is characterized by relatively smooth slopes that are overlapped by either active or inactive talus at the cirque headwall.

The deposits are stable and inactive at present. Where fine debris is present at the surface, it supports a tundra or scrub spruce vegetation and an azonal soil like that developed on till of the Temple Lake Stade. Elsewhere, the blocks are whiter and more pitted by weathering than on the younger rock glaciers. In the east cirque of Hogum Fork, large phenocrysts of feldspar in the blocks of quartz monzonite locally stand out as much as half an inch from the surface of the blocks. This differential weathering is, however, not necessarily younger than the deposit.

Fifteen rock glaciers of the historic stade were observed. They range in altitude from 9,300 to 10,640 feet (table 1) and average 9,955 feet. These deposits are like those of Temple Lake age in their topographic and internal aspects, but they are smaller, fresher in appearance, and bear neither soil nor vegetation. All grade headward into slopes on which talus is actively accumulating. Some of the deposits are of primary origin and lie upslope from moraines of the Temple Lake Stade. Others represent reactivation of the headward areas of rock glaciers of Temple Lake age.

The latter deposits are commonly characterized by a steep and highly unstable marginal slope, along the base of which are narrow channels, as much as 20 feet deep, that extend away from the front of the reactivated deposit across the rock glacier of Temple Lake age. The channels are not the product of ordinary surface erosion, for they are formed in very coarse blocks and contain enclosed depressions along their length. Rather, they appear to result from letting down of the surface blocks into gullies cut by streams flowing beneath the blocks on the underlying till-like core of the older deposits. The channels tend to occupy preexisting low areas, but locally they break across surface ridges without respect for topography. Obviously, the minor features of surface form of the rock glaciers are not everywhere reflected in the underlying till-like core. A coating of brownish stain on blocks along the sides of the gullies and fresh scars on the boulders—where they have rubbed together in the course of being let down—attest the recency of this process. Similar stained and rubbed boulders occur along the margins of rock glaciers of the historic stade, and in places on their upper surfaces. Although most of the deposits appear inactive at present, the cascading pattern of blocks along the fronts of those in the south and southwest cirques of Hogum Fork suggests that these masses may be currently active.

ALLUVIAL GRAVEL

Deposits of Recent alluvial gravel underlie the flood plain of Little Cottonwood Canyon, form large alluvial fans along the canyon wall, especially on the north side, and comprise local shallow fills along some of the tributary canyons and in Bells Canyon.

The material along Little Cottonwood Canyon consists mostly of subrounded boulders and cobbles in a sandy matrix. Some of the boulders are glacially soled and faceted. Extensive boulder bars characterize the flood plain along the lower third of the canyon.

The alluvial fans are composed of coarse angular to subrounded rock debris that is poorly sorted and crudely bedded. Most of the fans support a thin azonal soil and vegetation. They appear to be predominantly of Temple Lake age. Stream action on them is restricted to one or more gullies at the heads of which erosion is currently taking place while small deposits are being formed at their base.

Deposits in Albion Basin are largely fine grained. Those in the tributary canyons are composed of subangular boulders that, in some places, have settled together along stream courses to form spectacularly even surfaced boulder pavements.

TALUS, TALUS FLOWS, AND PROTALUS RAMPARTS

Talus, talus flows, and protalus ramparts of recent origin are mapped in two categories: inactive and active. The inactive deposits have a thin azonal soil and commonly support a sparse vegetation. Some can be shown to be of Temple Lake age through their stratigraphic or physiographic relations to moraines of the Temple Lake Stade; others cannot. Deposits presently accumulating commonly merge with or overlap rock glaciers of the historic stade.

These deposits tend to rim the upper sectors of the canyons. The active deposits are commonly confined within the cirques; the inactive ones extend along the canyon wall to a point where they overlap, or are entrenched within, deposits of Pinedale age (figs. 11, 16*B*). In places, they lens out against bedrock.

The talus deposits form sheets and compound cones at the base of cliffs. Most are of coarse blocky debris, but some contain fine-grained material along their upper slopes.

The talus flows, which are the lobate extensions of the toe of a talus resulting from solifluction and creep, lie along the base of the slope and extend out over the valley floor, in many places overlapping till of the Pinedale Glaciation (fig. 16*G*). They are also composed of coarse blocky debris, some blocks being as much as 15 feet in diameter. The deposits are characterized by abrupt fronts 5 to 30 feet high and by transverse arcuate ridges and furrows in their terminal zone. Most of the talus flows in the area are inactive, lie downslope from inactive talus (fig. 16*D*), and appear to be related to Temple Lake Stade. In some places, such inactive vegetation-covered talus flows are overlapped upslope by actively accumulating talus (fig. 16*C*). Only two talus flows whose very fresh appearance suggested that they might be active were noted. One, at the head of Gad Valley Gulch, is in part the product of solifluction of till from a moraine of Temple Lake age as a result of extensive seepage from snowbanks upslope.

Protalus ramparts are ridges of blocky debris resulting from the fall and transgression of talus across a snowbank (Bryan, 1934). One such deposit, currently being formed, was noted in the south cirque of Albion Basin. It is relatively large and lies at the foot of a talus slope, which for most of the year is overlain by a snowbank. However, most of the protalus ramparts in the area are inactive and are overlapped by actively accumulating talus (fig. 16*A*).

BLOCK RUBBLE

Two kinds of block rubble deposits occur in the area. One, here called simply frost rubble, is a mantle of blocky debris that has formed on bedrock slopes along the intercanyon divides. The debris is commonly 1 to 3 feet thick, and consists of angular fragments that range from 1 inch to about 2 feet in diameter. Some of it virtually is in place, but some has slid or rolled downslope. Both active and inactive deposits are included, but all are fresh in appearance and are probably of Recent age.

A second variety of block rubble is formed on mantle, commonly preexisting soil-covered talus or blocky till of Pinedale age. It consists of angular blocks or subangular boulders that have been exhumed from the subjacent mantle, probably as a result of frost heave, thawing, and removal of the fines. The boulders are commonly stained brown and are unstable. In places, sufficient downslope movement has taken place to form a rampart along the lower margin of the deposit. Excavation across the margin of the rubble reveals that the soil on the deposits of Pinedale age, from which the block rubble has developed, is truncated by the rubble, at the base of which only a thin band of humus has formed (fig. 16*F*). Most of these block rubbles therefore probably formed during the Neoglaciation.

