Glaciation of the Boulder River area, southcentral Montana
by Vance Keith Drain

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Science
Montana State University

Abstract:
The Boulder River area is on the northern flank of the Beartooth Range in southcentral Montana. Valleys which lie on either side of the Boulder River area have very different glacial chronologies. The Yellowstone Valley, to the west, has only Pinedale-age deposits while the Stillwater Valley, to the east, has the glacial sequence generally found within the Rocky Mountains, which is laterally extensive Bull Lake deposits which are breached by or contain younger Pinedale deposits. This study documents the sequence of glacial deposition in the Boulder River area using surf icial mapping and relative dating (RD) techniques. The glacial sequence is needed to analyze whether the Pinedale-age Yellowstone icecap, which was diverted to the Yellowstone Valley by rhyolite flows emplaced between the Bull Lake and Pinedale glaciations, contributed ice to the Beartooth (Boulder River area) icecap creating unusually extensive Pinedale equivalent deposits.

In the Boulder River study, RD criteria used to differentiate the glacial deposits include surface boulder weathering, moraine morphology, and soil characteristics. Deposits of two glaciations are found in the Boulder River area. Older McLeod (Bull Lake equivalent) deposits, breached by Nurses Lakes (PinedaIe equivalent) glaciers, are found in both valleys of the Boulder River system. Nurses Lakes lateral moraines are nested within the McLeod-age deposits. This sequence of glacial deposition is similar to other locations regionally except in the Yellowstone Valley.

The multiparametric clustering program, using the best RD variables, further subdivided the glacial sequence into stades. Only one stage of McLeod glaciation is recognized while the Nurses Lakes glaciation is divided into two stades. Based on regional correlation, McLeod deposits range in age from 150-140,000 yBP. The Nurses Lakes deposits range in age from 35-25,000 yBP (stade 1) and 15-10,000 yBP (stade 2).

Implications of the above findings are: 1) The Pinedale-age Yellowstone icecap did not contribute ice to the Beartooth icecap during Pinedale time. 2) Multiparametric cluster analysis has a limit of resolution of a two-fold age difference between glacial deposits, therefore ,deposits which are separated in age by less than a two-fold difference may be difficult to discriminate by this method.

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Vance Keith Drain

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

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INTRODUCTION

Purpose of the Study

Valleys on either side of the Boulder River area, in southcentral Montana, have a very different glacial chronology. The Yellowstone Valley, to the west, has only latest Pleistocene glacial deposits (Pierce, 1979) (Fig. 1). The Stillwater Valley, to the east, contains both Bull Lake and Pinedale deposits. Older Bull Lake terminal deposits are more extensive than younger Pinedale deposits (TenBrink, 1968). Relative dating (RD) techniques have been used in Idaho (Colman and Pierce, 1986) to subdivide glacial deposits into stades. In the Boulder River area, relative dating techniques were tested as a means to subdivide glacial stages into stades to yield a comprehensive glacial history.

Questions to be answered by this study are: 1) which relative dating variables best discriminate the relative ages of glacial deposits, and 2) did ice diverted by Bull Lake/Pinedale interglacial rhyolite flows on the Yellowstone Plateau, which greatly increased the magnitude of the Pinedale glaciation in the Yellowstone River Valley (Pierce, 1979), also contribute ice to the adjacent Boulder River glaciers and Beartooth icecap (Fig. 1)?

The objectives of this study were: 1) to map the glacial and lacustrine deposits, terraces, and landslides in the Boulder River area south of McLeod, Montana, 2) to document the stages and stades

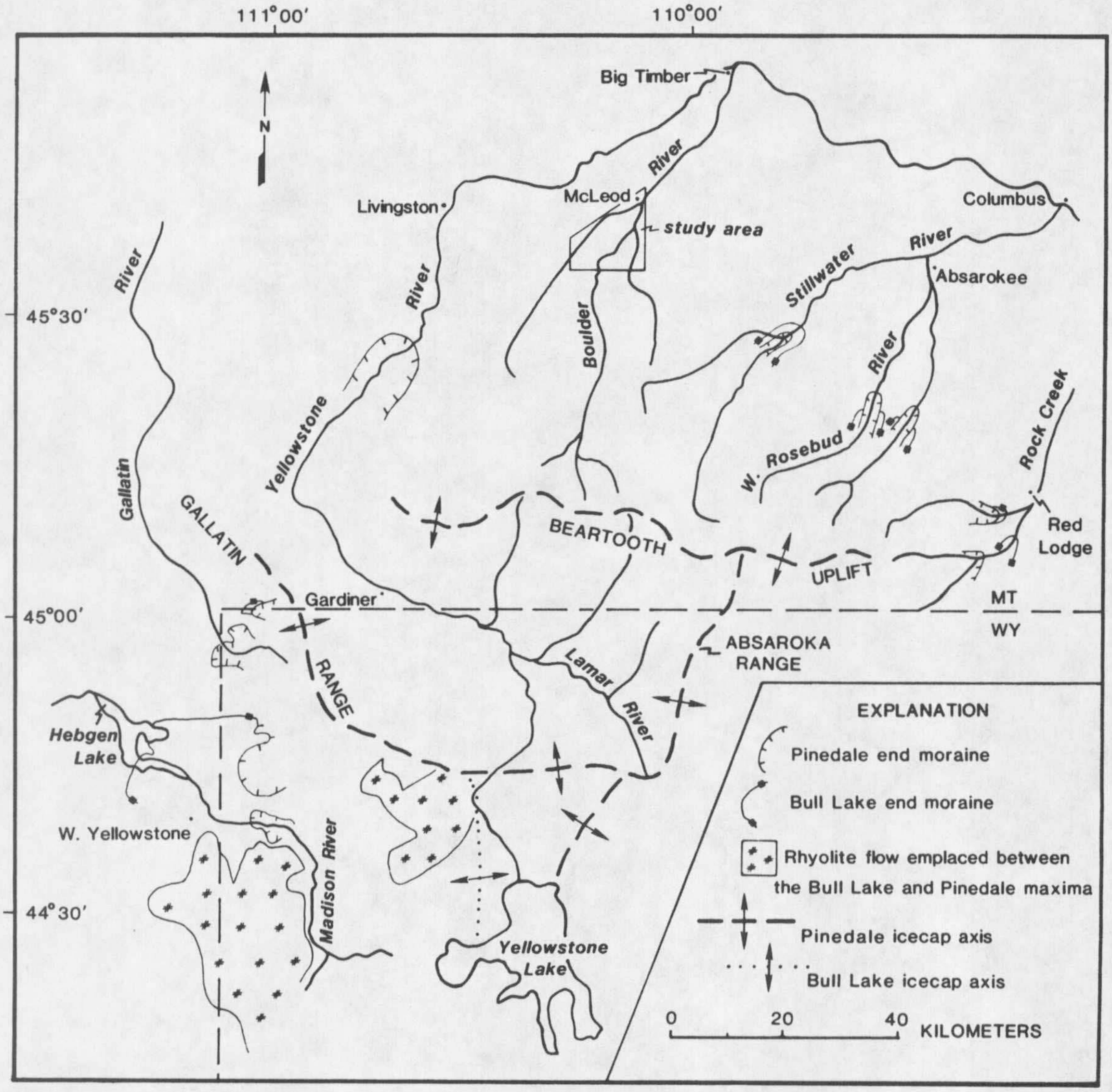

Figure 1. Generalized regional glaciation (modified from Pierce, 1979)

of glaciation represented in the McLeod area through statistical analysis of relative dating variables, 3) to determine how the Boulder River area glacial sequence correlates with deposits regionally, and 4) to produce a glacial history for the Boulder River valleys.

Field Area

The Beartooth Mountains of the Middle Rocky Mountains, in northwestern Wyoming and southcentral Montana, are an 80 by 40 mile block of Precambrian crystalline rocks elongated to the northwest. The Boulder River system (Fig. 1) drains the northwest corner of the Beartooth Mountains from elevations of about 11,500 feet to nearly 4,000 feet above sea level (a.s.l.) at the river mouth near Big Timber, Montana.

Bedrock

The Precambrian upland of the Beartooth Range is composed of planated metamorphic gneisses, amphibolites, Stillwater Complex mafic intrusives and other high grade crystalline lithologies. At the beginning of Laramide tectonism (mid Paleocene-early Eocene) approximately two miles of Paleozoic-Mesozoic sediments covered the Archean terrane. The Paleozoic section consists primarily of limestones and dolomites while the Mesozoic section consists mainly fine-grained clastic materials. The erodible upper Paleozoic and Mesozoic strata are represented by basins and lowered divides at the mountain front in the Boulder River area (Fig. 2). Excellent reviews of the pre-Quaternary stratigraphy in the Boulder River area and

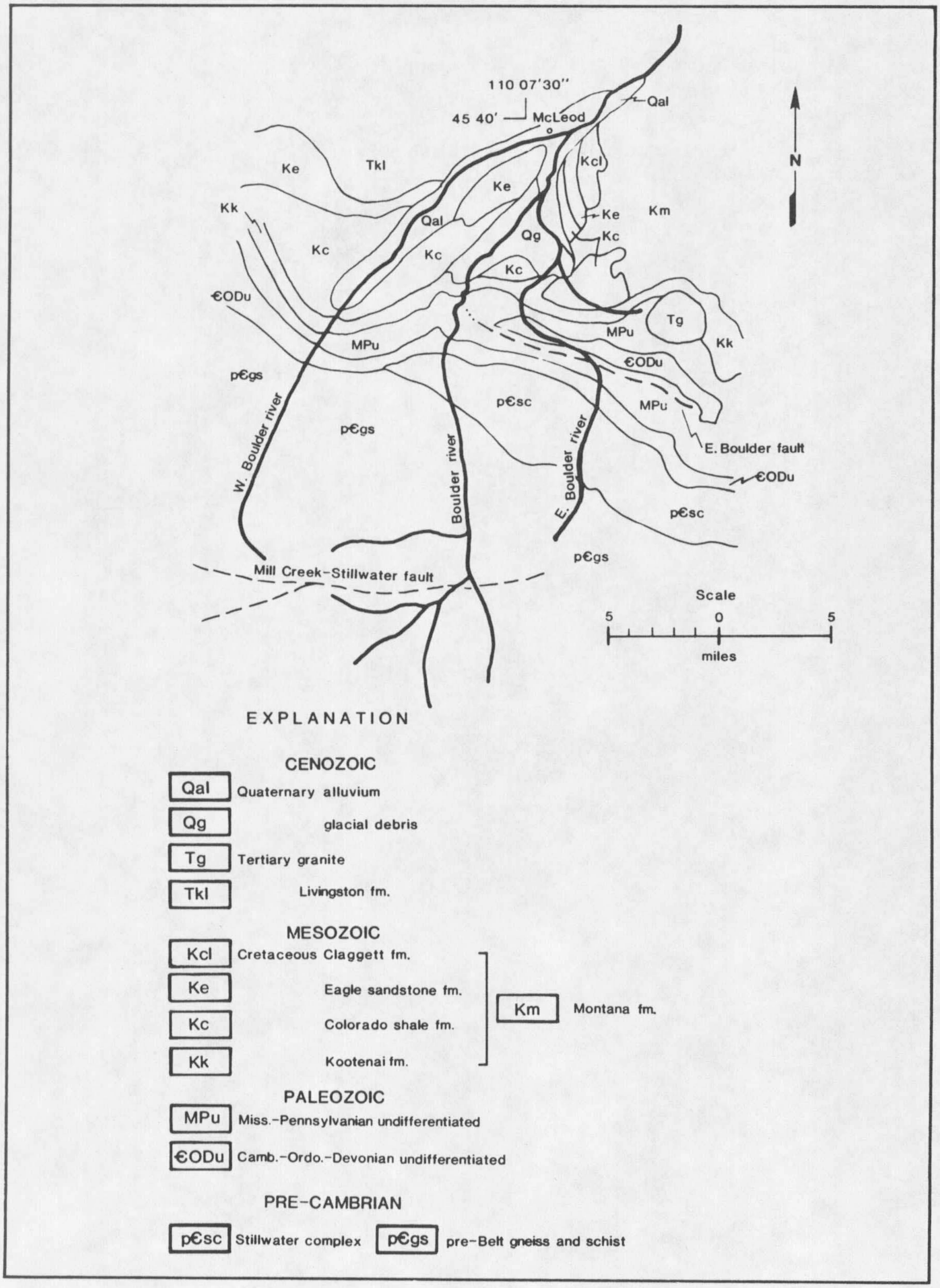

Figure 2. Generalized geologic map (modified from Foose and others, 1961).

Beartooth region have been done by Garbarini (1957), Richards (1957), Foose and others (1961), and Roberts (1972).

Geologic Structure

Structures in the Boulder River area are dominantly the result of Laramide tectonism. Laramide stresses reactivated preexisting Precambrian weaknesses to passively drape, fault, and fold the Paleozoic-Mesozoic sedimentary section (Foose and others, 1961). Most of the area drained by the Boulder River system lies within the North Snowy Block. This triangular block of uplifted crust is separated from the South Snowy Block by an east-west fault zone, the Mill Creek-Stillwater fault, (Wilson, 1936; Spencer, 1959; Foose and others, 1961; Roberts, 1972) (Fig. 2). The relative movement of the crust here during the Laramide was southward, opposite to the overall mountain rise along second order antithetic reverse slip faults (Richards, 1957; Foose and others, 1961; Schmidt and O'Neill, 1982; Lageson, personal communication, 1984). Continued Quaternary crustal movements in the nearby Big Horn Basin along the Nye-Bowler lineament, which continues along the northeast flank of the Beartooth Range, are possibly due to post-Oligocene fluvial erosion (Reheis, 1984). This fault zone extends into the Boulder region along the Dry Fork or East Boulder fault (Fig. 2). Also, extensional basin and range faulting is ongoing (Zoback and Zoback, 1980). In the Yellowstone Valley, to the west, Horberg (1940), Chadwick (1969), and Personius (1982) document recent tensional movements on the Deep Creek fault suggesting extensional normal faulting. The Beartooth block, to the east, continues to rise relative to the Yellowstone valley graben.

Most major structures, in the Boulder River area, parallel the mountain front. Laramide movement, in the Boulder River area, is manifest in a moderate to steeply north-dipping sedimentary section and northwest-plunging folds (Garbarini, 1957). Cuestas at the mountain front, with scarps facing south, formed barriers to northerly flowing glaciers. The north-dipping strata and cuesta flanks also provide the conditions for Quaternary landsliding within the Mesozoic sediments. Large Quaternary crustal movements have not been documented in the Boulder River area, but with the region's proximity to the Yellowstone Valley and location on the Nye-Bowler lineament Quaternary crustal movements are possible.

Peneplain Formation

As Laramide uplift slowed, the Oligocene Summit peneplain (plateau) and later the Pliocene Subsummit peneplain were formed (Bevan, 1925). Bevan (1925) attributes the second peneplanation to renewed crustal movements in middle Miocene. More recent studies by Horberg (1940) and Richmond (1960a) suggest that the uplands of the Beartooth Range result from only one erosional period, late Pliocene-early Pleistocene. In the Boulder River area, these erosional surfaces exist as the East and West Boulder plateaus, which lie nearly 10,000 feet a.s.l.

Terraces

Four well-preserved terraces, at various elevations above the present stream level, characterize major valleys of the region. Ritter (1967, p.470) states,

> "The terraces of any valley are often not, in most cases, physically continuous with terraces in other valleys. The fundamental terrace features, however, are essentially the same for every bench in the region, and the sequence of terrace levels is similar in each valley."

Ritter (1967) also includes the present day floodplain as a fifth terrace surface in his study.

Terraces in the region are believed to be the result of stream piracy, in which low-gradient plains streams capture high-gradient mountain streams, during glacial events (Bevan, 1925; Mackin, 1936, 1937; Ritter, 1967; Reheis, 1984). Reheis (1984) proposes that during a glacial event mountain streams begin to receive glacial debris and increased discharge. Discharge also increases on low gradient plains or tributary streams without glacial debris. This causes downcutting and headward erosion. The plains stream captures the mountain, glacier-fed stream and immediately aggrades, forming a glaciofluvial fill deposit. Terrace gravels then are apparently composed of glaciofluvial material although only the two youngest terraces have been definitely assigned to glaciations in the Rock Creek area (Ritter, 1967; Reheis, 1984).

In the Boulder River area, terraces were first described by Alden (1932) and later by Garbarini (1957) using Alden's nomenclature. Alden (1932) noted remnants of his terrace No. 1 on the east side of the Boulder River at McKenzie Flats, 6-8 miles south of Big Timber, Montana. The terrace lies at 550 to 600 feet above the river at an elevation from 4790 to 4900 feet a.s.l.

Alden (1932) describes terrace No. 2 as extensive gravel-capped benches on either side of the Main Boulder River below the confluence of the East and West Boulder rivers south of Big Timber. The terrace is 300 feet above the present day stream.

Terrace No. 3 is well preserved for 5-6 miles above the Big Timber bridge (approximately seven miles south of Big Timber) and borders the Boulder River Valley about 100 feet above stream level. Garbarini (1957) notes several small remnants as far upstream as the mouth of Castle Creek.

The lowest terrace (No. 4) is 10 to 20 feet above the Main Boulder River below the terminal moraine at McLeod, Montana. On this lowest terrace Garbarini (1957) reports boulders 3-4 feet in diameter 3 miles below the Main Boulder terminus and 1-3 foot boulders eight miles below McLeod. Alden (1932) goes on to say that terraces No. 3 and No. 4 merge upstream, presumably just below the McLeod terminal moraine.

Surface Runoff

Surface runoff, in the Boulder river system, is directly linked to the drainage basin area of each river. Drainage basin areas of the rivers at McLeod are: 1) 476 square miles for the Main Boulder; 2) 137 square miles for the West Boulder and 3) 85.6 square miles for the East Boulder.

Stations at the mouths of the major tributaries to the Main Boulder River near McLeod, Montana, show mean annual discharges of 75-80 cubic feet per second (cfs) on the East Boulder River and 188 cfs on the West Boulder River. The Main Boulder River discharge, near Big Timber, Montana, varies from a maximum of 9,840 cfs on May 28, 1956, to a minimum of 10 cfs about August 26 or 27, 1961. The 34 year average discharge is 543 cfs. Peak discharge on all branches of the Boulder river system occurs during late May and runs through July during the snowpack melt. Low flows occur during late August through September in response to the rapid snowpack loss of early summer and continued high evapo-transpiration during the late summer months.

Competence of the Boulder river system to incise Pleistocene deposits has been questioned. TenBrink's (1968) study of the Stillwater river system (Fig. 1) reveals that present streams are not competent enough to carry the large material of the glaciofluvial deposits. In the Boulder River area, many large boulders appear on glacial terrace treads and risers downstream from early to late Wisconsin maximum termini at McLeod, Montana. Incision is thought to be the result of: 1) glacial outwash waters carrying less than maximum load during waning stages of glaciation which used the surplus energy to erode earlier deposited material; 2) renewed vigorous fluvial activity associated with the next glaciation or 3) a response to some non-climatic factor (TenBrink, 1968).

