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The glacial geology of the West Tensleep Drainage Basin,
Bighorn Mountains, Wyoming

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The glacial geology of the West Tensleep Drainage Basin,
Bighorn Mountains, Wyoming

by

Gloria Butson Burggraf

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Graduate Faculty in Partial Fulfillment of
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Frontispiece. Headwaters of the West Tensleep
Drainage Basin, Cloud Peak,
upper left

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I. INTRODUCTION

A. Statement of Problem

The Quaternary history in the mountainous regions of the world is preserved as glacial erosional and depositional features. The individual glacial advances which are indicators of cooler, or more moist intervals, are placed in a regional model by correlation to those of a type area. The glacial moraines and associated outwash deposits in the Wind River Mountains of Wyoming serve as the model for Rocky Mountain glaciation. The relative ages of the glacial deposits have been determined by comparison of the surface morphologies as well as cross-cutting relationships. Comparisons of soil development and determination of weathered boulder frequencies have also been employed to indicate the relative age of the glacial deposits.

The purpose of this study in the Bighorn Mountains is threefold. First, the glacial deposits were to be delineated and a relative chronology established for the West Tensleep Basin. This was accomplished by using traditional geomorphic, topographic and stratigraphic relationships, as well as supporting evidence from soil data. Secondly, the glacial deposits of the West Tensleep Basin were to be correlated with the regional model, as first defined in the Wind River Mountains. Finally, a statistical analysis was completed on the density and weathering characteristics of the surficial boulders to determine their validity as indicators of relative age.

The area of this investigation lies within the boundaries of the Bighorn National Forest, including five 1:24,000 quadrangles, of which the greatest portion is contained in three: Brokenback Narrows, Meadowlark Lake, and Lake Helen. The area is bounded by latitudes $44^{\circ}07'30''$ to $44^{\circ}22'30''$ and longitudes $107^{\circ}15'$ to $107^{\circ}07'30''$. U.S. Highway 16 passes through the area of investigation. The major streams in the area are West Tensleep Creek and its tributaries Middle and East Tensleep Creeks, and Willow Creek. Meadowlark Lake lies along the eastern boundary of the area.

B. Geographic and Geologic Setting

The Bighorn Mountains are included within the Middle Rocky Mountain Province which is a heterogenous group of ranges and basins in Wyoming and parts of Montana, Utah and Colorado (Hunt, 1974). Separating the Powder River basin on the east and the Bighorn Basin on the west, the Bighorn Mountains form an arcuate range extending from southern Montana southward into north central Wyoming. To the north, the range is bounded by the Pryor Mountains and curves into the Owl Creek Range at its southern end. The range is an asymmetrical anticlinal uplift with the asymmetry reversing from steeply dipping beds along the western margin in the northern segment to the steeply dipping beds along the eastern margin in the central segment and reversing again to the steeply dipping beds on the western slope of the range in the southern segment (Demorest, 1941). Paleozoic and Mesozoic rocks cover the crest of the range in the northern and southern segments with Precambrian metamorphic rocks

exposed in the central segment. The core is composed of a complex of gneisses, quartz diorites, and monzonites; the diorites and monzonites are exposed in the northern half of the range and the gneiss generally is exposed in the southern part although the types grade into each other mineralogically and texturally (Heimlich and Banks, 1968). The core is exposed along a 40 mile (64 Km.) crest culminating in Cloud Peak at 13,165 ft. (4014 m.) above sea level.

The study area lies on the western slope of the range in the southwestern portion of the central segment. It is bordered by and extends into the lower Paleozoic rocks on the west and south. The major portion of the area lies within the Precambrian core. More recent work indicates two episodes of deformation and metamorphism within the study area have resulted in an older complex of trondjamite and tonalite gneisses and minor amphibolite and a younger sequence consisting of granodiorite and quartz monzonite. The younger granodiorite and quartz monzonite are the predominate rocks in the West Tensleep Basin, whereas the trondjamite and tonalite gneisses are exposed in the Middle Tensleep Creek valley (Barker, 1977, U.S.G.S., personal communication).

Darton (1906, p. 72) describes the general form of the glaciated valleys in the Bighorn Mountains. His description fits the study area very well. The valley consists of three portions which are described as follows:

- (1) An upper canyon portion in the mountain proper, often cirque-like, always deep, and in many places with gradients of 600-800 ft. (183-244 m.) per mile;

(2) A relatively shallow, open valley across the plateau on either side of the crest;

(3) A second narrow gorge across the Paleozoic rocks.

The smallest glaciers did not extend below the upper canyon portion, whereas the longest (such as the Tensleep glacier) crossed the plateau and entered the canyons of Paleozoic formations (Darton, 1906). The West Tensleep Glacier was the second longest of the valley glaciers, extending 18 miles (28.8 Km.) from the northernmost source area at more than 12,000 ft. (3658 m.) to an elevation of 6,500 ft. (1981 m.) within the Paleozoic rocks.

C. Climate and Vegetation

The range of temperature and precipitation averages for the Bighorn Mountains is similar to the ranges of climatic conditions in other locations of the Middle Rocky Mountain Province. Generally, the precipitation ranges from an average of 10 in. (25 cm.) a year in the basins to about 20 in. (51 cm.) on the mountain summits in this province. The average temperatures would be in the upper 40's (27°-32°C) for the basins and the lower 30's (12°-13°C) for the mountain summits (Hunt, 1974).

No climatic stations are located within the area of this report, but Table 1 summarizes the average climatic conditions for three sites in or near the Bighorn mountains which have U.S. weather bureau stations. Buffalo, Wyoming is located along the eastern boundary of the range; Hunter Ranger station is located within the Clear Creek Drainage Basin,

Table 1. Climatic data for the Bighorn Mountains. (From: U.S. Weather Bureau)

Climatic Station	Latitude	Longitude	Elevation above Sea Level	Mean An. Precip.	Mean An. Temper.
Buffalo, Wyo.	44°22'	106°48'	5240 ft. 1598 m.	16.22 in. 40.6 cm.	44.6°F 26°C
Hunter Ranger Station	42°22'	106°57'	7400 ft. 2256 m.	15.76 in. 39.4 cm.	36.3°F 18.3°C
Tensleep, Wyo.	14°13'	107°25'	4545 ft. 1386 m.	10.87 in. 27.8 cm.	47.2°F 29.2°C

just across the drainage divide from West Tensleep drainage; and Tensleep, Wyoming is at the western edge of the range in the Bighorn Basin. The data from Hunter Ranger station is similar to the climatic conditions assumed to exist in the West Tensleep Drainage Basin.

The general outlines for vegetation life zones have been defined for the middle Rocky Mountains by Preston (1968). The degree of expression of the zones are controlled by moisture, temperature, topography, and aspect, all of which determine the altitude to which a plant species will grow (Preston, 1968). A secondary influence on the vegetation of the mountain slopes is exposure (Hunt, 1974). As a general example, north facing slopes commonly support conifer forests whereas south facing slopes at the same altitude may have a sagebrush vegetation. The vegetation differences are due in large part to the cooler, moister conditions present on the north facing slopes. Figure 1 illustrates the life

Figure 1. Elevation - Vegetation map of the West Tensleep
Drainage Basin

- A West Tensleep Creek
- B Willow Creek
- C East Tensleep Creek
- D Middle Tensleep Creek
- E Meadowlark Lake
- F West Tensleep Lake
- G Mirror Lake
- H Lake Helen
- I Lake Marion
- J Mistymoon Lake
- K Lost Twin Lakes

EXPLANATION

VEGETATION ZONES

- ALPINE ZONE
lichen, dwarf grass
- CANADIAN ZONE
conifer forest
- TRANSITION ZONE
grass-sage

Boundary of glaciation

Stream

Contour, 400 ft. interval

Moraine crest

INDEX MAP

... recognized by Preston as applied to the West Tensleep Drainage basin.

The lower limit of the Alpine zone ranges from 9,000-12,000 ft. (2744-3658 m.). The Alpine Zone is characterized by arctic barren ground above timber line covered with snow for a large part of the year. The vegetation groups common to this zone include mosses, lichen, and in some places, dwarf willow and grasses. There are large areas of exposed bedrock. Within the study area, the Alpine zone extends from timberline, which is usually at 11,500 ft. (3506 m.) to the summits above 13,000 ft. (3963 m.). The lower limit of the Alpine Zone extends as low as the elevation of 9,600 ft. (2927 m.) on Bald Ridge.

The Hudsonian zone is basically a transition zone composed of stunted conifers just below timberline at approximately 8,000-9,000 ft. (2439-2744 m.). This zone is difficult to locate with accuracy within the study area, and does not appear on the map (Figure 1). The approximate location would be in those tributary valleys below timberline, with scattered patches of conifers in alpine meadows at approximately 9,600-10,800 ft. (2927-2988 m.).

The Canadian zone of the Middle Rocky Mountains occurs generally from 6,000-9,000 ft. (1829-2744 m.) above sea level. It is located on middle and high mountain slopes as well as valley floors. Forests of Englemann Spruce, true firs, Western and Lodgepole Pines, Aspen, Poplar and Mountain Ash are typical species occurring in this zone. In the West Tensleep basin, this zone occurs on the moraines in and along the Tensleep valley with many open parks occurring on the flood plains. The

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middle Rocky Mountains did not descend below the forested zone (Darton, 1906, Holmes & Moss, 1955; Nelson, 1970). The full significance of this will be expanded later in the text.

II. PREVIOUS INVESTIGATIONS

A. Development of the Regional Glacial Model

The work of Eliot Blackwelder (1915) is the basis for the development of the regional glacial model. In his work on the Pleistocene glaciation in the Wind River Mountains, Blackwelder suggested, based upon the depositional landforms, that three major glacial advances occurred. He proposed the name Buffalo for the earliest ice advance, equating it with the Pre-Wisconsin (Kansan or Illinoian) of the mid-continent. The Bull Lake was defined as early Wisconsin, based on its subdued morphology, and the youngest moraines were named Pinedale, their youthful appearance and immature soils suggesting to him a late Wisconsin stage of glaciation.