POST-TEMPLE LAKE SOIL

Soils developed on deposits formed during the Temple Lake Stade of Neoglaciation are thin and mostly azonal, though in a few places they have a very weakly developed B horizon (fig. 16). Such soils were not observed on deposits of the historic stade, but they do occur locally on pre-Temple Lake deposits.

The A horizon is 1 to 6 inches thick, dark gray (10*YR* 4/1 to 2.5*YR* 4/1), and consists of loose structureless humic slightly acid mineral matter. The base of the A horizon is abrupt to gradual.

The B horizon, where present, is 4 to 8 inches thick, pale brown (10*YR* 6/3) to light brownish gray (2.5*Y* 6/3), structureless, nonplastic, nonsticky, loose, and slightly acid to neutral.

The C horizon is commonly light-brownish-gray (10 *YR* 6/2 to 2.5*Y* 6/2) structureless loose stony sandy loam.

CORRELATION

No attempt is made here to correlate the glacial deposits of Little Cottonwood and Bells Canyons with those in other parts of the Rocky Mountains, except the Wind River Mountains of Wyoming, because the purpose of this paper is primarily to define the local stratigraphy and to relate it to that of Lake Bonneville. Correlation of the glaciations described here with the interpretations of other workers in this area is, of course, a necessary prerequisite.

One of the main problems for students of the Quaternary in this area has been the recognition of reliable criteria to interpret which deposits represent major glaciations separated by interglacial intervals—intervals of marked climatic amelioration and complete disappearance of the ice—and which deposits represent merely stades of re-advance or halts of the ice separated by interstades—minor climatic amelioration and partial recession of the ice. In other words, the environment of the area during recession of the ice or deglaciation is less well understood than the environment during the glacial maxima.

The writer differs with all other authors, except Blackwelder (1931), in considering that the major late Pleistocene interglaciation occurred after the formation of the two sets of moraines that extend beyond the fault at the mountain front and before the formation of

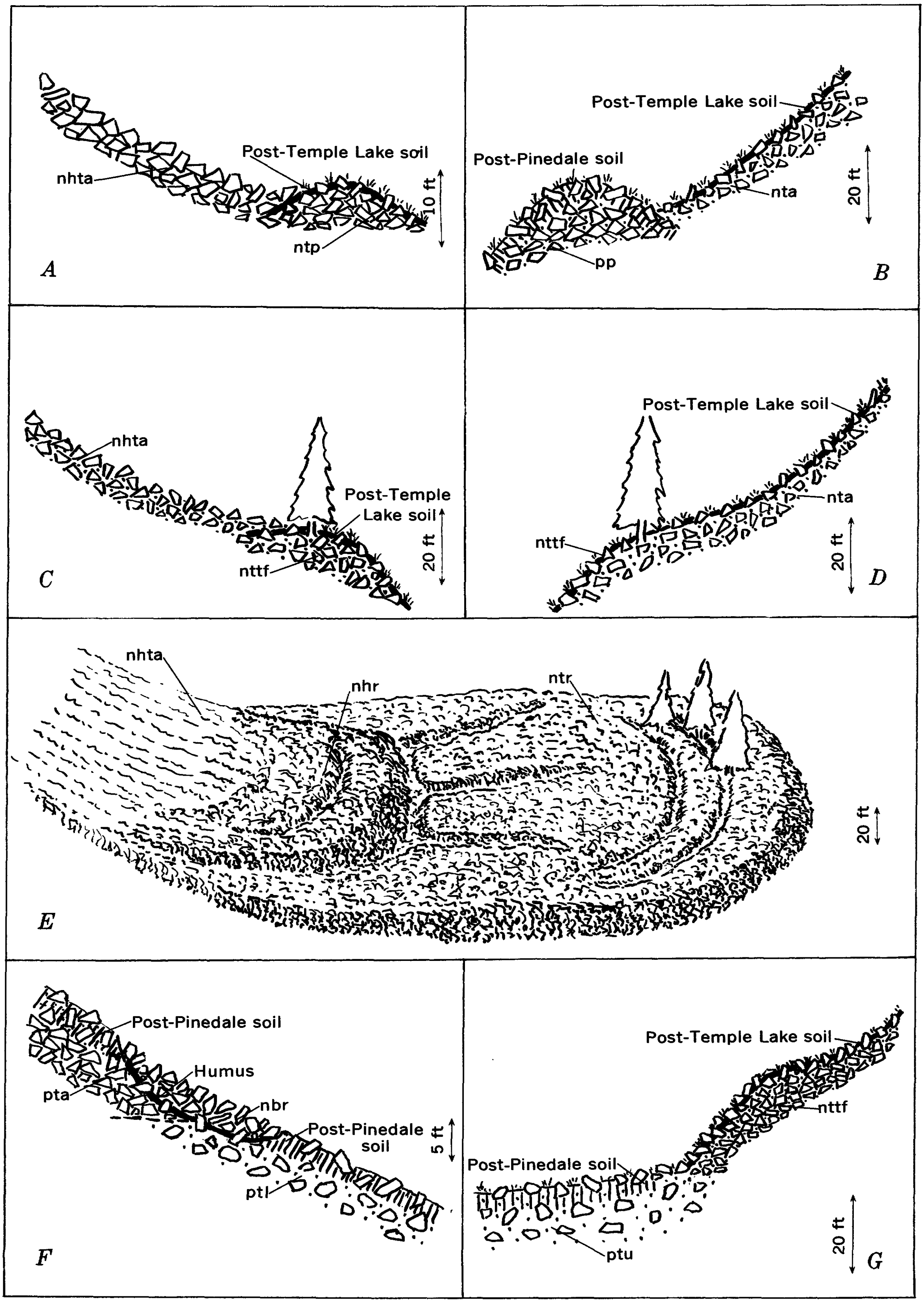
Post-Temple Lake soil
nhta
10 ft
ntp
A
Post-Temple Lake soil
Post-Pinedale soil
nta
20 ft
pp
B
nhta
Post-Temple
Lake soil
20 ft
nttf
C
Post-Temple Lake soil
nta
nttf
20 ft
D
nhta
nhr
ntr
20 ft
E
Post-Pinedale soil
Humus
pta
nbr
Post-Pinedale
soil
5 ft
ptl
F
Post-Temple Lake soil
nttf
Post-Pinedale soil
ptu
20 ft
G

FIGURE 16

the moraines higher in the canyons. Others have tended to infer that this interglaciation separated deposition of the outer moraines. This interpretation, based on differences in soil development, in erosion, and in the surficial and internal characteristics of the two groups of moraines, is a matter of degree, however, for, as shown by Gilbert (1890), an important disconformity and subaerial deposits separate the deposits of his two high stands of the lake, each of which he inferred to be correlative with a glaciation. R. B. Morrison (1961) has shown that this disconformity extends to altitudes at least as low as 4,700 feet, and that it may extend to 4,390 feet along the Jordan River (fig. 1).

