GLACIAL GEOLOGY OF THE FRYING PAN RIVER DRAINAGE, COLORADO

Thesis by

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ABSTRACT

On the west flank of the Sawatch Range, Colorado, evidence is found for six distinct glacial advances. One glaciation is pre-Wisconsin, four are Wisconsin, and one post-Wisconsin in age. In addition to end and lateral moraines of each advance, terrace remnants of six valley trains were identified and studied for a distance of 25 miles along Frying Pan River and its major tributaries. Elevations above stream level of these outwash terraces are 400$\pm$50, 90-120, 40-50, 20-30, 12-17, and 6-8 feet. Five of the tributary valleys contained ice streams which did not join the trunk Frying Pan glacier during the Wisconsin stage.

An extensive review and testing of the numerous criteria used to distinguish deposits of multiple glaciations shows that nine of these criteria can conveniently be expressed in parameters indicative of relative age. Estimates based on these criteria, coupled with a recent radiocarbon dating of late Mankato till in the Midwest, yield the following approximate ages for deposits of the six glaciations in Frying Pan Valley: 230,000, 63,000, 46,000, 17,000, 11,500, and 5,750 years. The accuracy and reliability of the procedure used cannot be evaluated without further absolute Carbon-14 age determinations.

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INTRODUCTION

GENERAL STATEMENT

Pleistocene glacial chronology in the Rocky Mountains of the United States has, at present, many variations and interpretations. This is partly due to the relatively short period of investigation in this region compared with the glaciated areas of the Midwest. Gradually, and with frequent revision, a reliable glacial chronology has emerged in midwestern United States which is withstanding the tests of time and critical examination. Continuing investigations will probably add to and perhaps revise some aspects of this glacial sequence, but a certain stability has been achieved which has not yet been attained in the Rocky Mountain provinces.

The small extent and disjointed nature of the glaciated areas in many mountainous regions are a natural hindrance to correlation. Inaccessibility makes it difficult for any one worker to attain a comprehensive regional knowledge of the scattered glacial deposits. Consequently, a body of literature, developed valley by valley and range by range, must necessarily accumulate before an accurate correlation is possible. The purpose of this report is to add one more valley system to this body of knowledge and to compare and contrast the results obtained with various chronologies previously published.

Field investigations were made in Frying Pan valley during six weeks in June and July of 1950, and eight weeks in July and August of 1951. One month of laboratory work, devoted largely to the analysis of glacial till samples, was completed after the 1951 field season.

LOCATION AND PHYSICAL FEATURES

Frying Pan River is a tributary of Roaring Fork which joins the Colorado River at Glenwood Springs, Colorado (figure 1). The area studied comprises about 250 square miles and lies just west of the Continental Divide in the Sawatch Range. It occupies portions of Pitkin and Eagle counties and the White River National Forest. The Frying Pan heads north of Independence Pass, runs northward for about four miles, and then turns west for 34 miles to its confluence with the Roaring Fork at Basalt. Tributaries of the Frying Pan within ten miles of its head radiate from due north through east to south as a consequence of the trends of the smaller mountain groups comprising the Sawatch Range. Routes of access are shown on the index map (figure 1).

Elevations in the glaciated area are 8,000 to 13,000 feet, and outwash terraces were traced down the valley to about 7,000 feet. In general, the forest cover is heavy and consists largely of aspen and lodgepole pine on the previously logged lower slopes. Engleman spruce, alpine fir and blue spruce continue up to timber line, which lies between 11,000 and 11,800 feet depending on slope steepness and orientation to wind and rainfall.

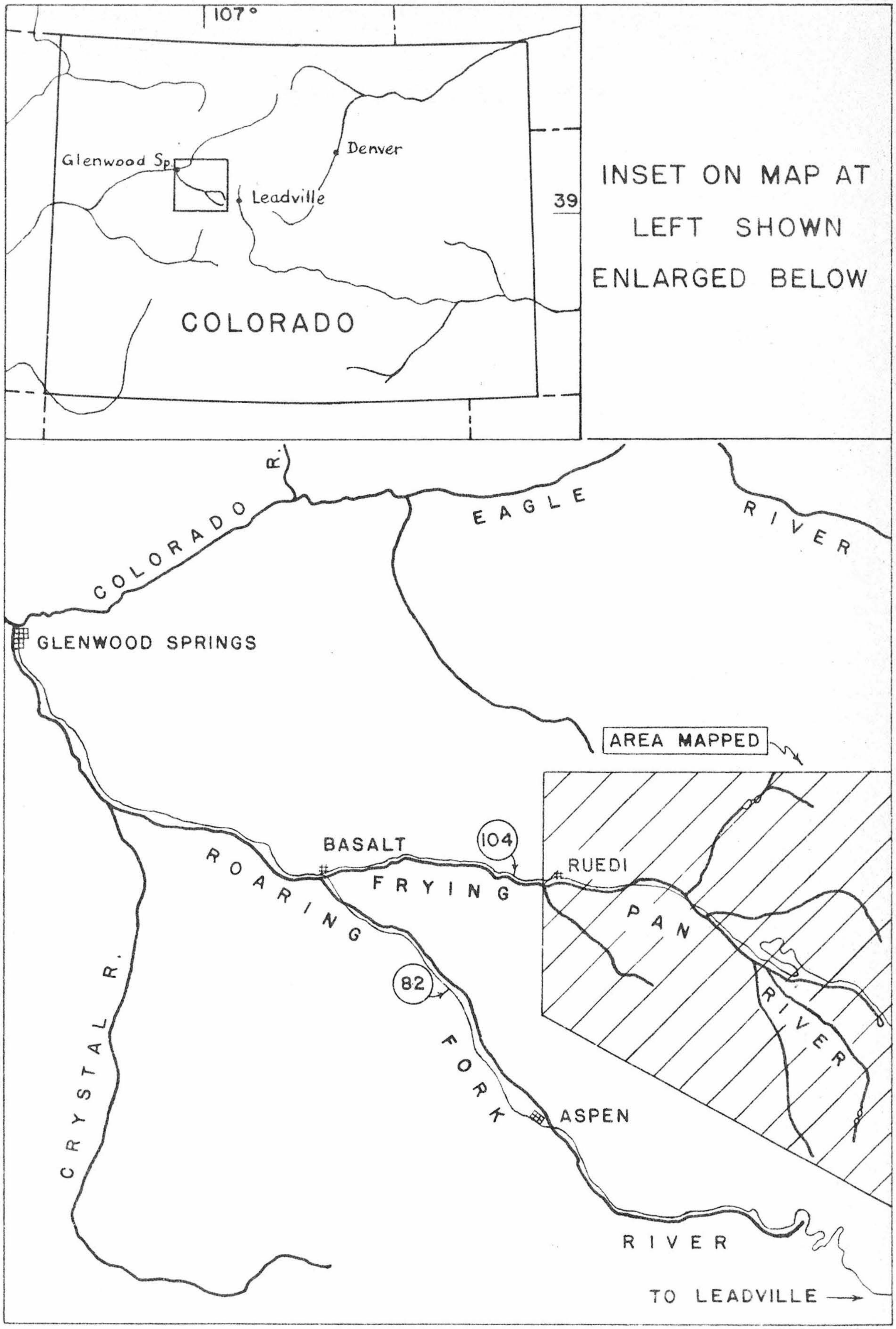

Figure 1. Index Map

STRATIGRAPHIC RELATIONS

A brief resume of the bedrock stratigraphic relations will be helpful in the discussion of glacial geology. Unfortunately, only reconnaissance maps by Johnson (1944) and Stark (1935) are available. Sufficient time was not available during this study for more detailed investigation of the areal geology.

Pre-Cambrian rocks underlie almost all of the study area. Schists and gneisses are the most prevalent and are considered migmatites by Stark (ibid., p. 3). The remainder of the Pre-Cambrian is a distinctive granite porphyry, with large pink orthoclase phenocrysts, which is useful in determining source areas of some glacial deposits.

One mile southeast of Thomasville the contact between the Pre-Cambrian and Paleozoic sedimentary beds intersects the Frying Pan with a generally northeast-southwest trend. One-half mile farther east the Biglow overthrust (Stark, 1934, p. 1007) causes repetition of the Cambrian-Ordovician (undivided) quartzite as a thin slice. Devonian-Mississippian (undivided) limestone, shale, and shaly sandstone overlie the Cambrian-Ordovician rocks near the mouth of Lime Creek. These are succeeded by soft Pennsylvanian and Permian shale to one mile west of Ruedi, where a great thickness of massive red Permian sandstone appears. The dip of Paleozoic beds is generally west and usually gentle.

DESCRIPTION OF GLACIATION

GENERAL STATEMENT

A study of the topographic sheet[1] for the Frying Pan drainage gives the impression that the maximum ice advance within the present valley system was to a point just west of Ruedi. At this point the relatively broad and smooth-bottomed valley gives way to a narrow, winding gorge. Careful search of this area has disclosed no glacial deposits, and the change in valley character is confidently attributed to a change from soft to hard Permian rocks. A similar relation involving the same rocks is seen on Rocky Fork.

Precise determination of the maximum extent of the oldest glaciation recognized (pre-Wisconsin) cannot be made with confidence. As explained in detail below, one exposure of this oldest glacial material is thought to be close to the terminal position. However, this interpretation is open to some question, and the length of 18 miles indicated for this glacier, measured from the head of the main branch of the Frying Pan, is possibly short of the maximum value.

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1. The Mt. Jackson, Colorado, quadrangle, with a scale of 1/125,000 and contour interval equal to 100 feet.

The maximum length of the trunk glacier during the Wisconsin was 17 miles. Several tributary valleys contained Wisconsin glaciers which did not join the Frying Pan glacier. Terminal moraines indicate lengths of $7\frac{1}{2}$, $7\frac{1}{4}$, 5, $4\frac{1}{2}$ and 3 miles for glaciers in Lime Creek, North Fork, Last Chance Creek, Miller Creek, and Rocky Fork, respectively. The extent of pre-Wisconsin ice in these five tributaries is not definitely known, but it is thought that only the North Fork and the Last Chance Creek glaciers joined the trunk ice stream during this older stage.

In the descriptions to follow, little evidence will be presented for age determination. An analysis of this matter is reserved for a later section. It is believed that careful and detailed description of the morainal deposits, and their spacial relation, is essential to future regional correlations. Such descriptions have been too brief or entirely lacking in some of the previous works. This need not be damaging to an author's conclusions about an area which he himself knows intimately, but it makes comparison and correlation difficult for other workers.

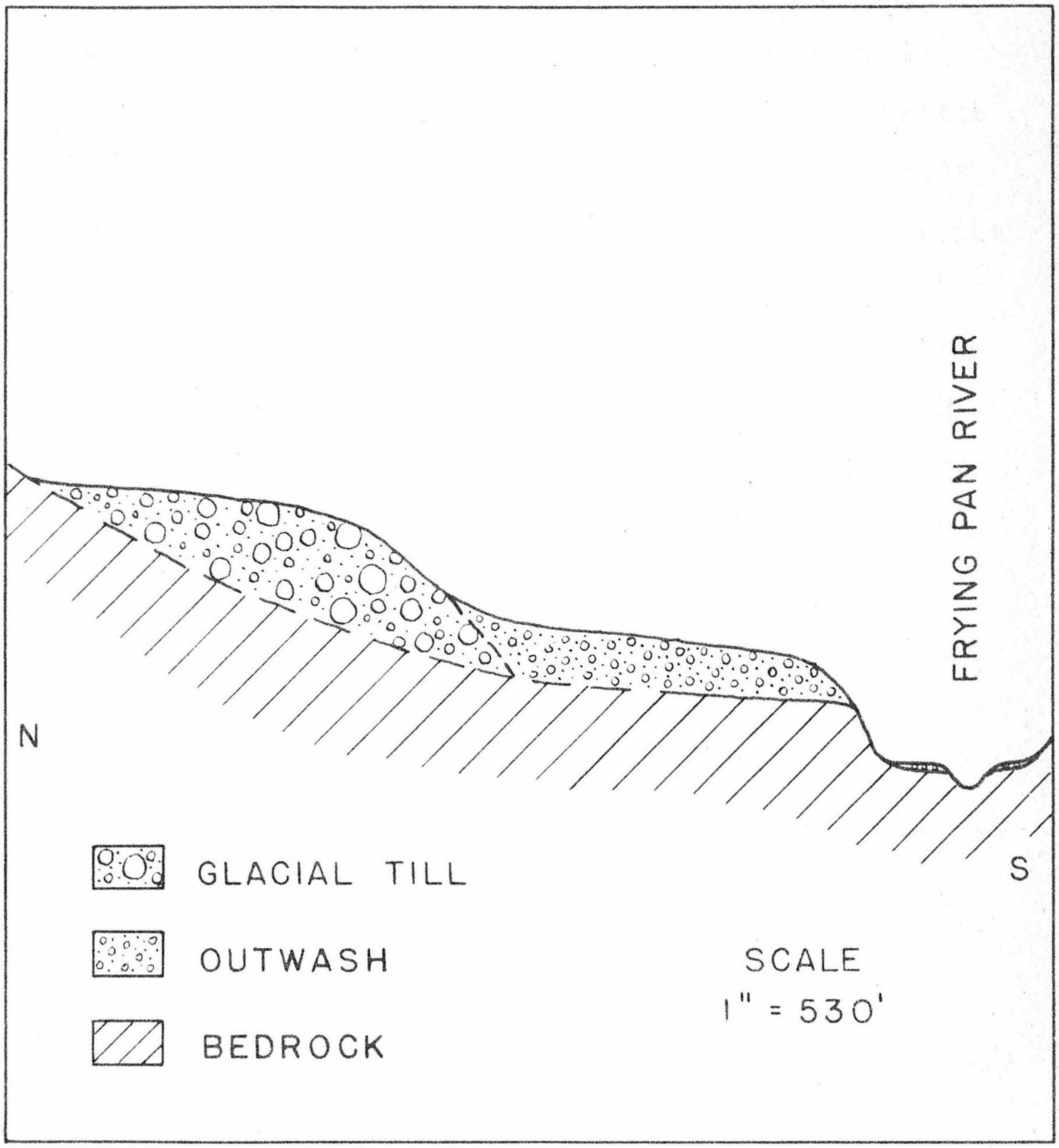
PRE-WISCONSIN GLACIATION (Lime Creek Stage)