Blackwelder's basic outline of the Pleistocene glaciation has been expanded by later studies. Holmes and Moss (1955) and Richmond (1962) have recognized, respectively, two and three pre-Bull Lake moraines and have suggested that the term Buffalo be abandoned (Richmond, 1965). Blackwelder's Wisconsin model has also been revised by later workers. Two sets of Bull Lake moraines and associated outwash terraces are recognized by Fryxell (1930), Richmond (1948) and Holmes and Moss (1955). The Pinedale Glaciation is now recognized as being more complex than originally defined by Blackwelder. Pinedale age moraines within the Wind River Mountains are expressed by an inner, middle and outer complex of moraines, each associated with its own outwash terraces (Richmond, 1948). Kiver (1972) located what he believed to be a fourth Pinedale

advance in the Medicine Bow Mountains. However, weak soil development and poor definition of outwash terraces make it difficult to identify in detail the glacial recessions and readvances within the Pinedale advance (Mears, 1974).

Later Pleistocene and possibly recent moraines and rock glaciers have been recognized near cirque heads in the Wind River Mountains. Matthes (1939) suggested that these deposits represent a glacial readvance which he called the Little Ice Age. Moss (1951) subdivided these deposits and suggested the term Neoglaciation be applied to them. The oldest Neoglacial moraine, Temple Lake, was interpreted by him to be post-Pinedale, but pre-Altithermal in age. Richmond (1960) gave the name Gannett Peak to fresh cirque moraines located up valley from the Temple Lake moraines. He also designated the Temple Lake moraine as the type deposit for the early Neoglacial in the Rocky Mountains. In some areas, Neoglaciation is represented by rock glaciers, protalus ramparts and talus (Richmond, 1965, and Birman, 1964). More recent developments expanding this basic outline are discussed in Mears (1974).

B. Recognition of Glaciation in the Bighorn Mountains

The only study on the glacial erosion of the Bighorn Mountains is by Francois Matthes (1900). The Bighorn Mountains were chosen because he believed that the glaciers had only modified the pre-glacial landscape. Cirques were recognized as the source of glacial ice and he concluded that the U-shape of the present valleys result from glacially modified V-shaped stream valleys. Although he did not work in the study area, he

recognized the sources for the West Tensleep and Paintrock glaciers which extended the farthest from the heads of the valleys.

The glacial deposits in the present study area were mapped by Salisbury and Blackwelder (1903). They recognized two series of deposits separated by a relatively long interval of time, and a third series which appeared to be much older than these two. These deposits were recognized in several valleys, although only reconnaissance studies of the deposits in Tensleep Canyon were undertaken. The major criteria used to judge the difference in relative age were freshness of the till, extent of weathering and erosion on the drift as well as the canyon walls, depth of oxidized till, retention of lakes, topographic expression of the drift and its distribution.

Darton (1906) completed a detailed geologic study of the Bighorn Mountains and surrounding area. The Quaternary geologic section, authored by Salisbury, contains the first detailed description and maps of the glaciation of the Bighorns. Using criteria similar to that of Salisbury and Blackwelder (1903) he identified two glacial advances of widely separated ages. From his observations, Salisbury concluded that altitudes of 9500-11,500 ft. (2896-3506 m.), with some variation due to exposure and the size of the catchment basin, were necessary to collect enough snow and ice to initiate glaciation.

The only other glacial study in the Bighorn Mountains is by R. S. Nelson (1970) in the Clear Creek Drainage Basin. His observations are limited to glacial deposits which he attributes to one Bull Lake, three Pinedale and two Neoglacial ice advances. He bases his conclusions on

weathering data obtained from surficial boulders, the composition and appearance of the till, topographic position in the valley, surface morphology of the moraines and the soil development on them.

III. METHODS OF STUDY

A. Field and Laboratory Procedures

Geologic mapping was initiated on color aerial photographs at a scale of 1:15,000. The drift locations, morainal crest trends, landslides, talus and large scale glacial erosional features were delineated on the photographs with the aid of a stereoscope. The area was field checked and mapped on 1:24,000 U.S.G.S. topographic maps. Data on the weathering of surficial boulders, and soil development were collected at this time.

Regression and correlation analysis were applied to the weathering data. Analysis of variance and correlations were used to identify the related variables. Regression analysis was used to predict age from a variety of independent variables. The statistical analysis utilized the Statistical Analysis System designed and implemented at the University of North Carolina by A. J. Barr and J. H. Goodnight (1972).

Sample sites for the weathering data were located on stable crests. This location reduces variation due to erosion and also yields the maximum soil development. At least three soil profiles were described for deposits of each age. Field descriptions were completed according to the standard procedure in Buol, Hole and McCracken (1973). A sample of approximately one pound (454 grams) from each horizon was collected of the matrix and rock fragment portion less than three in. (8 cm.) in diameter. The samples were disaggregated and sieved through the 4 phi (62.5) sieve. That portion of the sample passing the 4 phi size was

analyzed by pipette analysis to determine the content of silt and clay in each sample. The procedure follows Folk (1974). The grain size distribution of each soil was computed and an average distribution for each age deposit was graphed.

The samples contained a large amount of roots and other undecomposed organic debris. The largest roots and wood pieces were removed before disaggregation and methods such as flotation by water and treatment with hydrogen peroxide were used to remove the smaller components.

Qualitative determinations of the clay minerals present in the soils from the study area were attempted using sample preparation techniques and X-ray diffraction methods as discussed in Raup, (1962). The chemical and structural characteristics of the clay minerals have been discussed thoroughly elsewhere (Grim, 1968, Birkeland, 1974).

B. Weathering Parameters

The relative ages of the moraines are determined by comparing the morphology of the deposits with substantiating evidence based upon degree of weathering of surficial boulders and soil development. Quantitative measurement of relative age has been documented by various researchers. Blackwelder (1931) originally identified non-weathered, notably decayed, and greatly weathered surficial boulders on some glacial deposits of the Sierra Nevada Mountains and used this boulder weathering data as a major criteria for determining relative age of the deposits. R. L. Nelson (1954), Birman (1964), R. P. Sharp (1969) and R. S. Nelson

(1970) have extended the original observations of Blackwelder. All have concluded that boulder weathering analysis is a valid criterion for determining relative age relationships of various glacial deposits. Birkeland (1974, p. 157) states that surface weathering studies can give an indication of the amount of granitic rock breakdown (weathering) with time; with all other factors of variation remaining constant. Variables which might affect the validity of boulder weathering analysis include: (1) lithologic variation; (2) successive uncovering of fresh boulders by erosion of the matrix; (3) accidental covering of the boulders which may influence the ratio of weathered to non-weathered boulders; (4) differences in weathering due to exposure on slopes; (5) differences in altitude which affect precipitation, temperature and vegetation type; (6) amount of weathering prior to transport; and (7) personal bias. These variables are summarized in Birman (1964, p. 16).

Precautions were taken to reduce the variables influencing boulder weathering ratios to just one--the time required to weather the rocks. Rocks less than one foot in diameter and rocks other than those composed of a medium grained (1/8 - 1/4 in.) granodiorite, quartz monzonite, trondjamite or tonalite gneiss were eliminated from the analysis. The restrictions would reduce error due to exfoliation and shattering as well as differences due to lithologic variation in weathering.

The sample sites were limited to the tops of convex morainal crests and extended parallel to the divide in order to reduce the variation because of soil erosion or deposition. Because of the wide range in altitude of the drift (6,500-10,400 ft., 1982-3170 m.), the variation

due to temperature, precipitation, and vegetation differences were difficult to control, but their effects were noted by recording the vegetation type at each site. Burke and Birkeland (1976) have indicated vegetation and altitude effects on weathering ratios.

Terminal moraines have a higher ratio of weathered to fresh boulders on the surface (Birman, 1964). This factor was considered in the field and final analysis of the drift of the Tensleep drainage.

A weathered boulder, as defined by Birman (1964, p. 18) is one in which weathering has penetrated to at least the depth of the average grain size diameter on at least one half of the exposed surface of the boulder. Likewise, a fresh boulder is classified as one in which weathering is not completed to the depth of the average grain size on half of the exposed surface. The unexposed portion of the boulder was not considered because the covered portion of the boulder weathers at a different rate than the exposed portion (Birkeland, 1974). A weathered boulder in this report was recognized by close visual inspection and a rough surface to the touch.

Because the majority of boulders are only partially weathered, it was necessary to establish consistency in the measurements on the boulders. Attempts were made to eliminate spurious results due to personal bias following Birman's (1964) example. He measured groups of 100 boulders consecutively without tabulation of the results, then compared the results and found consistency within two to three percent (Birman 1964, p. 18). In this study, each group of 100 boulders was divided into two groups of fifty boulders each. Consecutive

measurements of the two groups were recorded successively without tabulation so the observer could not tell how the measurements were related. When measurements of the two groups were compared, they were found to be in agreement within two percent. This procedure established internal consistency of the method, and also justified the use of only 100 boulders in areas where 100 boulders could not be located.

Six other weathering phenomena were observed at each site. The number of boulders greater than one foot in diameter within a 2,000 sq. ft. (36 sq. m.) area was counted. The local relief between the adjacent ground level and the crest of the moraine at each sampling site was measured. Later, for simplicity, multiple measurements from each site were combined into one average relief measurement. Iron staining was recognized by the characteristic brown to orange stain on the surface of the boulder. Iron stained boulders were noted if this characteristic stain was observed over one-half or more of the exposed surface of the boulder. These parameters are a combination of those used by Birman (1954), Nelson (1954), and Nelson (1970). The significant number of boulders observed to be lichen covered, exfoliated and shattered led the author to include these factors in the observations made on the boulders. Skelton (1974, p. 59, 65) states that lichen may have a significant effect on weathering rates of rocks. Exfoliation and shattering have been linked to initial adjustment of rocks to their environment so it might be possible to indicate more recent deposits by this method. Internal consistency was established as before.

An exfoliated boulder is one which exhibits evidence of the spalling of the outer layers of the rock either by present attachment to the rock or flakes lying on the ground nearby. Shattering describes a boulder deterioration other than exfoliation in which the rock exhibits evidence of splitting and fragmentation into smaller, angular pieces. When evidence of this type of boulder weathering was encountered, the weathering data was taken without regard to it, as long as the other requirements were satisfied, to eliminate personal bias in the measurements. The fact that some boulders were exfoliated and shattered was recorded in the appropriate categories.