The writer believes, however, that with the lake at 4,700 feet altitude, or even at 4,390 feet, glaciers would still have existed in the mountains, whereas they would not have existed during the interval of complete or nearly complete desiccation of the lake that occurred between its second and third rises (Richmond and others 1952; Morrison 1961). Furthermore, a maturely developed zonal soil formed between the second and third rises (Richmond and others, 1952), whereas none has been recognized as forming between the first and second rises. The writer, therefore interprets the interval separating deposition of the two moraines of the Bull Lake Glaciation as an interstade and considers the interval separating these moraines from those of the Pinedale Glaciation higher in the canyon as an interglaciation.

CORRELATION WITH THE WORK OF OTHERS

Correlation of the nomenclature applied to specific moraines by previous workers with that of this report is shown in table 2. The complex terminal moraine at the mouth of Little Cottonwood Canyon, which, according to Gilbert (1890), shortly postdated the cutting of the Bonneville shoreline, and Gilbert's inferred older glaciation are both included in the Bull Lake Glaciation. At the mouth of Bells Canyon, the moraine of Atwood's "earlier epoch of glaciation" (1909) is the lower till of Bull Lake Glaciation of this report, and the large terminal moraine of his "later epoch of glaciation" is the upper till of Bull Lake Glaciation. The outer recessional moraines of Atwood's later epoch (Atwood, 1909, fig. 14, R and R′) are the lower till of Pinedale Glaciation; the inner recessional moraines (Atwood, 1909, fig. 14, R″ and R‴) are the middle till. Atwood (1909, pl. 10, fig. 17) mapped the end moraine at the mouth of Little Cottonwood Canyon, here called upper till of the Bull Lake Glaciation, as the terminal moraine of this later epoch of glaciation and correctly inferred that deposits of his earlier epoch, the lower till of Bull Lake Glaciation of this report, lay beneath the sediments of Lake Bonneville to the west. Upcanyon, moraines mapped by Atwood (1909, pl. 10) at the confluence of Hogum Creek and Gad Valley Gulch as recessional deposits of his later epoch are respectively the end moraines of the lower and middle tills of the Pinedale Glaciation of this report.

Blackwelder (1931) correlated moraines of Atwood's "earlier epoch" with the Bull Lake Glaciation and those of the "later epoch" with the Pinedale Glaciation, with which interpretation the writer is in disagreement. However, both in his map and in his text, Blackwelder (fig. 31, p. 916) considered the moraine at the mouth of Little Cottonwood Canyon, which Atwood included in his "later epoch," to be "older moraine" and of Bull Lake age. He further pointed out that glaciers correlative with the Pinedale Glaciation did not reach the canyon mouths. With these interpretations the writer is in complete accord.

Marsell (1946) was the first to discover high-level erratics of a glaciation that predated Lake Bonneville. These deposits, which he called "Glaciation No. 1," are correlative with those here called pre-Bull Lake in age. Moraines of his glaciations Nos. 2 and 3 are those of the lower and upper tills of the Bull Lake glaciation of this report. Marsell believed his glaciation No. 2 to be of pre-Bonneville age because of the deep weather-

FIGURE 16

DIAGRAMMATIC SKETCHES OF SOME STRATIGRAPHIC RELATIONS OF DEPOSITS OF THE TEMPLE LAKE AND HISTORIC STADES OF NEOGLACIATION

A, Protalus rampart (*ntp*) of the Temple Lake Stade on which the post-Temple Lake soil is developed, overlapped by actively accumulating talus (*nhta*) in cirque east of Mount Baldy at southwest corner of Albion Basin.

B, Protalus, rampart (*pp*) of the late stade of Pinedale Glaciation on which the post-Pinedale soil is developed, overlapped by inactive talus of Recent age (*nta*) on which the post-Temple Lake soil is developed. Locality, western cirque at head of Peruvian Gulch.

C, Talus flow of the Temple Lake Stade (*nttf*), on which the post-Temple Lake soil is developed, overlapped by actively accumulating talus (*nhta*) along west side of upper sector of Gad Valley Gulch.

D, Talus flow of the Temple Lake Stade (*nttf*), grading headward into inactive talus (*nta*) along east side of upper sector of White Pine Fork. Post-Temple Lake soil is developed across both deposits.

E, Rock glacier of the Temple Lake Stade (*ntr*) at head of Maybird Gulch showing upper part reactivated to form rock glacier of historic stade (*nhr*). Note "letdown" outwash channels extending outward from front of younger rock glacier.

F, Block rubble of Recent age (*nbr*) formed on talus (*pta*) and the lower till (*ptl*) of Pinedale Glaciation on which post-Pinedale soil is developed.

G, Talus flow of the Temple Lake Stade (*ntff*) on which the post-Temple Lake soil is developed, overlapping the upper till of Pinedale Glaciation (*ptu*) on which the post-Pinedale soil is developed on the east side of the head of Red Pine Fork.

ing of the boulders in its till. He was the first to observe, however, that, at the mouth of Little Cottonwood Canyon, the Bonneville shoreline is cut on the moraine which, he inferred, effectively prevented the lake from entering the canyon itself (Marsell, 1946; Marsell and Jones, 1955). He suggests that his glaciation No. 3 was probably correlative with the stand of the lake at the Provo shoreline during its fall from the Bonneville shoreline.

The interpretation of the succession of moraines by Ives (1950) differs in several respects from that of this report. Deposits mapped by him (Ives, 1950, fig. 8) as "Graniteville Erratics" on the north side of Little Cottonwood Canyon do not extend to the highway along the canyon floor (pl. 1), and those mapped below Bells Canyon appear to this writer to be concentrations of boulders reworked in Pinedale or Neoglacial time from alluvial fans correlative with Bull Lake Glaciation.