Glacial Deposits

Glacial deposits, in the Boulder River area, include lateral and terminal moraines, thin veneers of erratic-covered bedrock, and glaciofluvial deposits. In the Boulder River area, deposits were first described by Weed (1893), and later by Alden (1932), Bevan (1943), and Garbarini (1957). Deposits, in the Boulder River area, are here described from west to east.

The West Boulder River glacial terminus is 5.5 miles upstream from McLeod. The terminus has been modified by stream action

(Garbarini, 1957). Lateral moraines appear both east (in McLeod Basin) and west (in Ellis Basin) of the West Boulder River glacial path (Plate 1). Moraines of both the Main and West Boulder glaciers are very similar, except for the composition of boulders (Garbarini, 1957). Deposits of the West Boulder River area contain a much lower percentage of Stillwater complex lithologies when compared to the Main Boulder River deposits (Fig. 2). The bedrock of the West Boulder drainage contains only a small portion of the Stillwater complex while the Main and East Boulder river drainages dissect the complex.

The Main Boulder River terminal moraine is at McLeod, Montana, located at the confluence of the West and and Main Boulder river valleys. Alden (1932) initially misinterpreted this deposit as the terminus of the West Boulder River glacier and attributed a small hummocky area of drift 1.5 miles south of this terminus to the Main Boulder River terminus. On a later map, Alden (1953) correctly reinterpreted these moraines. The large Main Boulder River glaciers overtopped sedimentary cuestas at the mountain front and deposited lateral moraines in both the East and West Boulder drainages.

Alden (1932, 1953) assumed the East Boulder River glacier had extended downstream past the canyon mouth into the East Boulder River/Elk Creek area. However, Garbarini (1957) interpreted these glacial deposits as the result of Main Boulder ice deposition. Garbarini (1957) describes the glaciers in the East Boulder drainage as small in comparison to the West and Main Boulder glaciers. Deposits do not extend out of the lower East Boulder River canyon; the largest of the Wisconsin termini are just downstream of the confluence of the East Boulder River with Dry Fork Creek (Garbarini, 1957).

Garbarini (1957, p. 183) uses the blanket statement, "McLeod area glaciers are represented by the largest late Pleistocene glaciers", to describe the most extensive glacial deposits. The largest, most extensive, late Pleistocene glaciers as described by Garbarini (1957) were of the Bull Lake advance.

No lacustrine deposits were noted by previous investigators, although Garbarini (1957) speculated there may have been ice-dammed lakes in the valleys of the East and West Boulder rivers.

Landslides

Topography, structure, and stratigraphy of the Boulder River area combined with the cool, moist conditions of numerous Pleistocene glaciations created optimum conditions for mass movement. Many past and present slides, slumps, and flows originate in the Mesozoic section, frequently in the Cretaceous Colorado shales (Garbarini, 1957) (Fig. 2). The slides often move downward along water-saturated dip slopes. Each Pleistocene glaciation removed previous landslides' toe slopes and reactivated movement with retreat. Montagne (1971) attributes sliding on similar Cretaceous materials in the West Fork Basin, Gallatin County, Montana, to additional surface load in the form of Bull Lake till. In many cases, landslides are presently undergoing movement. Fresh crevasses on landslides and flowlines on air photos substantiate recent movements. Local landslides can be mistaken for morainal material, but may often be positively identified based upon large angular blocks of overlying bedrock within the slide and springs flowing from the lobate toe.

Climate and Soils

The steep mountain flanks, in the Boulder River area, with a vertical rise of 4-5000 feet, create their own climate. The mountain flanks lie at elevations ranging from 6-10,000 feet a.s.l. Temperatures in the area range from a July mean maximum of 86 degrees Fahrenheit at McLeod, to a January mean minimum of 12 degrees Fahrenheit on the plateau surfaces (Cordell, 1971).

Mean yearly precipitation also varies greatly from 16 inches per year at McLeod, to 50 inches per year on the upland surface. The majority of precipitation occurs during the December-May period (Philip Farnes, SCS, personal communication, 1985). Orographic effects of the Beartooth Range also influence Boulder River area precipitation patterns. Typical west-to-east Pacific air flow drops precipitation on the Gallatin/Absaroka crests before encountering the Boulder River area (Fig. 1). This rainshadow effect leaves the Boulder River area with little to no precipitation. The large precipitation events, both winter and summer, occur when abnormal east-to-west traveling, warm, moisture-laden Gulf of Mexico air masses encounter the steep northern Beartooth Mountain flanks (Philip Farnes, SCS, personal communication, 1985).

Potential average annual evapo-transpiration rates are 23.5 inches per year near McLeod, to 12.5 inches per year on the plateaus (Caprio, 1973), again due to the dramatic changes in elevation at the mountain flank.

TenBrink (1968), in a similar area, divides the climate into two major regimes according to Blair (1942). First, the moderate-subpolar regime classifies the area above 6,000 feet. The climate here is cool and moist. Vegetation consists of coniferous forests and short, thick grasses, which change to scrub at treeline near 9,500 feet a.s.l. Second is the middle latitude, semi-arid, steppe regime below 6000 feet a.s.l. The climate here is much more arid, typical of the Great Plains (Blair, 1942). Vegetation consists of short and tall grasses, bunch grasses, sage brush and cacti with cottonwood, willows, and conifers in the valley bottoms. The study area is largely confined to the area below 6000 feet.

The climatic variables of precipitation, timing of precipitation, temperature, potential evapo-transpiration, and vegetative cover influence soil development. Oscillating climatic factors during Pleistocene to Holocene glacial events also were important to soil development. Reheis (1984) believes that the glacial climate was somewhat cooler and evapo-transpiration less than present. This would lead to increased soil moisture (a water surplus) and therefore increased production and leaching of calcium carbonate and clay translocation.

Three soil types are developed in the Rock Creek drainage (Reheis, 1984) and presumably along most of the northern Beartooth flank (Ritter, 1964; TenBrink, 1968). The soils are 1) mountain front soils which indicate past increased soil moisture with clay iluviation but no accumulation of calcium carbonate; 2) basin soils showing a relatively continuous accumulation of calcium carbonate (Bk) in a semi-arid environment presumably through eolian contributions (Reheis, 1984; Birkeland, 1984); and 3) a transitional or polygenic

(Bryan and Albritton, 1943, as noted in TenBrink, 1968) soil lying in the zone between the basin and the mountain front sequences. Reheis (1984, p.28) describes the transitional soils, "These soils exhibit spotty or irregular distributions of calcium carbonate, which probably reflects periodic leaching and precipitation of calcium carbonate." Ritter (1964) agrees, noting that replacement of the non-calcareous yellow-brown B-horizon with caliche, or vise versa, is evidence of undulating humid and arid climatic conditions. The transitional soils have wavy, irregular upper boundaries that also suggest periodic dissolution of calcium carbonate. Ritter (1964) believes that transitional soils mark the Pleistocene limit of migration of the boundary between arid-basin and humid-mountain climates.

Regional Quaternary Stratigraphy

Naming of Pleistocene glacial deposits, in the Beartooth area, usually follows the nomenclature first given to individual Rocky Mountain glacial events by Blackwelder (1915). The three Blackwelder geologic-climate units were first named in the Wind River Range, west-central Wyoming. The glaciations are designated Pinedale, Bull Lake, and Buffalo from youngest to oldest. Blackwelder (1915) tentatively correlated these deposits to the mid-Western region based on: 1) depth of stream entrenchment and extent to which the glacial deposits have been reduced in area; 2) degree of preservation of glacial deposits; 3) the position of the moraines in relation to modern stream valleys and their terraces; 4) the weathering of moraine surface boulders and erosional surfaces and 5) depth of soil on moraines.

Blackwelder (1915) assigned the Pinedale Glaciation to late Wisconsin, Bull Lake to early Wisconsin, and the Buffalo stage to Illinoian or Kansas drift sheets. TenBrink (1968) notes that later changes in correlations by Blackwelder (1931) followed work of Alden (1912, 1926); Kay (1929,1931); and Leighton (1930, 1931) and his own work in the Sierra Nevada. Blackwelder (1931) concluded that the Buffalo stage probably included till as old as the Nebraskan-age in the midwest. Because of confusion over the Buffalo stage correlation with mid-western glaciations and misassignments of the name to deposits of more than one glaciation, Richmond (1965) favored abandonment of the term Buffalo glacial stage and instead called all deposits older than Bull Lake, Pre-Bull Lake.

Recently there has been a controversy over the Bull Lake assignment to the midcontinent early Wisconsin glaciation. Pierce and others (1976), using obsidian hydration and K-Ar dating techniques, correlate Bull Lake-equivalent terminal moraines, in the West Yellowstone, Montana area, to late Illinoian deposits of the midwest. This correlation seems to agree with oxygen-isotope analysis, foraminiferal studies, and changes in the character of sedimentation in deep-sea core and strandline deposit studies carried out by numerous investigators (Emiliani, 1966, 1972; Mesolella and others, 1969; James and others, 1971). Apparent absolute dates on glacial events are 11,000-75,000 yBP for Pinedale and 127,000-170,000 yBP for Bull Lake (Pierce and others, 1976).

Deposits of at least two glacial advances in the Beartooth region have been described by Weed (1893, 1896), Bevan (1923, 1941, 1944,

1946) and Alden (1932, 1953). Horberg (1940), Montagne (1964), Montagne and Chadwick (1982) describe glaciation of the Yellowstone Valley. Pierce (1979) also describes glacial deposits associated with the Yellowstone icecap, including those in the Yellowstone Valley. Garbarini (1957) describes glaciations in the Boulder River area, TenBrink (1968) in the Stillwater drainage, Ritter (1967) in Rock Creek area, and Bluemle (1962) in the Crazy Mountains north of the Beartooth Range. Richmond (1957a, 1965) describes the general sequence of glaciations in the Rocky Mountain region.

Alden (1932) E. Montana	Horberg (1940) Yellowstone Valley S. of Livingston, MT	Bluemle (1962) S.W. flank Crazy Mtns., MT	Ritter (1967) N.E. flank Beartooth Mtns., MT	Rayne (1982) Yellowstone Valley E. of Livingston, MT
No. 3 Bench Pre-Wisconsinan	Terrace 3 Pre-Early Wisconsinan	Surface IV Intra-Wisconsinan	Pinedale 5 Bull Lake 4 Terrace 3	Ty2 277,000 yBP Ty3
No. 2 Bench Pre-Iowan	Terrace 2 Pre-Kansan	Surface III Pre-Intra Wisconsinan	Terrace 2 Pre-Wisconsinan	490,000 yBP Ty4 1,500,000 yBP
No. 1 Bench Miocene-Pliocene	Terrace 1 Late Pliocene-Early Pleistocene	Surface II Pre-Wisconsinan	Terrace 1 Early Pleistocene	

Figure 3. Regional terrace correlation (after Rayne, 1982)

Terraces were first described in eastern Montana and the Boulder River area by Alden (1932) (Fig. 3). The highest terrace is Alden's terrace No. 1. This terrace surface correlates with the Collier and Thom (1918) Flaxville terrace in northeastern Montana. Alden (1932) assigned these highest terraces an age of Miocene or possibly Pliocene. Later investigators place a later age estimate on these highest terrace surfaces (Fig. 3).

Horberg (1940), in the Yellowstone Valley, assigned the age of late Pliocene to early Pleistocene on his Terrace 1 based on vertebrate fossil evidence. Bluemle (1962), in the Crazy Mountains, north and west of Big Timber, Montana, placed an age of early to mid Pleistocene on his Surface II which corresponds to the Alden No. 1 terrace. This was based on cross-cutting relationships in glacial and terrace deposits. Rayne (1982), studying terracing in the Yellowstone Valley east of Livingston, Montana, placed his oldest terrace four (TY4) from early to mid-Pleistocene.

The Rayne study placed absolute dates on terrace deposits based on correlation to nearby studies of weathering rind data on basalt cobbles and calcium carbonate accumulation (Colman, 1977; Machette, 1978). His terraces 1-4 are thought to be Pleistocene in age and 2-4 are probably older than Bull Lake based on Rayne's statement (1982, p.55) that, "although the Bull Lake outwash is extremely subdued (in the Boulder River area), it appears to be at a level well below the Yellowstone terraces at Big Timber".

The Airport Flats terrace (Alden No. 2) south of Big Timber on the east side of the Main Boulder River is more like a Boulder River terrace than a Yellowstone terrace, primarily based on cobble composition (Rayne, 1982). Rayne (1982) equates this terrace to his terrace four (TY4) on the Yellowstone terrace system because of elevation similarities between the two terrace surfaces.

Boulder River terrace surfaces and locations have been previously described. The terrace surface nomenclature follows Alden (1932) with all four terrace surfaces existing in the Boulder River area. At McLeod, terrace No. 2 (300 feet above present stream level) is presumed older than glaciation and No. 3 may be younger than the latest Pleistocene glaciation (Garbarini, 1957). It is interesting to note that all terrace surface locations are downstream from McLeod, the terminal zone for the latest Pleistocene glaciation.

In summary, it appears that the latest investigators believe the oldest terrace surfaces in the area surrounding the Boulder River system to be at most very late Pliocene, but generally Pleistocene in age (Fig. 3). Only the lowest one or possibly two terrace surfaces correspond to the latest recognizable glacial events, the Bull Lake and Pinedale glaciations.

METHODS

Initial interpretations of Boulder River area geomorphic features on air photography and topographic maps was conducted during the winter of 1983-84. A field check of the geomorphology was carried out during the summer and fall of 1984. Semiquantitative relative dating (RD) techniques were used to differentiate various ages of glacial deposits. Multiple RD techniques were employed because as Blackwelder notes (1931, p. 880),

> "Of all these criteria (techniques) only a few can usually be applied in any one place. One of them alone affords only a tentative opinion but when several of them all point to the same conclusion confidence (in age assignment) is much strengthened."

Most researchers of Quaternary stratigraphy use RD techniques originally outlined by Blackwelder (1931) and summarized by Burke and Birkeland (1979). Relative dating techniques used, in the Boulder River area (Table 1), followed Burke and Birkeland (1979) and Pierce (1979), but were modified where necessary in the field. Each of the time-dependent RD techniques will be described, although, the majority of these procedures have been outlined more completely in other publications. Omitted entirely are descriptive time-independent variables which are self-explanatory.

Table 1. Relative dating techniques (after Pierce,1979).

I. Time-dependent indicators of relative age

A. Weathering criteria

1. Surface boulder weathering
   a. Fresh to weathered ratio (% Weathered)
   b. Hammer blow weathering ratio (% Ring)
   c. Surface boulder frequency
   d. Diameters
   e. Maximum boulder diameter
   f. Lithologies

2. Moraine morphology measurements
   a. Crest width
   b. Proximal slope
   c. Distal slope

3. Soil development
   a. Thickness of the epipedon
   b. Soil structure
   c. Depth to calcium carbonate
   d. Clay enrichment of B-horizon
   e. Soil color change

II. Time-independent indicators of relative age

A. Cross-cutting relations in plan view

1. Moraine position
2. Ice dams, landslides, change in transport direction

B. Sequence relations

1. Position relative to ice source
2. Stratigraphic sequences
3. Required age relations by geologic history reconstructions

Burke and Birkeland (1979) find that various individuals using identical RD procedures on the same glacial deposits cannot produce similar results. Human error is attributable to each individual's interpretation of the RD procedure being used. As a result, I conducted all RD procedures to minimize variation in sampling results due to human error. Methods of relative dating are shown in Table 1.

All sample sites were located at moraine crests to minimize vegetation and wind variables and also to standardize the area to be sampled (Clark, 1967, as reported in Burke and Birkeland, 1979). Relative dating sites are locations at which relative dating procedures were conducted. Soil sites are locations where soil pits were dug and the profile sampled. Individual relative dating and soil sites were located at the same position or in close proximity along the moraine crests. Soil site RD variables should reflect trends in the data similar to those found for nearby RD sites on the same moraine crest. The similarity in data trends along a single moraine crest is attributable to the age of the deposit.

Surface Boulder Weathering

The measurement of surface boulder weathering assumes that with time, surface boulders are altered both chemically and physically (Crook and Gillespie, 1986). Although the chemical and physical processes operate at different rates, the resulting effects can be measured and shown to be significantly different between glaciations (Carroll, 1974; Burke and Birkeland, 1979).

Fresh to Weathered Ratio (% Weathered)

In the Boulder River area, fifty quartzofeldspathic boulders were analyzed at each site to determine the weathered percentage. A boulder is considered weathered if 50% or more of the exposed surface exhibits single grain relief (Burke and Birkeland, 1979). A weathered boulder is rough to the touch, an unweathered boulder is smooth.

Lithologies were not selected at random as Burke and Birkeland (1979) mention but the Precambrian granite-like lithologies were used exclusively. Weathering effects should be maximized on these lithologies. Also, granites and quartzofeldspathic gneisses are found throughout glacial deposits of the Boulder River area whereas other lithologies vary according to the valley from which they came.

Hammer Blow Weathering Ratio (% Ring)

This technique also uses also uses fifty boulders but of varying lithologies. In the Boulder River area, surface boulders were struck and classified as either; grusified- if the cobble disintegrates on impact, weathered- if it gives a dull thud, or fresh- if the boulder gives a sharp ringing sound (Burke and Birkeland, 1979). The findings were reported as the percentage which rang (% Ring).

Surface Boulder Frequency (SBF)

The frequency of large boulders on the surface of glacial deposits should decrease with age (Burke and Birkeland, 1979). Surface boulder frequency should be lower on Bull Lake deposits than on Pinedale deposits although original boulder deposition and site location probably have a great influence on surface boulder frequency (Burke and Birkeland, 1979; Colman and Pierce, 1986).

In the Boulder River area, boulders greater than 20 inches (50 cm) in diameter were counted, in an area enclosed by a 20 by 100 foot rectangle (2000 ft^2 or 186 m^2) This rectangular area was placed where there appeared to be a maximum boulder concentration. At each site one or more counts of boulders were made. To insure accuracy, more than one count was made at sites where there were many boulders greater than 20 inches in diameter. At those sites, the mean number of boulders was the final number used to represent surface boulder frequency.

The area used to measure the frequency of surface boulders varies from study to study. Both Sharp (1969) and Burke and Birkeland (1979) used similar rectangular areas (2000 ft^2), however, TenBrink (1968) in the Stillwater area used a 400 square foot area.

The diameter of surface boulders also varies according to the study cited. Sharp (1969) and TenBrink (1968) used boulders greater than 12 inches (30.5 cm) in diameter whereas Burke and Birkeland (1979) chose a diameter of greater than 20 inches (50 cm).

The present study follows parameters outlined for surface boulder frequency measurements by Burke and Birkeland (1979). A diameter size greater than 20 inches and a rectangular area 20 by 100 feet should produce enough boulders per count to reveal a statistical difference between first-order glaciations. Also, with the minimum diameter greater than 20 inches, measurement time will be more rapid.