It was observed in many areas under forest vegetation that tree tip was common. This phenomenon refers to fallen trees which have thrown up buried boulders with their roots. Rocks obviously exposed in this manner were excluded from the analysis because of differences of weathering rates between buried and exposed boulder surfaces (Birkeland, 1974).

Figure 2a. Glacial geologic map of the West Tensleep Drainage Basin,
South half

South Half

Location Map

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EXPLANATION

General description of till

Poorly sorted massive unconsolidated with clasts of many sizes and shapes. Matrix is friable, oxidized to variable depth, boulders composed of granodiorite and tonalite gneiss, expressed as lateral, terminal and ground moraine.

Mistymoon Moraine

Fresh moraine form, small deposits along streams less than 3 miles from source. Valley major streams incised less than 20 ft, terminal moraines common. Matrix broad and hummocky, scattered boulders on scoured bedrock surfaces. Matrix sandy gravel, yellowish brown (10 YR 5/8), surficial boulders common, weathered ratio 93/7, exposed thickness 20 ft.

Tyrrell Moraine

Lateral and terminal moraines steep, narrow crests, closed and well developed. Matrix extensive, mantles bedrock, deposits 3-13 miles from source. Valley major streams incised in till, weakly developed. Matrix sandy gravel, yellowish brown (10 YR 5/8), surficial boulders few to common (10/2000 sq ft), weathered ratio 93/7, exposed thickness 20 ft.

Pond

Stream perennial
intermittent

Road primary
secondary

Moraine crest

Contact
Concealed contact

Buildings
Campground

Sampling sites
Boulder analysis
Soil description
Boulder analysis and soil description

Bald Ridge Moraine

Flat broad crest, subdued morphology on lateral moraine. Matrix sandy loam, 800 ft above main stream, moderately developed soil, till matrix sandy loam (10 YR 4/2), surficial boulders common (13/2000 sq ft), fresh weathered ratio 52/48, estimated maximum thickness 200 ft.

Borrow Pit Dnt

Broad smooth surface, occupies interstream divide, till matrix sandy loam, brown (10 YR 5/3), surficial boulders uncommon (34/2000 sq ft), fresh weathered ratio 16/84, estimated thickness 200 ft.

Paleozoics, undifferentiated

Includes arkosic conglomerate grading into coarse-grained sandstone, sandy glauconitic limestone interbedded with green shales and white to tan dolomite and dolomitic sandstone.

Precambrian

Scoured bedrock lithology granodiorite and quartz monzonite gneiss with some augen gneiss, trondhjemite and tonalite gneiss with minor amphibolite, both are transected by dolerite dikes and quartz veins.

Precambrian undifferentiated

Glacial Geologic Map of the West Tensleep Drainage Basin

North Half

Glacial Geologic Map of the West Tensleep Drainage Basin

IV. GLACIATION OF WEST TENSLEEP DRAINAGE BASIN

The drift in the study area has been separated into four, and possibly five, morphostratigraphic units based on surface morphology and relative position in the valley (Figures 2a and 2b). The soil development on the moraines and weathering analysis on the surficial boulders provided supporting evidence. The older moraines (the Borrow Pit Drift and the Bald Ridge Moraine) are characterized by subdued topography and occur on the canyon rim. The location of the Squaw Creek, Tyrrell and Mistymoon Moraines within the modern valley indicates that they are younger than the canyon rim moraines. The youngest drift, the Mistymoon Moraines, rarely occur beyond the confines of the cirque valleys.

Little outwash is associated with the moraines. The most extensive outwash is associated with Tyrrell Moraines. A common meltwater phenomenon are boulder lines which are believed to be the result of meltwater removing the fine matrix, leaving a line of boulders at the edge of a moraine. These boulder lines are longer than wide and extend down steep slopes to disappear where the gradient decreases at the foot.

Till is the major glacial deposit. It is an unconsolidated, poorly sorted material with clasts of many sizes in a matrix of variable texture (Flint, 1971, and Sugden and John, 1976)(Figure 3d). In the study area, it has a lithologic composition similar to the bedrock in the source areas, which range from a quartz monzonite gneiss to a dark hornblende quartz diorite from the headwaters of West Tensleep Creek and tonalite and trondjamite gneiss from the Middle Tensleep drainage

Figure 3. Depositional features typical of the glaciation of the West Tensleep Drainage Basin

- a. View up-glacier toward the Squaw Creek terminal moraine
- b. View looking across the Squaw Creek moraine toward the Tyrrell terminal moraine. Road cut is in Squaw Creek lateral moraine
- c. West Tensleep Valley from above Meadowlark Lake. Ice flow from upper right to lower left
- d. Exposure of Squaw Creek till in road cut. Field assistant holding 5 foot rod
- e. Example of a boulder line. This particular one is located along Bald Ridge just to the south of the landslide

a **b** **c** **d** **e**

(Barker, 1976). The texture of the till matrix is generally a gravelly sand reflecting the bimodal distribution common to glacially derived sediments.

A. Glacial Deposition

1. Borrow Pit Drift

The Borrow Pit Drift is the oldest exposed drift within the study area. It lies upon the Paleozoic rocks of the western rim of Tensleep Canyon about 560 ft. (171 m.) above the present valley floor (Figure 3e) and one third of a mile (537 m.) away from any similar deposit. Although it is composed of metamorphic rocks, the nearest outcrop of metamorphics is four miles (6.4 Km.) to the north and no direct stream valley presently connects the deposit with its nearest Precambrian source area. The altitude of the deposit is 8,800 ft. (2683 m.) and the vegetation type is transition with sagebrush and scattered juniper covering the surface.

The Borrow Pit Drift is informally named from the borrow pit located within it. It is located near the forest service road to Battle Park. The surface of the deposit is broad and flat with steep slopes on three sides and abutting against an outcrop of Paleozoic rocks on the west. It extends 900 ft. (274 m.) in a north-south direction and 1300 ft. (396 m.) in an east-west direction (Figure 2a).

A vertical section of the deposit in the pit exposes stratified drift suggestive of a kame. Stratification exists as two lines of boulders one boulder thick, at seven and eleven ft. (2 and 3 m.) below

the surface, which can be traced laterally for about 30 ft. (9 m.). They consist of very weathered cobbles and boulders of the same lithology as found in the headwaters of the West Tensleep Creek. Below the 11 ft. (3 m.) boulder line, the deposit consists of a well-sorted gravelly sand, to the water table at a depth of 14 ft. (4 m.). Between the two boulder levels a fining upward sequence occurs. Individual cobbles and pebbles (4 in. to 1/4 in. dia., 10 cm. to .6 cm.) in a coarse sand matrix with lenses of cobbles and pebbles occur above the lower boulder line, and fine upward. Above the upper boulder line, cobbles are embedded in a sandy matrix. A brown weathered zone, recognized by clay skins surrounding the sand grains occurs in the upper 24 in. (61 cm.) of the material.

A boulder weathering analysis was completed on the surface of the deposit. Only 34 well-rounded boulders were exposed in 2,000 sq. ft. (186 sq. m.). An average of 84 percent of these boulders were weathered, but only 10 percent were iron stained. Lichen was found on 76 percent of the boulders. The effect of exfoliation was observed on 24 percent of the boulders, and 8 percent showed signs of shattering.

2. Bald Ridge Moraine

Bald Ridge is the gently sloping summit of the western canyon wall at West Tensleep Lake (refer to Figures 2a and 2b). The ridge is over 2,000 ft. (61 m.) wide and lies 800 ft. (244 m.) above the modern valley floor. The ridge at an elevation of 9,200 ft. (2805 m.) has an alpine vegetation. The glacial moraine which caps the ridge exhibits subdued morphology. A moraine with a similar morphology is located along the

Figure 4. Morainal forms of the glacial advances in the West Tensleep Drainage Basin

- a. View of Squaw Creek Moraine. Glacial flow was away from the observer
- b. View across Tyrrell Moraine. Glacial flow was away from the observer
- c. Bald Ridge Moraine on Bald Ridge. Remnant lateral moraine along right side of photograph. Flow of the glacier was away from the observer
- d. Mistymoon Lake, enclosed by Mistymoon Moraine with Lake Marion and Lake Helen in the background. Glacial flow was away from the observer
- e. Looking west across Tyrrell Moraine toward Borrow Pit drift, upper center, within gently dipping Paleozoic rocks. Glacial flow was right to left

a

b

c

d

e

eastern rim of the canyon. This moraine is covered with a conifer forest. Together the two moraines are informally termed the Bald Ridge Moraine and are considered to be older than the valley floor moraines, but younger than the Borrow Pit Drift.

The type description of the Bald Ridge Moraine is based upon the central $5\frac{1}{2}$ miles (8.8 Km.) of Bald Ridge. The moraine extends to an elevation of 10,000 ft. (3049 m.) where it is covered by a younger moraine with a crosscutting relationship. A similar situation exists to the south where two lateral moraines parallel each other for 1000 ft. (305 m.) before the Bald Ridge Moraine is overlapped by the younger moraine.

The boulder covered surface of the Bald Ridge Moraine indicates glacial deposition, but the distinctive hummocky depositional topography has been reduced to less than five ft. (1.5 m.) of relief. The former ridges are only recognizable because of the stronger concentration of boulders along their crest (Figure 4c). The morphology and location of the eastern portion of the Bald Ridge Moraine is similar to that just described and is especially well-expressed at Bear Park.