Evidence of pre-Wisconsin glaciation in the Frying Pan valley is limited to four exposures of transported igneous material high on the valley walls (figure 2; in pocket). Whether the deposits are of morainal or outwash derivation is uncertain because of their antiquity, hence the extent of pre-Wisconsin glaciation is not definitely known. Indirect evidence suggests that the trunk glacier terminus was near the junction of Lime Creek and the Frying Pan. This gives a length of about 18 miles for the pre-Wisconsin advance, here designated the Lime Creek glacial stage.

The most prominent accumulation of pre-Wisconsin glacial material occurs as a formless cap on the ridge between the Frying Pan and lower Lime Creek. The underlying bedrock ridge is wholly sedimentary, and the transported igneous debris mantles its crest for about one-half mile. The upper limit of the detritus is 820 feet above present river level. It is believed that this deposit is part of the end moraine of the pre-Wisconsin glacier as it appears to be on the floor rather than the walls of the old valley. The basis for this interpretation is the fact that at the spur tip the glacial material lies on an essentially horizontal plane cut on the quartzite bedrock. Most of the bedrock-debris contact is obscured by slumping of the glacial material, but stream action near the tip has cliffed the quartzite for two hundred yards around both sides, exposing the flat surface believed to be a remnant of the old valley floor now approximately 290 feet above present river grade throughout its observable extent.

The longitudinal profile of the ridge crest displays two crude but clearly discernible steps (figure 3). The surface of the upper tread and riser is sparsely dotted with sub-angular to sub-rounded igneous stones ranging from cobbles to boulders eight feet across. The surface of the lower step exhibits better rounded but fewer and smaller igneous boulders, none exceeding three feet in diameter. The crude sorting and rounding of the material on the lower step suggests that it is outwash deposited in a breach cut through the moraine making up the higher bench. Inasmuch as both the moraine and outwash debris appear to lie on the remnant of the same pre-Wisconsin valley-bottom, it seems likely that they are essentially contemporaneous. This association of moraine and outwash is in accord with the interpretation that the outermost terminal position of the ice was in this vicinity.

The possibility that this deposit is a medial rather than an end moraine is suggested by a small percentage of



Glacial deposits of the Lime Creek stage shown in a longitudinal section of the ridge separating Lime Creek and the Frying Pan.

Figure 3.

red sandstone pebbles and cobbles in the till. At present these fragments could have come only from a Permian formation which outcrops several miles down the Frying Pan, and five miles up Lime Creek west of Woods Lake. If the red sandstone has been brought down to the Frying Pan by a glacier in Lime Creek the deposit on the dividing ridge would have been in a medial position between the Lime Creek and Frying Pan glaciers. Such an interpretation is not consistent with the bedrock floor configuration described above and illustrated in figure 3. Furthermore, if the Permian formations west of Lime Creek are projected eastward up their dip, it is apparent that a source of red sandstone might easily have existed at an earlier stage of erosion in the Last Chance Creek drainage, tributary to the Frying Pan three miles upstream from the deposit in question. Thus no glacier need have come down Lime Creek to a junction with the trunk ice stream.

Further evidence supporting the conclusion that the pre-Wisconsin glacier terminated near the Frying Pan-Lime Creek junction is afforded by two deposits farther down the Frying Pan which are believed to be remnants of the pre-Wisconsin valley-train. A number of well rounded and water-worn porphyritic cobbles is found on the steep south wall one-half mile downstream from this junction. The cobbles are scattered about the slope at least 280 feet above the river. Some of the glacial detritus has apparently slumped below this level, but the overall relation is suggestive of outwash gravels lying on a remnant of the pre-Wisconsin valley floor which is exposed in the face of a limestone quarry at this location.

A far larger body of outwash forms a definite high-level terrace remnant on the south valley wall between Deadman and Miller creeks. The somewhat degraded upper surface is several acres in extent and approximately 450 feet above the Frying Pan. The flat has been dissected by Deadman Creek to a depth of 125 feet, and its edges are notched by gullies up to forty feet deep. Widespread slumping of the gravels, along both Deadman Creek and the Frying Pan, makes it difficult to determine the base of the deposit and hence the elevation of the bedrock surface on which it lies. Bedrock is exposed in Deadman Creek up to 225 feet above the Frying Pan, but this is undoubtedly a minimum figure because of burial of the actual contact under gravels reworked by the creek. A well-defined bench cut on bedrock on the north valley wall opposite the mouth of Deadman Creek is about 275 feet above present river grade and may supply a better figure for the elevation of the pre-Wisconsin valley floor at this point.

A fairly fresh exposure of the terrace detritus is seen in the canyon of Deadman Creek. Particles range from fine sand to two-foot boulders. The latter are crudely sorted and concentrated in zones up to four feet thick, separated by beds of finer material two to four feet thick. No sedimentary rocks were identified in the outwash. The presence of scattered boulders up to ten feet in diameter in the terrace deposit was at first thought to preclude a purely outwash origin. However, water transport of equivalent boulders in the Wisconsin terraces indicates that the distance of 2.25 miles over which these boulders were presumably carried is not out of reason. The upper limit of igneous debris is sharply defined on Deadman Creek, and no evidence was found upstream indicating a source in that drainage. Crude stratification of the detritus, the similarity in height above present stream grade of the upper and lower limits of this deposit with those of the previously deduced outwash near Lime Creek, and the presence of an extensive flat surface all suggest that it is a remnant of the pre-Wisconsin valley train and not a moraine. The degree and depth of dissection indicate a considerable age for the terrace.

The fourth occurrence of pre-Wisconsin glacial material is on the east wall of Rocky Fork four miles from its head. The deposit consists of several dozen igneous erratics up to six feet in diameter scattered along the slope 590 feet above present creek grade. The weathering of the boulders is considerable and on the same order of magnitude as those on the ridge crest between Lime Creek and the Frying Pan. It was not possible to determine whether these erratics are of morainal or outwash derivation, and the designation as pre-Wisconsin rests largely on the fact that the Wisconsin ice limit is at a point farther upstream and on the valley floor.

The four deposits described above, though all clearly related to the present drainage system and only moderately elevated above the present streams, represent the oldest glacial debris found in the Frying Pan drainage. This does not mean that older glaciations were lacking but simply that the evidence of possibly earlier advances has been destroyed or masked by subsequent erosion.

WISCONSIN GLACIATION

General Statement.

All the readily recognized glacial features in the Frying Pan and tributary valleys originated during this stage. The relatively small extent of the glaciers, the limited bulk and discontinuity of glacial deposits, and the subsequent high degree of destructive erosion related to the narrow and steep-walled nature of the valleys are largely compensated by the great variety of evidence available. Without rapid alteration by the exceptionally active weathering and erosion indigenous to a high mountain environment, however, the differentiation of geographically separated deposits of only slightly different age would be far more difficult.

One of the principal correlation problems in the Rockies concerns subdivisions within the Wisconsin stage. Previous workers have suggested from one to five substages. The following sections present descriptions of the four Wisconsin substages thought to represent distinct episodes of glacial advance in the Frying Pan drainage. In no case was it possible to determine the magnitude of ice recession between substages, but it is felt that the glaciers withdrew sufficiently in each substage interval so that the locally named advances do not have a recessional relation one to another. Detailed age discussion is again reserved for later analysis.

Thomasville Substage.

The trunk glacier of the Thomasville advance had a length of 17 miles and descended to an elevation of 8,100 feet (figure 2). A maximum thickness of approximately 1,300 feet was attained at the confluence of three large tributaries near Ivanhoe. As previously noted, five tributary valleys held glaciers which did not reach the Frying Pan during this and later Wisconsin substages. This was due largely to unfavorable orientation, low elevation, or small areal extent of the separate catchment basins, and to the considerable lengths of the tributary valleys.

On the Frying Pan, an end moraine thought to be the terminal of the Thomasville advance lies one mile upstream from Thomasville. On the north valley wall at this point is a formless deposit of till and erratic igneous boulders plastered on the hillslope, which terminates toward the river in a short morainal ridge. On the south side of the river only subangular igneous boulders scattered on the very steep slope indicate the former limit of the glacier. Separation of the north limb of the moraine from the valley wall is emphasized by a narrow gorge incised 30 to 40 feet into bedrock by a stream flowing along the margin of the glacier. A glacial origin for the gorge is attested by its diagonal course across the valley wall and by the lack of present drainage area at its head.

Deposition at the maximum of the Thomasville advance must have been relatively brief because remnants of Thomasville lateral moraines are small, inconspicuous, and discontinuous. Comparison with the much bulkier lateral moraines of the next younger substage suggests that this is due as much to small initial volume as to subsequent destruction by erosion. The maximum height and lateral extent of Thomasville ice is commonly marked only by a line of erratic boulders on the valley walls. Boulder frequencies (Blackwelder, 1931, p. 878) are usually low on these accumulations, but more because of burial by slope wash than because of disintegration. The boulder concentrations are interrupted and obscured by every large canyon and gully cutting the hillslope; a relation in marked contrast with the slight notching of lateral moraines of the next younger (Biglow) substage by the same drainage courses. The relative age of Thomasville lateral moraines is also indicated by almost complete burial under Biglow lake deposits in Seller and

Gowan parks, a relation to be later described in more detail.

Of the five smaller tributary valleys having separate glacier systems during the Wisconsin, four exhibit moraines which can be confidently dated as Thomasville. On Lime Creek just below Little Lime Creek, a thin deposit of large boulders and till rests on a scoured limestone floor. In its limited bulk, weak topographic expression, boulder frequency, and relation to younger deposits this material is identical to the Thomasville till in the Frying Pan. As elsewhere, the lack of morainal topography is attributed as much to the small initial volume as to age.

On Rocky Fork and Last Chance Creek, terminal moraines of this substage have not been identified. However, lateral moraines similar to those on the Frying Pan are found with identical relations to the bulkier laterals of Biglow age. This is most apparent near the Meredith-Aspen trail in Rocky Fork, but it is less obvious on Last Chance and Miller Creeks (figure 2). In the North Fork no deposits of Thomasville age have been positively identified. Largely through study of moraines of the succeeding Biglow substage, it is known that during the Thomasville, Frying Pan ice overflowed the ridge between the Frying Pan and North Fork, filling the lower end of that valley. End moraine deposition by the North Fork glacier of Thomasville age was apparently prevented by its actual or near confluence with this overflow ice about one mile upstream from the present river junction.

A recessional phase of the Thomasville glaciation is indicated at several locations by a linear boulder concentration parallel to, but somewhat below, the outermost Thomasville lateral moraine. This recessional phase is well expressed near Sellar where the deposits have better morainal form and greater bulk than those marking the maximum extent of the ice. Another clear example of this relation is seen at the west end of Gowan Park. The evidence for other recessional phases of the Thomasville glaciation, if any, has been destroyed or buried by the succeeding ice advances.

The crest of the north limb of the Thomasville terminal moraine on the Frying Pan is now 240 feet above stream grade, and it has been cut back about 200 yards from the present river course by erosion. This erosional breach has been partly filled with outwash gravels from younger glacial advances, so that exposures of the rock floor of the Thomasville valley are rare. At the junction of Lime Creek and the Frying Pan, Thomasville outwash gravels rest on a limestone floor 37 feet above the river. In a fresh stream cut between Jakeman and Deadman creeks, the base of the Thomasville outwash undulates across the cut 40 to 54 feet above present stream grade. These figures suggest that the pre-Thomasville valley bottom was not entirely smooth.