Ives follows Atwood and others in placing a major deglaciation between the two sets of moraines that lie west of the mountain front at the mouth of Bells Canyon. His "Bell Canyon Old Moraine series" and "Cottonwood A moraines" are, respectively, the moraines of the earlier glacial epoch and terminal moraine of the later epoch of Atwood (1909) and the upper and lower tills of Bull Lake Glaciation of this report.

TABLE 2.—*Correlation of nomenclature of the glacial deposits of Little Cottonwood and Bells Canyons*

[*Indicates informal usage of original author]

<table>
<tr><th rowspan="2">Gilbert 1890</th><th rowspan="2">Atwood 1909</th><th rowspan="2">Antevs 1945</th><th rowspan="2">Blackwelder 1931</th><th rowspan="2">Marsell 1946</th><th rowspan="2">Ives 1950</th><th rowspan="2">Eardley and others 1957</th><th colspan="4">This paper</th></tr>
<tr><th colspan="2">Rocks</th><th colspan="2">Climate-stratigraphic unit</th></tr>
<tr><td rowspan="10"></td><td rowspan="6"></td><td rowspan="6"></td><td rowspan="6"></td><td rowspan="10"></td><td rowspan="4"></td><td rowspan="6"></td><td colspan="2">Rock glaciers of historic stade</td><td>*Historic stade</td><td rowspan="3">Neoglaciation</td></tr>
<tr><td colspan="2">Azonal soil</td><td>Temple Lake—historic interstade</td></tr>
<tr><td colspan="2">Rock glacier or moraine of Temple Lake Stade</td><td>Temple Lake Stade</td></tr>
<tr><td colspan="2">Immature zonal soil</td><td colspan="2">Pinedale—Neoglacial interglaciation</td></tr>
<tr><td>Albion Basin Moraine</td><td rowspan="5">Till of Pinedale Glaciation</td><td>*Upper till</td><td>*Late stade</td><td rowspan="5">Pinedale Glaciation</td></tr>
<tr><td></td><td>Erosion</td><td>*Late interstade</td></tr>
<tr><td rowspan="4">*Recessional moraines of later epoch of glaciation</td><td rowspan="5">*Later epoch of Atwood</td><td rowspan="3">*Moraines higher in canyon</td><td>Gad Valley and Yellow Pine Fork Moraines</td><td>M4</td><td>*Middle till</td><td>*Middle stade</td></tr>
<tr><td>Interstadial</td><td rowspan="3"></td><td>Erosion</td><td>*Early interstade</td></tr>
<tr><td rowspan="3">Cottonwood B moraine in Bells Canyon. Cottonwood A moraines</td><td>*Lower till</td><td>*Early stade</td></tr>
<tr><td>Interglacial interval</td><td colspan="2">Mature zonal soil</td><td colspan="2">Bull Lake-Pinedale interglaciation</td></tr>
<tr><td>*Moraines at mouth of Little Cottonwood Canyon</td><td>*Terminal moraines of later epoch of glaciation</td><td rowspan="3">*Moraines at mouth of Little Cottonwood Canyon</td><td>*Glaciation No. 3</td><td>M3</td><td rowspan="3">Till of Bull Lake Glaciation</td><td>*Upper till</td><td>*Late stade</td><td rowspan="3">Bull Lake Glaciation</td></tr>
<tr><td>Interval of erosion</td><td>Interglacial epoch</td><td>Interglacial epoch</td><td>Interglacial</td><td>Interstadial</td><td>Interglacial</td><td>Erosion</td><td>*Intra-Bull Lake interstade</td></tr>
<tr><td>*Inferred older glaciation</td><td>*Earlier epoch of glaciation</td><td>*Earlier epoch of Atwood</td><td>*Glaciation No. 2</td><td>Bell Canyon Old Moraine Series</td><td>M2</td><td>*Lower till</td><td>*Early stade</td></tr>
<tr><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td>Interglacial</td><td>Interglacial</td><td>Interglacial</td><td colspan="2">Very mature zonal soil</td><td colspan="2">Pre-Bull Lake-Bull Lake interglaciation</td></tr>
<tr><td>*Glaciation No. 1</td><td>Graniteville Erratics</td><td>M1</td><td colspan="2">Till of a pre-Bull Lake glaciation</td><td></td><td>Pre-Bull Lake glaciation</td></tr>
</table>

Ives' "Cottonwood B moraine" in Bells Canyon is the middle till of Pinedale Glaciation of this report. In Little Cottonwood Canyon, only alluvial-fan gravel and ground moraine of the upper till of the Bull Lake Glaciation were found at the site of his "Cottonwood B moraine." Upcanyon, Ives identified two moraines of a middle-canyon glaciation—one at the mouth of "Yellow Pine Fork" that, from the description given, is probably the moraine at the mouth of White Pine Fork, and one at the mouth of Gad Valley Gulch. These deposits, both of which are the middle till of Pinedale Glaciation of this report, are the terminal moraines of two separate glaciers—one along White Pine Fork and the other formed by the confluence of the glaciers in Little Cottonwood Canyon and in Gad Valley Gulch. Ives considered them to be successive deposits of a single glacier in Little Cottonwood Canyon.

Correlation of the Albion Basin moraines of Ives is somewhat uncertain in the mind of the writer. They are described by Ives (1950, p. 113) as being less than 1.5 miles from the cirque heads, generally of fresh appearance, little weathered, undissected, and bearing little soil. He correlated them with deposits of the "Little Ice Age" of Matthes (1939, 1942) and indicated their age to be not more than 4,000 years. Although this physical description and estimate of age corresponds to those of moraines of the Temple Lake Stade, such moraines are rarely as much as half a mile from the cirque headwalls, and equally short rock glaciers are far more common to this stade than are moraines. In contrast, their position as described by Ives corresponds to that of moraines of the upper till of Pinedale Glaciation, which are commonly from ½ to 1½ miles from their cirque headwalls.

Ives describes rock glaciers as common to the cirque heads of the area, indicating that all are post-Little Ice Age in origin and that some are still active. Though the writer would agree that some were formed during the latter part of Recent time (historic stade of Neoglaciation), many are older deposits formed in the earlier part of Recent time (Temple Lake Stade of Neoglaciation).