The till is poorly sorted with a matrix of compact gravelly sand which is dark grey brown (10 YR 4/2). The surface boulders on the moraines along Bald Ridge are quartz diorite and granodiorite, whereas, the boulders from the eastern moraine consist of dominantly tondjamite and tonalite gneiss.

a. Outwash Little evidence for outwash deposits associated with the Bald Ridge Moraine exists and no outwash occurs adjacent to the

Figure 5. X-ray defraction patterns for clay in B and C horizons of Bald Ridge drift

moraine. Terraces, 10-20 ft (3-6 m.) above the present stream level, occur along Dry Tensleep Creek (personal communication, R. C. Palmquist, Iowa State University). The position and weathered appearance of these terraces indicate early deposition and possibly may be related to the Bald Ridge glaciation.

b. Soil development The soil development on the Bald Ridge Moraine is variable. The soil on the western moraine has a 10 in. (25 cm.) thick silt loam A horizon which is friable, non-acidic, very dark brown (7.5 YR 3/2) and has a weak granular structure. A sharp irregular boundary exists with the B horizon. The clayey sand B horizon is 15 in. (38 cm.) thick and has a weakly developed angular blocky structure. The color is brown to dark brown (7.5 YR 1/4) and has root penetration to 30 in. (76 cm.). The gravelly sand C horizon does not have structure. Numerous cobbles are present in a dark grey-brown (10 YR 4/2) matrix which is friable and non-acidic. As a contrast, a soil on the eastern Bald Ridge Moraine has a sandy silt A horizon two in. (5 cm.) thick, displays no structure, and is dark grey-brown (10 YR 4/2). There is plant litter on the surface, but the horizon is non-acidic. No B horizon is present and the boundary with the C horizon is sharp and irregular. The C horizon is dark brown (10 YR 5/4) gravelly sand with no apparent structure and many cobbles present. This soil is anomalous to the soil on Bald Ridge. X-ray defraction of the silt-clay fraction of the B and C horizons indicates that kaolinite is the dominant clay in the B horizon, whereas the C horizon has mica and mixed layer clays (Figure 5).

c. Boulder analysis The Bald Ridge Moraine has the greatest average boulder density with 132 boulders per 2,000 sq. ft. (186 sq. m.) with a range of 88 boulders at site 51, under conifer vegetation, to 200 boulders at site 63, under tundra vegetation. The mean number of weathered boulders is 48 percent, with a range of 17 percent weathered to the most weathered boulders in the study area, 69 percent. An average of 8 percent of the boulders are iron stained; 20 percent of the boulders are shattered and 30 percent are exfoliated. Lichen covers 43 percent of the boulders.

3. Squaw Creek Moraine

The Squaw Creek Moraine extends the farthest from its source, about 17 miles (27 Km.) and is situated on the modern valley floor within the canyon of Paleozoic rocks recognized by Darton. The moraine is a mile (1.6 Km.) in length and 200 ft. (61 m.) in width. It is bounded by Tensleep Creek on the east and U.S. Highway 16 on the west (Figure 2a). To the north, a younger moraine, the Tyrrell Moraine, overlaps it. Because of its position within Tensleep Canyon, the Squaw Creek Moraine is believed to be the oldest exposed moraine on the modern valley floor, younger than either the Bald Ridge Moraine or the Borrow Pit Drift. The dominant vegetation is grass and sagebrush with scattered juniper. Small groves of aspen occur in marshes.

The glacial depositional topography is well-preserved. The lateral moraines are sharp crested, less than 20 ft. (6 m.) wide, and rise 20 ft. (6 m.) above the enclosed ground moraine. The lateral moraines outline the deposit along the east and west where they rise 80 to 100 ft.

(25-30 m.) above Tensleep Creek; they curve at the southern end into a prominent terminal moraine (Figure 3a). The terminal moraine rises 160 ft. (49 m.) above Tensleep Creek. Its crest is 100 ft. (30 m.) wide and it has been breached by an intermittent stream which drains a seasonal pond just behind the crest.

The ground moraine consists of subparallel ridges and trenches trending diagonally from the morainal axis. The ridges are boulder strewn and are five to ten ft. (1.5-3 m.) above the trenches in which boulders are absent. Only a few of the trenches are enclosed and these contain water seasonally (Figure 4a).

a. Outwash Sinuous channels and boulder strewn ridges below and to either side of the terminal moraine are the only remnants of Squaw Creek outwash. These ridges and channels, located at sites 9, 36, and 37 (Figure 2a), slope toward Tensleep Creek. Their position as well as height above the creek indicate a post-Squaw Creek age.

b. Soil development Soils developed on the Squaw Creek Moraine have only a slight horizonation. The soil description to follow is under grass-sage vegetation on a stable ridge crest. The A horizon, typically, is 5 to 7 in. (13-18 cm.) thick with a sandy loam texture. It has a weak granular structure and is dark brown (10 YR 2/2). Plant litter on the surface and root penetration to 20 in. (50 cm.) occurs in this soil. The boundary with the B horizon is gradual and diffuse. The B horizon is dark yellow brown (10 YR 4/3) and has a silty sand texture. No apparent structure or reaction with HCL occurs. Pebbles and cobbles are occasionally found. The boundary with the C horizon is diffuse. A

sandy gravel texture with abundant pebbles and cobbles and a dark brown (10 YR 4/3) color characterize the C horizon. X-ray defraction of the B and C horizons indicates mica clays present in the fine fraction of the soil.

c. Boulcer analysis The boulder analysis for the Squaw Creek Moraine has some variations. The number of boulders in 2,000 sq. ft. (186 sq. m.) averages 118, which is less than that for Bald Ridge. The average number of weathered boulders exposed is 45 percent, not significantly different from Bald Ridge. Squaw Creek Moraine boulders have the least percentage, one percent, of shattered boulders, whereas, similar to other moraines, 28 percent are exfoliated. The lichen cover of 74 percent is the highest, exceeded only by the Borrow Pit Drift.

4. Tyrrell Moraine

The moraine informally named the Tyrrell Moraine is the most extensive of the glacial deposits. It extends three to thirteen miles (4.8 to 20.8 Km.) from the source and includes the four vegetation zones at elevations of 7,400 ft. (2256 m.) to 10,400 ft. (3171 m.) above sea level. West Tensleep Creek flows the entire length of the moraine with several tributary streams joining it. Willow Creek and East and Middle Tensleep Creeks are perennial creeks, with many unidentified intermittent streams (Figures 2a and 2b). This moraine is considered to be younger than both the Bald Ridge and Squaw Creek Moraines because of its cross-cutting relationships with them, as well as its fresher geomorphic expression.

The most prominent features of the Tyrrell Moraine are the sinuous lateral moraines which extend its entire length. Tyrrell Ranger Station is situated just below and inside the western lateral moraine complex, along the road to West Tensleep Lake. The western Tyrrell lateral moraine is characterized at the type area by two to three high sharp crested ridges less than 20 ft. (6 m.) across. The ridges here are 1000 ft. (305 m.) apart and rise 100 ft. (30 m.) above the valley floor. Between these ridges, lies a moraine characterized by randomly oriented closed depressions most of which are roughly circular in shape and are commonly filled with water. Ten to twenty ft. (3-6 m.) above these kettles are circular knobs and ridges, also in a random orientation. Along the western margin near sites 28, 24, and 17, transverse recessional moraines extend from the lateral moraine (Figure 2a). The recessional moraines connect the ridges within lateral moraine complexes.

The eastern lateral moraine is similar to the western lateral moraine. The till forming the eastern lateral moraine, covered on the north by a block field, caps the valley wall in which scoured bedrock is exposed. The lateral moraine consists of one ridge as far south as Willow Creek (Figure 2a). At this point, the lateral moraine becomes more complex with two sharp crested ridges less than 20 ft. (6 m.) across, enclosing a system of knobs and kettles, with differences in relief of 15-20 ft. (5-6 m.). Two transverse recessional moraines occur near Meadowlark Lake, but they do not join the two morainal ridges. The major, and outer, lateral moraine extends along Meadowlark Lake until

it curves to intercept the western lateral moraine, which together form the terminal moraine.

The terminal Tyrrell Moraine (Figure 3b) is less well-developed than the Squaw Creek terminal moraine. The Tyrrell lateral moraine overlooks and cuts across the Squaw Creek moraine. The narrow ridge forming the Tyrrell terminal moraine rises 56 ft. (17 m.) above the Squaw Creek moraine and is 15 ft. (5 m.) wide. It has been breeched by former drainage which constructed a lower bench outside the moraine.

Enclosed within this system of lateral and terminal moraines lies the ground moraine, which mantles the bedrock on the modern valley floor. It covers the area between West Tensleep Lake and Meadowlark Lake. South of Meadowlark Lake, the ground moraine becomes hummocky with drained depressions and unoriented ridges rising 5 to 15 ft. (3-5 m.) above them (Figure 4b).

A medial moraine exists extending from West Tensleep Lake to near Bear Lake (Darton, 1906). The moraine is a low relief feature 15-20 ft. (5-6 m.) above the creeks which dissect it, with a rounded crest 100 to 300 ft. (30-91 m.) wide. The moraine occurs where the ice of the Middle Tensleep and West Tensleep glaciers converged.

a. Outwash The most extensive evidence of outwash in the study area is related to the Tyrrell Moraine. A terrace situated just north of West Tensleep Lake rises six ft. (2 m.) above the present stream level and is surrounded by channels of the present stream. Two terraces are observed in Boulder Park Campground, five ft. (2 m.) and two ft. (0.6 m.) above the present stream level. Near site 46, along Willow Creek, the

remnants of a terrace 4-5 ft. (12-15 m.) above the creek are recognized.

Many boulder lines are located along intermittent streams between Lake Helen and West Tensleep Lake. They are commonly 10 to 20 ft. (3-6 m.) across and extend from near the morainal crest to the valley floor, where they abruptly disappear. One well-developed boulder line is positioned immediately south of the landslide along Bald Ridge near West Tensleep Lake (Figure 3e). The depth of the deposit is unknown. At site 28, a boulder line occurs at the crest of the moraine where it has a pool and rifle topography. It trends down the outer slope of the lateral moraine, and is covered at the foot by finer material which is part of a terrace along Dry Tensleep Creek. Another example of a boulder line is located near Deerhaven Lodge. This boulder line follows a present intermittent stream from near site 35, to a boulder terrace just above the convergence with Tensleep Creek. Boulder Park Campground is located on outwash associated with the Tyrrell Moraine. Boulder strewn ridges trend southeast toward Tensleep Creek.

Post glacial modification of the eastern lateral moraine is indicated near the point where East Tensleep Creek crosses the moraine and joins Tensleep Creek. Sites 30 and 31 (Figure 2a) are located on the lateral moraine which has been cut by three channels 30 ft. below. East Tensleep Creek flows along one of these channels as an intermittent stream at the present time.