Thomasville outwash deposits are not found in contact with the terminal moraine, for almost complete removal of the terminal loop has also carried away the subjacent outwash gravels. However, gravel deposits believed to represent contemporaneous outwash debris are found on both walls of the valley only 200 yards below the moraine. On the steep south wall are patches of water-worn igneous pebbles and cobbles up to 120 feet above present river grade. On the north side, well weathered gravel occurs as a cap on the low ridge between Lime Creek and the Frying Pan 100 feet above stream grade. The upper limit of scattered outwash gravels resting on the Thomasville valley floor near Jakeman Creek ranges between 92 and 105 feet above the river.

The largest terrace of Thomasville age is a rock-defended deposit, several acres in extent, just west of Lime Creek and north of the river. The lip of this flat is 105 feet above river level, but the terrace slopes upward slightly toward the valley wall to about 115 feet. Other terrace remnants of this age are shown in figure 2 and the terrace chart (figure 11).

Biglow Substage.

Till and glacifluvial materials of this age comprise seventy to eighty percent by bulk of the Wisconsin deposits. This does not necessarily mean that the Biglow advance was more vigorous or of much longer duration than the Thomasville, as it may be partly a matter of preservation. A much larger proportion of the area covered by the Thomasville ice was reinvaded by younger advances, possibly destroying Thomasville deposits. It should be emphasized that bulk and age need not be related, as suggested by some of the literature on mountain glaciation.

The terminal moraine of the Biglow substage is one-quarter mile upstream from that of the preceding advance in the Frying Pan valley (figure 2). The proximity and conformable arrangement of Thomasville and Biglow end moraines gives an initial impression of similar age. However, the impression of successive advances closely related in time is dispelled by a detailed study of topographic form, internal and external properties as affected by weathering and erosion, and of remnants of the separate outwash trains. The Biglow trunk glacier was 16.75 miles long and terminated at an elevation of 8,150 feet, 40 feet above present stream grade. A maximum ice thickness of 1,100 feet was attained near Ivanhoe.

Evidence of Biglow glaciation in Frying Pan valley. The Biglow terminal moraine crosses Frying Pan valley at the west edge of the Biglow ranch pasture. The morainal loop is best preserved on the north side of the valley as a smooth narrow ridge 150 feet above river grade. Gullies on the morainal slopes are usually less than ten feet in depth. The river has cut a breach 150 yards wide through the north limb, but the gap has subsequently been partly filled with outwash debris. The south valley wall at this point has been cliffed by the Frying Pan following deposition of the Biglow terminal loop, completely destroying the south limb.

Lateral moraines of the Biglow substage are particularly prominent and persistent, extending in some instances almost to the heads of tributary valleys. The great bulk of the till in the moraines is due to superposition of successively lower lateral crests formed during repeated recessional halts in the withdrawal of Biglow ice, a history to be discussed more fully below. In countless locations these large lateral moraines have partly dammed small canyons and gullies in the valley walls. At these points the age difference between the Thomasville and Biglow substages is clearly indicated. The Thomasville laterals have generally been breached and largely removed while those of the Biglow substage are only narrowly notched.

A striking example of the composite Biglow lateral system borders Sellar Park, as noted and pictured by Behre (1933, p. 793) on a reconnaissance trip through the valley. The park represents a large detritus-filled lake of Biglow age which was held in by a two-mile section of the lateral moraine (figure 4). Gowan Park on the south wall, formed by damming of the hanging valley of Foster Creek by the Biglow lateral, and Henderson Park on North Fork are identical in origin. In Gowan Park and at Sellar, the older Thomasville till is preserved only on bedrock spurs and islands rising above the lake fill. Chapman Lake, on the ridge between Chapman Gulch and South Fork, is held in on the west and east respectively by Biglow laterals of those two tributaries, and on the north by a short section of the trunk lateral. Unlike the previous examples, this lake, although stagnant, has not been filled with detritus. This is largely because it has no major inlet, getting its water solely from surface runoff on the surrounding slopes. The bordering tributary laterals are striking, rising 150 to 250 feet above the lake, and are clearly shown on the topographic map.

Evidence of periodic halts or slight readvances during retreat of the Biglow glacier from its maximum is exceptionally well preserved. Thirty-one discrete recessional moraines from five to one hundred feet high were

A. Biglow lateral moraine, behind charcoal ovens, near Sellar. Note boulders of a Thomasville lateral on spur tip in foreground.

B. Lateral moraine, and filled glacial lake, of Biglow age near Sellar.

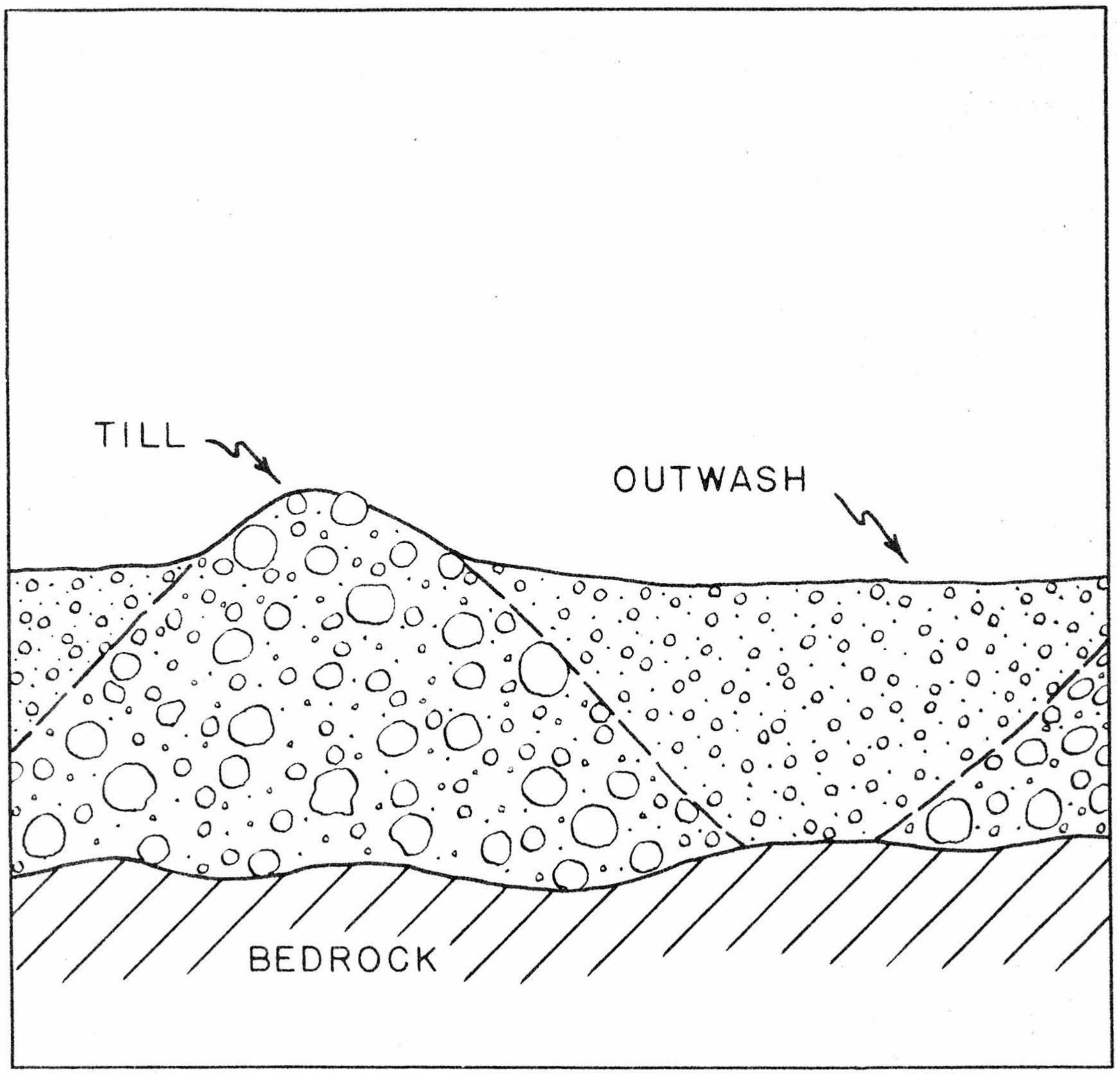
Figure 4.

counted between the terminal moraine and a point two miles upstream east of Norrie. These moraines were mapped independently along both banks of the river, and comparison yielded a perfect fit. Differences in width, height, and spacing proved sufficiently critical to allow the identification of particular end loops even when only a few of the series were seen at any one place. These same criteria also make possible identification and correlation of the related recessional crests in the composite lateral moraines higher on the valley walls. Identifications originally made on the end moraines were duplicated in several different places on the laterals. These end and lateral moraine relations indicate that snout recession during retreat of the ice was about ten times as rapid as reduction in thickness of the glacier two miles upstream from the snout.

Outwash terraces of Biglow age exhibit the greatest areal extent and continuity of all terraces in the Frying Pan system (see figure 2). From Thomasville to Ruedi, hand-levelled elevations of this surface rarely depart more than two feet above or below 40 feet from present river grade. The base of the gravel fill resting on the pre-Biglow valley floor is exposed in many river and road cuts 20 to 30 feet above stream grade. The relation of the Biglow and Thomasville valley trains offers evidence of a long time interval between the two ice advances.

Gravel deposits clearly related to Biglow glacial till lie 50 to 70 feet below Thomasville terraces and attest to a considerable period of valley dissection before the Biglow aggradation took place.

An interesting and informative association of outwash and moraine is exhibited by the Biglow deposits. From the terminal moraine upstream to Norrie, the recessional loops described above appear to lie on the surface of an older outwash terrace. Fortuitously, the road bed of the defunct Colorado Midland Railroad, now followed by the auto road, was cut along the edge of this flat exposing a vertical section parallel to the river and nearly perpendicular to the end loops. This section, where it cuts both outwash and moraine, shows that the moraine and outwash deposition were essentially contemporaneous. During successive ice recessions, meltwater first breached the end moraine of the preceding pause and then largely buried it in outwash debris while the next moraine was being built. Figure 5 is a sketch of one such example near the mouth of North Fork where the Biglow outwash apron has subsequently been cut back sufficiently to expose a section of the end loop till. A similar relation for the active Iliama glacier is beautifully illustrated in a photo by Washburn accompanying a paper by Chamberlin (1940, following p. 52).



Vertical section showing Biglow end moraine and outwash gravel relation in road cut near Biglow. Scale: 1 inch equals 35 feet.

Figure 5.

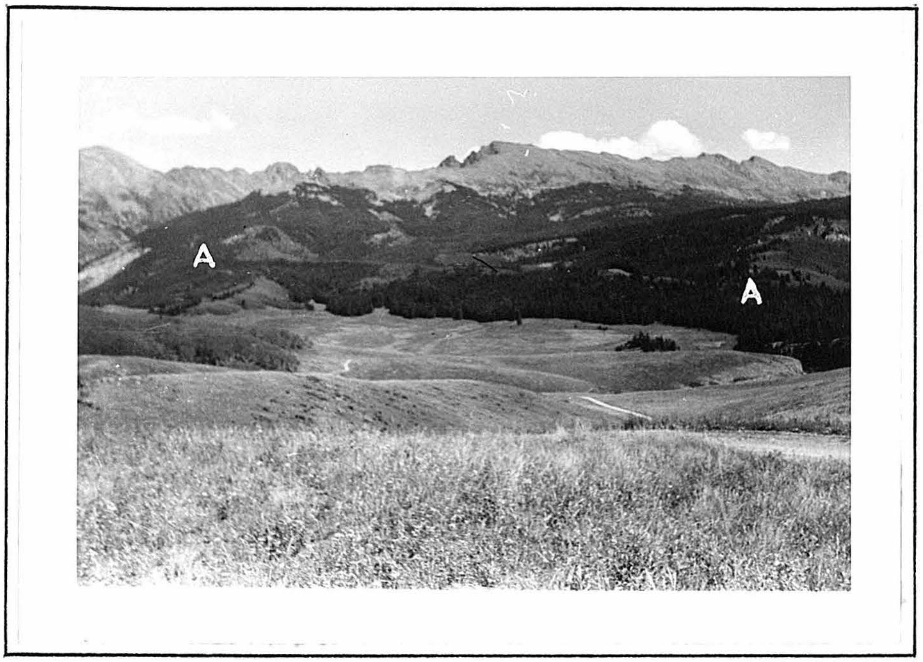
The height of the end moraines and width of breaching decreases, and the depth of burial increases upstream from the terminal moraine. The gradual rise of the valley train level upstream through the progressively smaller recessional loops, the fact that it forms an apron surrounding the breached ends of these loops in places, and the lack of outwash remnants at corresponding elevations immediately upstream from the last of the Biglow end moraines all suggest that the outwash material is of Biglow age and not the product of a younger glacial advance which terminated farther upstream.