Diameters

Diameters of individual lithology were measured at each RD site to reveal which lithologies weather more quickly and if the individual diameter measurements were significantly different between glaciations in the Boulder River area deposits. In the Boulder River area, thirty boulders greater than 20 inches in diameter, were randomly measured along their largest axial diameter at each RD site.

Maximum Boulder Diameter

The diameter of largest erratic at each site was recorded. This RD measurement was carried out to see if the maximum boulder diameter was consistently larger in any particular glaciation. Maximum boulder diameter should decrease with time as do the other surface boulder weathering criteria (Burke and Birkeland, 1979).

Lithologies

Burke and Birkeland's (1979) statement that with age less resistant lithologies will become less frequent was tested in the Boulder River area by lithology data collection. The lithology data collection also assists in determining provenance of McLeod area glacial deposits (Garbarini, 1957).

In the Boulder River area lithology analysis, thirty boulders greater than 20 inches in diameter were selected at random and classified by lithology at each site. To expedite data gathering, certain lithologies were grouped together. The four resulting lithology groupings include: 1) Quartzofeldspathic gneisses and granites which were grouped together as they possess similar texture and composition. 2) Precambrian Stillwater Complex lithologies which include gabbros, anorthosites, norites, and troctolites. 3) Sedimentary lithologies which include limestones, sandstones, conglomerates, and 4) "Other lithologies" which include Precambrian mica schists, amphibolites, metabasalts, quartzites, and garnet bearing quartzofeldspathic gneisses, were retained in the final group.

Moraine Morphology Measurements

Although the original morphology is unknown, it is assumed that with time moraines generally will exhibit wider crests and more subdued proximal and distal slopes (Burke and Birkeland, 1979). In the Boulder area, several measurements were made on lateral, terminal, and disintegration moraines in an attempt to use modification of original topography as an indicator of age.

Measurements follow procedures outlined in Colman and Pierce (1986) and are perpendicular to the moraine crest. Definitions of the three morphology measurements taken are: a) Crest width is the distance between two points one eye-height below the crest on either side of the crest. b) Proximal slope is the moraine slope nearest the former ice position measured by clinometer. c) Distal slope is the slope away from former glacial ice. Where moraine type was unknown, bearing directions were used to indicate the slope being measured.

Soils

Numerous investigators of the Quaternary of the Rocky Mountains feel that soil characteristics can be used to reveal relative age of glacial deposits (Richmond, 1962a; Sharp, 1969; Pierce 1979; Shroba, 1981; Machette, 1982; Colman and Pierce, 1986; Reheis, 1984). With time, soils generally show: 1) thickening of epipedon; 2) more developed soil structure; 3) increase in concentration of calcium carbonate and a larger zone of calcium carbonate accumulation; 4) clay enrichment of the B horizon (Bt); and/or 5) reddening of the soil. The degree to which any of these soil characteristics is developed depends upon climatic conditions and parent material.

In the McLeod area, successive lateral moraines of differing ages, at similar elevations, and with a nearly identical climate and vegetation, provide ideal areas for soil studies. Thirty soil profiles were sampled and described following the Soil Survey Staff (1975). Samples were taken of each major horizon every 6-9 inches in a vertical channel except where unusual areas occurred within the profile. An unusual area might be a unique color change or a mottled area within a designated horizon. Such areas were separately sampled. Recorded at each soil profile were individual horizon depth, color (moist and dry), texture, percentage coarse fragments by volume, structure, consistence, boundary characteristics and pH. Also, general information of site location, vegetative cover, presumed parent material, physiography, relief, elevation, slope, aspect, drainage, moisture depth, total profile depth, depth to $CaCO_3$, and stoniness were noted. Additional unique characteristics of each individual site were also noted, for example, an indurated $CaCO_3$ horizon, organic matter, possible local age relations, and on-site intuition of factors contributing to individual soil characteristics.

RESULTS

Deposits from two episodes of glaciation are found in the Boulder River area (Plate 1). They are termed McLeod (older) and Nurses Lakes (younger) from the areas in which they are best displayed. These deposits were mapped and sampled in the field prior to statistical analysis of the relative dating (RD) data. The older glaciation is recognized principally by subdued morphology, extensive breaching of deposits by perennial streams, and a topographic position outside of or lateral to younger adjacent moraines. The younger deposits have irregular surfaces composed of numerous small mounds and depressions. Many of the depressions are undrained and often there are irregular drainage patterns. These moraines are generally lower in elevation than older deposits at a given distance from the mountain front and are roughly parallel to the present streams.

In-the-field observations include nested lateral moraine crests, ice marginal drainages, terminal moraines, distribution of erratics, elevation of possible glacial lake shorelines, and flood bars from jokulhlaups. Glacial features will be described first on the eastern flank, then on the western, then at the terminus in both the Main and West Boulder valleys.

Main Boulder River Deposits

As the ice of the last two glaciations exited the confined Main Boulder Valley it spread laterally, flowing both east and west over the large north-dipping cuestas. The main ice mass flowed in a northerly direction, skirting the cuestas, toward the West Boulder River and East Boulder River/Elk Creek areas.

Eastern Flank

The eastern flank of the Main Boulder glacier flowed into the East Boulder River/Elk Creek area, depositing lateral moraines (Fig. 4). This series of lateral moraines lies between 6000 and 5500 feet a.s.l. Lateral moraines are identified on the basis of location parallel to the glacier margin and ice flow direction and the presents of distal and proximal slopes (Sugden and John, 1982). In the field, two glacial events are evident. The older McLeod lateral moraines generally have wider crests and lower proximal and distal slopes than younger Nurses Lakes lateral moraines in any series of nested lateral moraines.

The ice marginal channel patterns reflect both the movement of ice and the shape of the topography (Sugden and John, 1982). The channels are identified by their position parallel the lateral glacier margin. Ice marginal channels can be followed along most of the prominent lateral moraines. Some channels can be traced from the lateral moraine locations to the valley floor (Fig. 5). Ice marginal channels are used to define ice margins but do not provide the basis for stage subdivision.

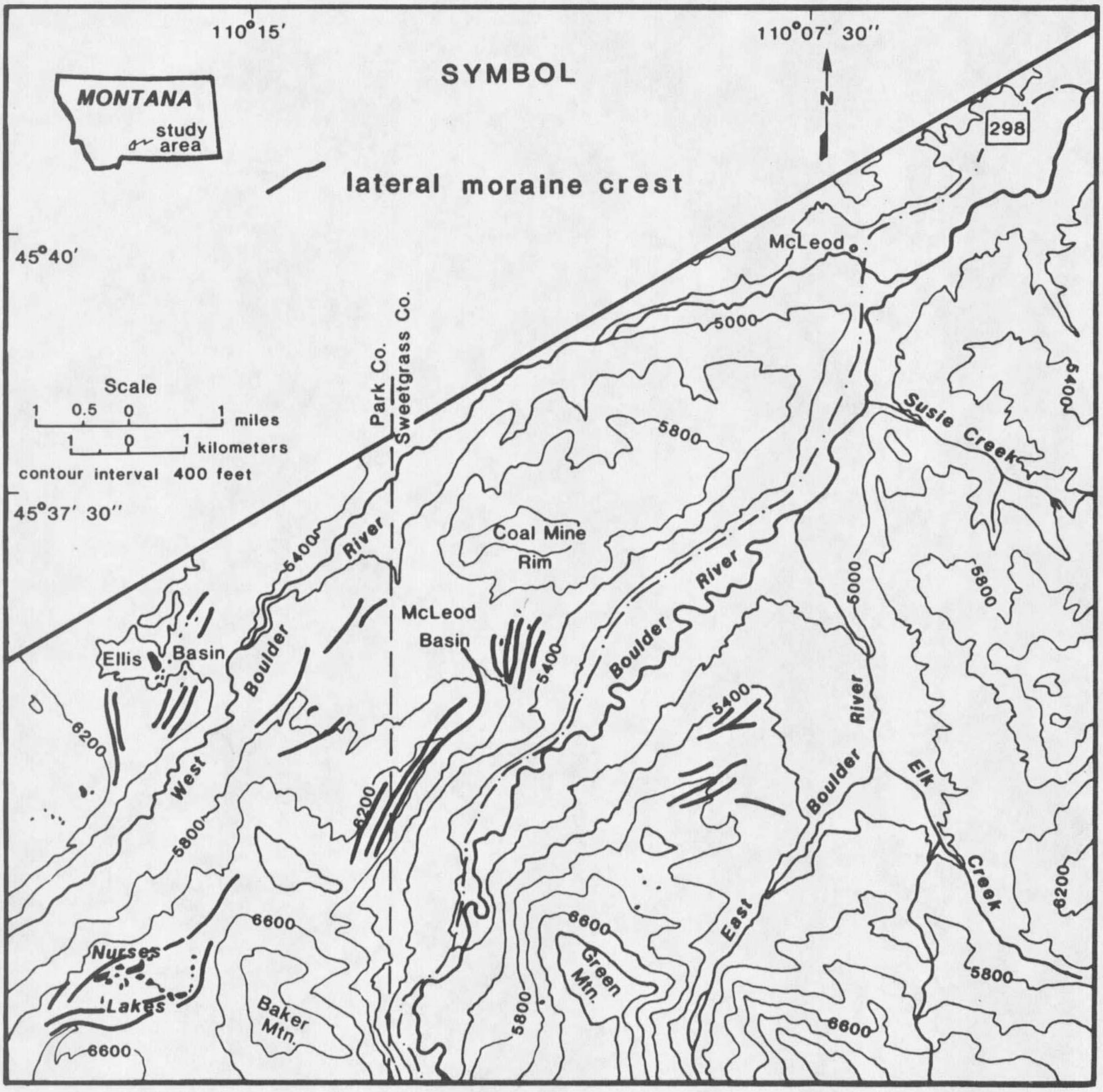

Figure 4. Location of lateral moraine crests

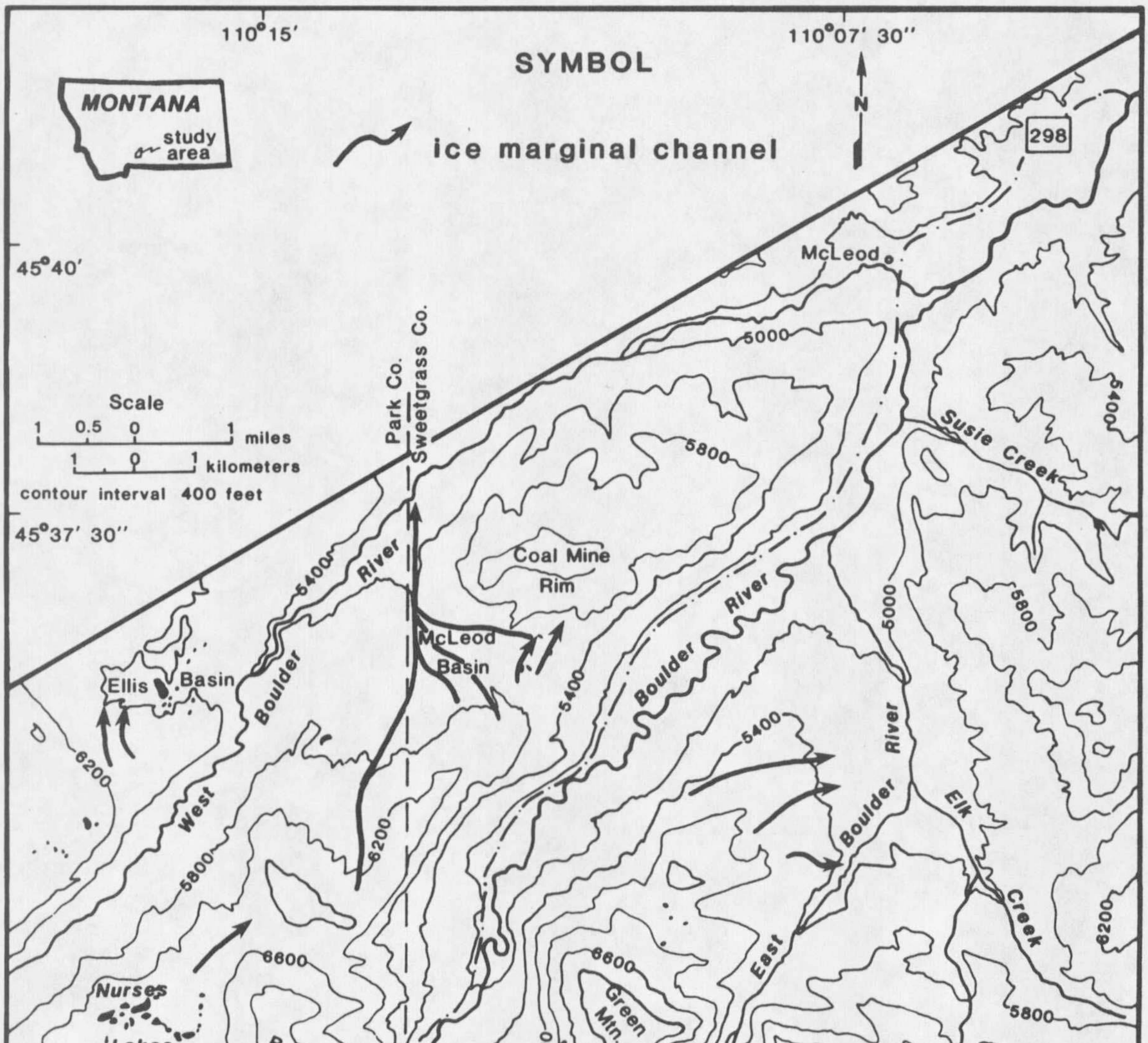

Figure 5. Location of large ice marginal channels

<u>Glacial lakes and associated deposits:</u> The eastern flank of the Main Boulder glaciers spilled across the East Boulder River/Elk Creek drainage to the Cretaceous Eagle Sandstone cliff to the north, thereby damming the streams and creating glacial lakes (Fig. 6). Lake stands were identified on the basis of ice-rafted dropstones and shoreline terraces. The small, poorly defined lake shoreline terraces were identified largely on topographic and air photograph coverage of the area. High stand for the lake was 5600 feet, while the lower lake level is 5500 feet. The two terrace/lake levels are tentatively correlated with the two major glacial advances on the based on position of each glaciation's lateral moraines on the East Boulder River/Elk Creek cuesta and maximum extent of glaciation as marked by erratics at the lake outlets to the north.

Surficial deposits in the lake bed area include ice-rafted erratics and thick deposits of glacial, glaciofluvial, and lacustrine materials which have been dissected by the East Boulder River and Elk Creek. Garbarini (1957) notes that in some areas the deposits have been incised up to 100 feet by the East Boulder River. The East Boulder River/Elk Creek valley floor areas also exhibit many ice disintegration features: hummocky terrain, and undrained depressions associated with the latest glacial advance and withdrawl from the area. Much of the former lake bed is presently used for irrigated alfalfa production and has been picked clean of the smaller erratic cover making RD methods and strandline deposits impossible to use in age determinations.

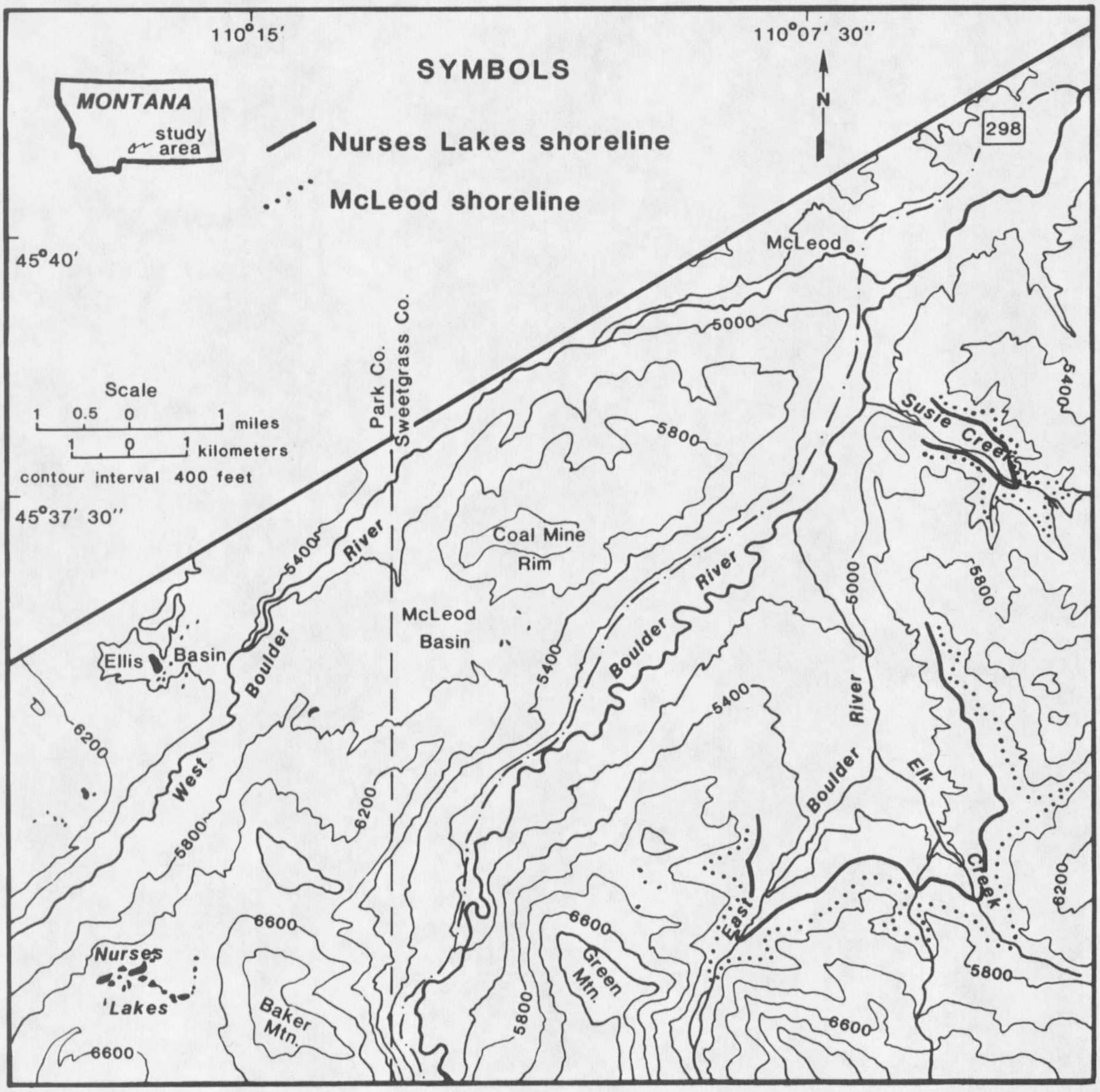

Figure 6. Location of glacial lake shorelines.