Darton (1906) reported the existence of extensive lake deposits along the eastern margin of the West Tensleep moraines apparently

located at the site of Meadowlark Lake. The adjacent Sitting Bull Campground may be part of this deposit. Its surface has a low relief and is devoid of boulders. Near the campground, boulders in a fine matrix were found at two levels in an exploration pit. The flat ground surface slopes up to the moraine, suggesting alluvial fan or terrace sediments.

b. Soil development Minimal soil development is present on Tyrrell moraines. An undecomposed O horizon extends to a depth of $1\frac{1}{2}$ to 2 in. (3-5 cm.). The A horizon has a silty sand texture with many cobbles, is 2 to 3 in. (5-7 cm.) thick with a weak granular or no structure present. The A horizon is a dark brown (10 YR 4/3). The lower boundary is indistinct. No B horizon is present. The C horizon is dark grey brown (10 YR 4/2) to dark yellow brown (10 YR 4/4), gravelly sand matrix surrounding boulders of greater than one ft. (0.3 m.) in diameter. X-ray defraction patterns on the silt and clay sized particles in the C horizon indicates the presence of quartz and feldspar as well as some mica clay.

c. Boulder analysis The weathering parameters for the boulders on the Tyrrell Moraine have the greatest range in values of all the glacial deposits. The range for boulder density in 2,000 sq. ft. (186 sq. m.) is 15-234 but the average, 102, is the lowest for all the glacial deposits. The moraine has the greatest range of iron stained boulders, but a very low mean. The average percentage of weathered boulders is 21 percent, less than one-half of the average for the Squaw Creek Moraine. The other statistics are summarized in Table 2.

Table 2. Geomorphic field data used to differentiate glacial deposits

	Climatic Zone(s)	Elevation above sea level	Position in valley	Height above major stream	Geomorphic feature(s)	Size and shape of terminal moraine
Mistymoon Moraine	Hudsonian, Alpine zones	9600 - 10,400 ft.	3 mi. from source	20 ft.	Ground, Lateral, Terminal moraines,	rounded crest 350-400 ft. wide, 40-80 ft. high
Tyrrell Moraine	Canadian, Transition zones	7,400- 10,200 ft.	3-13 mi. from source, on modern valley floor	100- 600 ft.	Ground, Lateral, Recessional Terminal, moraines	sharp crested 20 ft. wide 120 ft. high
Squaw Creek Moraine	Transition zone	7,200- 7,400 ft.	17 mi. from source on modern valley floor	85- 90 ft.	Ground, Lateral, Terminal, moraines	rounded crest 100 ft. wide 100 ft. high
Bald Ridge Moraine	Alpine, Hudsonian, Canadiar zones	9,200- 10,000 ft.	4-10 mi. from source on drainage divide	800 ft.	Lateral moraines	none
Borrow Pit Drift	Canadian zone	8,800 ft.	11 mi. from source on drainage divide	560 ft.	outwash	none

Table 2. Continued

	Characteristics of ground moraine	Size & Shape of lateral moraine	Associated outwash	Soil development	Color of till matrix	Shape of surficial boulders
Mistymoon Moraine	scattered and scarce	If present, narrow and small; few closed de- pressions	Boulder lines	shallow; 1-2 in. A hori- zon No B horizon	yellowish brown 10 YR 5/8	Angular
Tyrrell Moraine	mantles bedrock; waterfilled depressions common	complex of moraines closed de- pressions commonly filled with water narrow crests 20 ft. wide rise above moraine be- tween	Boulder lines, terraces along major streams, modification of lateral moraine	shallow; 2-3 in. A horizon no B horizon	pale brown 10 YR 6/3	Subangular to rounded
Squaw Creek Moraine	knob and kettle topo. few closed depressions	narrow crest 20 ft. wide 20-27 ft. a- bove ground moraine	stream terraces	weakly devel- oped; 3-6 in. A horizon Color B hori- zon 5-8 in.	brown 10 YR 5/2	Subangular to rounded
Bald Ridge Moraine	none	broad flat crest, 2500 ft. wide, on drain- age divide		moderately de- veloped; 5-10 in. A horizon 608 in B hori- zon	dark grey brown 10 YR 4/2	Rounded
Borrow Pit Drift	none		kame		brown 10 YR 5/3	Rounded

Table 2. Continued

	Boulder frequency	Percent weathered boulders	Percent iron stained boulders	Percent lichen covered boulders	Percent exfoliated boulders	Percent shattered boulders	Local relief (ft.)
Mistymoon Moraine	10 ^a 123 43.5 61-185	10 ^a 7 6.4 0-20	10 ^a 4 5.2 0-16	10 ^a 55 28.75 4-88	10 ^a 32 11.2 19-53	10 ^a 22 11.3 5-37	10 ^a 12 6.9 5-25
Tyrrell Moraine	40 102 50.6 15-234	40 21 9.2 4-42	40 9 20.8 0-97	40 73 23.5 5-100	40 26 13.5 9-66	40 28 17.2 0-76	38 25 15.6 5-55
Squaw Creek Moraine	8 118 38.9 67-168	8 45 9.2 27-59	8 11 8.3 1-28	8 71 17.3 50-97	8 28 13.2 12-47	8 6 4.2 0-9	8 24 9.3 17-42
Bald Ridge Moraine	8 132 53.5 88-200	8 48 15.2 17-69	8 8 8.63 2-29	8 43 28.6 0-79	8 30 20 13-65	8 20 7.7 9-33	8 17 7.8 5-25
Borrow Pit Drift	1 34	1 84	1 10	1 76	1 24	1 8	0

^aFor all data on surficial boulders, the numbers represent: Number, Mean, Std. Dev., Range.

5. Mistymoon Moraine

Many small deposits of glacial drift are situated in the ice scoured portion of the study area. These deposits characteristically occur in the hanging tributary valleys and are rarely more than three miles (4.8 Km.) from local source areas. The deposits represent a weak glacial advance younger than the Tyrrell Moraine. The altitudes of these moraines range from 9,600 ft. (2927 m.) in the Hudsonian vegetation zone to 10,400 ft. (3171 m.) within the Alpine vegetation zone.

The Mistymoon type area is located at Mistymoon Lake, near the headwaters of West Tensleep Creek at the northern boundary of the study area (Figure 2b). The moraine rises 80 ft. (24 m.) above the downstream valley floor, is 350 ft. (107 m.) wide and encloses Mistymoon Lake which is 20 ft. (6 m.) below its crest. West Tensleep Creek has incised a shallow (20 ft.) (6 m.) valley through the center of the moraine. The moraine is characteristically hummocky but lacks closed depressions on its surface (Figure 4d). It extends around the lake on the west and north, with swampy depressions and scattered boulders defining the surficial glacial features.

Although each of the moraines exhibited the same morphology, variations exist depending on local valley conditions. Mirror Lake, situated along a tributary stream of Middle Tensleep Creek is dammed by glacial drift, but no evidence of any moraines exist along the valley walls. Post glacial erosion has not modified the perennial outlet of the lake because of an overflow channel near the center of the terminal moraine. Above Mirror Lake and along the stream is another deposit of till with

pronounced closed depressions containing water and swamp vegetation. High, rounded knobs rise 10 to 15 ft. (3 to 5 m.) above the ponds in a random assortment. This area is also surrounded by steep scoured valley walls.

Other moraines are situated in tributary valleys to the north and south of Middle Tensleep Creek which enter the main valley. The moraines are not extensive, but do exhibit the characteristic hummocky, boulder strewn surfaces typical of glacial deposits. All of these moraines are less than two miles (3.2 Km.) from the local sources. The valleys, other than Middle Tensleep, have well-developed terminal moraines, marking the farthest extent of ice in the valley for this most recent advance.

a. Outwash As with the other glacial deposits, little evidence remains of outwash deposits associated with Mistymoon glaciation. Boulder lines, confined between moraine and valley walls, are found at Mirror Lake and at site 59 in the valley north of Mirror Lake; both are too small to be represented on the map (Figure 2b).

Another outwash deposit resembling an alluvial fan is associated with the moraine in the valley north of Bear Park. The surface of the deposit contains sinuous channels and bars typical of alpine outwash deposits. The bars are boulder strewn; the channels are usually less than five ft. (1.5 m.) below the bars. They trend parallel with the valley, sloping off the moraine.

b. Soil development Minimal soil development is characteristic of Mistymoon Moraines. A typical soil consists of a 1-2 in. (3-5 cm.)

thick, organic-rich, dark yellow brown (10 YR 3/3-4/2), silty sand A horizon which exhibits no structural development, except that associated with roots. This overlies a yellowish brown (10 YR 4/4), sandy gravel C horizon in which clasts greater than four in. (10 cm.) in diameter often lie in contact with each other. X-ray patterns on the C horizon indicate the presence of kaolinite.

c. Boulder analysis The average number of boulders counted per unit area are 123, more than either Squaw Creek or Tyrrell Moraines, but fewer than counted on Bald Ridge Moraines. An average of seven percent of the boulders appeared to be weathered, less than half of the percentage of weathered boulders observed on the Tyrrell Moraine. The other statistics for the surficial boulders are summarized in Table 2.

B. Glacial Erosion

Although the major emphasis of the study is on the distribution and relative age relationships of the glacial deposits, the features developed by glacial erosion are included here. The features in the study area are typical of the forms recognized in all glaciated terrains.

The types of erosional features can be subdivided into two groups which are large-scale and small-scale features. The valley through which West Tensleep Creek flows changes in cross-sectional slope along its length. It is U-shaped near the cirques of the tributary valleys, but changes to a more rectangular shape on the upper plateau (Figure 3c). In the lower gorge, the shape changes again to U-shaped. The glacially

Figure 6. Erosional and associated features typical of the scoured bedrock of the West Tensleep Drainage Basin

- a. Talus cones at the foot of scoured valley wall near the Fortress Lakes
- b. North-facing cirque above Lost Twin Lakes, with rock glacier at foot. Upper Lost Twin Lake is in foreground
- c. Scattered boulders on glacially polished surface near Mirror Lake
- d. Glacial striations on scoured bedrock surface. Notice the exfoliation. Glacial flow was away from the observer
- e. Flat valley floor which represents a possible former Lake bed

a **b** **c** **d** **e**

scoured area has been outlined on the map of the study area (Figures 2a and 2b) and many of the tributary valleys are included. These are hanging valleys because of the sudden drop in the valley floor formed when the ice of the tributary valley met the main glacier. Other large-scale features are valley steps, formed parallel to the ice flow, cirques and tarns (Flint, 1971, Embleton and King, 1968).