A discussion of the morainal sequence by Eardley, Gvosdetsky, and Marsell (1957) in general follows the conclusions reached earlier by Marsell (1946), but recognizes, in addition, the moraine at the confluence of Gad Valley Gulch and Little Cottonwood Creek. They correlate the old high-level erratics with the Buffalo Glaciation of the Wind River Mountains, Wyo., the moraines of the earlier epoch of Atwood (1909) with the Bull Lake Glaciation, moraines of the later epoch of Atwood (1909) with the Pinedale Glaciation, and the moraine at the confluence of Gad Valley Gulch and Little Cottonwood Creek with the Temple Lake Stade.

CORRELATION WITH THE DEPOSITS OF LAKE BONNEVILLE

The stratigraphy of Lake Bonneville in the area west of Little Cottonwood and Bells Canyons has been studied by R. B. Morrison, and will be described in a separate report. The correlation of the glacial stratigraphy with that of the lake shown in figure 17 was determined jointly by Morrison and the writer, and will be discussed further by Morrison. In this report, the formal nomenclature applied to the lake deposits is that of Hunt, Varnes, and Thomas (1953).

Correlation of the lower and upper tills of the Bull Lake Glaciation and their associated outwash deposits with the Alpine and Bonneville Formations is made on a direct basis, for their intertonguing relations can be traced.

Correlation of all stratigraphically higher units is of necessity indirect because the lake deposits are not in contact with the glacial deposits. The Provo Formation extends no higher than 4,824± feet altitude, and deposits of three successively younger lake rises recognized by R. B. Morrison (1961) extend no higher than 4,770±, 4,470±, and 4,410± feet altitude. These four units are correlated, respectively, with recessional deposits of the upper till of Bull Lake Glaciation and the lower, middle, and upper tills of Pinedale Glaciation. This correlation is based on three lines of reasoning. The first is an assumption that a hydrologic system necessary to maintain the lake at these levels would require precipitation and temperature conditions under which glaciers would exist contemporaneously in the mountains. A second line of reasoning stems from the fact that coarse alluvial gravel deposits on each of four successively higher terrace sequences extend downstream from the narrows of Little Cottonwood Creek in the moraines at the mountain front to the upper limit of each of the four lake deposits, respectively. Such gravels could be of either glacial or nonglacial origin, but if glaciers were present when the lake deposits were being formed, the gravels were probably deposited by glacial melt waters.

A third line of reasoning is based on the fact that the soil on the lake deposits at the Provo shoreline and the soil on the highest of the four alluvial terrace gravels are mature zonal soils like that on till of the Bull Lake Glaciation. However, as the highest alluvial terrace gravel extends through the end moraines of Bull Lake Glaciation into the lower sector of Little Cottonwood Canyon (pl. 1), the Provo Formation is probably re-

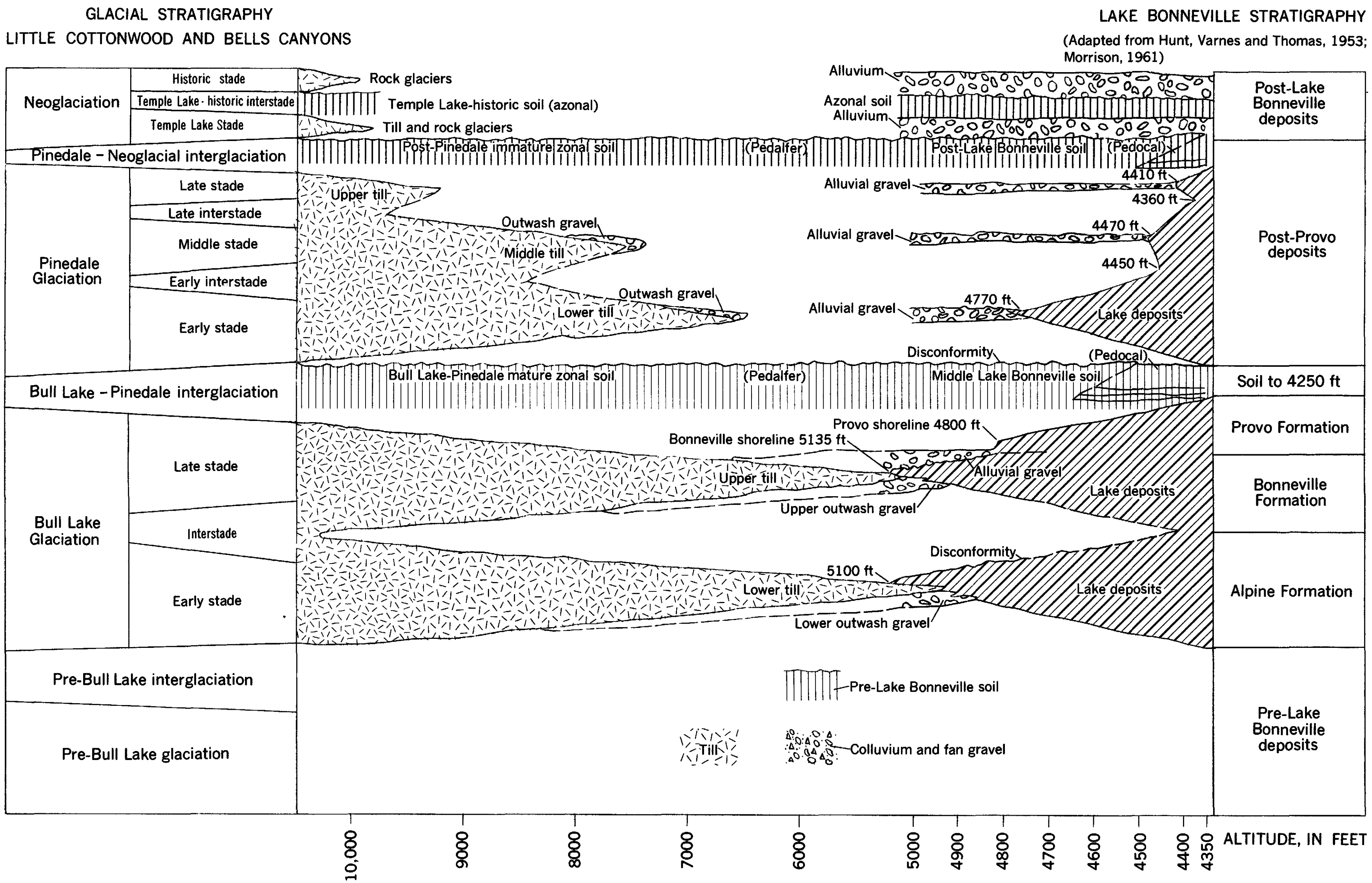

FIGURE 17.—Correlation of the glacial stratigraphy of Little Cottonwood and Bells Canyons with the stratigraphy of Lake Bonneville.

lated to the recessional phase of Bull Lake Glaciation. In contrast, the soils on deposits at the three post-Provo shorelines and on the lower three alluvial terrace gravels along Little Cottonwood Creek west of the mountain front are relatively immature zonal soils like those on the lower, middle, and upper tills of Pinedale Glaciation.