Further north, the eastern flank of the Main Boulder River glaciers also dammed the steep-walled Susie Creek drainage. Glacial lake shorelines range from 5300 to 5100 feet a.s.l. Lake-shore elevations are identified of the basis of dropstones and erratics marking the various glacial maxima at the canyon mouth.

No channels were observed from the glacial lake outlet areas. Garbarini (1957) also found no outlet channels. In the outlet areas, either the channels: 1) were cut but not preserved in the Eagle Sandstone cliffs because they have been altered beyond recognition by weathering processes or 2) never existed because the ice marginal stream could not cut the Cretaceous cliffs or the the ice was rafted before the lake was completely filled.

Outburst Floods (Jokulhlaups)

To the north of the study area, in the Main Boulder Valley, there is evidence of glacial flooding (jokulhlaup) from catastrophic drainage of these ice-dammed lakes. The jokulhlaups came from rafting of the ice dams at the mouth of Susie Creek and near the East Boulder River confluence with the Main Boulder River. The glacial outwash plain, north of McLeod, is composed of a mixture of relatively fresh to weathered lithologies presumably from both first-order glacial events, and is a result of reworking by the jokulhlaups. Large flood related, midchannel stream bars are well defined to the first bridge 3.5 miles below McLeod and extends with somewhat less definition to a second bridge, some 7-8 miles below McLeod. The deposits are not well sorted. Boulders as large as 3-4 feet in diameter occur on the flood deposited bars to 3 miles below the Main Boulder terminus and 1-3 feet in diameter to 8 miles below the terminus. These large boulders are intermixed with sand and gravel size particles. Much of the visible flood related deposits lie from 20-30 feet above the present day Main Boulder River channel. This area during flooding events at the present is the location where the fines would be deposited as the flood waters decreased in velocity depositing the suspended load. Terraces preserved along the eastern margin higher than 30 feet above the present day river, 0.5 miles downstream of the Main/West Boulder river confluence, have erratic strewn over their treads and risers, presumably the result of the jokulhlaups.

Western Flank

The western flank of the Main Boulder River glacier flowed into the McLeod Basin depositing numerous lateral moraines which lie from 6300 to 5700 feet a.s.l. (Fig. 4). As was found on the eastern flank, the older deposits are higher in elevation than the younger deposits.

Large, topographically subdued McLeod-age lateral moraines are found at the basin head. Only in this location can two stades of McLeod glaciation possibly be identified. This speculation is supported by separation of two McLeod-age lateral moraines by a large ice marginal stream channel.

During both glacial maxima, ice spread into the McLeod Basin coalescing with ice of the same glacial advance in the West Boulder drainage. McLeod-age ice reached a maximum elevation of 5900 feet, marked by erratics, on the northern rim of the McLeod Basin. This represents a vertical drop of 200 ft/mi in the McLeod-age deposits, from the highest entry point into the McLeod Basin to this northern rim position (Plate 1). The Nurses Lakes maximum elevation on this northern rim is very similar.

The McLeod basin floor is covered with a veneer of dropstones and hummocky topography which is much like the deposits of the East Boulder River/Elk Creek area to the east. The topographic features are a result of the stagnation of the combined West and Main Boulder river glacial ice. In the northern portion of the southeast quarter of section 34, R12E, T2S, (Plate 1) there are a series of subparallel morainal ridges which are roughly parallel to the direction of flow during the last glaciation. These relatively minor features are fluted ground moraines. Sugden and John (1982) indicate that features such as these are the result of a complex interaction between erosional and depositional processes. The lineations or streamlined features result from variations in stress on the bed of the glacier itself and are parallel to the direction of glacial movement. Sugden and John (1982) state that such features are usually found in the youngest till but in some cases older drift may also be involved. In this instance, these features are of the youngest identifiable drift because of their position near the valley floor where the latest Nurses Lakes glaciers flowed.

From the Coal Mine Rim, ice continued north downvalley along the Cretaceous cliffs leaving a thin veneer of erratics on both sides of the Main Boulder River. No lateral moraines were left by glacial ice and relatively minor concentrations of dropstones leave little material for RD measurements. Ice of both glaciations overtopped the ridge just south of McLeod on the west side of the river and flowed northwest toward the West Boulder River (Plate 1). A line of erratics marks the maximum margins of the various stages of glaciations over the interfluve. The only unmodified portion of the Main Boulder maxima terminal moraines lies here, in the West Boulder valley mouth, and has morphologic characteristics of the Nurses Lakes glaciation.

Terminus

The Main Boulder terminus is a complex montage of material from the most recent, extensive Pleistocene glacial events. The glaciers terminated at 4800 feet a.s.l. The termini of the McLeod and Nurses Lakes glaciations must have then displaced the West Boulder River north, pinning the river against the Cretaceous bluff just north of McLeod (Plate 1). West Boulder river channels of Nurses Lakes-age can be traced to their confluence with the Main Boulder River north of the present day confluence. The present day West Boulder River dissects the glacial outwash and terminal deposits of both the last large Pleistocene glaciations, south of the glacial maximum position.

A triangular terminal deposit occurs near McLeod, just north of the interfluve in the West Boulder River Valley. The present topography is hummocky with many undrained depressions. This deposit remained unaltered because it was shielded from East Boulder River/Elk Creek and Susie Creek jokulhlaups by the Eagle Sandstone ridge (Fig. 2). Other Main Boulder terminal deposits were extensively reworked by fluvial processes associated with the large terminal rivers from both the Main and West Boulder glaciers as well as the catastrophic jokulhlaups.

Another relatively unmodified terminal deposit occurs 1.5 miles south of McLeod on the Main Boulder valley floor. This small, lobate deposit is at an elevation of 4810 feet, just west of the Susie Creek confluence with the Main Boulder River. Because of the deposit's location upstream of the glacial maxima, this small terminus is considered a late stade terminus of Nurses Lakes glaciation or a recessional terminus from the extensive Nurses Lakes advance. This moraine is considered to have been deposited after glacial outburst flooding because of its fresh, relatively unaltered topography, even though it is positioned on the valley floor downstream of the East Boulder River/Elk Creek glacial lake. At the time of the moraine deposition, neither Susie Creek or the East Boulder River/Elk Creek glacial lakes existed. The deposit is presently being removed by the Main Boulder River as a large landslide from the west side of the Main Boulder Valley carries it into the Main Boulder River.

Terraces

The two lowest terraces in the McLeod area are graded to the most extensive terminal deposits. The highest of these terraces corresponding to the McLeod terminal deposits are from 60-80 feet above the present day river (Plate 1). Lower remnants correlating to the Nurses Lakes terminal deposits are from 20-40 feet above the present stream.

West Boulder River Deposits

The West Boulder glaciations have a similar sequence of deposits to those of the Main Boulder Valley. The similarity in morphology and position justifies the use of the same terms to refer to older (McLeod) and younger (Nurses Lakes) deposits.

Eastern Flank

The highest deposits of the West Boulder glaciers are best preserved in the Nurses Lakes area, along the eastern flank of the West Boulder River (Plate 1). In this area are a series of nested moraines at from 6650-6300 feet a.s.l. (Fig. 4). The older moraines (McLeod) have been extensively breached by streams, are more subdued, and lie outside the younger moraines (Nurses Lakes). Younger lateral moraines of the area have diverted streams which flowed during the interstage between McLeod and Nurses Lakes glacial advances. The area has extensive undrained kettle topography associated with ice stagnation and disintegration during the Nurses Lakes glacial event.

Further north, West Boulder glaciers flowed into the McLeod Basin along its eastern margin. The highest elevation of entry to the McLeod Basin is 6100 feet a.s.l. During both McLeod and Nurses Lakes glacial events the Main and West Boulder glaciers coalesced forming an expanse of ice which spread east to west a distance of approximately 11 miles from the East Boulder River/Elk Creek area to Ellis Basin (Plate 1). No lateral/medial moraines were deposited at this location, probably as a result of the location between converging ice masses (Fig. 4) (Sugden and John, 1982). The extensive Nurses Lakes advance flowed over McLeod deposits at this location, not being contained by older lateral or medial moraines. Preliminary relative dating of erratics indicates no separation into different stages can occur as McLeod-age deposits are not found along this eastern margin. Nurses Lakes erratics are the only deposits found at this location.

North, beyond the McLeod Basin (deposits previously described in discussion of the Main Boulder glaciers' western flank), in Sections 26 and 35, T2S, R12E, lateral deposits possess field criteria which indicate a McLeod-age and Main Boulder River origin. There is an increase in Stillwater lithologies. On the eastern flank of the West Boulder terminus, the deposits seem to be a homogenous mixture of Main and West Boulder river glacial debris.

Western Flank

The western flank of the West Boulder glaciers near Horseshoe Lake (Plate 1) was not studied because of inaccessibility and the fact that landowners would not permit access. Maximum glacial extent was mapped with binoculars from across the valley and from air photograph interpretation. Lobes of the glacier surely extended into the head of several creeks in the area during McLeod and Nurses Lakes maxima. The erratics of the West Boulder glacier mark the path taken by the glacier along the western margin.

As was the case along all the glacial ice margins described earlier, the glaciers skirted the north-dipping strata and flowed into Ellis Basin. The McLeod-age glacier overtopped the western divide at 6340 feet. Subsequent Nurses Lakes glaciers flowed into the basin at elevations, below 6200 feet. A series of discontinuous lateral moraine ridges are preserved from 6300-5800 feet a.s.l., some separated by large ice marginal stream channels (Figs. 4 and 5). The glacial streams which created the channels flowed between the glacial ice edge and older lateral moraine ridges.

McLeod-age lateral moraine deposits exhibit a single ridge crest and the same subdued topography seen elsewhere but also exhibit extensive fluvial/alluvial alteration. The area is flat and composed of smaller cobbles than other similar locations and is possibly a kame terrace. There is no evidence for two McLeod-age glaciations in this location. Ellis Basin, because it is ice marginal, is an ideal location for glaciofluvial landforms. Sugden and John (1982, p.333) state,

> "......fluvioglacial landforms persist only in ice marginal and pro-glacial situations. This is partly because valley glaciers often remain active during retreat, inhibiting the survival of subglacial or englacial meltwater forms and also.... because meltwater features built on valley floors are often destroyed or buried by pro-glacial fluvial processes which have to operate on narrow valley floors."

Rogen or push moraines of Nurses Lakes-age are present in the NW 1/4 of Section 8, T3S, R12E, perpendicular to ice flow. Sugden and John (1982) associate these features with normal compressive flow in warm based glaciers. They state (1982, p. 245), "They (the Rogen moraines) may be due to the presence of large scale bedrock obstructions transverse to the direction of ice flow." This is similar to the Ellis Basin area because here there is an ice marginal situation with north-dipping strata perpendicular to ice flow.

Ellis Basin has many dead ice features associated with rapid disintegration of glacial ice following the latest stade of Nurses Lakes glaciation. It is an area where excess, slow moving ice would be located. As the latest Nurses Lakes glaciers went into recession, ice wasn't fed into the basin area. This caused the ice at this location to stagnate, rapidly disintegrate, and preserve hummock and kettles.

Terminus

The West Boulder River terminus is located at 5200 feet a.s.l. The terminal moraine of the West Boulder River glacier appears to be a combination of materials from the Main and West Boulder glaciers of McLeod and Nurses Lakes age. The maximum extent of McLeod-age terminal deposits is preserved as a veneer of erratics covering the sandstone rim west of the terminus. On the valley floor, the maximum advance of the Nurses Lakes glaciers were contained within the McLeod terminus (Plate 1). The outwash from the Nurses Lakes advances did alter the lobate terminal moraine deposits of McLeod-age, leaving only the remnants of the older glaciation preserved as a veneer of erratics high on the western flank of the terminus.

A younger terminal moraine is found on the valley floor 2 miles upstream from the maximum West Boulder termini at an elevation of 5340 feet. This terminus could represent a late readvance of Nurses Lakes glaciers, be a recessional of a late Nurses Lakes advance, or be the result of the lack of contribution of Main Boulder ice to the West Boulder River area during the last extensive stade of the Nurses Lakes glaciation. Without ice contribution from the Main Boulder River glaciers during the latest Nurses Lakes stade, the West Boulder River glaciers might terminate well upstream of the maximum terminus.

Terraces

Paired terraces from the McLeod and Nurses Lakes glaciation are preserved on either side of the West Boulder River (Plate 1). They are identified with the two first-order glaciations because they are graded to the corresponding glacial termini. The McLeod terraces are from 60-80 feet above the present day river at an elevation of 5260 feet. The later and lower Nurses Lakes-age terraces are at 5220 feet, 20-40 feet above the West Boulder River.

Post-Glacial Landslides

The Boulder River area has extensive landslides associated with the Cretaceous shales (Fig. 2, Plate 1). Because the landslides offset many of the latest glacial features and many are presently active, all are considered to be post-glacial. There is a range of ages of movement represented by slides exhibit different morphological characteristics. The older slides have a subdued topography, have been stabilized by vegetation in some instances, and exhibit a conspicuous lack of water flow from their toes. Many of the slides have been reactivated by irrigation (principally flood) on their surfaces.

In the McLeod area, most of the slides are located in or adjacent to the basin areas because these basin areas are created in and floored by the easily eroded Cretaceous shales. In some areas, the capping sandstone cliffs have been left unsupported by the friable shales and have collapsed onto the steep colluvial/landslide slopes at the cliff toe (e.g., NW 1/4 Sec.33, R13E, T3S).

Relative Dating Data

Raw relative data, including surface boulder weathering characteristic and moraine morphology, lithology and diameter measurements, and soil RD variables (Table 2) document the two field designated glacial stages. The complete results of the RD data are in Appendix A-C and on file with Dr. William Locke in the Earth Science Department. Soil and relative dating sites locations are shown in Appendix D.

Table 2. Mean RD results of field-designated first order glacial events.

GLACIATION	SBF[1]	%WX[2]	%RING[3]	MXB[4]	PROX[5]	DISTAL[6]	CREST[7]
McLeod-ML	0.015	88.0	93.0	11.0	8.1	7.8	43.6
	±0.002	3.0	1.0	1.6	1.4	1.6	10.9
Nurses Lakes-NL	0.019	63.0	95.0	7.7	11.6	11.4	26.7
	±0.001	3.0	1.0	0.6	1.1	0.8	1.0

	LITHOLOGIES[8]					DIAMETERS[9]				
	Qfgn	Amph	Sed	p€s	other	Qfgn	Amph	Sed	p€s	other
ML-M[10]	16.1	0.1	2.1	11.4	0.0	39.6	0.0	25.4	27.5	20.0
	±3.3	0.1	0.4	3.3	--	5.9	--	2.3	4.0	--
ML-W	28.5	1.5	0.0	0.0	0.0	--	--	--	--	--
	±0.5	0.6	--	--	--	--	--	--	--	--
NL-M	15.5	0.5	4.3	9.7	0.1	32.8	23.0	28.5	29.3	20.0
	±1.6	0.2	0.6	1.5	0.1	1.4	1.0	2.0	0.8	--
NL-W[11]	26.3	1.9	1.1	0.3	0.4	38.7	29.4	32.8	22.0	33.8
	±0.7	0.5	0.4	0.2	0.3	2.0	1.9	5.6	2.0	2.8

SOILS

	thkA[12]	pHA[13]	thkB	pHB	$CaCO_3$DP[14]	sA[15]	siA	cA	sB	siB	cB
ML	7.0	7.3	8.0	7.4	11.1	55.3	30.6	14.1	51.0	31.8	17.1
	±0.6	0.2	0.7	0.2	1.8	1.8	1.5	1.1	2.7	1.5	2.0
NL	6.4	7.3	8.0	7.7	11.3	51.7	32.3	16.0	48.6	32.8	18.5
	±0.5	0.1	1.2	0.1	1.7	1.8	1.5	2.0	1.9	1.7	1.3

1 surface boulder frequency (boulders/ft^2)
2 percent weathered (out of 50 boulders)
3 percent ring (out of 50 boulders)
4 maximum boulder diameter (feet)

Table 2 (cont.)

[5] proximal slope (degrees)
[6] distal slope (degrees)
[7] crest width (feet)
[8] mean of 30 boulders; quartzofeldspathic gneiss, amphibolite, sedimentary, Precambrian Stillwater, and other lithologies
[9] mean maximum axial diameter (inches)
[10] McLeod age-Main Boulder River area
[11] Nurses Lakes age-West Boulder River area
[12] thickness of the A-horizon (in inches)
[13] pH of the A-horizon
[14] depth to $CaCO_3$ in inches
[15] sand, silt, and clay percentages in the A- and B-horizons
$\pm$ indicates one standard error on the estimate

Data Trends

Surface Boulder Weathering and Moraine Morphology: Patterns of weathering are in general similar to those observed by earlier workers: decreases in surface boulder frequency, percent ring, proximal and distal slopes and increases in percent weathered and crest width with time. Maximum boulder diameter differs from the other variables significantly increasing in size with age. This result is contrary to the general concept of chemical/physical breakdown over time and a resulting decrease in boulder size with age (Burke and Birkeland, 1979) Of these RD variables all but ring percentage are statistically significant at the 10% level between glacial episodes.

Lithologies: The lithologies follow trends outlined by Garbarini (1957). The West Boulder River glacial deposits contain a much smaller proportion of Stillwater lithologies and a higher percentage of quartzofeldspathic lithologies than the Main Boulder River area (Table 2) in both ages. All of the Nurses Lakes and McLeod age lithologies are significantly different (<10%) between drainages but not between ages.

Within-drainage comparison of different age lithology numbers indicates there is a conspicuous lack of sedimentary, amphibolites, and other lithologies in the older deposits of both drainages. In sedimentary lithologies there is a significant difference between glacial events in both drainages (Table 2).

Diameters: Diameter measurements within the Main Boulder River area show an insignificant decrease with age (Table 2). Quartzofeldspathic gneisses increase in diameter with time. The West Boulder River McLeod-age diameters were not measured, therefore, trends between glacial ages cannot be analyzed in the West Boulder River area.

Comparisons of diameters between drainages of Nurses Lakes-age indicate that erratics in the West Boulder drainage have significantly larger diameters. Stillwater lithologies differ being significantly smaller in diameter in Nurses Lakes deposits of the West Boulder River area.

These findings are explained by the difference in length of the West Boulder River and Main Boulder River glaciers. The West Boulder River glaciers have a much shorter transport distance from their source to the terminus than the Main Boulder River glaciers. As a result, the West Boulder glaciers have less time to abrade the erratics contained within the ice. The results are larger boulder diameters in the West Boulder River deposits with the exception of Stillwater lithologies.

The Stillwater lithologies entering the West Boulder Valley are coming with the Main Boulder River ice through the McLeod Basin. No deposits in the West Boulder River area upvalley of the Main Boulder ice confluence contain Stillwater lithologies. As a result, deposits which were sampled in the West Boulder River area near the terminus are combined ice deposits. The Stillwater lithologies here are from the Main Boulder glaciers and are smaller than the mean Stillwater lithologies of the Main Boulder drainage, again, as a result of the mean distance of transport.

Soils: None of the variables shown here are significantly different. Explanations for these results are presented in the discussion section which follows.