Evidence of Biglow glaciation in tributary valleys. The relatively large bulk of the Biglow deposits makes their identification in the tributary valleys easier than in the instance of Thomasville glaciation. Post-Biglow stream dissection has removed most of the end moraine and outwash material from the narrow valley floors, but large ridge or bench-like lateral deposits on the valley walls allow reconstruction of the former ice surface and approximate terminal positions. Large lateral moraines are beautifully developed on Lime Creek below Woods Lake at 9,250 feet. Most striking is the moraine mantling and extending the dividing ridge between Slim Gulch and Lime Creek on the east bank (figure 6 A). A comparable volume of morainal debris mantles the ridge separating

Lime and Little Lime creeks almost to the present Lime Creek valley floor, and therefore is probably not far removed from the position of maximum extent of the Biglow glacier.

On the North Fork, south of the stream, and on the east side of Rocky Fork, recessional moraine/outwash relations like those previously described for the Frying Pan are repeated on a much smaller scale and in cruder form. Large bench-like laterals in both localities give further evidence of terminal positions for the Biglow ice at 9,150 and 9,750 feet in the two valleys, respectively. Time did not permit working out details of the recessional sequence of either stream, but the first ten phases on North Fork appear to correspond in arrangement and relative size to those of the Frying Pan.

In Last Chance Creek a scattered mass of glacial debris in the narrow gorge at an elevation of 9,360 feet is all that remains of Biglow end moraines. A lateral moraine almost completely blocks off a large, deep gulch entering Last Chance Creek from the north, one-half mile below the creek's only tributary. The bulk and position of the till, as well as its surficial appearance, indicate a Biglow age for the moraine. A smaller but similar lateral moraine is one-quarter mile upstream from the supposed end moraine on the south side of the creek.



A. Biglow lateral moraine (A-A) on Lime Creek below Woods Lake.

B. Ivanhoe end moraine at Woods Lake on Lime Creek.

Figure 6.

In Miller Creek a formless concentration of glacial till at 8,160 feet represents all that remains of the former Biglow end moraine system. The nearest lateral moraine remnant of recognizable form is slightly more than one mile upstream on the east valley wall at 9,000 feet.

Ivanhoe Substage.

Ice of this substage was notably less extensive than that of the preceding Wisconsin substages. The area just east of Ivanhoe, the point of maximum ice thickness during previous advances, was at this substage an ice-free zone being encroached upon by the Frying Pan, South Fork, and Ivanhoe Creek glaciers (figure 2). The substage derives its name from this critical location. The trunk glacier, presuming that term to be still applicable, consisted only of ice in the main branch of the Frying Pan and tributary ice from Granite and Marten creeks. The important pre-Ivanhoe tributary valleys of Chapman Gulch, South Fork, and Ivanhoe Creek now had independent ice streams. In the sections to follow, observations common to all the morainal deposits are compiled, and this is followed by brief discussions of noteworthy relations in particular valleys.

The volume of material, both glacial and glacifluvial, attributed to the Ivanhoe substage is intermediate between that of the Thomasville and Biglow, but closer in magnitude to the latter. This comparison is based on present deposits and does not necessarily apply to initial volumes prior to degradation by later ice and normal fluvial erosion.

The fresh, youthful aspect of all Ivanhoe moraines is immediately apparent. This impression stems largely from the irregular pattern of abutting and intersecting mounds and ridges, and the variety of planes and angles making up their surface slopes. These features are particularly characteristic within the lobate end moraines formed by expanded-foot glaciers from Chapman Gulch and South Fork. Gullying on the steep morainal slopes is minor, and the breaches and channels that are found can usually be attributed either to contemporaneous marginal meltwater streams or to present intermittant streams with catchment areas on the mountain slopes above. Estimates of bedrock cutting by axial creeks since the Ivanhoe substage are of wide range and difficult to obtain. Some streams have succeeded in cutting as much as ten feet into bedrock underlying the moraines, while others are still engaged in removing till dumped in their paths.

Another youthful feature of the Ivanhoe moraines is the large number and evident freshness of surficial boulders. The four sets of end moraines of this substage within two miles of Ivanhoe all have three to four times as many boulders at the surface as any of the Biglow moraines. The Lime Creek end moraines of Ivanhoe age inexplicably have few surficial boulders, as is evident in figure 6B, but other aspects of the deposits make their assignment to this substage relatively certain.

Ivanhoe outwash, deposited after incision of the Biglow valley train, is 20 to 30 feet above present stream grade. Downstream from the mouth of Chapman Gulch an average elevation of 27 feet is obtained from many observations. Upstream from Chapman Gulch, the tendency for outwash surfaces to rise at an increasing rate toward the source of debris, noted previously in connection with Biglow deposits, causes a considerable difference in terrace elevations. For this reason, further discussion of Ivanhoe outwash is reserved for consideration of the individual morainal systems.

The most easily studied of Ivanhoe moraines is the lobate complex at the mouth of Chapman Gulch. This ice stream was seven miles long and descended to a terminus at 8,650 feet. The terminal moraine is a heterogeneous complex of knobs and ridges produced by minor fluctuations of the glacier snout. Recessional loops which branch from an essentially common lateral are truncated by others at wide angles. Chapman Gulch has been left hanging by overdeepening of the Frying Pan, and the ice descended 700 feet in its last half mile. This undoubtedly produced a chaotic descent and adversely affected the deposition of end moraines.

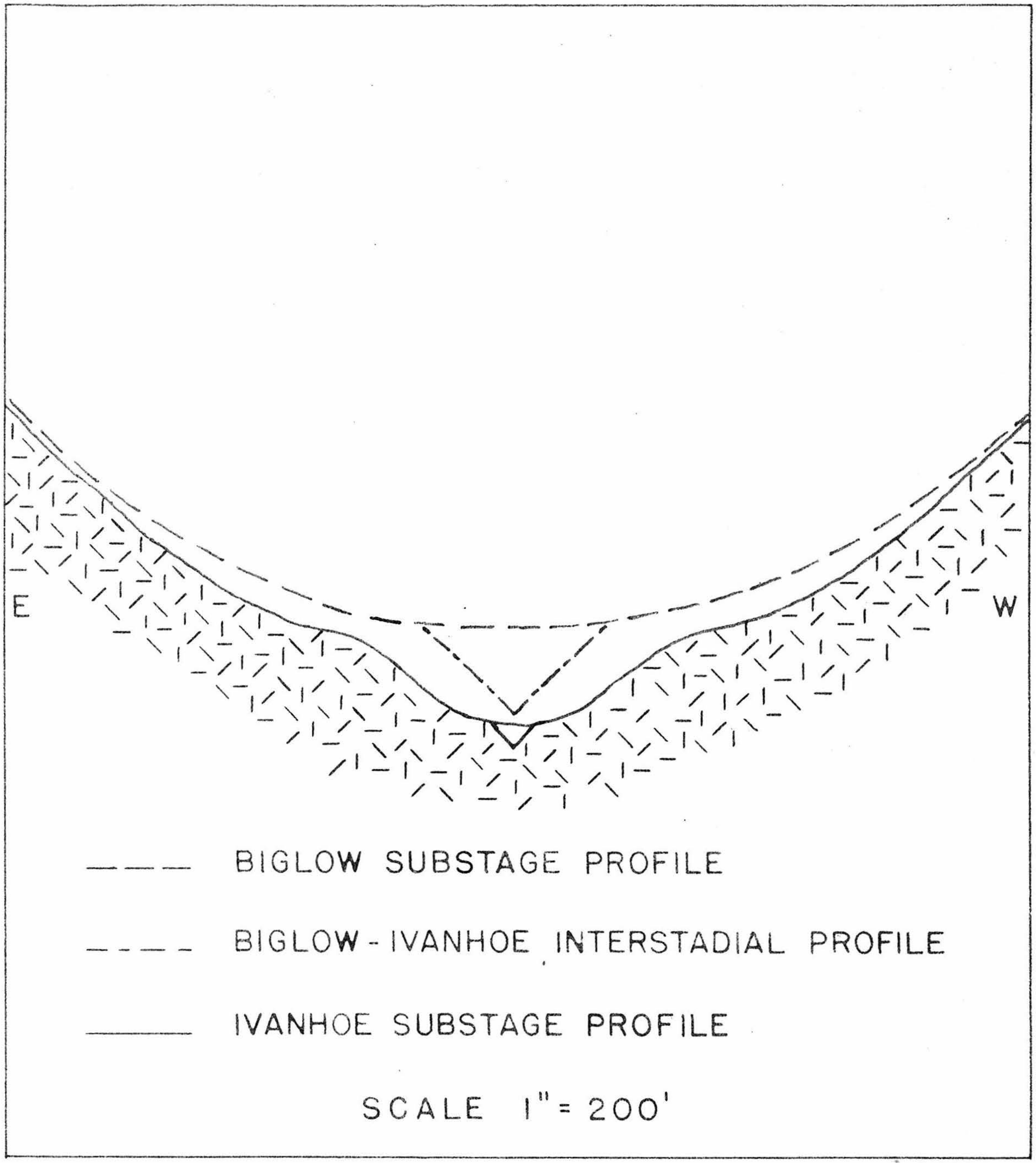
Lateral moraines of the Chapman Gulch glacier are fairly regular and extend sharply up the Frying Pan valley wall as steep, clear-cut ridges. Above the sill of the step, however, the laterals blend into the hillslope and can be differentiated from the Biglow ground moraine in only a few places. The best-preserved lateral moraine was built by the tributary Sawyer Creek glacier near its junction with the Chapman Gulch ice stream. Poorly defined recessional loops are found over a distance of two miles upstream from the terminal moraine but the phases cannot be counted with certainty and no outwash deposits are associated with them.

Ivanhoe outwash gravels are in direct contact with the terminal moraine just west of Chapman Gulch. Here an outwash remnant lies 32 feet above stream grade, five feet higher than elevations one-half mile farther down the Frying Pan.

The South Fork glacier, three-quarters of a mile farther up Frying Pan valley, was similar to the Chapman Gulch glacier in many respects. It was 10.5 miles in length and plunged over the lip of its hanging floor to a lobate terminus at 8,700 feet, the expanded foot extending a short distance up as well as down Frying Pan valley. The frontal moraine is sharp, continuous, and up to fifty feet high in the vicinity of Ivanhoe. Inside this moraine, recessional loops become complex and discontinuous, and the related laterals trend almost vertically down the steep valley walls. Elevations of outwash flats on both banks of the Frying Pan between Chapman Gulch and South Fork range between 28 and 34 feet, reaching a maximum of 36 feet in contact with the South Fork terminal moraine.

The South Fork hanging gorge, now cutting rapidly back into the gentle valley above, displays an interesting relation. Reshaping by Ivanhoe ice of a V-gorge cut during the Biglow-Ivanhoe interval is readily apparent. Figure 7 illustrates the cross profile at the lip of this hanging valley. It is thought that the U within a U profile indicates a considerable interval between glacial advances during which normal valley erosion was active. This precludes the possibility that the Ivanhoe moraines merely represent recessional halts in the withdrawal of Biglow ice. How far the Biglow ice withdrew up the South Fork is not known, but it was clearly well above the lip of the hanging valley

Moraines of Ivanhoe age in the Frying Pan valley above Ivanhoe are extensive but poorly preserved as to



Schematic profile of vertical section transverse to South Fork at the lip of its hanging valley. Large "V" was cut in Biglow-Ivanhoe interval and altered to "U"-shape during Ivanhoe advance.

<u>Figure 7.</u>

topographic form and continuity compared to those of the Chapman Gulch or South Fork glaciers. Subsequent destruction by axial stream erosion in the narrow valley has reduced the former end moraines to disconnected piles of morainal debris up to 70 feet high. The outermost of these till masses is at 9,040 feet, ten miles from the valley-head cirque. River gradient increases perceptibly through the glacial material, and small cascades and falls in its course indicate that the river is still cutting down through the morainal fill. The cascades are interrupted every few hundred yards through the series of end moraines by marshy flats wherever a particularly large recessional loop has caused temporary damming and filling. Bedrock is nowhere exposed in the river channel, but numerous ice-planed and smoothed surfaces are close to river level. Despite its hardness, the coarse grain of the exposed granite porphyry does not favor the retention of striae and only coarse grooving was observed.

As in Chapman Gulch, there is here evidence of a series of recessional end moraines on the valley floor extending for almost two miles above the terminal position. Eighteen such loops were counted, but this can only be a minimum figure owing to the poor state of preservation of the moraines. Occasional outwash remnants, 30 to 40 feet above river level, are interspersed with the recessional moraines. Such a terrace carries through the lowermost end loops on the south river bank, duplicating in crude form the terrace apron associated with Biglow loop moraines near Biglow. Kame gravels are spread widely, up to 370 feet above the river, on the south wall from the terminal moraine to Granite Creek.