If this correlation is correct, it may be speculated that, as the Pinedale glaciers had attained their maximum advance (average alt, 6,570 ft) at the time the level of the lake was at about 4,770 feet, the Bull Lake glaciers probably extended to a similar position in the canyons at the time the lake stood at 4,825 feet (the Provo shoreline) and the alluvial gravel on the highest of the four terraces was being deposited.

REVISED CORRELATION

After this report had been prepared, additional evidence was found which shows that Lake Bonneville rose to the Bonneville shoreline at least once in Pinedale time, and that its fall to the Provo shoreline, owing to erosion of the outlet at Red Rock Pass, and its subsequent stillstand at the Provo shoreline occurred in Pinedale time.

The evidence in the Little Cottonwood area consists of deposits of bedded clean lake sand and sandy well-rounded lake gravel that have the post-Pinedale soil developed on them and that overlie the post-Bull Lake soil on older deposits at the Bonneville shoreline. At one locality, in a recent cellar excavation in NW¼ NE¼ sec. 11, T. 3 S., R. 1 E., this lake sand, containing local pebble lenses, rests on the post-Bull Lake soil developed on lake gravel of the second rise of Lake Bonneville (Bonneville Formation of Hunt and others, 1953) at an altitude of 5,135 feet.

Another locality at an altitude of 5,140 feet on the north bluff of Little Cottonwood Creek about 1,100 feet south of the Murray City Power Plant in SE¼SE¼ sec. 2, T. 3 S., R. 1 E., provides additional evidence. Here, a deposit of lake gravel 7.5 feet thick, which is ascribed to the Bonneville Formation on page D16 of this report, was found to rest on a partly eroded profile of the post-Bull Lake soil that is developed on the upper till and associated outwash gravel of the Bull Lake Glaciation.

Following development of the post-Bull Lake soil, the lake must thus have risen again to the Bonneville shoreline in Pinedale time. Erosion of the lake outlet at Red Rock Pass and the fall of the lake to the Provo shoreline must have been subsequent to this rise and therefore also in Pinedale time. A revised correlation of the glacial and lake deposits is given in the following table:

GLACIAL STRATIGRAPHY		LAKE BONNEVILLE STRATIGRAPHY
Post-Pinedale soil		Post-Lake Bonneville soil
Pinedale Glaciation	Upper till	Post-Provo deposits (lake maxima at 4,410, 4,470, 4,770 ft)
	Middle till	Provo Formation (stillstand at 4,800 ft) and unnamed lake deposits (at least one lake maximum at 5,140 ft)
	Lower till	
Post-Bull Lake soil		Middle Lake Bonneville soil
Bull Lake Glaciation	Upper till	Bonneville Formation (lake maximum at 5,135 ft)
	Lower till	Alpine Formation (lake maximum at 5,100 ft)

CORRELATION OF NEOGLACIAL DEPOSITS

Correlation of deposits of the Temple Lake and historic stades of Neoglaciation with those of Great Salt Lake is extremely tenuous. Eardley, Gvosdetsky, and Marsell (1957) have described beaches and wave-cut benches at an altitude of 4,240 to 4,245 feet in the basins of Great Salt Lake and the adjacent Great Salt Lake Desert, to which they apply the term "Gilbert Beach." They noted (p. 1156) that this beach does not coincide with the expansion rim (alt., 4,221 ft) which separates the two basins and at which a temporary stand of the lake might be expected. They concluded (p. 1196) that the beach "may mark an expansion-stability level of the lake in its general retreat from the Stansbury (shoreline) to the present"; or that "it may also mark a minor pluvial maximum." The fact that the Gilbert Beach is 20 to 25 feet above the expansion rim suggests to the writer that it marks a minor pluvial maximum that could correlate with the Temple Lake Stade of Neoglaciation. The historic stade is probably correlative with the modern sediments of Great Salt Lake, which probably include not more than about the top 5 feet of these sediments if the radiocarbon dates of cores of the upper 40 feet of bottom sediments of the lake are meaningful (Eardley and others, 1957, p. 1169–1170).

GLACIAL HISTORY OF LITTLE COTTONWOOD AND BELLS CANYONS

PREGLACIAL SETTING

Available data for Little Cottonwood and Bells Canyons provide few clues as to the appearance of the Wasatch Mountains at the close of Tertiary time. According to Eardley (1944), very late Pliocene or early Pleistocene tilting along a system of normal faults bordering the west side of the range uplifted an already mountainous area along whose summits were preserved remnants of a widespread erosion surface—the Herd Mountain surface of late Oligocene or Miocene age. No remnants of this surface were observed in the Little Cottonwood area.

EARLY AND MIDDLE PLEISTOCENE TIME

The history here postulated for early and middle Pleistocene time can be described only as speculative. Profiles of the high ridges that separate the tributaries of Little Cottonwood Canyon suggest that a broad valley 10 miles long, 2 to 3 miles wide, 700 feet deep at its head, and 2,000 feet deep at the mountain front was carved into the mountain upland at some time after at least 2,000 feet of uplift by normal faulting had occurred.

This valley lay in the present drainage of Little Cottonwood Canyon, but probably also included the present north-trending drainage of Bells Canyon. The writer infers that this broad valley was probably the surface down which ice of a first major glaciation in the area advanced in early Pleistocene time.

Erosion resulting from uplift along normal faults at the margin of the range continued after recession of the ice, and deep broad valleys were cut into the older surface along creeks ancestral to both Little Cottonwood and Bells Canyons. The valley along the site of Little Cottonwood Canyon was ½ to ¼ mile wide. Its headward sector was cut about 200 feet below the older surface, and its floor is at least 2,500 feet below that surface at the mountain front.