DISCUSSION

The raw data were statistically analyzed to further subdivide the field designated first-order glacial events. Treatment tests (T-tests) were performed to determine the best relative dating (RD) parameters to be used later in the cluster analysis. The best RD variables are those which best divide the data into McLeod and Nurses Lakes glaciations. While utilizing the best RD variables, output from the cluster analysis (Dixon, 1983) determines the most favorable number of clusters, further subdividing the glacial sequence into stades.

Raw data measurements of all RD variables were statistically analyzed using the Statistical Package for the Social Sciences (Bowman and Cahill, 1975). Relative dating data were grouped according to field-designated age and location. In this analysis, age 1 equals the McLeod-age glacial deposits and age 2 the Nurses Lakes deposits. Locations 1 and 2 indicate the Main and West Boulder drainages respectively. This creates four groups or subfiles according to age and location. For example: age 1, location 1, (A1L1) are McLeod-age deposits in the Main Boulder drainage. Age 2, location 2, (A2L2) are Nurses Lakes deposits in the West Boulder drainage and so on. Statistics on each subfile of RD variables include mean, mode, median, skewness, kurtosis, variance, range, maximum, minimum, standard error, and standard deviation.

Use of a T-test assumes a normal distribution of values in the analysis. Some of the RD variables had to be transformed to more closely approximate a normal curve. Data modifications were conducted when excessive skewness or kurtosis occurred in a subfile. Data transformations included omitting extremes in the data, log 10 transform of the value, or multiplication by 10^n to achieve a normal distribution of data. In all statistical groupings (Table 3a,b,c) the small size of the subfiles, especially in the between- and within-drainage analysis, leads to excessive skewness and/or kurtosis. The above manipulations of the data were carried out to normalize the variable distribution but where these transformations were unsuccessful data was not used in T-tests.

Parametric T-tests (Table 3) are used to analyze group statistical separation and answer the question, "Are there significant differences between populations (groups)?" T-Tests are carried out to accept or reject a null hypothesis which in this case is establishing if the RD variable is separating the data into 2 groups. The significance level or probability value chosen is 10% or .10 (the upper limit for statistical separation). With upper limit of statistical separation at 10% or less there is less of a chance of excluding RD variables which truely separate the data set into two groups. However, there is also a chance of including a variable which is not truely separating the data into two statistically separate groups (Huntsberg and Billingsley, 1981).

Groups (subfiles) were selected in such a way as to statistically analyze 1) between-drainage differences in a specific age group, e.g., A1L1 vs A1L2 or A2L1 vs A2L2; 2) within-drainage age differences, e.g., A1L1 vs A2L1 or A1L2 vs A2L2; and 3) a combined-drainage age analysis, e.g., A1L1 and A1L2 vs A2L1 and A2L2.

Table 3. T-test probabilities (P-values) of a. same age variables compared between drainages, b. different age variables compared within one drainage and c. combination of one age in both drainages and comparison to the other combined age group. Abbreviations as in Table 2.

		SURFACE BOULDER VARIABLES				MORAINE MORPHOLOGY		
GROUPS		SBF	%WX	%RING	MXB	PROX	DISTAL	CREST
a. A1L1[1] A1L2	P-values	.51	1.00	---	.88	.25	.47	.20
A2L1[2] A2L2		---	.20	.13	.46	.18	.01	---
b. A1L1 A2L1		.51	---	.83	.25	.02	.06	.88
A1L2 A2L2		---	---	.09	---	.25	.05	.20
c. A1L1,A1L2 A2L1,A2L2		.09	.00	.18	.03	.13	---	.18

	LITHOLOGIES				DIAMETERS			
	Qfgn	Amph	Sed	PCs	Qfgn	Amph	Sed	PCs
a. A1L1 A1L2	.01	.10	.01	.04	---	---	---	---
A2L1 A2L2	.00	.01	.00	.00	.03	.05	---	.01
b. A1L1 A2L1	.84	.14	.01	.61	.30	---	.36	.68
A1L2 A2L2	.06	.64	.07	---	---	---	---	---

c. No combination of diameters and lithologies possible between drainages because of missing data.

Table 3 (cont.)

SOILS

	thkA	pHA	thkB	pHB	$CaCO_3DP$	sA	siA	cA	sB	siB	cB
a. A1L1 A1L2	.17	.02	.79	.01	.67	.41	.05	.31	.56	.39	.13
A2L1 A2L2	.15	.09	.83	.17	.16	.03	.46	.01	.43	.49	.04
b. A1L1 A2L1	.38	.92	.88	.85	.62	.02	.55	.03	.51	.88	.41
A1L2 A2L2	.44	.32	.73	.06	.92	.52	.11	.96	.48	.98	.27
c. A1L1 A1L2; A2L1 A2L2	.45	---	.99	---	.92	---	---	---	.45	---	.57

[1] A1 equals McLeod glaciation, L1 is the Main Boulder drainage
[2] A2 equals Nurses Lakes glaciation, L2 is the West Boulder drainage
--- means T-test is inappropriate because of excessive skewness and/or kurtosis, are a lack of values, or previous T-test excluded the later test.

Variables of a single age need to be analyzed between locations (Table 3a). If there are significant differences between drainages in variables of the same age, combination of those variables and subfiles is unjustified. Combining similar variables from both the Main and West Boulder by age is done to maximize observations (sites) for any single age group. Combination increases the statistical validity of the results by increasing the data set size and normalizing the data distribution (Table 3c). In some variables, without subfile combination, observations are too few for statistical validity.

Within each drainage individual RD variables can be analyzed for significant differences between field designated glacial events (Table 3b). The first analysis (Table 3a) tells us of similar aged variables which could be combined between drainages. If no combination can occur, further useful results are extracted from the RD variables within each drainage. Although the subfiles are small, with numerous variables, within drainage analysis is the only way of further analyzing the data.

The final purpose of the T-test analysis was to find the best RD variables ($p \leq 0.1$) for separating age groups. The lower the P-value the better that RD variable discriminates between glacial ages. The "best" variables were then used in the multivariant cluster analysis.

T-Test Analysis Discussion

Surface Boulder Variables

Included in this section are the variables surface boulder frequency (SBF), fresh to weathered ratio (% WX), hammer blow weathering ratio (% RING), and maximum boulder size (MXB).

Surface boulder frequency: T-tests between surface boulder frequency of the same field age but different drainages (A1L1 vs A1L2; A2L1 vs A2L2, Table 3a) show no significant differences, therefore combination of surface boulder frequencies to increase the data set size may be carried out. Within-drainage results of T-test analysis by age were inconclusive because of insufficient data and a lack of a normal distribution of values (Table 3b).

Combining locations by age of the deposits yields some overlap of values, however, the means and standard deviations indicate a separation of groups by age with surface boulder frequency data (Table 3c). Extremes at both ends of the data were dropped. Field records indicate those areas dropped were a kame terrace and terminal moraine while all other data are from lateral moraine positions. Numerous researchers (Janda, 1966; Sharp, 1969, 1972; Burke and Birkeland, 1979) have shown that relative dating data are much more variable in terminal moraines than lateral moraines. T-Tests with these data modifications in place have a probability of .09 for surface boulder frequency comparisons (Table 3).

Explanations for the moderate success of the surface boulder frequency RD variable include the fact that the concentration of surface boulders varies along the moraine crest according to original ice deposition (Colman and Pierce, 1986). Additionally, when sampling is carried out the location of the sampling grid in the "maximum" concentration of boulders is a subjective decision. No systematic, scientific way for grid placement has been established.

The minimum boulder diameter is based on previous surface boulder frequency studies (Burke and Birkeland, 1979) for direct correlation. In each study area, mean diameter of surface boulders is a complex interplay between length of transport distance, bedrock joint spacing, length of the interglaciation, and the length of the weathering interval since deposition. As a result, the critical minimum diameter may be excluded from the data collection when minimum diameter has been established (Burke and Birkeland, 1979). The surface boulder count has to be large enough to statistically test any variability due to age.

Finally, post-depositional events such as loess deposition and disturbance of surface boulders influences surface boulder frequency effectiveness (Burke and Birkeland, 1979; Colman and Pierce, 1986).

Fresh/Weathered ratio (or % Weathered): The fresh-to-weathered ratio of Precambrian granites and gneisses is the best RD indicator for separation of deposits into ages found in the Boulder River area. No significant differences in similar aged deposits were found between drainages, therefore combination of similar aged fresh/weathered ratios was carried out. T-Tests reveal a two tail probability of p=.00 (Table 3c).

This finding is best explained by the fact that, in the Boulder River area, nearly all the boulders are found in grassland areas. Grassland fires are quick burning and lacking in heat. This lack of heat fails to spall surface boulders. The excellent weathering results imply that forests, where fires may cause rapid boulder decomposition, probably have not occupied the field area (Burke and Birkeland, 1979).

Hammer blow weathering ratio (or % Ring): The hammer blow weathering ratio was a poor indicator of deposit age with a probability of p=.18 (Table 3). This is in accordance with the predictions of Burke and Birkeland (1979).

Maximum boulder diameter: The last surface boulder measurement, unique to this study, was the maximum boulder diameter. Between drainage analysis by age reveals no significant differences, therefore, combination of similar age maximum boulder data can be carried out.

Within-drainage analysis indicates maximum boulder diameter is questionable in delineating age (Table 3b). The West Boulder River data are excessively skewed and so has to be dropped. The Main Boulder River data have a probability of deposit separation into two age groups based on maximum boulder diameter of p=.25.

The original combined-drainage data were transformed by a log 10 multiplication of the values. McLeod-age deposits have a significantly larger mean maximum boulder diameter (11.0 feet) than the Nurses Lakes moraines (7.7 feet) (Table 3). Combined-drainage analysis yields T-test probabilities of p=.03 for separating the moraines into two ages based on transformed maximum boulder size.

If within-drainage analysis had confirmed the combined-drainages probability, then the basis for a reliable relative dating variable would have been laid. In this case, doubt of the reliability of the maximum boulder variable leads to the conclusion that this variable should be further studied to confirm or deny its reliability as a relative dating variable.

Explanations for mean diameter change with time of specific lithologies have been outlined in the surface boulder frequency discussion. However, the combined-drainage result of the maximum boulder diameters in the older deposits is contrary to the weathering processes which decrease the size and number of surface boulders with time (Burke and Birkeland, 1979). Possible explanations for the above discrepancy between maximum boulder diameter and normal weathering breakdown of lithologies with time include: 1) a change in the ablation area joint spacing. This would assume a lower joint frequency during the McLeod glaciation and as the glaciers eroded more deeply the joint frequency increased in Nurses Lakes glaciations. 2) differences in abrasion rates between Nurses Lakes and McLeod glaciers. This possibility assumes dirtier, more abrasive Nurses Lakes glaciers which decrease boulder diameters in transit. If this is true, then all mean diameters should be larger in McLeod deposits when compared to Nurses Lakes deposits (Table 2). In the Main Boulder drainage, only quartzofeldspathic gneisses follow the maximum diameter trend. The other diameters decrease with age, however, none of the diameter differences are significant (Table 3). Regardless, the possibility exists that the diameters of Stillwater lithologies, amphibolites, and sedimentary rocks are more susceptible to weathering processes other than englacial abrasion.

The largest boulders are always granites (quartzofeldspathic gneisses) or Stillwater lithologies. These lithologies are the most resistant to weathering.

Moraine Morphology

Quaternary investigators (Blackwelder, 1931; Nelson, 1954; Sharp, 1972; Burke and Birkeland, 1979; Pierce, 1979; Colman and Pierce, 1986) have noted that moraine proximal and distal slopes decrease and crest widths increase with time. Similar age deposits were analyzed between drainages to determine if moraine morphologies were significantly different (Table 3a). Moraine crest widths and proximal slopes have no significant differences ($p>.10$) between drainages in either age. Distal slopes, however, show significant differences in age 2 deposits (p=.01), therefore, no between-drainage combinations of age 2 distal slopes can be made.

Within-drainage differences in moraine morphology of both ages reveals that distal slopes at both locations are significantly different (A1L1 vs A2L2, p=.06; A1L2 vs A2L2, p=.05; Table 3b). Distal slopes are excellent indicators of relative age within each drainage. Proximal slopes are significantly different in the Main Boulder River area (p=.02), but not in the West Boulder River area (p=.25). Proximal slopes then are not always a dependable RD variable nor are crest widths.

Data are combined by age regardless of location to maximize age group observations for the moraine morphology variables (A1L1,A1L2 vs A2L1,A2L2). Data extremes were found where the measurements were taken on features other than lateral moraines. These "outliers" were dropped from the analysis. T-Tests performed (Table 3c) on the modified data combined by age indicate that crest widths (p=.18) and proximal slopes (p=.13) are at best poor indicators of age.

Moraine morphology depends upon original deposition and subsequent weathering (Colman and Pierce, 1986). Proximal slopes are formed at the ice/moraine interface and may be of any configuration as ice melts in waning glacial conditions. Crest widths are highly dependent on original deposition so, like proximal slopes, are suspect in relative age determinations. Distal slopes, however, are away from the ice/moraine interface and are probably deposited at or near the angle of repose. With advance and retreat of the glacier, the distal slopes of the older lateral moraine are "protected" and the slope angle systematically decreases with time. Colman and Pierce (1986) plotted maximum slope angle against the logarithm of moraine height. Distal slope regression lines for their investigation are approximately parallel while crest widths and proximal slopes are not. These graphic results of distal slopes show a logarithmic or exponential decrease in slope angle with age which can be systematically measured much like fault scarp data reported by Bucknam and Anderson (1979). As a result, distal slopes are believed to decrease in a predictable manner and so should be the most reliable of the moraine morphology RD variables. The Boulder River study supports these findings.

Lithologies

The analysis of boulder frequency as a function of lithology is complex in the Boulder River area because of the provenance differences between the Main and the West Boulder River glacial deposits (Fig. 7).

In analysis of the lithology variability between drainages, it is evident that in each age group all lithology numbers are significantly different (Table 3, Fig. 7). These probabilities indicate that you can positively differentiate any age deposit in either drainage based on lithology percentage. In the West Boulder River area, 86 to 95% of the boulders are granite. The Main Boulder River area contains only 52 to 53% granites. As a result, there can be no combination of similar lithologies between drainages in either age group.

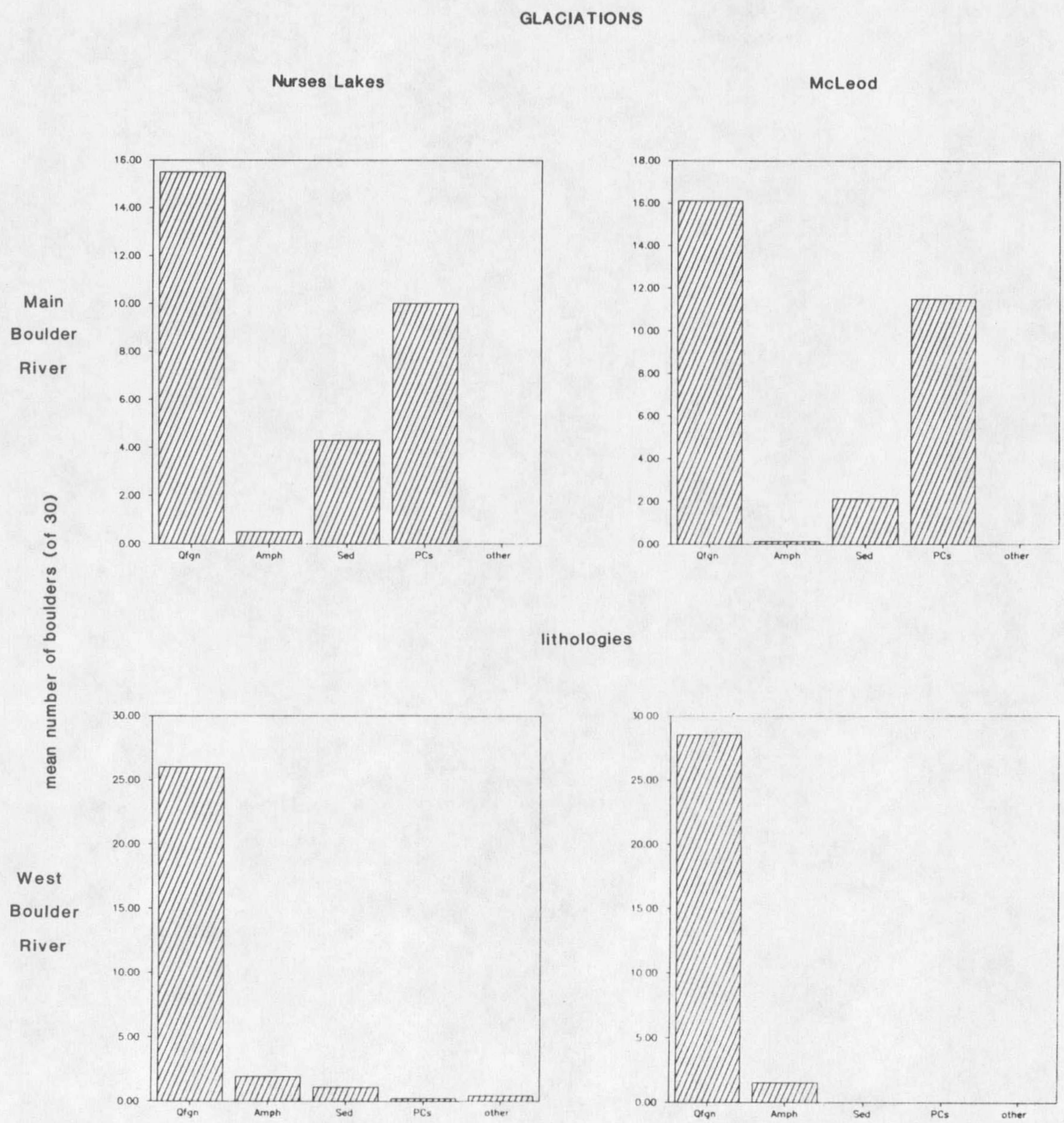

Figure 7. Lithology numbers in both drainages from McLeod and Nurses Lakes glaciations.

Within-drainage analysis reveals that only sedimentary lithologies significantly decrease in number with time in each of the drainages. Granites significantly increase in number with age in the West Boulder drainage. The sedimentary lithologies are rapidly removed by weathering processes in the time interval since the first recognizable glacial event and the present. As sedimentary lithologies decrease granites increase, a cause-effect relationship. The granitic proportion of the lithologies counted increases, in this case, significantly. This same trend is seen in the Main Boulder River area but the proportional increase in lithology with age is taken up with two resistant lithologies: Precambrian granites and Stillwater lithologies (Fig. 7). As a result, neither of these lithologies increase significantly. This is unlike in the West Boulder drainage where all the decrease in easily weathered lithologies (sedimentary lithologies and amphibolite) with time is consumed by one resistant rock type.