Ivanhoe lateral moraines are in general poorly defined on the Frying Pan valley walls. An exception just west of Granite Creek allows an interesting reconstruction of the ice surface. The trunk lateral moraine, where joined by the steeply descending Granite Creek lateral, is almost on a level with the floor of the tributary valley and indicates that the tributary ice stream was superposed on the trunk glacier. This may account for the lack of a definite upper limit to the scattered kame gravels. A marginal stream flowing against an ice body which was gradually sinking from a superposed to an inset position as it moved downstream might well leave kame gravels over a wide vertical range on the valley wall.

The ice advance of this age in the narrow canyon of Ivanhoe Creek is shown only by a series of large, well-defined lateral moraines on the north valley wall. Their downstream ends trend steeply down the hillslope to within 50 feet, vertically, of the creek. Assuming that the outermost of these lateral-terminal loops marked the farthest advance, the glacier was 6.75 miles long and terminated one-quarter mile above Ivanhoe at 8,770 feet.

Mammalated bedrock exposures on the south valley wall confirm this reconstructed ice maximum. Polish and striae have been destroyed, but the fresh, smooth granite surfaces contrast markedly with rock scoured only by previous advances. The limit of recent scouring is correlative with the lateral moraines on the north wall. Ivanhoe outwash gravels are no longer in direct contact with the Ivanhoe Creek moraines, but the surface of remnants only one hundred yards below the outermost lateral are 28 to 30 feet above creek grade.

Deposits of Ivanhoe age in the other independent valley systems are much less well defined. However, marked concentrations of youthful morainal debris on the valley floors can in most instances be assumed to represent approximately the terminal position of the individual ice streams, especially where associated with the 25-35 foot outwash terrace. The downstream limit of recent ice scouring on valley-floor bedrock knobs and ledges is frequently a useful criterion in determining the points of maximum advance. An Ivanhoe age for morainal remnants is usually easily determined by their topographic position, surficial boulder frequency, and degree of weathering and dissection.

End and lateral moraine remnants of Ivanhoe age in Rocky Fork, Miller Creek, Cunningham Creek, North Fork, Last Chance Creek, and Lime Creek are shown in figure 2. Moraines are particularly well developed in Lime Creek and the North Fork, and outwash gravels are associated with the end moraines at the latter locality. Other Ivanhoe outwash remnants are shown in figure 2.

Hell Gate Substage.

The time interval between the Ivanhoe and Hell Gate glaciations was considerably less than that between earlier Wisconsin substages. Careful application of the more quantitative criteria for age differentiation, however, leaves little doubt that the Ivanhoe and Hell Gate are distinct and separate advances. The type locality for deposits of the Hell Gate advance is on Ivanhoe Creek one mile above the precipitous Hell Gate gorge. As in the previous section, a general description of features common to all Hell Gate deposits is followed by a discussion of significant characteristics in the separate valleys.

Glaciers of this substage were short and thin, and the volume of morainal material is small. End moraines are low, seldom exceeding 40 feet in height, but are usually clearcut with sharp outlines and steep ungullied slopes. Characteristic hummocky morainal topography is retained to an unusual degree. Moraines on the valley floors are generally grass and bush covered, only infrequently supporting forest growth. Boulders on the surface of the moraines are seldom over two feet in diameter, but they are approximately three times as numerous as those on the Ivanhoe moraines. All are very fresh and sound to the hammer.

The valley-bottom moraines appear to rest on a rock floor at present stream level. In most instances the axial creek is still actively engaged in removing the glacial material which has been dumped in its path. Stream gradients are characteristically steepened through the moraines and considerably reduced upstream therefrom. Almost invariably there is a grassy bog behind each series of end loops. A map of valley-bottom lakes and swampy flats above 10,000 feet would include the location of nearly all the Hell Gate moraines. Marshes dammed by rockslides would produce the only ambiguity, and they are usually upstream from terminals of this substage.

Dissection of the twenty-five foot Ivanhoe outwash terrace occurred prior to the Hell Gate glaciation and its outwash filled the new valleys to a depth of about 15 feet above present stream grade. Remnants of Hell Gate outwash, though narrower and not as bulky, are generally more continuous and have better preserved surfaces than those of older substages (figure 2). Proof of a Hell Gate age for the 15-foot terrace level is provided by ice-contact outwash deposits with similar elevations immediately adjacent to the Hell Gate end moraine in Ivanhoe Creek and the South Fork. In Ivanhoe Creek this gravel deposit is a flat-topped terrace remnant over one acre in extent. It has been dissected and largely removed north of the creek but is remarkably plane where preserved, being gullied only near the edges. The height to this level surface is 17 feet. Several shallow kettles dot the terrace, one containing a clear pond (figure 8A). Along the South Fork, stream dissection has converted the Hell Gate outwash into a series of flat-topped hills and ridges, none exceeding 18 feet above stream grade (figure 8B).

The number and arrangement of recessional moraines of the Hell Gate advance are significant and similar in many valleys occupied by ice during this substage. The usual arrangement features a terminal group of three to five end loops which is distinctly separate from a single recessional moraine farther up the valley. For example, on Ivanhoe Creek the downstream group consists of four,

A. Outwash gravels in contact with Hell Gate moraines above Hell Gate. Note water-filled kettle in center.

B. Remnant mounds of Hell Gate outwash on South Fork near the terminal moraine.

Figure 8.

or possibly five, end loops. These are separated from a broad single moraine one-half mile farther upstream by a soggy marsh across which the creek meanders. The lateral moraines corresponding to these end loops are well preserved in step-like progression on the south valley wall. From the single recessional loop at the upper end of the marsh to the head of the valley only small patches of ground moraine, partly buried in a thick peaty soil, are found.

Lyle Creek, a steep tributary of Ivanhoe Creek, has a group of five lateral-terminal loops between 10,800 and 11,050 feet. The single upper moraine is at 11,320 feet and dams lower Lyle Lake. In Frying Pan valley, the two upper Frying Pan lakes are dammed at 10,900 feet by four moraines of the lower group. The upper loop is one-third mile farther up the valley. In Marten Creek only three separate phases in the downstream group can be differentiated. They mark the terminal position of the glacier at 10,400 feet. Again the pattern is completed by a single upstream loop at 10,600 feet. Four moraines are found in South Fork and in Mormon Creek at 10,780 and 10,500 feet, respectively. A series of three recessional loops is found in Chapman Gulch, Granite Creek, and Basin Creek, at elevations of 10,470, 10,600, and 11,000 feet respectively. This latter glacier was little more than a thin ice sheet with limited mobility, which may account for its relatively higher terminal elevation.

Fragmental remains of Hell Gate moraines are found in three other valleys. A clear-cut segment of a Hell Gate lateral is seen on North Fork just above the junction of Mormon Creek at 10,400 feet. In Carter Creek a morainal pile across the valley at 11,200 feet is probably of this age. The relations in Cunningham Creek are hard to unravel because of an especially heavy brush and timber cover. It is thought that the east and middle forks supported confluent ice masses which terminated a short distance below the mouth of the west fork. This latter valley, possessing a much smaller accumulation area, had a short separate ice stream terminating at 10,400 feet. Boulder frequency, degree of weathering, surface configuration, and topographic position lead to the belief that the moraines confining Savage Lake, Sawyer Lake, and the unnamed lake 1.5 miles west of Sawyer Lake are of this age. All these are cirque lakes lying on cirque floors behind morainal dams.

Neither Miller Creek nor Rocky Fork appear to have been glaciated during this substage and their cirques are now grassy basins in which little bedrock is seen, and the few outcropping cliffs are being buried in their own talus. Though Rocky Fork was not glaciated during the Hell

Gate substage, gravel terrace remnants of the 15-foot level are clearly preserved at two places (figure 2). This filling was due to the rise of baselevel through alluviation at the junction with the Frying Pan below Ruedi. Hell Gate moraines were not identified with certainty in the upper valley of Last Chance Creek. The fresh, largely talus-free compound cirque at its head, with floor elevations in excess of 11,300 feet, is similar in appearance to those known to have been occupied by Hell Gate ice. It is probable that the moraine damming Josephine Lake in the southernmost cusp of the valley head is of Hell Gate age. Lime Creek was not studied above 9,500 feet, and its Hell Gate history is thus unknown.

Chapman Gulch Glaciation.

Because of the limited nature of the deposits and the small ice masses involved, some may doubt that the Chapman Gulch glaciation qualifies as a "substage" compared with the others previously discussed. The proper relation of this most recent episode of climatic refrigeration to the Wisconsin substages discussed above is a problem. If some of the age estimates for seemingly comparable deposits in other Rocky Mountain areas are correct, the Chapman Gulch glaciation may not fall within the Wisconsin, as generally understood. The matter of chronological relation is deferred until a later section, but the field relations are described here.

This episode derives its name from a till deposit at 11,400 feet in Chapman Gulch (figure 2). The till is 900 feet higher and 1.75 miles upstream from the well-defined Hell Gate moraines, and 0.5 to 0.75 miles from the cirque headwalls. Chapman Gulch heads in a large compound cirque with two prominent cusps of elevation and orientation especially favorable to snow accumulation. It appears to be the only cirque in the Frying Pan drainage in which a sufficient body of ice accumulated during the Chapman Gulch glaciation to move debris out past the cirque lip.

The downstream front of the morainal accumulation rises abruptly 30 to 40 feet from the valley floor and is only partly cut through by a narrow creek gorge at its eastern edge. The till is deposited in two patches of coarse debris 200 and 150 yards in breadth separated by a boggy meadow. Fine components of the till are spare and coarser than previously seen. The numerous pebbles are so loosely held in a sandy matrix that they may be dug out by hand. Cobbles and boulders almost completely mantle the surface and are fresh and sound to the hammer. No staining of the quartz or pale orthoclase by decomposition of the mafic minerals was observed.

The cirque floor, at 11,700 to 11,900 feet, slopes downward toward the moraine and consists of broad ledges and bosses of freshly scoured bedrock where not overgrown by a thick peaty turf. Huge loose blocks, up to 20 feet in diameter, are scattered about the floor and were apparently deposited _in situ_ from the melting ice mass. Talus at the foot of the cirque walls is fresh and consists of very large angular blocks. The quantity of talus is noticeably smaller than in cirques at lower elevations. Timberline lies between the cirque floor and the moraines and mature spruce grow between the numerous boulders on the latter.

Positive identification of comparable moraines within or near other cirques of similar elevation at the heads of South Fork, Granite Creek, Marten Creek, and the Frying Pan was not made. The floors of these cirques are 11,800, 11,800, 12,100, and 12,000 feet in elevation, respectively. All four cirques exhibit protalus ramparts (Bryan, 1934, pp. 655-56), but none of these deposits is believed to be truly morainal. The lack of glaciers in these valleys was probably due to the smaller size and relative position of their cirques. These latter cirques are oriented at least as favorably for snow accumulation as the Chapman Gulch cirque with respect to the sun, but this is not true with respect to the accumulation of wind-drifted snow.

Immediately to the west of Chapman Gulch is a broad area of gentle relief. Snow picked up in this area by a westerly wind would be deposited largely in the first major gash transverse to the wind direction. Thus Chapman Gulch apparently served as the principal snow trap, and progressively smaller increments reached the parallel valleys farther east.

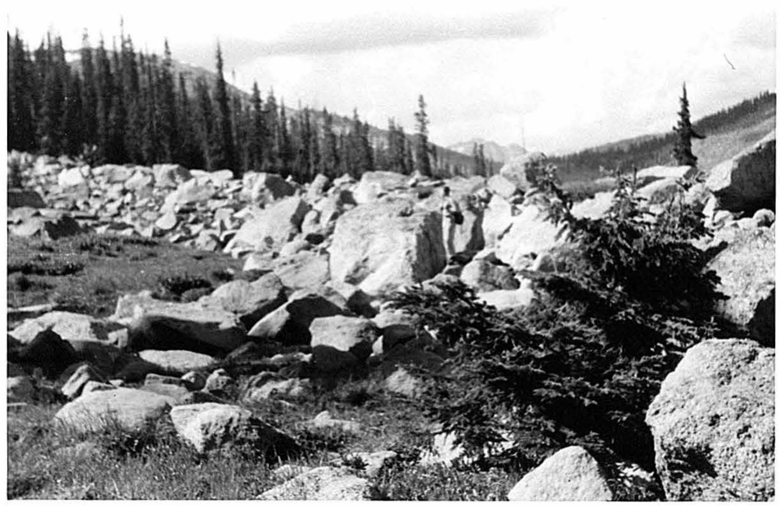
Many cirques and side-wall corries with floors in excess of 11,450 feet have protalus ramparts presumably developed during the Chapman Gulch glaciation. The high-level corries were probably excavated during earlier advances but were occupied only by perennial snow banks under this less severe climatic refrigeration. The two Granite Lakes, at 11,675 and 11,450 feet, are dammed by ramparts. These dams have appreciable amounts of fine material filling the spaces between rock blocks so the material closely resembles till. Reconstruction of the snow-bank profile from the deposit to the highest point on the corrie headwall yields a maximum possible thickness for the snow of only about 225 feet. This figure neglects the considerable surface concavity seen on present-day snow banks and the fact that the snowbank probably did not extend clear to the top of the headwall cliff. One-hundred and fifty feet is perhaps a better thickness estimate. As probably less than half of this thickness was actually glacier ice, it is not thought that true flowage and debris transport could have occurred. Similar reasoning leads to the conclusion that upper Lyle Lake, at 11,600 feet on Lyle Creek (figure 9A), has a rampart rather than a morainal dam. Figure 9B shows an unnamed lake on the south wall of Ivanhoe Creek across from Lyle Creek at 11,525 feet. In this instance some ice movement is indicated by the convex shape of the debris ridge toward the valley, and its distance from the corrie headwall. One-half mile farther west, however, another protalus rampart of very obvious youth is preserved at 11,200 feet. The rampart is about 300 yards in length, up to 30 yards broad at the base, and a maximum of 30 feet high. Figures 10A and 10B clearly show the fresh nature of the jumbled rock blocks. Its relatively lower elevation is attributed to favorable orientation of the corrie with respect to the sun shadow.