An impressive feature of glacial erosion in the study area is the large, north-facing cirque containing Lost Twin Lakes (Figure 6b). The relief of the cliff is over 1,100 ft. (335 m.) from base to summit. It appears to have undergone very little modification since deglaciation, although accumulations of colluvial debris are located along the valley floor. The majority of the tributary valleys in the West Tensleep Drainage head in low relief rounded features with gentle slopes.

The smaller-scale erosional features present in the study area are roche moutonnees, striations and glacial polish. Roche moutonnees are located near Mistymoon Lake and in the headwaters area of the Middle Tensleep drainage (Figure 2b), and exhibit steep downstream sides as compared to gentle upvalley slopes. Very little evidence of striations and glacial polish are found in the valley. Figure 6d indicates a possible reason why this is so. The striations can be observed, but the exfoliation and weathering of the upper layer of bedrock has destroyed most of this phenomenon. This is commonly the case, except upvalley from the latest glacial advance, where glacial polish and striations are observed on the bedrock (Figure 6c).

Lakes of several different origins exist in the West Tensleep Drainage Basin. Darton (1906) discusses four major types of lakes associated with glaciation. They include (1) tarns; (2) lakes in bedrock, but ponded by till; (3) the lakes and ponds enclosed by till; (4) the ice marginal lakes. Lakes from all four groups are represented in the study area. Lakes Helen and Marion, as well as Colden, Fortress, Gunboat, and Lost Twin Lakes are examples of glacial tarns. West Tensleep Lake, Mistymoon, and Mirror Lakes are examples of lakes bounded by scoured bedrock but which are ponded by till. Bear Lake as well as many small ponds and unnamed lakes are examples of the group surrounded by till. The presence of many former lakes are indicated by marshes along the major drainages (Figure 6e).

Meadowlark Lake is a reservoir along East Tensleep Creek. It occupies the bed of a former ice-marginal lake which was recognized by Darton (1906). The glacial lake was located along the eastern boundary of the West Tensleep Glacier at the southern terminous of the East Tensleep Glacier.

C. Periglacial Features

Under the term periglacial features are features and processes related to the zone peripheral to glacial ice (Embleton and King, 1968). The features in the study area are talus, block fields and block streams, rock glaciers, and landslides. Freeze-thaw action is one process which produces some of these features. The details of this process are discussed in Birkeland (1974) and in Sparks (1972).

1. Talus

Talus forms cone shaped accumulations of coarse and/or fine debris at the foot of cliffs. Many small accumulations of talus occur at the foot of slopes at or above 10,000 ft. (3048 m.) in the study area. However, the largest talus deposit is located at the base of a cliff in the Paleozoic rocks at an elevation of 6,500 ft. (1981 m.) near the southern border of the area.

The talus slopes at the higher elevations are characterized by a lack of vegetation resulting from their instability and lack of matrix. The cones commonly merge to form a wedge along the base of the vertical cliffs (Figure 6a). Aspect is of minor importance at the higher (9,600 ft., 2927 m.) elevations, as indicated by talus accumulations at the foot of differently oriented cliffs.

The large talus accumulation near the southern edge of the study area in Tensleep Canyon is situated at the base of a south facing cliff. Approximately three ages of talus can be distinguished by the type of vegetation, vertical succession and slope angle (not determined in this study) of the deposit. The youngest deposit is the smallest, consisting of intermittent cones, devoid of vegetation located at the foot of the cliff. The middle talus is a larger accumulation of debris which has been stabilized by grasses and scattered sagebrush. These cones have combined to form a uniform slope along the valley wall. The oldest accumulation is the sagebrush covered gentle slope at the base of the middle talus deposit. Intermixed with the dolomitic boulders and matrix of this deposit are granodioritic boulders. This suggests some

intermixing of glacial and periglacial zones. Because of the position of boulders beyond the limits of Squaw Creek Moraine, they are related to an older glacial advance which at the present time cannot be dated.

2. Block fields and block streams

Coarse angular blocks composed of locally derived rocks are located on mountain slopes above the limit of glaciation and usually above an altitude of 10,000 ft. (3048 m.). The feature has been termed a block field or felsenmeer. White (1976) recognizes two types which are block fields and block streams. Block fields result from freeze-thaw action on the local bedrock, resulting in thin accumulations of angular blocks found on mountain slopes parallel to the contours, while block streams are similar, they extend downslope normal to the contours and into the valleys. Neither type contains any fine interstitial matrix, which is supposed to have been removed by fast flowing water during a periglacial time (White, 1976).

3. Rock glaciers

Rock glaciers resemble talus deposits, and often occur adjacent to them at the foot of a slope. Rock glaciers exhibit evidence of movement such as flow lines, hummocks and depressions. White (1976) presents a thorough historical review of the development and recognition of rock glaciers. He recognizes two major types of rock glacier based upon the shape, with subdivisions based upon the arrangement of ice within it. Tongue-shaped rock glaciers usually are located on cirque floors. This group has been subdivided into two types. The ice-cored rock

glaciers are characterized by meandering furrows, collapse pits, and a central depression located at the foot of the cliff. The ice-cemented, tongue-shaped rock glaciers do not generally exhibit these features, but have parallel and transverse ridges, and furrows. The second major group of rock glaciers are called lobate rock glaciers and commonly occur along valley walls below talus accumulations. They are usually broader than long and extend at right angles to the tongue-shaped rock glaciers (White, 1976).

The best developed, lobate rock glaciers in the Bighorn Mountains are located just outside the study area in Florence Canyon, the headwaters of Clear Creek. In the study area, only one tongue-shaped rock glacier occurs. It is located at the base of the cirque wall at Lost Twin Lakes (Figure 6b). It is characterized by a steeply sloping front and a central depression between the cliff headwall and the deposit. Its dimensions are approximately 800 ft. (244 m.) wide and 1,000 ft. (305 m.) long and 180 ft. (55 m.) high. The presence of lichen on the rock surfaces indicate that it is stable at the present time. No excavation was undertaken on the deposit so the type of ice present, if any, is not known. Several small lobate rock glaciers occur along valley walls in Paint Rock and Middle Paint Rock canyons.

Most of the talus and rock glaciers occur within the limits of the Mistymoon ice advance. This indicates that they are younger than it and of Neoglacial age.

4. Landslides

Three areas of landslides occur within the study area. The most extensive area is along the north-facing slope in Tensleep Canyon, near the southern boundary of the area (Figure 2a). It is characterized by a hummocky surface morphology with very few closed depressions. A conifer forest is well established on it which indicates its stability. Within the landslide complex, a small area exhibits a younger morphology. It has areas which lack vegetation and contain springs, all of which indicate more recent movement. A fresh scarp is not associated with this landslide complex.

Two smaller landslides are located near West Tensleep Lake (Figure 2b). The smaller one exhibits a subdued morphology, a conifer forest and sagebrush cover, and no springs. A remnant scarp exists along the crest of the ridge. The larger landslide is west and north of West Tensleep Lake. It has a prominent semi-circular scarp, hummocky topography downslope, numerous closed depressions, and actively flowing springs. The deposit is covered with conifer vegetation.

Relative ages of landslide deposits have been determined in Shell Canyon in the Bighorn Mountains by Bible (1977). These are based on the surface morphology of the deposits. Comparison of the surface morphology of the four landslides in Tensleep Canyon to the descriptions of the activity classes in Bible (1977) follows. The largest landslide has a passive 3 morphology which is post Bull Lake - pre Pinedale I in age. The smaller landslide within it has a passive 2 morphology which is post Pinedale I - pre Pinedale II in age. The smaller landslide west

of West Tensleep Lake exhibits a passive 3 morphology, whereas the larger one has a passive 1 morphology. These last two landslides must be post Pinedale II in age.

V. COMPARISON OF GLACIAL DEPOSITS WITHIN THE WEST TENSLEEP BASIN

A. Geomorphic Criteria

In this study, topographic position and surface morphology are used to determine the relative age relationships of the moraines. As a general rule when comparing two moraines, the moraine located up-valley, the moraine enclosed by the other moraine or the moraine which truncates the pre-existing moraine is the younger glacial deposit (Easterbrook, 1969). Likewise, the degree to which a moraine has been preserved as compared to the other moraines indicates the amount of time which has elapsed since its deposition. Generally, older moraines exhibit a surface of little relief, few closed depressions and greater stream dissection than younger moraines.

To briefly review the age relationships given in the section on the description of the moraines, the Borrow Pit Drift is considered to be the oldest glacial deposit because of its location on the canyon rim and lack of hummocky topography as well as its isolation from any similar deposit. The Bald Ridge Moraines are older than the valley floor moraines but more recent than the Borrow Pit Drift because of their position on the canyon rim and their subdued, but still recognizable depositional morphology. The moraines on the valley floor, the Squaw Creek, Tyrrell, and Mistymoon Moraines, are significantly younger than the Bald Ridge Moraines because of their well-preserved depositional morphology and valley floor location. The differentiating characteristics are shown in Table 2. The outermost Squaw Creek Moraine is

believed to be the oldest. The cross-cutting relationship between it and the Tyrrell Moraine which is located up valley indicate that the Tyrrell Moraine is younger.

Differences in the surface morphology between Squaw Creek and Tyrrell deposits are subtle. Both moraines display fresh glacial topography but differ in the abundance of water filled depressions. The absence of extensive outwash between the Tyrrell and Squaw Creek moraines suggest that complete deglaciation did not take place and it is concluded that they are stadials of the same glaciation. The cross-cutting relationships of East Tensleep Creek, the terraces along West Tensleep Creek and Lake, and the boulder lines leading to major drainage ways can only be dated as post Tyrrell, because their relationship to the Mistymoon Moraines can not be determined.