Diameters

Diameter measurements are somewhat limited by the lack of measurements in age 1 deposits of the West Boulder River area. When one compares age 2 deposits, significant differences are seen in the diameter of all lithologies between drainages (Fig. 8, Table 3a). As a result, no combination of similar age diameters may occur between drainages. The West Boulder River area diameters are significantly larger. This is probably the result of the shorter glacial transport distance in the West Boulder drainage when compared to the Main Boulder River area (discussion in results).

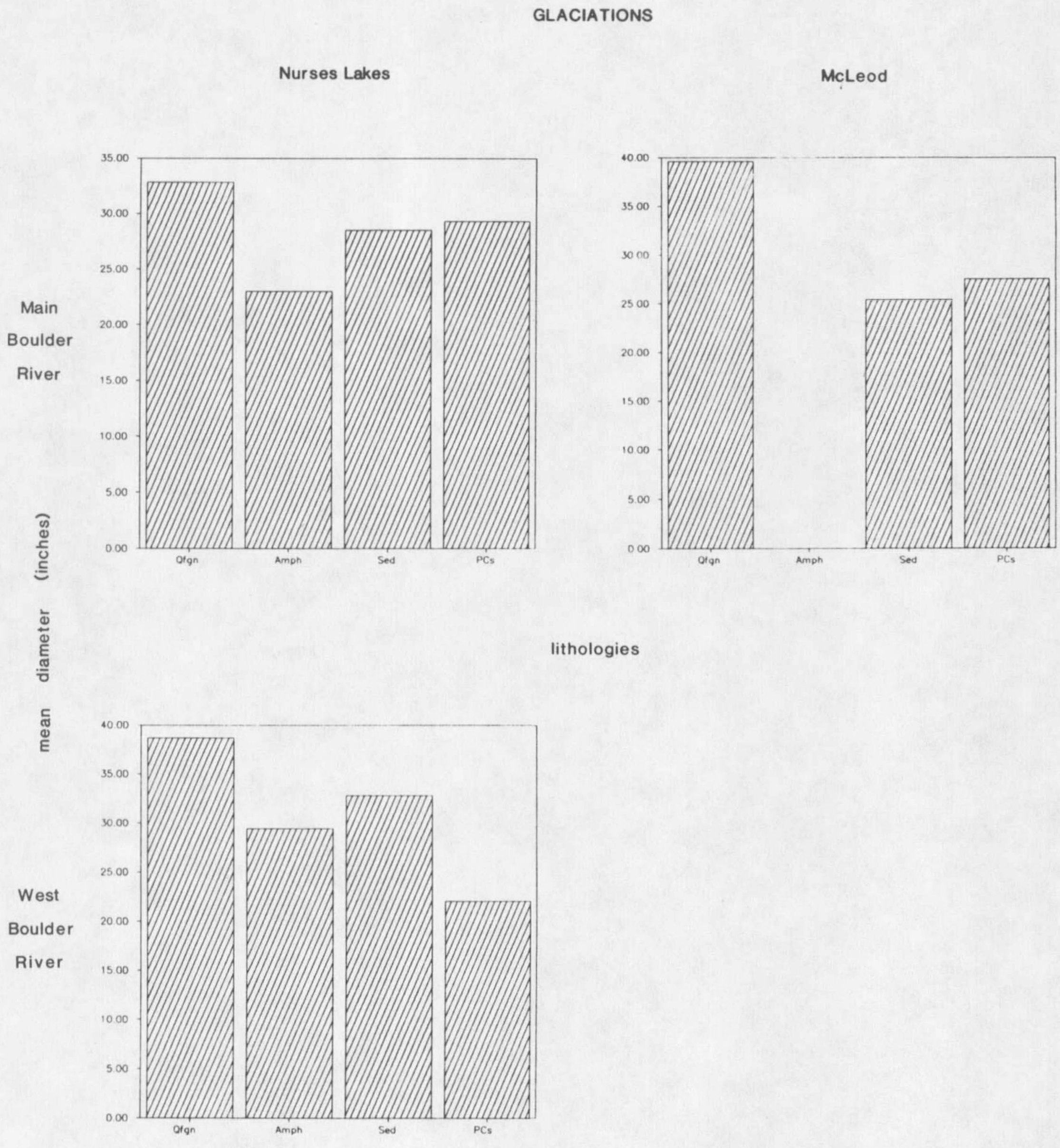

Figure 8. Diameters in both drainages of both glaciations.

Within-drainage analysis can only be carried out in the Main Boulder River area (Table 3b, Fig. 8), since diameter measurements were not taken in McLeod-age deposits in the West Boulder drainage. There are no significant differences in Main Boulder River diameters with age. The reason for the lack of significant changes in diameter between glaciations might be the fact that there was insufficient time between glaciations to cause significant changes in the diameter of the lithologies found in the Boulder River area (Birkeland, 1984).

Soils

Thirty soil variables were tested for significance in similar age deposits between drainages of the Boulder River area (A1L1 vs A1L2; A2L1 vs A2L2, Table 3a, Appendix C). The complete T-test results (with additional variables) may be found on file with Dr. William Locke in the Earth Science Department. Significant differences between drainages are found in the age 1 soil variable of percentage silt in A-horizon (p=.05) and the age 2 soil variables of percentage sand and clay in the A-horizon (p=.03 and p=.01, respectively) and percentage clay in the B-horizon (p=.04). As a result, sand, silt, and clay in the A-horizon and clay in the B-horizon cannot be used in the combined age analysis.

Significant differences in sand, silt, and clay percentages between drainages may be a direct result of differences in original till composition. The Main Boulder drainage has a higher percentage of clay-rich Cretaceous sedimentary lithologies within the glacial deposits (Fig. 2). As a result, higher percentages of clay in both the A- and B-horizons are observed when the Main to the West Boulder river soils are compared (data on file with Dr. William Locke, Department of Earth Sciences). The differences between drainages are significant in age 2 deposits. Similarly, there is a higher percentage of Precambrian granites in the West Boulder deposits which is reflected in a significantly higher percentage of sand in the A-horizon of age 2 deposits when compared between drainages. Note that all of the significant differences in sand and clay percentage occur in Nurses Lakes deposits. Possibly these deposits are recent enough to reflect provenance differences. The McLeod deposits reflect weathering processes which are breaking down sand to silt and translocating clay to the B-horizon. Silt percentage is significantly higher in the A-horizon of McLeod-age deposits.

Also, as sites move toward the termini in both drainages, clay percentages increase as more and more Cretaceous sedimentary material is incorporated in the glacial debris. In the Main Boulder drainage, many more soil profiles were sampled near the glaciers' terminal position than in the West Boulder drainage, resulting in inflated clay percentages in the Main Boulder.

Between-drainage results indicate significant differences in age 1 pH values in both the A- and B-horizons (Table 3a). Age 2 deposits are significantly different in the A-horizon. A similar inconsistency of sampling affected each age pH data in both the Main and West Boulder River soil pits. $Ca(OH)_2$ is formed in the presence of $CaCO_3$ and H_2O. The moderately strong base results in a pH which can approach 8.5 (Birkeland, 1984). Lower pH levels indicate less base formation and more acidity. The $CaCO_3$ accumulation zone is an elevation above which there are no $CaCO_3$ accumulations and below which there are calcic soils (Birkeland, 1984). In the West Boulder drainage, some soil sites were located above the $CaCO_3$ accumulation zone which gives lower overall pH levels than if all sample locations were below the $CaCO_3$ accumulation zone. In the Main Boulder drainage, all of the samples were taken below the $CaCO_3$ accumulation elevation.

Age of the deposit also influences the elevation of the $CaCO_3$ accumulation zone. Richmond (1962a); Birkeland (1984); and Reheis (1984) document that in older Quaternary deposits the $CaCO_3$ accumulation level moves upward in elevation. In the Boulder River area, the $CaCO_3$ accumulation elevation is 6300 feet for the older McLeod-age deposits and 6000 feet for the Nurses Lake-age deposits. The $CaCO_3$ accumulation zone should have been determined for all age deposits during the sampling stages of the glacial investigation, which would have eliminated inconsistent sampling of pH levels.

Soil characteristics of each age group were compared within each drainage (A1L1 vs A2L1 and A1L2 vs A2L2, Table 3b). The pH of the B-horizon in the West Boulder River area and sand and clay percentages of the A-horizon in the Main Boulder River area were the only soil variables to show significant differences between ages. No variable is significantly different in both the Main and West Boulder drainages. That fact, when combined with soil pit locations and lack of normal distribution of a number of soil characteristics, suggests that none of the soil variables were suitable for relative age separation in either drainage.

Combining of soil characteristics was done to increase sample size (A1L1,A1L2 vs A2L1,A2L2) (Table 3c). Of particular interest were: depth to $CaCO_3$, thickness of the A- and B-horizons, and enrichment of the B-horizon in secondary clay (cB). Others have successfully used these parameters in relative dating (Burke and Birkeland, 1979; Pierce, 1979; Colman and Pierce, 1986). In the Boulder River soils analysis, because the between drainage T-tests indicate there may be no combination of many of the soils variables (Table 3a), only thickness of the A-and B-horizons, depth to $CaCO_3$, and sand percentage in the B-horizon may be combined. Of these soil characteristics none showed significance levels below the 10% alpha level (Table 3c).

In summary, it appears as if most soils variables in the Boulder River area are of limited use in differentiating the glacial deposits into events. Burke and Birkeland (1979, p. 25) agree stating, "Our soils data are often inconclusive and do not always support the age differentiations of other data." Hall and Heiny (1983), in soil studies in the Tobacco Root Mountains of southcentral Montana, also found limited use for soil variables. However, they did mention clay enrichment as a good indicator of relative age. The glacial deposits of the Tobacco Root Mountains are similar to deposits in the Boulder River area. Pierce (1979) and Colman and Pierce (1986) both favor all soil morphology criteria for age determinations. They attribute noticeable differences with age to a warmer and wetter climate and clay rich lithologies in their study areas when compared to others in the Rocky Mountains.

In the Boulder River area, possible explanations for the lack of significant differences between McLeod and Nurses Lakes age soil variables include: 1) a cool, dry climate and insufficient time for soil variation to be statistically reflected in the soil RD variables. 2) problems with sample site locations reflected in sand, silt, and clay percentage data and pH data in both drainages and at each age, and 3) the fact that a small sample size may give inaccurate or misleading results.

Best Relative Dating Variables Comparison

In the Boulder River study, after analyzing T-test results, the best RD variables have been determined for the cluster program which follows. Needed in the cluster analysis are RD variables which best separate the glacial deposits into two age groups. Included in the best RD variable category are the RD variables: percent weathered, distal slope angle, surface boulder frequency, proximal slope angle, and maximum boulder diameter (Table 3).

Others have used these same surface boulder RD variables with varying success. Surface boulder frequency was favored by Hall and Heiny (1983). Colman and Pierce (1986), as well as Burke and Birkeland (1979), found surface boulder frequency unacceptable for relative age discrimination. Fresh to weathered ratio (% weathered) is well accepted as a reliable indicator of relative age. Both Burke and Birkeland (1979) and Carroll (1974) used fresh to weathered ratio successfully for RD determinations. Pierce and Colman (1986) find the fresh to weathered ratio marginally useful in relative dating as do

Hall and Heiny (1983).

Moraine morphology, especially distal slope angle, was found to be marginally useful in RD determinations by Colman and Pierce (1986). In contrast, Burke and Birkeland (1979), found no relationship between moraine morphologies and the relative age of their deposits.

Maximum boulder diameter has only been used as an RD variable in this study so comparison with others cannot be carried out.

Cluster Analysis

The best relative dating variables were decided upon after interpreting T-test probability values. If these variables were best at differentiating the deposits into stages, then they might also be best at subdividing the stages into stades. The multiparametric cluster program (Dixon,1983) was run to further subdivide the two field designated glacial stages into stades.

PKM cluster program groups from two to five clusters, depending upon the researchers' instructions. Engelman and Hartigan (1983, p. 464) describes the clustering process:

> "PKM partitions a set of cases (observations) into clusters. At the completion of the run each case belongs to the cluster whose center is closest to the case. The Euclidean distance is used to measure the distance between each case and the center of each cluster (mean of cases in the cluster). The program begins with user-specified clusters and splits one cluster into two clusters at each step. When the requested number of clusters is reached, cases are iteratively reallocated into the cluster whose center is closest."

Output from the cluster program includes a description of each variable for each cluster--the mean, minimum, and variance; the distance of the cluster center to each case; and histograms displaying the distances for cases in a cluster and cases not in the cluster; and a scatter plot of the orthogonal projection of cases into the plane defined by the centers of the three most populous clusters. For each variable the program provides a summary of the cluster means and standard deviation and an analysis of the variance with descriptive F-ratio that compares the between-cluster mean square to the within-cluster mean square; and a cluster profile---a graphical display for each cluster that shows the mean of each variable relative to the overall mean, and marks the center plus or minus one standard deviation.

As more RD variables are added to the cluster program, more information should be attained. This follows the Burke and Birkeland (1979) contention that a large multiparametric data base should give the highest degree of resolution on relative age. However, the PKM multivariate procedures limit the missing values per case to one-half the number of variables used. If more than one-half the values are missing per case, then the cluster program automatically omits that site from the analysis. In the Boulder River field study, as a result of an incomplete RD data set at individual sites, analysis with the maximum number of RD variables is impossible. This limits the combination of more than four, and in some instances five, best RD variables in any one cluster run. In the Boulder River area cluster analysis, there is a balance between the maximum number of RD variables input and the maximum number of sites per cluster represented in the output.

Cluster analysis of specific multiparametric data reveals that when select relative dating (RD) variable values are combined they cluster best into three groups. Since the RD variables presumably discriminate on the basis of age, most weathered being the oldest, the 3 clusters are interpreted as different age groups. The 3 clusters delineate deposits of the McLeod and Nurses Lakes glaciations; also, the Nurses Lakes glaciation is broken into 2 groups.

In the 3-cluster grouping, all of the RD variables are positioned in the field by degree of weathering logically (Fig. 9). For example, percentage of surfaces boulders which are weathered changes from 80% weathered on outer (older) moraines to 55% weathered on inner (younger) moraines. Of 44 sites, 41 group in a manner which is consistent with field-designated ice-margins. Sites 19, 42, and 43 are in the wrong locations stratigraphically, intermediate in weathering but innermost by position (Fig. 9, Appendix D). Possible explanations for this include: 1) 19, 42, and 43 are correctly grouped, in which case 6 others are incorrect by position. This is unlikely with respect to field morphology and the degree of weathering of RD variables. 2) Sites 42 and 43 may have been effected by the glacial lakes in the Ellis Basin area. Shorelines are estimated to be as high as 5500 ft during the Nurses Lakes glaciation. (Fig. 6). This hypothesis seems most likely. Site 19, then, is probably an anomalous site. Also, if sites 19, 42, and 43 are all anomalous sites then 3 of 44 sites are incorrect, a 7% error overall. A 7% error is statistically valid.

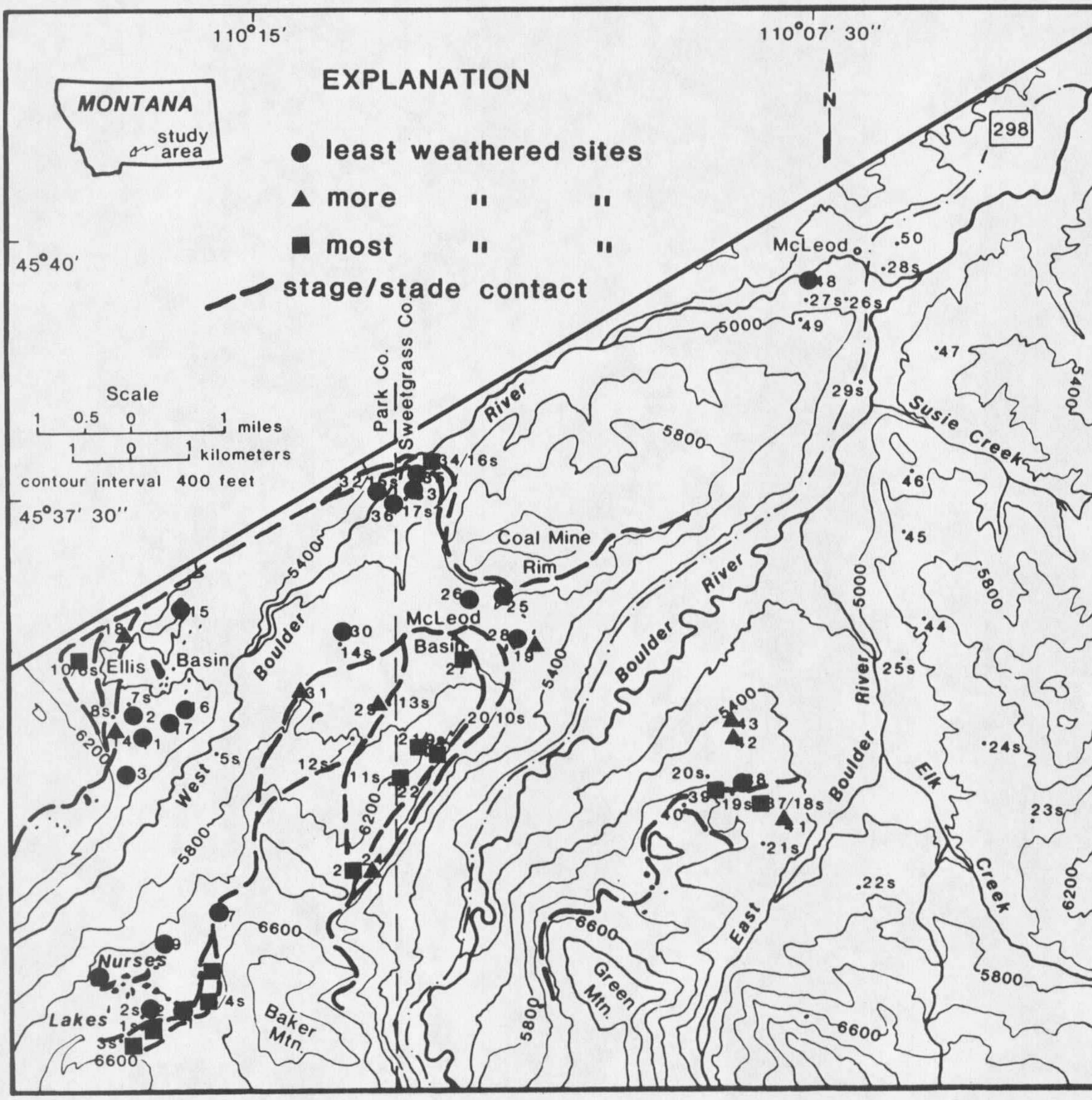

Figure 9. Three-cluster grouping with cluster rank assigned from least to most weathered using the RD variables of surface boulder frequency, weathered percentage, proximal and distal slopes. Soil and RD sites locations are shown in Appendix D.

Table 4. Four-cluster grouping (A-D) each RD variable was ranked from least (1) to most modified (4) based on the mean values.