A. Upper Lyle Lake, a protalus rampart-dammed lake of Chapman Gulch age.

B. Protalus rampart- or moraine-dammed lake on Ivanhoe Creek, opposite Lyle Creek, of Chapman Gulch age.

Figure 9.

A. Protalus rampart of Chapman Gulch age south of Ivanhoe Creek above Hell Gate.



B. Close-up of protalus rampart above. Man in center for scale.

Figure 10.

AGE CRITERIA AND SUBSTAGE SEPARATION

GENERAL STATEMENT

Glacial deposits in the Frying Pan River drainage seem in general less continuous and of smaller volume than those reported from many other areas within the Rocky Mountains. The wide separation of fragmental remnants of once continuous moraines and outwash terraces makes qualitative study of their interrelations difficult and valley-to-valley correlation uncertain. Quantitative study, on the other hand, is not hampered by the lack of interrelation between deposits caused by poor preservation and initially small areal extent. All that is required is a moraine or till sample which, owing to its environment, is representative of the original deposit. For this reason, criteria for the determination of relative age between deposits have been critically reviewed and evaluated. Some less well-known techniques were employed, with variable measures of success. It is to be emphasized that all criteria used in this study are purely relative in nature. Materials suitable for absolute age determination by the methods now available to science were constantly sought but never found.

It is hoped that in the future it will be possible, with the help of radiocarbon dating, to learn a great deal more about the rates of the various weathering and erosional processes. Until such time, relative age estimates based on a comparison of the products of such processes must be uncertain at best. Certainly these processes are usually not linear functions of time. We cannot say that a till oxidized to 20 inches is twice as old as one oxidized to only ten inches; or that five feet of bedrock valley floor incision took half as long as ten feet. A general knowledge of the absolute rates of some geologic processes acting under differing environmental conditions now seems in prospect, and when obtained it will find wide use in areas where radiocarbon sources are not found.

Several authors have listed some of the common criteria for age differentiation of glacial tills in mountainous regions (Blackwelder, 1931, pp. 870-80; Ives, 1938, pp. 1052-56; Sharp, 1938, pp. 300-304). These criteria are treated in the section to follow, together with some new criteria used in this study.

AGE CRITERIA UTILIZED

Topographic Expression. Criteria of this type, as applied to glacial moraines, may be divided into four classes: surface form; position; type; and size. The first includes such aspects as the retention of surficial boulders, effects of post-glacial erosion as manifested by the depth and degree of development of rills or gullies and the arrangement and angles of the slopes, and modifications by axial streams such as the degree of breaching of terminal or end moraines. The second, topographic position of morainal deposits, is utilized in two ways. The older deposits are usually higher above, and farther away from, the present drainage courses. It is also generally true that the younger deposits are upstream from the older ones. These criteria are of more use in a preliminary identification than in actual age differentiation.

The type of moraine is also useful primarily in identification of glacial advances. Older till is generally preserved only as lateral moraines whereas younger deposits are more likely to be looped across the valley bottom. More or less isolated erratics or linear trains of erratic boulders indicate a still greater age. The final class of criteria is concerned with the relative bulk and size of glacial deposits. The older, more extensive glaciers commonly deposited a greater volume of morainal and outwash debris. This criterion can be entirely outweighed by other influences as is shown in the instance of the Thomasville and Biglow deposits.

Weathering. The numerous weathering processes yield a group of criteria which can profitably be broken down into subgroups. One may consider the weathering of constituent materials or of the till deposit as a whole. In the former subgroup, Blackwelder's granite weathering ratio (Blackwelder, 1931, p. 877) was found most critical and useful. The occurrence of fragments of the same granite porphyry in Frying Pan moraines of all ages allowed wide application of the criterion. The degree of spalling on surficial boulders was also studied, but its resolving power proved to be too low for anything but very general comparison. The degree of development of weathering rims on cobbles and boulders of comparable lithology and texture was useful in age differentiation, especially for the younger tills.

The effect of weathering on the till as a whole is perhaps best reflected in the depth of soil developed on its surface. Test pits were dug and the color, texture, humus, and chemical profiles studied. Unfortunately, the conditions in high mountains are not as favorable to soil formation and preservation as in areas such as the Middle West where soil studies have proved a powerful tool in the study of glacial deposits. Intrazonal soils predominate in mountainous regions because of the considerable influence of passive factors of soil formation such as topography and relief. Active run-off, colluviation, and frost mixing tend to remove or stir up the developing profiles making study difficult, especially on the steeper slopes of younger moraines. In addition, repeated climatic oscillations have superposed differing processes which make the end result difficult to interpret.

Twenty-five pebbles were taken from each of the test pits for type counts and weathering study. An additional criterion was established by digging the pit in such a way that the volume of till required to supply 25 pebbles and cobbles 2 to 5 inches in diameter could be determined. This is in effect a measure of subsurface cobble frequency. The volume is not always easily estimated because of irregularities produced by larger buried fragments, but the criterion is at least as sensitive as others applied to the bulk till.

The reduction in number of surficial boulders on moraines of all types may be due to many processes. Chief among these are burial by slopewash from adjacent valley walls and decomposition by weathering. Blackwelder's boulder frequency (ibid., p. 878) was used extensively in quantitatively describing this aspect of the moraines.

Outwash Terrace Development. This criterion is so commonly used as to require little explanation. It is to be emphasized, however, that outwash gravels must be traced to a morainal source for effective age correlation. This was not always possible for the older terraces in the area studied. The degree of dissection of an outwash terrace before deposition of the next younger valley train is a function of so many unknown variables that it is generally of little use as an age criterion. It is not known here whether the incision of successive outwash valley trains was the result of intermittent uplift, tilting, or merely the return to normal processes and stream grade.

Preservation of Polish and Striations. Rock types in the area under study are unfavorable to the wide use of this criterion. True glacial polish was seldom seen and the degree of freshness of smoothed and scoured bedrock was normally utilized.

Modification of glaciated valleys by erosion and filling. The most useful criterion in this group is the depth of bedrock cutting by axial creeks. It is usually not difficult to apply and, aside from uncertainties introduced by preglacial relief of the now dissected valley bottoms, yields generally reproducible values. Differences arise from relative stream size, gradient, and the rock types involved and must be considered. Allied with this criterion is the degree of post-glacial attack by tributaries on the sills of their hanging valleys. The amount of post-glacial filling by talus, slopewash, and landslide debris is often useful, especially in comparing the parts of valleys above and below a deposit suspected to represent the maximum of an ice advance.

Cirque Freshness. Applied to the cirques themselves, the preceding criteria find another use. The glacial succession in an area can theoretically be predicted by the progressive alteration of cirques at different elevations by talus and soil filling. Thus, if four distinct degrees of freshness can be ascertained in cirques whose elevations increase progressively, one may propose four different glacial periods.

Destruction of lakes by draining and filling. The post-glacial alteration of glacial lakes by aggradation and degradation, respectively, of the inlet and outlet streams is a broadly useful criterion. Special cases and conditions need to be taken into account in some instances.

Mechanical Analysis of glacial tills. This often powerful tool of the sedimentary geologist proved somewhat disappointing in this study. The extremely variable nature and heterogenity of till, which makes it less suited to such analysis than some other types of sediments, and the practical limitations for securing truly representative samples are two possible causes for the lack of success. There is need for a special study by sedimentary analyses of morainal systems already dated by other criteria to establish the value of this procedure for identifying and differentiating tills of different ages.

Almost all of the above criteria have limitations and qualifications brought about by variations of the geologic conditions involved. Usually the application of any one criterion leaves uncertainties which make its results indicative only. But the accumulated weight of many and varied age criteria is believed to have established the glacial succession here proposed. In the next section appropriate criteria are utilized to differentiate deposits recording six periods of glaciation in the Frying Pan drainage.

APPLICATION TO FRYING PAN DEPOSITS

The criteria involving topographic expression have largely been discussed and evaluated in the descriptive sections above. Position, type, and size of moraines have been adequately described. The widths of breaching of end moraines by the Frying Pan River are summarized in Table I. Water volume, width of channel, and gradient differ greatly at the localities involved, but reduced cutting power of the river farther upstream is largely offset by a proportional reduction in the volume of till to be removed. Also, several of the deposits are close enough together to minimize the variation of river characteristics, in space if not in time. The degree and depth of gully development is not included in the table because the data are incomplete. Lime Creek and Thomasville moraines do not appear gullied, but extreme gullying is probably a cause of their present limited extent. A maximum gully depth of about ten feet was observed on Biglow moraines. Three or four feet is an average figure for Ivanhoe moraines, and gullying on Hell Gate and Chapman Gulch deposits is negligible.

Modification of the glaciated valleys by post-glacial erosion and detrital filling is often a good qualitative check on hypothetical ice advances arrived at by other means, but generally lacks the definitive qualities necessary for age differentiation. An exception is the depth of bedrock valley-floor incision by axial creeks in the intervals between separate ice advances. The processes involved are probably not linear with time, but the deepening measured broadly suggests proportionate times involved. Figures derived from estimates of the heights of the old valley floors above the present valley bottom are summarized in Table I.

The weathering of till and of fragments within the till lends itself well to the brevity and clarity of tabulation. Average boulder frequencies and granite weathering ratios for moraines of the separate glacial advances are given in Table I. Some explanation of these figures is desirable. In the granite weathering ratios the first figure represents the percent of samples almost completely unweathered internally, the second figure those notably decayed, and the third the percent of the samples more or less completely rotten. Only one rock type was used, but textural similarity was not always what one might wish. The boulder frequency as here used is expressed as the number of boulders of a distinctive granite porphyry, one foot or more in diameter, per acre.

TABLE I

	Pre-Wisconsin	Wisconsin				Latest or post-Wisconsin
	Lime Creek Stage	Thomas-ville Substage	Biglow Substage	Ivanhoe Substage	Hell Gate Substage	Chapman Gulch Glaciation
Boulder Frequency	75	200	500	1600	1900	5000
Granite Weathering Ratio	8-52-40	28-68-4	40-60-0	88-12-0	96-4-0	100-0-0
End moraine Breaching (width in yards)	650	250	200	50-75	25	negl.
Subsequent Valley Deepening (feet)	280	45	25	0-10	negl.	none
Outwash Terrace Levels (feet)	350	90-120	40-50	20-30	12-17	6-8

Where the degree of alteration of mineral constituents is slight and does not penetrate far into the rock, a study of weathering rims or halos on broken fragments is rewarding. The effects of textural variation assume an even greater importance here and must be evaluated. The porphyritic granite was again selected as the rock type to be studied and the samples were all taken from a depth of 12 inches in the till. The results are shown in Table II. Pebbles and cobbles of Chapman Gulch age showed no weathering rim development whatsoever. Limonite staining of the light-colored feldspars from the decomposition of biotite cannot be observed with the handlens. In samples of Hell Gate age this staining has proceeded to a depth of two to four millimeters. Ivanhoe samples seldom show depths of staining less than 12 millimeters, but the maximum limit differs widely. Boulders on Biglow moraines up to one foot in diameter are often stained to the core.

Before discussing soils on the moraines, it is perhaps best to include a statement on the method of sampling. The choice of test pit locations is of considerable importance to the soil studies, and it is desirable to select sites which have been acted upon by erosional and weathering processes at similar rates throughout their histories. To this end the sites were always located on morainal crests. A broad, flat area was selected which gave no indication of having been a hollow or a subsidiary knob, with consequent accelerated deposition or erosion. It was also desirable to limit the locations to areas with only a grass or brush cover. The fact that this requirement could not always be met probably accounts for certain anomalies in the humic layer thickness, but averaging helps remove such differences. The above requirements were usually met to a degree which renders the profiles comparable.