The Mistymoon Moraines are confined to the tributary valleys and are poorly developed. These moraines are judged to be the most recent because of the lack of glacial material closer to the source.

B. Soil Development

In order for soil development to be used in support of relative age relationships, all of the soil forming factors except time, must be constant. A study in the Medicine Bow Mountains (Sansom and Reider, 1974) indicates that differences in soil development were more dependent on the vertical climatic and vegetational zonation than upon time. The wide range of climatic zones in the study area (Figure 1) may have influenced the weathering characteristics and soil development on the

Figure 7a. Textural analysis for soils developed on moraines of different ages. A and B horizons

Figure 7b. Textural analysis for soils developed on moraines of different ages. C horizon

Tensleep glacial deposits. With all other factors held constant, a more mature soil is indicated by the development of a B horizon. In the absence of a B horizon, the thickness of the A horizon can be used as an indication of the amount of time the deposit has been exposed to weathering processes (Birkeland, 1974). The particle size distribution of the till matrix is usually bimodal and may even be polymodal (Flint, 1971). Figures 7a and 7b illustrate the textural distribution for each deposit as compared by similar horizon. The bimodal characteristic can be traced in all C horizons, but becomes more subdued in older soils with the development of A and B horizons.

Based on these characteristics, speculation on time of exposure is possible for the soils of the study area (Table 2). Bald Ridge soils have been exposed to weathering processes for the longest time, as indicated by the development of a moderately strong B horizon. The textural distribution of the average Bald Ridge soil indicates the greatest change from C to A horizon. Squaw Creek and Tyrrell soils have texturally similar soils. The presence of a color B horizon in the Squaw Creek soils indicates a longer period of exposure to weathering than the Tyrrell soils, which lack a B horizon. The textural distribution as well as the lack of horizon development of the Mistymoon soils indicates a very short period of exposure.

The introduction of climatic variation into the observations on soil development does not appear to change the prior conclusions in the soil development. The soils developed in the Alpine Zone are the Bald Ridge and Mistymoon soils; which have been established as the end points

of soil development for this study. Under these similar environments, it is apparent that Bald Ridge soils have undergone more weathering than Mistymoon soils. Another climatic zone in which comparison of different age deposits is possible is in the Transition zone. The Squaw Creek and Tyrrell soils have been considered to be similar in development, but the small differences are attributed to age, rather than environmental variations.

The X-ray defraction patterns of the 4 phi fraction of the B and C horizons of the soils are inconclusive. Although the presence of layer silicates can be shown (Figure 5), the identification of the clay types cannot be more specific than mica-clays, mixed-layer clays and kaolinite. More detailed work would be necessary before any firm conclusions about the differences in the type of clay present can be made.

In summary, soil development can be used as a supportive evidence of relative age of the glacial deposits described in this report. Comparisons of the soil morphology and texture on an age basis as well as by climatic zones yield similar conclusions.

C. Regional Correlation

Regional correlation of alpine glaciations in the Rocky Mountains has been suggested by Blackwelder (1915, 1931), Holmes and Moss (1955), and Richmond (1965). Richmond (1962 and 1964) proposed that the glacial deposits in the Wind River Mountains should be the regional standard. However, Nelson (1954) and J. D. Love (personal communication, 1977)

indicate that regional correlation is at best tentative and interpretive because of its basis on the physical association of deposits of similar age, which rarely exists in one mountain range and never between ranges.

There have been very few absolute dates obtained from Rocky Mountain glacial deposits. Most dates available come from widely separated areas in which glacial deposits have been correlated to the deposits in the Wind River Mountains on traditional geomorphic and stratigraphic grounds. Recent work indicates that the pre-Bull Lake glaciation may be as old as the Illinoian of the Midcontinent (Mears, 1974). Early dates for Bull Lake and Pinedale glaciations came from lake deposits related to the Lake Bonneville erosion levels in Utah (Richmond, 1965). The radiocarbon dates tentatively bracketed Bull Lake glaciations between 70,000 yrs. to 30,000 yrs. B.P. (Mears, 1974, p. 23). Pinedale glaciations were approximated at 25,000 yrs. B.P. The last Pinedale glaciation was suggested to be 7,780 yrs. B.P. at low elevations and 6,190 yrs. B.P. at higher elevations (Richmond, 1965, p. 225).

New investigations from the Yellowstone area, where glacial deposits and lava flows interfinger, are based on K/Ar and Obsidian/Hydration methods. The data from K/Ar dating reveals that no Bull Lake materials could be younger than a 107,000 yr. B.P. date obtained from an overlying rhyolite flow (Mears, 1974, p. 24). Pinedale glaciations also began more than 45,000 yrs. B.P. Late Pinedale deposits dated by radiocarbon methods, from a peat bog associated with such deposits in the

Rawah Mountains, would place the latest Pinedale glacial advance at 6,700 yrs. B.P.

No absolute dates were determined for the present study area, thus relative age determinations can only be suggested. The following regional correlations are based on comparisons of geomorphic criteria, stratigraphic relationships, and soil development. The most probable correlations are illustrated in Table 3.

Table 3. Correlation of West Tensleep moraines with regional model

West Tensleep Drainage Basin	Regional Model	Sources
Talus, Lost Twin Rock glacier	Neoglacial	W. C. Mahoney, 1974, p. 239
Mistymoon Moraine	Late Pinedale	Richmond, 1965, p. 224-5
Tyrrell Moraine	Middle Pinedale	Richmond, 1965, p. 224-5
Squaw Creek Moraine	Early Pinedale	Richmond, 1965 p. 224-5
Bald Ridge Moraine	Bull Lake	Mears, 1974, p. 23-4
Borrow Pit Drift	Pre-Bull Lake	Mears, 1974, p. 23-4

The regional model and results of the present study agree in many aspects. The geomorphic criteria such as morainal forms, position in the valley, and distribution of deposits in the West Tensleep Drainage basin are similar to those identified in the Wind River Mountains. The lack of outwash in the study area is one primary difference in determining relative age of the deposits, that was an important factor used in the regional model. In spite of the many local environmental factors

that influence the extent of glacial advances, Table 3 represents the most reasonable correlation of the West Tensleep Drainage Basin deposits with the regionally proposed model.

VI. STATISTICAL ANALYSIS OF SURFICIAL BOULDERS

Statistical methods are usually applied to weathering data from surficial boulders on glacial moraines in order to determine their relative age relationships (Blackwelder, 1931; Birman, 1964; and Nelson, 1970). Comparison of the means, correlation and stepwise multiple regression techniques were employed in this analysis of the data when separated into the four age groups as based upon geomorphic criteria. The single weathering value from the Borrow Pit Drift was not included in the analysis. The data used in the analysis appears in Appendix and is summarized in Table 2.

Analysis of variance was used to determine the significance of variations between weathering parameters when classified by moraine. Weathering variables included are the number of boulders present in 2,000 sq. ft. (186 sq. m.), the degree of weathering, and the degree of iron staining. The amount of exfoliation, shattering, lichen cover related to the boulders, as well as the elevation and average relief of the site are included to determine the influence of the local environment. The degree of weathering ($F=40.01$), lichen cover ($F=4.24$), and shattering ($F=5.68$) are all significantly different. On the other hand, the number of boulders per unit area ($F=0.68$), iron staining ($F=0.33$), and exfoliation ($F=0.76$), average relief were not significantly different between the age groups.

Table 4. Means and t-statistics for different Ages, grass-sage vegetation

	Squaw Creek $\bar{X}$	Tyrrell $\bar{X}$	Significance ^a t_c	
Boulder frequency	133	138	No	0.28
Degree of weathering	57	74	Yes	2.77
Exfoliation	24	18	No	1.68
Shattering	4	2	No	0.42
Lichen cover	74	66	No	0.69

^aTwo-tailed test of significance level .01.

An examination of the environmental effects of vegetation upon the weathering of exposed boulders is possible between the Squaw Creek and Tyrrell Moraines. The Squaw Creek Moraine is dominantly under grass-sage vegetation, whereas the Tyrrell Moraine has both conifer forest and grass-sage vegetation within 1,000 ft. (350 m.) elevation. Boulder weathering variables which might be effected by environmental controls are number of boulders per unit area, degree of weathering, exfoliation, shattering and lichen cover. The analysis of boulders on the Squaw Creek and Tyrrell Moraines under grass-sage vegetation indicates that on deposits of different ages but with the same vegetation, the only significantly different mean (Student's t) is the degree of weathering (Table 4). The comparison between variables on

boulders in different vegetation--conifer forest and grass sage--but of the same age (Tyrrell) indicates that the boulder frequency, exfoliation and shattering are significantly affected by a change in vegetation (Table 5). The amount of lichen cover is not related to either vegetation or age. These comparisons verify the control of vegetation upon the weathering parameters.

Table 5. Means and t-statistics for same age deposits (Tyrrell), different vegetation

	Grass-Sage $\bar{X}$	Forest $\bar{X}$	Significance ^a t_c
Boulder frequency	138	68	Yes 4.74
Degree of weathering	74	81	No 1.18
Exfoliation	18	28	Yes 3.19
Shattering	2	39	Yes 8.00
Lichen cover	66	74	No 0.68

^aTwo-tailed test of significance level .01.