The writer believes that ice of a second major glaciation in the area advanced over this surface in early middle Pleistocene time, and deposits inferred to be till rest on a remnant of the surface of the mountain front.

Following recession of this ice, erosion resulting from continued uplift of the range along normal faults cut the present inner gorge of the canyon, which is about three-quarters of a mile wide. The floor of the canyon is 400 feet below the next higher surface along its headward sector and about 1,000 feet below it at the mountain front. It is virtually at the present level of the stream, which thus appears to have been established in middle Pleistocene time after more than 6,000 feet of uplift and dissection of the mountain front since the beginning of Pleistocene time.

A third major glaciation, represented by the till of pre-Bull Lake age on the divide between Little Cottonwood and Bells Canyons, probably occurred in late middle Pleistocene time.

Little is known of the character of the interglacial intervals separating these three major glaciations, except that a thick red clayey soil formed during the last interval.

LATE PLEISTOCENE AND RECENT TIME

BULL LAKE GLACIATION

Bull Lake Glaciation comprised two advances of the ice, an early stade and a late stade, separated by an interstade of erosion and glacial recession.

Early stade.—During the early stade, glaciers formed in all the cirques in the drainage of Little Cottonwood and Bells Canyons and advanced down each tributary into the main canyons to form a single mass (pl. 2). They covered an area of about 26.2 square miles, and had an estimated volume of 3.61 cubic miles. In Little Cottonwood Canyon the ice extended about a mile out into the basin beyond the mountain front to an altitude of 5,040 feet. From Bells Canyon it extended about three-quarters of a mile west to an altitude of 4,920 feet. Aprons of bouldery outwash gravel extended beyond the fronts of the moraines. Subsequently, Lake Bonneville, which had been gradually rising in response to the pluvial climate under which the glaciers advanced, rose over the crests of the moraines to an altitude of 5,100+ feet (pl. 2) and deposited lake sediments of the Alpine Formation on them. The fact that these sediments contain no bouldery outwash suggests that the ice may have withdrawn slightly from the terminal moraines, behind which outwash was trapped.

Intra-Bull Lake interstade.—During the intra-Bull Lake interstade the ice receded and the lake fell to altitudes at least as low as 4,390 feet (Morrison, 1961). The extent of the fall suggests that the ice probably receded at least to the upper parts of the canyons, if not to the cirque heads, but that it probably did not disappear entirely. Valleys as much as 150 feet deep were cut into the deposits of the first rise of the lake and underlying till, but no evidence that a soil formed during the interval was found in the area studied. A soil at this stratigraphic position at an altitude of about 4,700 feet along Parleys Canyon in the southeastern part of Salt Lake City was shown to Morrison and the writer by R. E. Marsell in 1950. Its swamp-type profile and occurrence in lake sediments suggested that it formed near the border of the lake, but provided no evidence as to the regional climate.

Late stade.—During the late stade the glaciers advanced again from each tributary into the main canyons and attained a position at the canyon mouths only a short distance back of their termini during the early stade (pl. 2). The glacier from Little Cottonwood Canyon reached an altitude of 5,080 feet; that from Bells Canyon, an altitude of 5,100 feet. They covered an area of 25.5 square miles, were 1,000 feet deep along parts of the canyons, and had an estimated volume of about 3.57 cubic miles. The second rise of Lake Bonneville lapped against the fronts of the moraines at an altitude of 5,135± feet, the Bonneville shoreline (pl. 2), where a bench was cut and lake gravel of the Bonneville Formation was deposited on it. The glaciers had probably ceased to advance at the time the lake attained its maximum, but could not have receded noticeably for, as pointed out by Marsell (1946), the lake did not enter the lower part of Little Cottonwood Canyon below 5,135 feet altitude.

The fact that the second rise of the lake was 135 feet higher than the first, whereas the late advance of Bull Lake Glaciation both in this area and in most others in the Rocky Mountains known to the writer is less extensive than that of the early advance, suggests that some local factor influenced the lake. R. C. Bright (oral communication, 1959) has suggested that divergence of the waters of the Bear River (fig. 1) into Lake Bonneville at this time may have been responsible for this excessive rise and the overflow of the lake at Red Rock Pass, Idaho.

Erosion of the outlet of the lake to the level of the Provo shoreline (alt, 4,825± ft) was accompanied by recession of the ice and the deposition of bouldery gravel along Little Cottonwood and Dry Creeks from the narrows through the moraines to the Provo shoreline. Analogy with conditions during Pinedale Glaciation suggests that during the stand of the lake at the Provo shoreline the terminus of the ice may have lain at an altitude of about 6,500 feet in Little Cottonwood Canyon and at about 5,700 feet in Bells Canyon.

BULL LAKE-PINEDALE INTERGLACIATION

The glaciers disappeared entirely from the cirques during the Bull Lake-Pinedale interglaciation, and Lake Bonneville may have become completely desiccated (Morrison, 1961). Slopes stabilized and a mature Brown Podzolic soil formed from the tops of the mountains down to the upper slopes of the basin. Toward the close of the interval as the climate became wetter, Little Cottonwood and Dry Creeks lowered their courses about 20 to 30 feet at the mountain front.

PINEDALE GLACIATION

The record of Pinedale Glaciation comprises a maximum advance followed by two recessional halts or minor readvances of the ice. These are here called the early, middle, and late stades of Pinedale Glaciation. They are separated by two interstades of recession and erosion that were probably short lived.

Early stade.—During the early stade, glaciers developed anew in all cirques tributary to Little Cottonwood and Bells Canyons, except those at the head of Grizzly Gulch and that on the south side of Flagstaff Mountain northwest of Alta, which had been occupied during Bull Lake Glaciation. The glaciers of each tributary, as far west as Hogum Fork, merged with the glaciers along Little Cottonwood Canyon to form a single mass of ice that terminated at an altitude of 6,600 feet adjacent to, but not coalescing with, the glacier in Hogum Fork (pl. 2). The ice front was abrupt. It rose 1,400 feet in the first half mile, but upslope from this point along Little Cottonwood Canyon it had an average gradient of 450 feet per mile, which is about the same as that of the canyon floor. The gradient of the ice along tributary valleys was at least 1,000 feet per mile. The glacier in Bells Canyon extended down to an altitude of 5,680 feet, or nearly to the mouth of the canyon. Its gradient, if parallel to that of the canyon floor, was about 1,000 feet per mile, or about the same as that on the tributaries to Little Cottonwood Canyon.