Soil profiles may be described upon five principal properties: color, texture, humus content, chemistry, and structure. The first three types of profiles proved most valuable in this brief study. The immature nature of soil profiles in regions such as this has been discussed. Since separation of the profile into A, B, and C horizons and subdivisions thereof was possible only in the soil on the Lime Creek moraine, some modification of the normal methods of profile description is required. Color change and textural variation are here treated for the soil as a whole rather than horizon by horizon. Thus the color profile is essentially a measure of the depth of staining. This is given in Table II as the depth to fresh till. The thickness of the humus layer was found to be somewhat sensitive to difference in age, and as it can be given in terms of numbers it too is included in Table II.

TABLE II

	Pre-Wisconsin	Wisconsin				Latest or post-Wisconsin
	Lime Creek Stage	Thomas-ville Substage	Biglow Substage	Ivanhoe Substage	Hell Gate Substage	Chapman Gulch Glaciation
Depth to fresh till (inches)	More than 50	31	25	12½	10	6
Humus Layer Thickness (inches)	6+	3½	3	1½	1	2
Weathering Rim Development (milimeters)	(More	than	25)	More than 12	2-4	None
Volume of till producing 25 cobbles (cubic feet)	6	3	2	1½	1	½

Determinations of pH were made every three inches in all test pits, but the results are disappointing. Only generalities may be drawn from the data. The near surface pH is usually more acid for the younger tills, and this condition seems also true of unweathered fresh till to a lesser degree. The profile usually becomes more acid with depth, although the reverse relation is not uncommon. Thin younger soils have about as great a range of pH across their profiles as the older ones. Minimum and maximum values of pH in the soils were four and seven.

Texture profiles can also be described only in terms of broad trends. The older the till, the greater the development of size stratification in the soil. Clay sizes are removed from the upper horizon by chemical and mechanical eluviation and redeposited farther down in the profile. Results of this process were fairly easy to detect, although identification of definite horizons on this basis was not generally possible.

The red-brown podzolic soil on the Lime Creek till is mature and well developed. The humus layer is about six inches thick, and organic stains derived from the humus can be detected on the mineral grains for another two inches. The next 14 to 16 inches is light reddish brown in color and of a loamy texture. The last 18 to 20 inches is chocolate brown with a yellowish cast. The texture is tight, and a layered structure of the eluvial clays makes digging difficult. At 40 inches, where the pit was discontinued, the yellow color was beginning to predominate and the texture was becoming looser. It is estimated that fresh till would have been reached in another 10 to 15 inches.

Soils studied on the Thomasville moraines are from 26 to 36 inches thick. The tight-textured B horizon is easily found but its exact limits are indistinct. It is invariably darker than the A horizon, usually a dark tan, and many of the included pebbles can be cut through with the shovel. The fresh till is a yellowish buff in color.

Soil thickness on Biglow moraines ranges from 18 to 30 inches. The fresh till is in general a tannish buff with considerably less yellow than the Thomasville. A and B horizons can be separated on the basis of a darker color and somewhat tighter texture in the lower horizon. All samples were from tree-free locations, but the humus thickness is variable. The humus layer is easily delineated and therefore useful, but it is also the layer most affected by differences in drainage and runoff.

In the Ivanhoe till no separate soil horizons are noticeable. The texture is open, at times sandy, throughout the entire soil layer, and a clay rich zone was not found. Humus thicknesses are given in Table II, as are the soil thicknesses. The fresh till is tan which contrasts well with the generally reddish-brown soil. Most pebbles are fresh and are broken with difficulty.

Hell Gate tills seem exceptionally sandy and rich in small pebbles. The color of fresh till is yellow brown and the soil color slightly more reddish. Only the humus makes a recognizable layer. All included pebbles are very fresh. The Chapman Gulch soil is similar in all characteristics except thickness. Three or four inches of pinkish brown soil is topped by a variable humic layer two to three inches thick. A thin Spruce cover on the only available sampling area may account for a higher humus thickness than that of the Hell Gate soils. The fresh till is yellow brown, sandy, and of very loose texture.

The volume of till required to produce 25 pebbles and cobbles two to five inches across is given in Table II for each substage.

The dissection of outwash valley trains of each glacial advance to form a series of terrace remnants has been treated in the previous sections. Table I presents a summary of their elevations above present high-water level. All levelling was by hand-held Brunton compass. Areal distribution of the major terrace remnants is shown in figure 2.

Figure 11 is a longitudinal terrace profile along the Frying Pan River. The gradient of the Frying Pan is here taken as horizontal. A total of 296 terrace remnants were measured on all streams, but, with one exception, only those taken along the Frying Pan are used here. The exception is the inclusion of a reading to the pitted plain in front of the Hell Gate terminal on Ivanhoe Creek. Its position was projected across to the Frying Pan an equal distance above the intersection of the two streams. Below Ruedi the canyon is so narrow that only a few points on Thomasville outwash were found. Outwash terrace remnants of the Lime Creek stage are few and doubtful so are not included.

The dashed parts of the lines require explanation. They show the rise in outwash height upstream through the recessional moraines of each advance. The solid line continues back through this recessional zone because true levels are sometimes observed where wide breaching of the recessional end loops occurred prior to outwash deposition. The problem of representation is more difficult for the Ivanhoe terrace profile because of complication near moraines of the two expanded

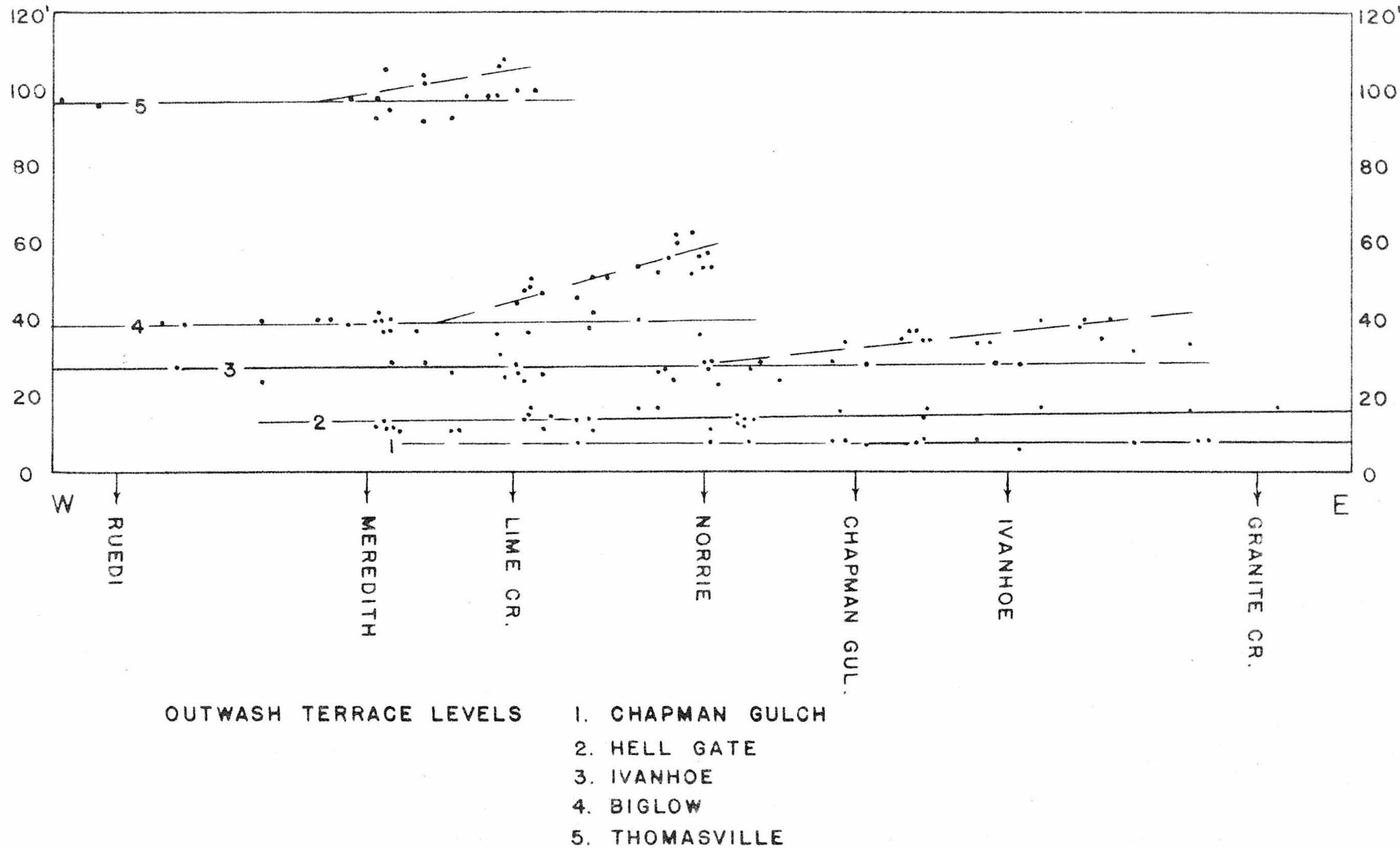


Figure 11. Longitudinal outwash terrace profiles along Frying Pan River, with its gradient taken as horizontal, from Marten Creek to Ruedi.

foot glaciers which reached the bottom of Frying Pan valley well downstream from the terminal moraine of this substage on the Frying Pan. The rise in gradient attending a source of supply thus occurs three times.

Because the Frying Pan River is tributary to the Roaring Fork at Basalt and must have been graded to it at each of the substage valley levels, parts of two days were spent measuring terrace levels on the latter river. About 1.5 miles above the junction of Colorado Routes 82 and 338 a beautiful sequence of terraces rises one above the other (figure 12, A and B). The levels measured at this locality were at 8, 15, 28, 45, 102, and about 350 feet. The 28-foot level has been completely removed in the part of the bend shown in figure 12A, but is preserved just one hundred yards upstream where figure 12B was obtained. The highest level could not be shown in the photographs, and its height is uncertain because a well-defined upper surface was not preserved. This uppermost level, probably correlative with the Lime Creek advance in the Frying Pan, was also measured opposite Brush Creek and found to be about 375 feet above present river level.

Roaring Fork valley below Aspen is carved in soft Paleozoic rocks and is therefore much wider than the comparable section in the Frying Pan an equal distance

A. Dissected outwash terrace flats on the Roaring Fork River. The 15, 45, and 102-foot levels are shown.

B. Another view of terraces shown in A. The 15, 28, 45, and 102-foot levels can be seen.

Figure 12.

below the Wisconsin moraines. For this reason, outwash remnants are better preserved and elevations more consistent. Terrace heights in Frying Pan valley are grouped as follows: 6-8; 12-17; 20-30; 40-50; 90-120; and approximately 350 feet above stream grade. The agreement in number and elevation of these levels with those measured on Roaring Fork lends confidence to the identifications made on Frying Pan River.

Many age criteria for the differentiation of glacial deposits were used throughout the course of the field study which are not suited to tabular or graphical presentation. Identification and delineation of glacial deposits on the basis of the degree of preservation of glacial lakes, cirque freshness, bedrock polish and scour, and the typical transverse valley profiles are locally invaluable, but the results are difficult to formulate as parameters. The use of these other critera, where applicable, has been discussed in the descriptive sections.

In addition to utilization of the field criteria, 30 samples of both fresh and weathered till from all types and ages of moraines in Frying Pan valley were subjected to mechanical analysis in the laboratory. No consistent definitive characteristics in the different tills were apparent in the usual statistical parameters derived from cumulative curves of particle size distribution. Size fraction histograms indicate that younger weathered tills are richer in coarse fragments and poorer in fines than older weathered tills, but the differences are too small to allow confident use of this criterion.

AGE DETERMINATIONS

From the data presented in the previous sections, it is concluded that the Frying Pan River drainage shows evidence of six distinct glacial advances in the Pleistocene Epoch. Several lines of evidence suggest that these advances were separated by intervals of warmer climate and that their deposits are appreciably different in age. Explanation of the younger deposits as simply reflecting recessional pauses in the retreat from a single, more extensive advance is not consistent with the data. It is entirely possible that a greater number of glaciations has occurred, but they are probably pre-Lime Creek in age.

An estimate of the magnitude of these age differences is desirable. The usual procedure is to take the time since the last glaciation as a unit and to compare the deposits of older advances to the youngest in the light of this yardstick. Recent radiocarbon dating of organic materials in Mankato tills of the Midwest (Flint and

Deevey, 1951) yields a figure of approximately 11,500 years for such a time "unit." Unfortunately, we must make an assumption as to which of the advances recorded in the Frying Pan is Mankato in age. In the discussion to follow the Hell Gate advance has been considered as most likely correlative of the Mankato, but the Ivanhoe substage cannot be completely eliminated as a possibility. Further assumptions as to the rates of geologic processes producing significant till modification are also required. For simplicity, and from the lack of anything better, all processes are considered linear functions of time.