The existence of a systematic relationship between time and the weathering and environmental variables which differ significantly between moraines (degree of weathering, lichen cover, and shattering) can be investigated by correlation analysis and stepwise regression. Correlation analysis indicates that both degree of weathering and lichen cover are correlated with age, whereas shattering is not (Figure 8). Stepwise regression of these parameters indicates that age is significantly related to the degree of weathering (equation 1). The environmental

Figure 8. Relationships established by correlation of weathering parameters

Figure 9. Comparison of boulder weathering data from several areas in the Western United States (Modified from Birkeland, 1974, p. 158)

parameters lichen cover and shattering are not age dependent (equations 2 and 3). This relationship suggests that only the degree of weathering is age dependent. The other variables have no systematic variation with either age or elevation. Lichen cover varies inversely with the percent of exfoliation (Figure 8, equation 2), but exfoliation is not controlled by elevation, and thus is not controlled by the climate. The relationship between shattering and boulder frequency (Figure 8, equation 3) is related to the method by which boulders are counted. The more shattered boulders, the fewer boulders with diameters greater than one foot, and the lower the resulting boulder frequency, as well as a lower degree of weathering. The negative correlation between lichen cover and age (Figure 8) is suggested to be the result of the correlations between age, lichen cover, elevation and exfoliation.

$$\begin{aligned} \text{Equation 1. Degree of weathering} &= 55 + 0.0003 \text{ Age} - 0.005 \text{ Eleva-} \\ &\quad \text{tion} - .12 \text{ Shattering} \\ R^2 &= 0.74 \end{aligned}$$

$$\begin{aligned} \text{Equation 2. Lichen cover} &= 110 - 0.76 \text{ Exfoliation} - 0.12 \text{ Boulder} \\ &\quad \text{frequency} - 0.44 \text{ Average relief} \\ R^2 &= 0.27 \end{aligned}$$

$$\begin{aligned} \text{Equation 3. Shattering} &= 53 - 0.14 \text{ Boulder frequency} - 0.33 \text{ Degree} \\ &\quad \text{of weathering} \quad R^2 = 0.28 \end{aligned}$$

$$\begin{aligned} \text{Equation 4. Age} &= -111,204 + 2313 \text{ Degree of weathering} + 10 \text{ Ele-} \\ &\quad \text{vation} \quad R^2 = 0.71 \end{aligned}$$

The degree of weathering has been shown to be significant in relation to relative age by three different methods of statistical analysis.

Stepwise analysis for age (equation 4) indicates that the degree of weathering alone accounts for 64 percent of the variation in age. The addition of elevation, which accounts for 7 percent of the variation of age, indicates a weak environmental control on weathering. The total of 71 percent of the variation in age is accounted for by these two variables. The means for degree of weathering on the three youngest moraines, Mistymoon, Tyrrell, and Squaw Creek, are significantly different (Students t, $\alpha = 0.05$). However, the means for the degree of weathering for surficial boulders on Squaw Creek and Bald Ridge Moraines are not statistically different. The insignificance of these means may be related to the amount of shattering which takes place on the surficial boulders. The means for shattering for the four age groups (Table 2) indicate that less shattering occurs on boulders of Squaw Creek age. Stepwise regression and correlation indicate that boulders which have not been shattered, have a greater degree of weathering (equation 1, Figure 8). The amount of shattering is related to vegetation type (Table 5) rather than to age of the glacial material. It is speculated that the vegetation influence enters through forest fires which may cause shattering. Based on these relationships, the boulders on the Squaw Creek Moraine seem to be "over-weathered" when compared to the other deposits in this study and similar studies in other areas (Figure 9).

The portion of the study which relates surficial characteristics of boulders to the time of exposure is not the first of its kind, but the investigation of the influence of local environments on boulder

weathering is relatively new. A similar study conducted in the Sierra Nevada Mountains suggests that former boulder weathering analyses may be suspect because of variations in local environmental conditions (Burke and Birkeland, 1976). However, the results of the several studies which have used boulder weathering ratios are all similar in that the degree of weathering increases with age (Figure 9).

The inverse correlation established between average relief and elevation (Figure 8) indicates that moraines at high elevations, such as the Bald Ridge and Mistymoon moraines of this study, have low surface relief. It is suggested here that the relationship is subject to the time of exposure (Bald Ridge moraine) and conditions of the glacial advance (Mistymoon moraine) rather than any systematic change in regard to the two variables.

Other factors which have been used in previous studies as age determinants, are found not to be related to relative age in this study. For example, the boulder frequency on glacial moraines has been cited by many authors as an age criterion (Blackwelder, 1931; Nelson, 1954; Richmond, 1965; Nelson, 1970; and Birkeland, 1974). This study suggests that boulder frequency is related to the amount of shattering (equations 2 and 3) as well as the type of vegetation (Table 5). All of these variables are related to local environmental changes, rather than age of the glacial moraine.

Previous studies have used the amount of iron staining present on surficial boulders as an important criterion of age (Nelson, 1954; Richmond, 1965; and Nelson, 1970). Although the data were analyzed for iron staining, no relationship between it and any other variable could be

established. It may be that the exfoliation and shattering effects obscure the amount of iron staining. It is also possible that the composition of the rocks in the study area do not contain sufficient iron for it to be significant. However, the use of boulders of similar composition in all studies should not make this a significant factor.

In conclusion, the degree of boulder weathering is related to time of exposure and may be used to determine relative age of a moraine with some confidence (equation 4). The other conclusions of this study support the premise that in areas with large elevation differences, the validity of weathering parameters, such as degree of weathering, boulder frequency, and iron staining, for the prediction of relative age is to be suspect because of the micro-climatic effects as measured in this study by exfoliation, lichen cover, shattering, and vegetation.

VII. SUMMARY

The glacial deposits in the West Tensleep Drainage Basin represent a sequence of four glacial advances as determined by such geomorphic criteria as moraine morphology and position within the valley, with supportive evidence from the degree of soil development and weathering of surficial boulders.

The Borrow Pit Drift represents a stage of glaciation much older and more extensive than the subsequent glaciations. It is correlated with pre-Bull Lake deposits.

Bald Ridge moraines represent the next major stage of glaciation in the study area. The subdued morphology and extensive erosion of the valley indicate a significant length of time between this and the subsequent Squaw Creek advance. It is correlated with the Bull Lake of the regional model which may be either early Wisconsinian or Illinoian in age (Mears, 1974).

Squaw Creek and Tyrrell moraines are considered as stages of the same glaciation. Squaw Creek deposits terminate the farthest from the source with Tyrrell deposits ending within a mile (1.6 Km.) up valley. The fresh appearance of both deposits along with the lack of significant outwash deposits between them indicate a probable recession of the glacier rather than a complete deglaciation. These have been correlated, respectively, with Early and Middle Pinedale of the regional model.

Mistymoon moraines represent the most recent glacial deposits in the drainage basin. The position of the deposits in the tributary valleys near the source areas indicate the final accumulation of glacial

debris in the valley. These deposits are correlated with the Late Pinedale of the regional model.

The boulder analysis is of supportive value in the study. Weathering ratios are closely related with time of exposure (age), but other factors such as number of boulders exposed on the surface, iron staining, lichen cover, and exfoliation are more closely related to environmental factors than to age.

Soil development is useful in determining the end members of the age spectrum. The most mature soils observed in the study area are those on Bald Ridge Moraines, whereas the least developed solum is on the Mistymoon Moraines.

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X. APPENDIX: RAW BOULDER ANALYSIS DATA

Table 6. Raw boulder analysis data

Observation Number	Number of Boulders/ 2000 sq. ft.	% Weathered	% Ironstained	% Lichen Covered
1	150	46	28	99
2	145	32	24	72
3	150	30	9	71
4	146	35	3	87
5	111	41	8	72
6	145	47	13	86
7	145	59	14	55
8	72	50	3	87
9	67	49	12	50
10	234	25	0	99
11	100	25	10	51
12	175	26	2	100
13	145	42	23	64
14	125	33	5	99
15	164	28	2	92
16	120	13	0	95
17	147	25	0	90
18	108	22	2	85
19	102	25	1	75
20	108	27	4	69
21	58	16	0	70
22	98	13	97	38
23	99	16	2	70
24	61	35	1	76
25	94	53	6	55
26	106	50	3	61
27	48	20	0	96
28	89	15	4	27
29	63	32	4	82
30	93	33	88	92
31	113	22	3	66
32	50	12	0	95
33	52	18	0	94
34	65	18	0	88
35	41	26	0	94
36	168	27	9	62
37	180	16	8	5
38	146	69	8	79
39	181	17	8	51
40	155	20	16	58

% Exfoliation	Type of Vegetation	Type of Deposit	Age	% Shattered	Average Relief
12	6	2	35000	0	--
18	6	5	16000	0	7.5
14	6	5	16000	0	32.5
32	10	2	16000	35	25.5
17	6	2	35000	0	17.0
20	6	5	35000	0	42.5
33	6	5	35000	0	27.5
47	6	5	35000	0	20.0
41	6	1	35000	0	15.0
19	6	3	16000	0	32.5
9	6	2	16000	0	32.5
10	6	2	16000	0	30.0
28	6	2	16000	0	17.5
14	7	2	16000	0	40.0
21	6	2	16000	0	15.0
18	7	5	16000	55	38.0
14	7	5	16000	20	27.5
30	10	2	16000	53	20.0
17	6	5	16000	0	50.5
22	7	5	16000	0	55.5
24	10	2	16000	52	7.5
34	10	5	16000	39	12.5
18	10	2	16000	32	5.0
30	10	5	16000	45	25.0
13	5	5	145000	15	25.0
18	5	5	145000	26	5.0
12	10	5	16000	76	32.5
25	10	5	16000	32	40.5
10	6	5	16000	2	20.0
10	10	5	16000	15	20.5
35	10	5	16000	14	55.5
12	10	5	16000	28	25.0
16	10	5	16000	40	22.5
34	10	2	16000	38	20.0
22	10	2	16000	44	5.0
38	7	1	35000	3	20.0
18	7	5	16000	24	48.0
37	6	1	145000	9	17.5
44	5	2	10000	17	20.0
33	5	3	10000	10	7.5

Table 6. Continued

Observation Number	Number of Boulders/ 2000 sq. ft.	% Weathered	% Ironstained	% Lichen Covered
41	69	12	10	32
42	42	4	0	24
43	47	8	0	94
44	91	7	1	67
45	71	6	2	82
46	75	16	0	90
47	182	11	1	89
48	64	20	0	76
49	15	10	6	86
50	97	60	29	18
51	88	17	10	15
52	34	84	10	76
53	105	6	3	64
54	61	4	0	72
55	124	4	0	64
56	90	4	0	88
57	83	4	0	4
58	94	4	0	75
59	156	0	4	77
60	27	32	8	60
61	166	16	37	59
62	154	19	5	39
63	197	46	8	51
64	200	43	4	0
65	185	10	6	6
66	--	52	2	68
67	89	41	1	63