CLUSTER GROUP	A[a]	B[b]	C[c]	D[d]
Variable:				
SBF/m^2	1	3	4	2
PROX	1	3	4	2
DISTAL	2	3	4	1
CREST	1	2	4	3
WX %	2	1	4	3

a- includes sites 2,8,9,12,26,28,32,33,36,48
b-................13,14,18,19,24,29,31,40,42,43
c-................4,6,10,21,22,23,27,34,37,39,41
d-................1,3,5,7,11,15,16,17,20,25,30,35,38

The 4-cluster grouping does separate McLeod deposits from Nurses Lakes deposits, however, it does not consistently rank Nurses Lakes deposits from unweathered to weathered or inner to outer or youngest to oldest (Table 4). In Table 4, most modified (4) indicates most weathered which in the field translates to an outermost position meaning an oldest age. Cluster C is always ranked most modified (4) in Table 4. Sites associated with cluster C fall within the field-designated McLeod boundaries. The RD variables of the 4-cluster grouping, however, fail to subdivide the Nurses Lakes deposits favorably (Table 4). Surface boulder frequency and proximal moraine slopes do have the same ranking of variables from least (1) to most modified (4), but there is no consistent ranking of deposits represented by the other variables in Table 4. Therefore, using the same RD variables which favorably subdivided the glacial deposits into 3 clusters, the 4-cluster grouping does not separate the Nurses Lakes deposits logically.

Of the 44 sites plotted, with weathered-ranking assigned by surface boulder frequency and proximal slope, 8 sites are incorrect by position (Fig. 10, Appendix D). For example, in the Ellis Basin area the least weathered (youngest) star-sites which are ranked 1 should be found on the West Boulder valley floor. Site 12, however, is found among the circle-sites ranked 2, outboard of its assigned position (Table 4). Sites 3, 5, 12, 19, 20, 40, 42, and 43 are either outboard or inboard of their assigned ranking by position. This is ~18% error overall which is beyond the 10% upper limit for statistical confidence in the results. There is no stratigraphic support for the subdivision into 4 clusters.

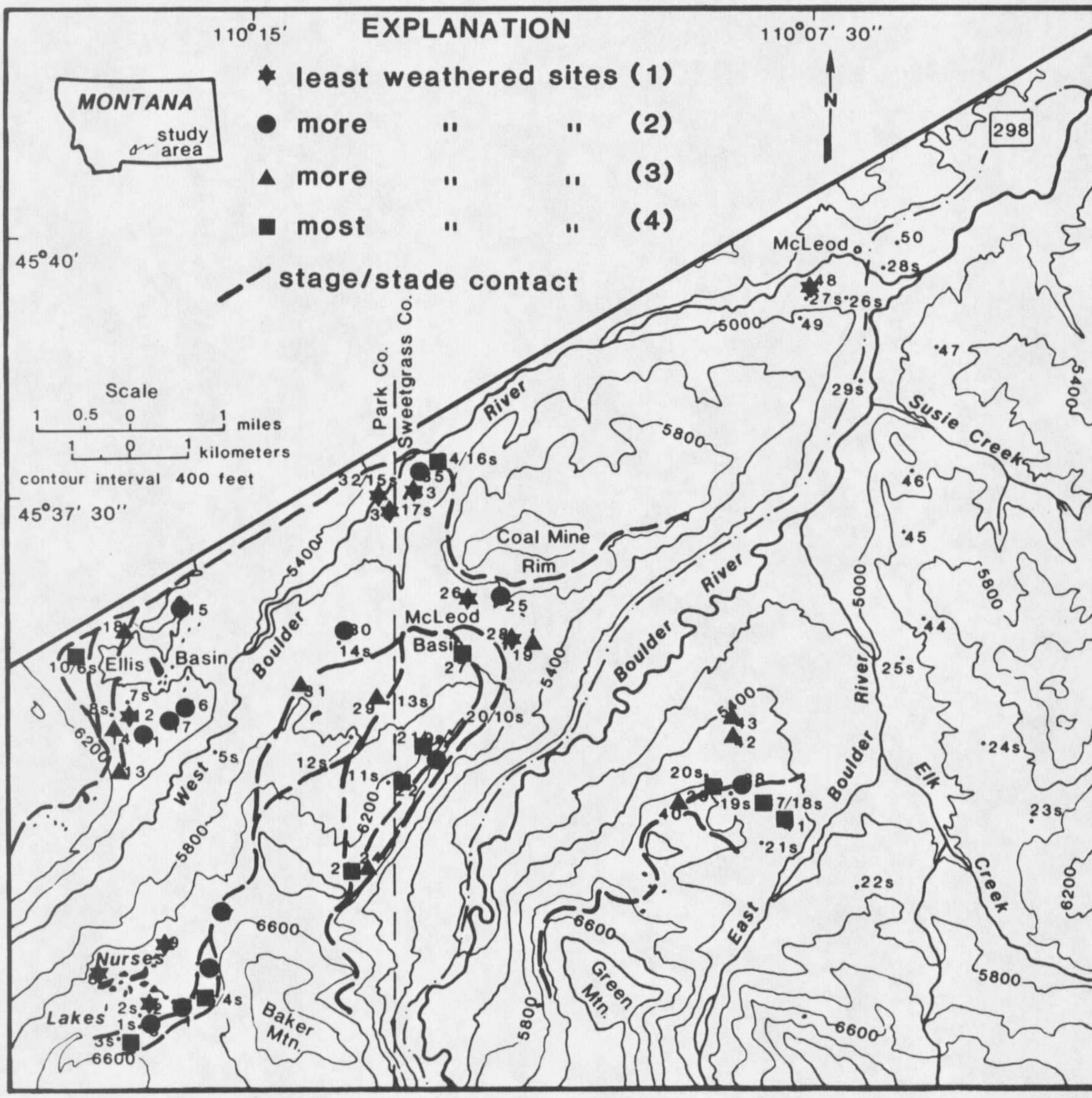

Figure 10. Four-cluster grouping with cluster rank assigned from least (1) to most weathered (4) using the RD variables surface boulder frequency and proximal slope in Table 4. Soil and RD sites locations are shown in Appendix D.

Correlations

Morphostratigraphic Correlations-Stage Level

Classic Buffalo (Pre-Bull Lake), Bull Lake, and Pinedale deposits of the Rocky Mountains have been described morphostratigraphically first by Blackwelder (1931), with additional refinement by Richmond (1965) and numerous other investigators. Pre-Bull Lake sequences are poorly understood and locally occur only as high level, gravel capped terrace remnants (TenBrink, 1968). Few if any scattered erratics remain in the deposition area. TenBrink (1968) reasons that, because of the Pre-Bull Lake deposit locations on high mountain divides near the mountain fronts and on interior uplands as lobate masses, the ice did not advance as a typical valley glacier. The ice probably consisted of one or more sheets which slowly expanded over the Beartooth plateau surface and down shallow valleys from growing centers of accumulation. TenBrink (1968) notes these two or possibly three very early, largely undocumented glaciations were also neither as long as, or as thick as, later recognizable valley glacier deposits in the Beartooth Range. In the Boulder River area, because only the lower deposits of obvious glacial morphology were studied, no deposits interpreted as Pre-Bull Lake equivalent were discovered even though in all likelihood they are present at higher elevations.

Bull Lake glaciers constructed massive moraines (Blackwelder, 1931; Horberg, 1940; Bevan, 1923, 1941, 1943, 1944, 1946; Ritter, 1964; Richmond, 1965; TenBrink, 1968; Pierce, 1979). These moraines form smooth, gently sloping ridges which contain few closed depressions. Bull Lake deposits usually lie outside later Pinedale deposits which often breach the Bull Lake terminal zones in most of the Beartooth Range (TenBrink, 1968; Pierce, 1979). Pierce (1979) finds that Bull Lake moraines near West Yellowstone, Montana, are also widely breached by local streams. The morphological characteristics of Bull Lake deposits correlate well with the Boulder River area McLeod deposits (Table 5).

The Pinedale glacial deposits (Tioga in the Sierra Nevada) are from the last major glaciation in the Rocky Mountains (Blackwelder, 1915, 1931; Nelson, 1954; Richmond, 1965; Sharp, 1969, 1972; Burke and Birkeland, 1979; Hall and Martin, 1983; Birkeland, 1984; Colman and Pierce, 1986) and specifically, the Beartooth area (Ritter, 1967; TenBrink, 1968; Pierce, 1979). In general, Pinedale deposits occur in moraines which lie medial to and lower than Bull Lake till and roughly parallel the present streams (TenBrink, 1968). These glaciers often breached earlier glacial terminal deposits. The surface of Pinedale moraines is extremely irregular and composed of numerous small mounds and depressions. Many depressions are undrained (Blackwelder, 1915, 1931; TenBrink, 1968; Pierce, 1979). These glaciers left the most visible record, and most surficial deposits date from this glaciation (Pierce, 1979). In the McLeod area, the deposits of Nurses Lakes-age correlated well morphostratigraphically with deposits of Pinedale-age (Table 5).

Table 5. Correlation of regional glacial stages (P=Pinedale, BL=Bull Lake) based on RD variables mean values.

	DRAIN McLeod,MT 1986			TenBRINK Still. area,MT 1968			COLMAN AND PIERCE McCall,ID 1986			PIERCE W.Yel.,MT 1979	
event:	NL[1]	ML	NL/ML	P	BL	P/BL	P[2]	BL[3]	P/BL	P	BL
VARIABLE											
SBF/m^2	0.2	0.2	1.0	1.8	0.91	2.0	0.51	0.23	2.2	---	---
WX %	62.8	88.2	0.7	35.0	59.0	0.6	86.7	97.3	0.9	---	---
PROX (degrees)	11.6	8.1	1.4	---	---		15.2	10.7	1.4	---	---
DISTAL	11.4	7.8	1.5	---	---		18.0	11.0	1.6	---	---
CREST(m)	8.1	13.3	0.6	---	---		23.7	35.1	0.7	---	---
THK A+B(cm)	36.4	37.9	1.0	---	---		56.0	128.0	0.4	16.0	53.0

1 Nurses Lakes-stades 1 and 2
2 Pinedale-Pilgrim Cove and McCall stades
3 Bull Lake-Timber Ridge stade

Relative Dating Correlations-Stage Level

Relative dating (RD) information of many investigators is qualitative or critically different. This makes stage correlations with their areas difficult and in some cases impossible. The following correlation discussion will focus on RD variables for which others have reported their data. Some of the RD variables used are not the best at separating the deposits of the Boulder River area into stages. Therefore, problems and success in the correlation of Boulder River RD variables with others' will be discussed.

Surface boulder frequency: The Boulder River study uses a minimum boulder size of 20 inches (50.8cm) in a 2000 square foot (186 m^2) area. TenBrink (1968) uses as criteria for surface boulder frequency, surface boulders greater than 12 inches (30.5cm) in a 400 square foot (37.2 m^2) area. Surface boulder frequency data gathered by Colman and Pierce (1986) near McCall, Idaho, also varies from the Boulder River study. They used a smaller site area (60 m^2) and boulder size (>30cm). Principally because of differences in boulder size and possibly because of sample site size differences, the results cannot be compared. This observation is supported by the fact surface boulder frequency does provide correlation between TenBrink (1968) and Colman and Pierce (1986) in the ratio of younger to older glaciations (Table 5). Both studies have minimum boulder sizes which are similar.

Weathered percentage: The percentage of weathered boulders in each glacial stage correlates well between the Boulder River area and the Stillwater drainage, to the east (Table 5). However, the percentage of weathered boulders does not correlate as well with Colman and Pierce (1986). One would expect a favorable correlation between adjacent glacial deposits with similar lithologies. Nurses Lakes and McLeod deposits of the Boulder River area correlate favorably with TenBrink's Pinedale and Bull Lake stages of glaciation.

Moraine morphology: Moraine morphology offers hope of regional correlation when the ratio of older to younger deposit measurements are compared between the Boulder River area and McCall, Idaho. In this case, Nurses Lakes stades 1 and 2 morphology measurements are combined and compared to McLeod-age morphology (age 1) measurements. Colman and Pierce's (1986) Pilgrim Cove and McCall moraine data (younger) are combined and compared to the Timber Ridge morphology measurements (Table 5).

Results of the ratios (Table 5) indicate that comparison of younger to older moraine morphology measurements are remarkably similar. McLeod deposits' ratios correlate well with Timber Ridge and Nurses Lakes deposits correlate with combined McCall and Pilgrim Cove. If Williams Creek stade morphology measurements are used in the compilation of younger Wisconsinan deposits (McCall and Pilgrim Cove), then the comparisons between the Boulder River area and McCall, Idaho, are poor. More discussion concerning the omission of Williams Creek data is forthcoming in the stadial correlation section.

Soils: In the Boulder River area, although most soils variables do not subdivide the glacial sequence into stages, one variable which was mentioned in the discussion of soil T-tests does help with the subdivision. The soil $CaCO_3$ accumulation zone is the elevation or zone above which no $CaCO_3$ accumulates and below which we see calcic soils. Older soils generally have a higher $CaCO_3$ accumulation elevation (Birkeland, 1984) at any one particular latitude. In the Boulder River area, which lies slightly north of the 45th parallel, the limit of $CaCO_3$ accumulation is 6300 feet (1920m) for the older McLeod deposits and 6000 feet (1830m) for the Nurses Lakes soils. This agrees nicely with Birkeland's (1984) figure 11-21 for soils on Illinoian glacial deposits (Bull Lake equivalents) and soils buried by late Wisconsin glaciers (Pinedale equivalents). McLeod-age deposits then correlate with Bull Lake equivalents and Nurses Lakes-age deposits with Pinedale equivalents.

Regional Correlations-Stadial Level

Colman and Pierce (1986) have the only RD data which can used in correlations to the stadial level. They have subdivided their glaciations, from youngest to oldest, into Pilgrim Cove (PC), McCall (Mc), Williams Creek (WC), and Timber Ridge (TR). The Williams Creek glacial stade was included in the correlation, however, the Colman and Pierce (1986, p.78) statement that, "To our knowledge, Williams Creek deposits are the only strongly documented early Wisconsin glacial deposits in the Rocky Mountains,........", strongly suggests that deposits of Williams Creek age may not be present in the McLeod area. Ratios in Table 6 indicate correlations using Williams Creek weathering data, in most cases, does not work. Ratio correlations are best between the Colman and Pierce (1986) youngest Pinedale equivalent stades which are Pilgrim Cove and McCall and Nurses Lakes 2 and 1, respectively. This supports observations that Pinedale-age glacial deposits which are preserved locally are of middle Pinedale-age and younger (Hall and Heiny, 1983). The older Timber Ridge stage correlates best with the McLeod stage of glaciation in the Boulder River area.

Table 6. Correlation of weathering data between the Boulder River area and the McCall, Idaho area (Colman and Pierce,1986). Glacial stades, in the Boulder River area, are; Nurses Lakes 1 and 2 and McLeod glaciation. In the McCall area, stades are, from youngest to oldest; Pilgrim Cove, McCall, Williams Creek, and Timber Ridge.

MEAN STADIAL DATA

	NL2	NL1	ML	PC	Mc	WC	TR
PROX (degrees)	15.1	10.4	8.0	18.0	13.8	7.3	10.8
DISTAL	12.6	10.2	7.8	22.7	16.0	7.0	11.0
CREST(m)	6.9	8.1	13.3	19.0	26.8	53.2	35.6
SBF/m^2	0.25	0.17	0.12	0.51	0.33	0.23	0.39
WX %	56.9	55.6	78.6	86.0	85.5	94.0	97.3

CORRELATION RATIOS

	NL2/NL1	NL1/ML	NL2/ML	PC/Mc	Mc/WC	WC/TR	PC/WC	Mc/TR	PC/TR
PROX	1.5	1.3	1.9	1.3	1.9	0.7	2.5	1.3	1.7
DISTAL	1.2	1.3	1.6	1.4	2.3	0.6	3.2	1.5	2.1
CREST(m)	0.9	0.6	0.5	0.7	0.5	1.5	0.4	0.8	0.5
SBF/m^2	1.5	1.4	2.1	1.5	1.4	0.6	2.2	0.9	1.3
WX %	1.0	0.7	0.7	1.0	0.9	1.0	0.9	0.9	0.9

Additional Regional Correlations

Since many previous investigators with whom I have correlated locally ended their discussion and deposit analysis at the stage level, additional correlations were needed with contemporary investigators whom have also subdivided to the stadial level. Many contemporaries have used absolute as well as different relative dating criteria in the subdivision of their glacial stages, therefore, I must discuss the evolution of absolute dating regionally. By correlating indirectly (through Colman and Pierce, 1986) with investigators who have generated absolute dates of their deposits my correlation will be complete.

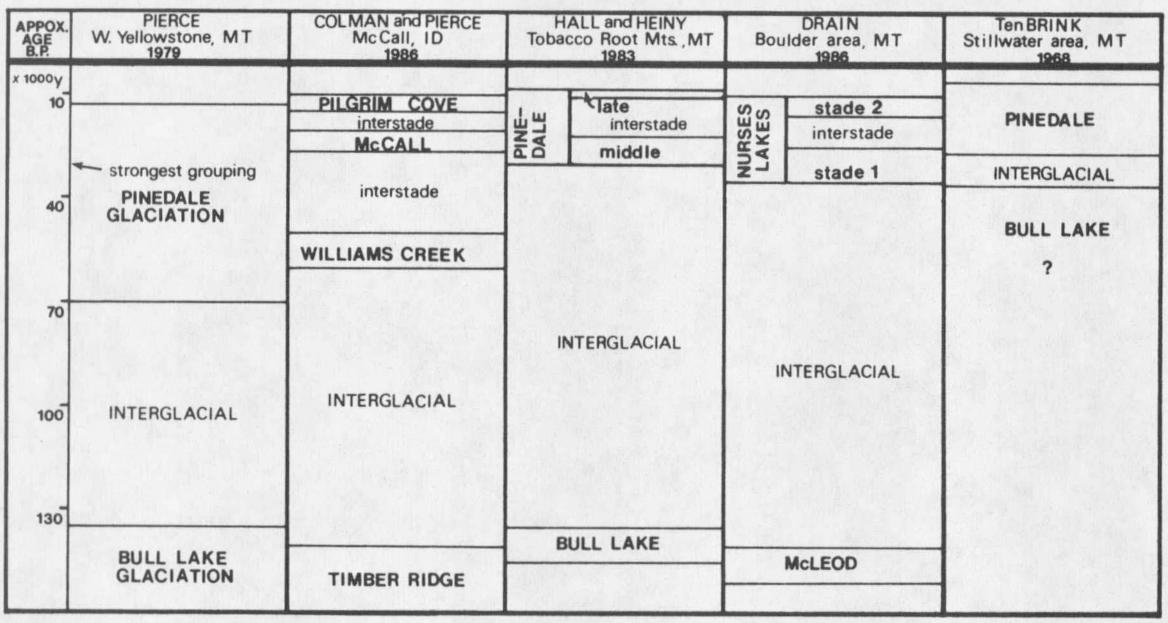

Figure 11. Regional correlation chart

Pierce and others (1976) dating by obsidian hydration and K-Ar place Pinedale deposits from 14-45,000 yBP (most dates are from 30,000 yBP) and Bull Lake deposits from 130-155,000 yBP. When these time window designations for Pinedale and Bull Lake glaciations are compared to the marine record based on oxygen-isotope analysis, foraminiferal studies, and changes in sedimentation character, there is a good correlation (Pierce and others, 1976; Fig. 5).