The quantities in Tables I and II were used to arrive at figures representing the ages of the other glacial deposits, relative to the Hell Gate moraines. Values in the Hell Gate columns were taken as unity and the remaining figures reduced or increased in proportion. In the row containing the granite weathering ratios, only the first parameter (percent of samples showing almost no weathering) was used because it is not zero for any of the samples. It is realized that certain of these criteria are probably better suited for age comparisons than others. However, inasmuch as any selection would be largely subjective, all of the parameters were used in this analysis. The degree of agreement between such widely differing approaches is surprising, and averaging of random combinations produces little change in the final results.

Table III is an average, reduced to the nearest half unit, of all the criteria tabulated, except for subsequent valley deepening which yields infinite values. The rightmost column is the absolute age determined from the unit time of 11,500 years. The average of the data for the Lime Creek glaciation was actually fifteen units. This has been weighted upward to the value shown because the three low figures pulling it down are all in the "soils" group of criteria, the formative processes for which, it can safely be assumed, decelerate with time. This is the only value so altered.

TABLE III

GLACIATION	"UNITS"	AGE
Lime Creek Stage	20	230,000 years
Thomasville Substage	5½	63,250 "
Biglow Substage	4	46,000 "
Ivanhoe Substage	1½	17,250 "
Hell Gate Substage	1	11,500 "
Chapman Gulch Glaciation	½	5,750 "

On the basis of these results, and not forgetting the original basic assumption that the Hell Gate advance represents the Mankato maximum, it is suggested that the six Frying Pan glaciations consist of one pre-Wisconsin advance, four Wisconsin advances, and one post-Wisconsin advance. It is somewhat surprising how well the early Wisconsin figures agree with those heretofore proposed. (See Bryan and Ray, 1940, p. 67 for a recent summary.) Only a general order of magnitude agreement was anticipated. Fitting the pre- and post-Wisconsin glaciations into the standard Pleistocene chronology remains a problem. Possible correlations of the Chapman Gulch glaciation with post-Wisconsin deposits in other areas is discussed in the next section.

The deposits of Lime Creek age seem clearly pre-Wisconsin, but the age figure does not give a wholly satisfactory indication of which pre-Wisconsin stage is represented. The deposits do not seem as old as some of the pre-Wisconsin deposits described by other workers in the Rockies and elsewhere and usually attributed to the Kansan stage. On the basis of topographic position, probable associated outwash, surficial and internal appearance, and the age figure determined above, an Illinoian age for deposits of this advance is preferred.

CORRELATION

In the preceding section an attempt has been made to relate the glacial deposits in the Frying Pan system to the general Pleistocene chronology. In addition to such a broad correlation, it seems desirable that more specific correlation, no matter how tentative, should be made where possible. The value of some of the published literature has not been fully realized because the author was unwilling to hazard a correlation of his area to others already studied. Where such a lack is coupled with incomplete or insufficient descriptive sections, as is sometimes the case, the usefulness of the study to other students of Pleistocene problems is greatly decreased.

Many of the earlier students of mountain glaciation in western United States have described two glaciations in their respective areas (Westgate, 1905; Capps, 1909; Henderson, 1910; Bastin and Hill, 1917; Morey, 1927; Thornbury, 1928; Atwood, Jr., 1937; Miner, 1937; Sharp, 1938; Miner and Delo, 1943). Even more workers have described three glacial advances (Dickerson, 1908; Atwood and Mather, 1912; Blackwelder, 1915; Worcester, 1920; Fryxell, 1930; Atwood and Mather, 1932; Behre, 1933; Powers, 1933; 1935; Bradley, 1936; Horberg, 1938, Page, 1939; Horberg, 1940; Sharp, 1942; Alden, 1943; Jones and Quam, 1944). Recognition of a still older Pleistocene advance in the Sierra Nevada has produced a four-phase chronology (Matthes, 1929; Blackwelder, 1931; Putnam, 1949). To this may be added a very young post-Wisconsin phase deduced for the Sierra by Matthes, (Matthes, 1941). Ives (1938) found four advances in Grand County, Colorado, and with further study he has expanded this to seven (Ives, 1942). The six periods of glaciation recognized in the Frying Pan valley are matched in number but not necessarily in age by the sequence proposed by Bryan and Ray (1940), and Ray (1940). Recent work in the Wind River Mountains by Holmes (1949) and Moss (1949; 1951b) has produced a chronology consisting of five glacial maxima. The meaning of such a diversity certainly demands attention and explanation before any unified chronology can grow out of the previous work.

Assuming a reasonable degree of contemporaneity of the climatic change necessary to cause glaciation, a premise which seems probable but is not yet proved, it must be concluded that deposits of some of the advances have either been removed by post-glacial weathering and erosion, have been included with the deposits of other advances, or have been overlooked entirely. Correlation of stages and substages described in many of the above reports indicates that the principal discrepancy lies in the number of Wisconsin and post-Wisconsin advances recognized. It is doubted that removal of evidence for the later advances can completely explain these differences. A more likely explanation is that the evidence of certain advances has been overlooked or included with that of other glaciations. Several of the authors listed above describe recessional phases which they state might possibly represent younger glacial advances (e.g., Sharp, 1938, pp. 305-306; Jones and Quam, 1944, p. 223).

The six periods of glaciation recognized here would seem to have little correlation with most other areas, as that number has been proposed by only two other workers. This is not wholly the case. If the Thomasville-Biglow, and Ivanhoe-Hell Gate moraines are considered to be products of single substages, an interpretation termed unlikely above, the whole Frying Pan sequence bears a striking similarity to that of the Wind River Mountains reported by Holmes (1949) and Moss (1949; 1951, a and b). Both authors describe the early and late Wisconsin deposits (Bull Lake and Pinedale) as double advances of somewhat different age, associated with separate outwash terraces.

The bipartite character of the earlier Wisconsin advances is also described in Rocky Mountain National Park by Jones and Quam (1944). Their Park Border moraine is commonly composed of three lateral-terminal loops, the outer of which has a better soil profile and is distinctly older than the other two. The topographic position and soil development of the Old Moraine Remnants in this same locality suggests their correlation with the Frying Pan deposits of Lime Creek age. Jones and Quam are unwilling to correlate this "in-valley" stage with "inter-valley" Kansan moraines such as Ray's (1940) Prairie Divide or Wahlstrom's (1940) Tungsten Mountain tills.

Twenty-four miles southeast of Norrie are the Twin Lakes on Lake Creek, a tributary of the Arkansas River just south of Leadville. The glacial deposits of this locality have been studied and described by a number of workers, most recently by Ray (1940). It is the type locality for his W I substage. The author has studied Ray's W I and W II deposits at the east end of the lakes and would correlate them with the Thomasville and Biglow moraines of the Frying Pan. Surficially the tills are similar, and the topographic relation of the younger lapping up on the older lateral-terminal loop is identical with their relation on the Frying Pan. The remaining substages in Ray's Wisconsin sequence, W III, W IV, and

W V (Bryan and Ray, 1940), are possibly correlatives of the Ivanhoe, Hell Gate, and Chapman Gulch advances.

Correlation of the glacial sequence in the Frying Pan valley with that proposed by Ives (1938, 1942) in Monarch Valley, Colorado, does not seem possible. Till descriptions, topographic relations, and the general "fit" of the sequences are dissimilar. The Frying Pan has five advances Wisconsin or younger in age, while in Monarch Valley there seem to be four, or seven if we count the phases within substages which Ives correlates with the North German sequence (Ives, 1942, p. 450).

Correlation with moraines in still other areas, purely on the basis of published descriptions, is possible. Biglow moraines are probably correlative of the well known Bull Lake, Tahoe, Durango, Home (W II), Blacks Fork, and Lamoille deposits. The Ivanhoe moraines are correlatives of the Pinedale, Tioga, "Wisconsin," Corral Creek (W III), Smith Fork, and Angel Lake of the corresponding localities. (For references to these localities and deposits see Antevs, 1945, Table II). No great importance should be attached to such comparisons, but the similarities are in many cases striking.

The foregoing comparisons do not constitute a detailed correlation of Frying Pan deposits, in themselves, with the standard Pleistocene chronology of the Midwest.

This is a far more difficult problem, but some possibilities are perhaps worthy of mention. It was seen above that an Illinoian age is preferable for the Lime Creek moraines, although an older, Kansan, age is possible. The latest or Chapman Gulch moraines, and the related protalus ramparts, are clearly youthful. In view of the age given above, however, it is questionable whether they are recent enough to be correlated with the deposits of Matthes' (1941, 1945) neoglaciation. Matthes estimates that the "Little Ice Age" began 4,000 years ago, but its culmination was presumably much more recent. Most of the moraines described in the literature which have been correlated with the neoglaciation are essentially in contact with present ice masses and are devoid of all vegetation. Moss (1951 a, p. 881) describes and pictures a moraine of the Little Ice Age in the Wind River Mountains which is not at all similar to the Chapman Gulch deposit. The Chapman Gulch moraine exhibits a measurable soil development and spruce cover, and extends up to one-half mile beyond the cirque lip.

These considerations have led to the conclusion that the Chapman Gulch advance is younger than Wisconsin but older than the climatic optimum and the neoglaciation. Lack of evidence for the Little Ice Age is attributed to the low latitude of the Frying Pan drainage. On the basis of published descriptions, the Chapman Gulch advance is best correlated with the Temple Lake of Hack (1943, p. 239) and Moss (1951, a and b). Much more work on these younger deposits, and their radiocarbon dating, is desirable.

There remain four glacial advances to be correlated with the standard chronology. A simple and desirable solution would be to correlate the four advances with the four substages of the Wisconsin given in the standard sequence. Some credence for such a scheme is given by the age estimates of Table III; which indicate that the Thomasville-Biglow and Ivanhoe-Hell Gate intervals are short relative to the interval between the Biglow and Ivanhoe. This corresponds to the short Iowan-Tazewell and Cary-Mankato intervals, and the longer Tazewell-Cary interval of the classical section (Flint, 1950, pp. 1460-61; Ruhe, 1950, pp. 1500-1; and Flint and Deevey, 1950).

In opposition to the identification of the Hell Gate as Mankato is the fact that the Tioga and its correlatives, here considered contemporaneous with the Ivanhoe advance, is considered to be Mankato, particularly by Antevs (1945). Study of continental ice sheet deposits in southern Alberta by Horberg has disclosed the presence of moraines which occupy the proper position geographically to be Tazewell-Cary, i.e., in front of the Altamont and behind the Illinois-Iowan (Horberg, 1951, personal communication). This seems to throw considerable doubt on the validity of Antevs' reasoning that the Keewatin center was inactive during Tazewell-Cary time. It is largely on the basis of this reasoning that the Pinedale has been dated as late Mankato in age (Antevs, 1941, pp. 40-41).

In view of the possible telescoping of the Pleistocene time scale by recent C-14 dating, the tentative correlation suggested on the right side of Table IV may eventually find use. The horizontal rows contain correlations by the author of Frying Pan valley substages with those of Moss (1951 b). The leftmost column is the dating Moss proposes for Wind River Mountain deposits.

TABLE IV

Wind River Mountains		Frying Pan Drainage	
Dating	Glaciations	Glaciations	Dating
(Little Ice Age)	Neo-glaciation	-	-
Cochrane	Temple Lake	Chapman Gulch	Cochrane(?)
Mankato	Pinedale II	Hell Gate	Mankato
	Pinedale I	Ivanhoe	Cary
Tazewell-Cary(?)	Bull Lake II	Biglow	Tazewell
	Bull Lake I	Thomasville	Iowan
Iowan(?)	Buffalo	Lime Creek	Illinoian(?)

It is almost an axiom in the history of Rocky Mountain glacial studies that the more recent the work, the greater is the number of separate glacial advances described. This seems to be the result of more intensive effort in smaller areas and of the utilization of more quantitative approaches. That this trend is the correct one is still to be demonstrated, but it is noteworthy that such a trend does not seem to be taking place in the Sierra Nevada. The recent excellent work of Putnam on the eastern flank of the Sierra, where the morainal systems are particularly well developed, contains no mention of upper valley deposits (Putnam, 1949). Thus there are apparently no correlatives of the Hell Gate or Chapman Gulch advances. If the correlation proposed with Blackwelder's Sierra sequence is correct, one might also expect to find Wisconsin deposits, equivalent to the Thomasville, which are somewhat older than Tahoe in age. Blackwelder (1931, p. 918-19) wrote that a glacial stage between the Tahoe and Sherwin is possible but that the data were not conclusive. However, an Illinoisan rather than Wisconsin age was postulated for this possible addition to the glacial succession.

Recent studies in the Cordillera from Mexico to Alaska would seem to require a more complex Wisconsin glacial history than that now proposed for the Sierra, and thus indicate a greater degree of contemporaneity of climatic refrigeration with the Rockies and Midwest than Blackwelder's and Putnam's chronology would suggest. The deposits of the younger substages, and the one just older than Tahoe, appear to have been overlooked. Possibly such deposits no longer exist or, more probably, their significance as representing separate advances has not been recognized. It is felt that further, more detailed work in the Sierra should bring out a chronology more like that now beginning to emerge in the Rocky Mountains.

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