The depth of the ice ranged from 600 to 700 feet in the canyon of Little Cottonwood Creek and from 400 to 600 feet in the hanging tributary valleys. The ice covered an area of about 17.0 square miles in Little Cottonwood and Bells Canyons, and had an estimated volume of about 1.75 cubic miles. During this stade, Lake Bonneville rose again to an altitude of 4,770± feet (Morrison, 1961).

Early interstade.—During the early interstade of Pinedale Glaciation the ice probably receded between 1 and 2½ miles along Little Cottonwood Canyon and its tributaries and separated in such a way that individual glaciers existed along each tributary west of Gad Valley Gulch. The precise extent of the recession is not known. Lake Bonneville was lowered by evaporation to an altitude at least as low as 4,450± feet (Morrison, 1961).

Middle stade.—During the middle stade, glaciers from the heads of Little Cottonwood Canyon, Collins Gulch, Peruvian Gulch, and Gad Valley merged to form a single terminal moraine on the canyon floor at an altitude of 7,760 feet (pl. 2). Separate glaciers in White Pine Fork and Red Pine Fork also reached the floor of Little Cottonwood Canyon, where they formed moraines at 7,240 and 6,970 feet altitude, respectively. Glaciers in Maybird Gulch, Hogum Fork, and Coalpit Gulch failed to reach the hanging rim of these valleys above Little Cottonwood Canyon. The glacier in Bells Canyon extended to 5,720 feet. The average altitude of all end moraines formed during this stade is 7,525 feet. The glaciers had about the same gradients as those formed during the early stade of Pinedale Glaciation. They covered an area of about 14.3 square miles and had an estimated volume of about 1.36 cubic miles. During this stade, Lake Bonneville rose to an altitude of 4,470± feet (Morrison, 1961).

Middle interstade.—During the middle interstade the glaciers receded at least from a quarter of a mile in the western part of the area (Hogum Fork and Bells Canyon) to 4 miles in the eastern part of the area (Albion Basin) and disappeared entirely from some cirques in the eastern part of the area. The precise extent of recession is not known. Lake Bonneville was lowered by evaporation to an altitude at least as low as 4,360± feet (Morrison, 1961).

Late stade.—During the late stade of Pinedale Glaciation the ice was so separated that individual glaciers existed in all tributaries to Little Cottonwood Canyon, and in some, such as White Pine Fork and Albion Basin, the ice had subdivided into two or three separate masses (pl. 2). The lower limits of the glaciers lay at altitudes ranging from 9,840 feet in Collins Gulch and Maybird Gulch to 6,560 feet in Bells Canyon. Their average altitude, including that in Bells Canyon, is 9,195 feet. The ice was relatively shallow; maximum thickness in the several canyons was probably between 100 and 250 feet. The total area covered by the ice was only about 6.45 square miles, and the estimated volume of ice was probably only about 0.50 cubic mile. During this time Lake Bonneville was at an altitude of about 4,410± feet (Morrison, 1961).

PINEDALE-NEOGLACIAL INTERGLACIATION

The Pinedale-Neoglacial interglaciation occurred during the "altithermal age" of Antevs (1948) from about 4000 to 2000 B.C. The ice disappeared entirely from the cirques, and Lake Bonneville was probably completely desiccated. Slopes in the mountains stabilized as solifluction and frost action gradually ceased. An immature zonal Brown Podzolic soil formed on all deposits of Pinedale age, as well as on older exposed deposits, from the tops of the mountains down onto the basin slopes. Toward the close of the interval, Little Cottonwood and Dry Creeks lowered their channels 10 to 15 feet as the climate cooled and rainfall increased somewhat.

NEOGLACIATION

The Neoglaciation is the "Little Ice Age" of Matthes (1939, 1942), which includes the time since about 2000 B.C. Glaciers or rock glaciers have twice formed, and melted away in the cirques.

Temple Lake Stade.—During the Temple Lake Stade —from about 2000 B.C. to shortly before the birth of Christ—10 small glaciers and 20 rock glaciers formed in the more sheltered north- or northeast-facing parts of cirques that had been fully occupied during Pinedale Glaciation (pl. 2). Many cirques were not reoccupied —such as the one at the head of Collins Gulch and the east and west cirques of Albion Basin which have high floors and low headwalls. The lower limits of the glaciers and rock glaciers ranged in altitude from 9,160 to 10,200 feet and were, in general, lower in the western part of the area and higher in the eastern part. Their average altitude was 9,800 feet. The ice covered an area of about 1.55 square miles and had an estimated volume of about 0.05 cubic mile.

Temple Lake-historic interstade.—During the Temple Lake-historic interstade, from shortly before the birth of Christ to about A.D. 1400, the ice probably disappeared entirely from the area for a short time. Moraines and other deposits of the Temple Lake Stade stabilized and an incipient azonal soil began to form on them.

Historic stade.—During the last or historic stade, which is estimated to have extended from about A.D. 1400 to the present and to have attained a maximum in the latter part of the 19th century, 15 rock glaciers formed in those cirques which had been occupied during the Temple Lake Stade and whose high headwalls offered the most shelter (pl. 2). Some of the rock glaciers formed back of moraines of Temple Lake age; others were the product of regeneration of the headward parts of rock glaciers of Temple Lake age. Their termini range in altitude from 9,300 to 10,600 feet and average 9,955 feet. They cover an area of about 0.5 square mile and had an estimated volume of only about 0.01 cubic mile.

OTHER EVENTS OF RECENT TIME

The record of solifluction and frost activity in Recent time is much more complete than during earlier glaciations. Frost action, as reflected in the formation of talus, protalus ramparts, and upland frost rubble, was widespread throughout the area during the Temple Lake Stade, but appears to be largely restricted to the cirque heads at present. Solifluction, as reflected in the formation of talus flows, was also widespread during the Temple Lake Stade, but appears to have occurred in relatively few localities in historic time. Conditions favoring the formation of block fields were never widespread and are not active at present.

Great Salt Lake is known to have fluctuated in Recent time. One such fluctuation, marked by Gilbert Beach (Eardley, and others, 1957), is believed to have taken place during the Temple Lake Stade. The level of the lake at the time the area was first settled (alt, 4,207 ft) may have been contemporaneous with the maximum of the historic stade.

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