Pierce (1979), in the West Yellowstone area of Montana, finds Pinedale deposits ranging from 13-70,000 yBP and Bull Lake from 135-160,000 yBP (Fig. 11). Colman and Pierce (1986), using principally weathering rinds and soil measurements, interpreted three stades of Pinedale glaciation having ages of 14,000, 20,000, and 50-60,000 yBP. Bull Lake equivalents, in the McCall, Idaho area, date from 140-150,000 yBP.

Hall and Martin (1983), working in the Tobacco Root Range of southwestern Montana, used hornblende etching studies to determine ages of 8,800-10,500 yBP for minor late Pinedale deposits and 22-28,000 yBP for middle Pinedale. They excluded an early Pinedale advance based not only on their hornblende etching but on studies by Madole (1980a, 1980b) and Hall and Heiny (1983) in Colorado and Montana. Hall and Martin (1983, p. 18) believe: "the early Pinedale glaciation (in southwest Montana) was not the most extensive and that middle Pinedale ice overrode these earlier deposits to build prominent moraines downvalley." The early Pinedale obliteration theory is supported by the graphs which show smaller amplitude and shorter duration of sea level stands on Barbados (Mesolla and others, 1969), oxygen-isotope data (Emiliani, 1955a, 1958a, 1964, 1966, 1972) and foraminiferal studies (Kennett and Huddlestrum, 1972). All of these curves are compared in Pierce and others (1976), figure 5. Hall and Martin (1983) also assumed Bull Lake ages of 135-145,000 yBP.

TenBrink (1968)in the Stillwater Valley to the east, because his study was before K-Ar dating of glacial deposits (Pierce and others, 1976), dates Pinedale based on correlation with Richmond (1965) from 6-25,000 yBP. His Bull Lake deposits range from 29-37,000 yBP and earlier.

Summary

The cluster program (Dixon, 1983) grouped the sites best into three clusters based the RD variables and field designated ice marginal positions. One cluster grouped McLeod deposits and the other two clusters subdivided the Nurses Lakes glaciation into two events.

Correlations followed initially from morphologic similarities between Nurses Lakes and Pinedale deposits, and McLeod and Bull Lake deposits. Relative dating criteria were then used to further substantiate the stage subdivision and correlate the Boulder River area with the work of other investigators (Table 5). There is excellent agreement of moraine morphology ratios (younger/older) between the Boulder River area and McCall, Idaho. Weathered percentage ratios between the Boulder River area and the Stillwater drainage to the east are also encouraging. Again, combined Nurses Lakes deposits correlate with Pinedale deposits and McLeod with Bull Lake deposits.

Finally, the means of the RD variables associated with individual glacial events (stades) were correlated between the Boulder River area and McCall, Idaho (Table 6). Although the raw mean values do not compare favorably, the ratio of younger to older indicates a solid connection between Nurses Lakes 2 and Pilgrim Cove stades, Nurses

Lakes 1 and McCall stades and McLeod and Timber Ridge glaciations.

As a result of indirect correlation, I believe Nurses Lakes stades 1 and 2 to be close in absolute age and younger than early Pinedale deposits (Hall and Martin, 1983). If I assume a mean absolute date of 30,000 yBP for Nurses Lakes 1 deposits (Pierce, 1979) and a mean absolute date of 15,000 yBP for Nurses Lakes 2 (Colman and Pierce, 1986), then Nurses Lakes 1 advance is twice as old as the Nurses Lakes 2 stade. McLeod glaciation would range from 140-150,000 yBP based on Colman and Pierce (1986). This indicates an approximately five-fold difference between the McLeod glaciation and Nurses Lakes 1 stade and an order of magnitude difference between the McLeod and Nurses Lakes 2 stade.

The RD variables alone will discriminate between glaciations, however, they need to be combined and cluster analyzed to separate stades. Stades closer than a two-fold difference may be difficult to discriminate. For example, if two McLeod-age stades were present in the Boulder River area, then they would need to be separated by 150,000 years assuming that a McLeod-age of 140-150,000 yBP is used. Maximum separation for the two possible Bull Lake advances is 40,000 years (Pierce and others, 1976). That is much less than a two-fold difference and probably would not be separated even by combined RD variables such as were used in the Boulder River area. Plate 1 shows the differentiation of the deposits within the Boulder River-Beartooth Mountain front region.

CONCLUSIONS

Major conclusions of the Boulder River area begin with the discussion of the relative dating (RD) criteria which helped to define stages and stades of glaciation. The best relative dating techniques for glacial age determinations were surface boulder frequency, percentage of weathered granitic lithologies in the glacial deposits, and all moraine morphology measurements with distal slope angles being especially good. Alone, each of these RD variables will discriminate to the stage level. When combined in a cluster analysis program (Dixon, 1983), the variables will discriminate to the stadial level. This powerful program indicates site numbers associated with each cluster within the best cluster grouping. Final stadial interpretations on the surficial map of the area are based on the best cluster groupings. As a result of in-field mapping and RD variable analysis the glacial history of the Boulder River area is as follows.

Glacial History of the McLeod Area

The depositional history of the Boulder River glaciers follows late Pleistocene accumulations of ice in the Beartooth Mountains. As glaciers exited the confines of the intermontane valleys, they spread out on the sedimentary cuestas. Although deposits interpreted as Pre-Bull Lake equivalent were not noted in the McLeod area, they may occur at higher elevations (TenBrink, 1968).

The earliest deposits are of the McLeod glaciation which correlate to Bull Lake deposits elsewhere in the Rocky Mountains. One stade of McLeod glaciation is mapped although in the McLeod Basin area there may have been two stades which the RD variables fail to differentiate. These deposits are recognized by their subdued morphology, by the fact that they lie outside the younger deposits, and they have older RD characteristics (Table 2). Generally, there are significant differences in the percentage of weathered granitic stones and moraine morphology measurements (Table 3) between younger deposits and those of McLeod-age. The McLeod-age glacier from the Main Boulder River area combined with the glacier of the same age in the West Boulder River area creating an expanse of ice which measured 11 miles from west (Ellis Basin) to east (East Boulder River/Elk Creek area). The Main Boulder glacier dammed the East Boulder River and Susie Creek creating glacial lakes. The ice dams often failed and the resulting jokulhlaups extensively reworked glacial deposits at the terminus. Deposits of the jokulhlaups are found well downstream of the terminus in the Main Boulder Valley. The McLeod-age glacier, in the Main Boulder drainage, terminated at the confluence of the Main and West Boulder rivers at 4800 feet a.s.l. The McLeod-age glacier in the West Boulder drainage terminated at 5200 feet a.s.l. Absolute dates for McLeod-age deposits, through correlation, range in age from 150-140,000 yBP.

The interglaciation, as interpreted through correlation, probably lasted about 70-80,000 years, from 140-70,000 yBP (Pierce, 1979; Colman and Pierce, 1986). Following the interglaciation, deposits of classic Pinedale are represented by two stades in the Boulder River area, named Nurses Lakes stades 1 and 2.

The ice readvanced following the interglaciation possibly in early Pinedale time only to be obliterated by larger mid-late Pinedale advances (Hall and Martin, 1983). No deposits interpreted as being early Pinedale equivalents were found in the Boulder River area. Nurses Lake-age deposits are recognized by their hummock and kettle topography, by the fact that they usually lie inside the older deposits, and by the fact that they have more youthful RD characteristics (Table 2). Overall, they have significantly less weathered granitic lithologies and are younger moraine morphology measurements than McLeod-age deposits (Table 3). The Nurses Lakes glaciers followed a similar route as the McLeod glacier again spreading over the sedimentary cuestas. The Nurses Lakes glaciers were smaller (less volume) than the McLeod glacier because Nurses Lakes deposits are generally contained within the McLeod deposits. The Nurses Lakes-age termini are at the same elevation as McLeod-age terminus, in both the Main and West Boulder valleys, and Nurses Lakes terminal deposits are contained within the McLeod terminus.

Both stades of the Main Boulder River combined with the West Boulder River glaciers of the corresponding Nurses Lakes advance, much as they did during the McLeod advance creating a large expanse of ice. The two stades of the Nurses Lakes advance in the Main Boulder Valley dammed the East Boulder River and Susie Creek creating two glacial lakes. Outburst floods as a result of failed ice dams modified the terminal deposits in the Main Boulder Valley and deposited material as far as 8 miles downstream of the Nurses Lakes-age termini. The latest Nurses Lakes 2 jokulhlaups modified the terminal deposits of both stages of glaciation in the Boulder River area.

The Nurses Lakes stades were of nearly the same size although the latest Nurses Lakes 2 deposits can be identified generally within the Nurses Lakes 1 deposits based on cluster analysis and field criteria. The Nurses Lakes 1 deposits are thought to be twice as old as the Nurses Lakes 2 deposits based on correlation. The Nurses Lakes 1 advance is thought to span from 35-25,000 yBP. That gives a midpoint of 30,000 yBP which correlates to the majority of Pierce's obsidian hydration dates near West Yellowstone, Montana. The Nurses Lakes 2 advance is thought to span from 15-10,000 yBP correlating to Colman and Pierce (1986) in the McCall, Idaho area. The Nurses Lakes 2 advance was not extended to include younger dates, as Hall and Heiny (1983) note that the late Pinedale advance was relatively insignificant and ranges in age from 10,500-8,800 yBP in the Tobacco Root Mountains of southwestern Montana.

Following the last recognizable Nurses Lakes advance in the study area, the ice may have deposited one terminus well within the intermontane valleys of the McLeod area. This deposit would correlate to the late Pinedale advance recognized by Hall and Heiny (1983). Ice accumulations and deposits have been relatively insignificant to the present (Richmond, 1965).

Regional Conclusions

The Beartooth icecap probably contributed similar amounts of ice to Beartooth valley glaciers during all Wisconsin glaciations. Even during the Pinedale advance which was extensive in the adjacent Yellowstone Valley, the rhyolite diverted Yellowstone icecap (Pierce, 1979) did not augment the Beartooth icecap causing abnormally large Pinedale equivalent deposits in the Boulder River area (Plate 1).

Suggestions for further study

Calcium Carbonate Rind Study

One observation that may be of benefit to future Quaternary researchers with deposits rich in $CaCO_3$ is the $CaCO_3$ rind thickness. In the Boulder River area, on successive lateral moraines at similar elevations one could break off and measure the $CaCO_3$ rinds on numerous cobbles in each soil profile, where first encountered in the profile. A range of rind thicknesses could be assembled for each age deposit at specific elevations. This may provide a valuable RD variable for subdivision of glacial deposits.

Calcium carbonate rinds are possibly a good RD variable because: 1) with any reworking of the till by a subsequent glacial or fluvial event the relatively fragile $CaCO_3$ rinds would be broken off. If no breakage occurs the rinds, which grow on the cobble bottom, would probably not come to rest with the rind down as originally deposited. All cobbles exhibiting $CaCO_3$ accumulations in suspect locations could be eliminated from the rind study and the sample site abandoned. 2) As long as the samples were below the $CaCO_3$ accumulation level, all deposits of the same age and elevation would have been subjected to the same glacial/interglacial events (Birkeland, 1984). 3) Range of glacial till composition within one drainage might be assumed similar.

Terrace Correlations

Correlations between the McLeod and Nurses Lakes age terminal deposits and the corresponding terraces were made on the assumption that the terraces were graded to the maximum McLeod and Nurses Lakes age deposits. What is needed here is a rigorous RD variable study to correlate the Boulder River terrace sequence to those studies which have been conducted nearby (Ritter, 1967; Rayne, 1982; Reheis, 1984). The more recent studies have used relative dating techniques to date their deposits. Often they then correlate the terrace sequence to glaciations in the Rocky Mountain area.

Jokulhlaup Deposits

The large lenticular deposits, composed of a wide range of particle sizes, found in the Main Boulder Valley are interpreted as glacial lake flood deposits. However, relative age designations as determined through cross-cutting relationships and other RD techniques have not been used on the outburst deposits. In the Boulder River area, a comprehensive relative dating study is needed to accurately determine the sequence of jokulhlaup deposition.

Sequence of Landslides

The post-glacial landslides in the Beartooth area have not been dated in any way even though it is obvious that there are different ages of slides. Needed is a study using RD techniques and possibly radiocarbon to give the sequence of post-glacial landsliding.

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APPENDICES

APPENDIX A

Surface Boulder and Morphology Data

McLeod Glaciation

Site #	SURFACE BOULDER WX CHARACTERISTICS				MORAINE MORPHOLOGY[5]		
	SBF[1]	FR/WX[2]	RING/THUD[3]	MXB[4]	PROX	DISTAL	CREST
	(of 50 cobbles sampled)			(ft)	(degrees)		(ft)
1.	48	1/49	49/1	10	14	5	40
3.	35	3/47	46/4	12	0	17	50
4.	25	0/50	46/4	10	4	12	55
5.	40	2/48	46/4	14	10	4	0
6.	31	2/48	45/5	15	10	4	20
10.	19	11/39	46/4	7	8	9	100
21.	21	10/40	44/6	7	4	6	20
22.	13	10/40	48/2	6	–	–	–
23.	22	14/36	47/3	9	7	5	20
34.	24	7/43	46/4	6.5	10.5	9	25
44.	–	3/47	–/–	20	–	–	–
45.	–	3/47	–/–	10	–	–	–
47.	–	2/48	–/–	4	–	–	–
48.	52	17/33	–/–	5.5	–	–	–
50.	–	5/45	–/–	25	–	–	–
Mean	30.6	5.9/44.1	46.3/3.7	11	8.1	7.8	43.6

Nurses Lakes Glaciation

2.	50	30/20	47/3	–	24	12	20
7.	36	14/36	49/1	9	10	9	50
8.	49	21/29	47/3	10	25	14	25
9.	47	22/28	50/0	9	13	14	25
11.	35	15/35	46/4	8	–	16	45
12.	47	20/30	47/3	7	–	–	30
13.	38	23/27	47/3	7	16	15.5	30
14.	35	20/30	48/2	6.5	11	18	35
15.	46	12/38	46/4	6	–	16	–
16.	41	18/32	45/5	16	–	18	22
17.	43	13/37	45/5	6	–	–	–
18.	32	21/29	44/6		10	4	30
19.	26	25/25	49/1	5	11	14	15
20.	32	11/39	45/5	14	14	10	20
24.	31	19/31	48/2	8	10	9	15
25.	38	12/38	45/5	6	9	10	15
26.	51	14/36	47/3	5.5	10	9	20
27.	29	14/36	47/3	6	6	7	20
28.	53	25/25	47/3	11	14	10	15
29.	39	32/18	49/1	6	6	9	25
30.	41	16/34	50/0	5	–	–	30

Appendix A (cont.)

31.	37	33/17	50/0	9.5	13	6	45
32.	64	11/39	47/3	7.5	-	-	-
33.	49	31/19	48/2	6	9	10	30
35.	38	16/34	48/2	12	15	8	55
36.	51	20/30	48/2	5	18	20	15
37.	9	7/4	-/-	4.5	-	8	-
38.	41	17/33	-/-	10	13	-	-
39.	30	12/38	49/1	7	-	-	-
40.	41	23/27	-/-	5.5	8	10	15
41.	24	17/33	-/-	3.5	9	14	45
42.	18	27/23	-/-	6	10	10	20
43.	15	33/17	-/-	8	-	-	-
46.	-	13/37	-/-	15	-	-	-
49.	-	5/45	-/-	3.5	-	-	-
Mean	37.2	18.6/31.4	47.3/2.7	7.7	11.6	11.4	26.7

[1] surface boulder frequency
[2] fresh/weathered ratio
[3] audible sound
[4] maximum boulder diameter
[5] moraine morphology measurements of proximal and distal slopes and crest width

APPENDIX B

Lithology and Diameters Data

McLeod Glaciation

Site #	LITHOLOGIES (out of 30)					DIAMETERS (in inches)				
	Qfgn[1]	Amph[2]	Sed[3]	PЄs[4]	other[5]	Qfgn	Amph	Sed	PЄs	other
1.w	29	1	0	0	0	–	–	0	0	0
3.w	29	1	0	0	0	–	–	0	0	0
4.w	0	0	0	0	0	0	0	0	0	0
5.w	28	2	0	0	0	–	–	0	0	0
6.w	27	3	0	0	0	–	–	0	0	0
10.w	0	0	0	0	0	0	0	0	0	0
21.m	26	0	4	0	0	38.9	0	25.8	0	0
22.m	14	0	2	13	1	46.3	0	24.5	36.5	–
23.m	26	1	3	0	0	36.4	–	24.3	0	0
34.m	27	0	1	2	0	35.4	0	22.0	36.0	0
44.m	8	0	2	20	0	25.5	0	20.0	30.1	0
45.m	14	0	2	13	1	32.5	0	25.5	29.6	20.0
47.m	1	0	3	26	0	23.0	0	38.0	30.5	0
48.m	14	0	1	15	0	37.4	0	20.0	30.6	0
50.m	26	0	0	4	0	76.4	0	0	80.0	0

Nurses Lakes Glaciation

Site #	Qfgn	Amph	Sed	PЄs	other	Qfgn	Amph	Sed	PЄs	other
2.w	27	3	0	0	0	0	0	0	0	0
7.w	28	2	0	0	0	43.0	25.0	0	0	0
8.w	0	0	0	0	0	0	0	0	0	0
9.w	0	0	0	0	0	0	0	0	0	0
11.w	0	0	0	0	0	0	0	0	0	0
12.w	0	0	0	0	0	0	0	0	0	0
13.w	23	3	2	0	2	46.7	27.7	35.5	0	36.5
14.w	0	0	0	0	0	0	0	0	0	0
15.w	0	0	0	0	0	0	0	0	0	0
16.w	0	0	0	0	0	0	0	0	0	0
17.m	0	0	0	0	0	0	0	0	0	0
18.m	0	0	0	0	0	0	0	0	0	0
19.m	20	0	5	4	1	29.8	0	28.6	27.5	20.0
20.m	21	0	3	6	0	37.0	0	30.0	29.0	0
24.m	19	0	5	6	0	32.0	0	30.4	25.3	0
25.m	21	2	2	5	0	32.3	22.5	30.5	25.8	0
26.m	21	0	2	7	0	33.1	0	28.5	28.0	0
27.m	22	2	3	3	0	33.9	25.0	22.7	27.6	0
28.m	18	0	10	2	0	44.8	0	30.2	25.5	0
29.w	26	1	3	0	0	35.7	36.0	23.7	0	0
30.w	27	1	1	1	0	34.1	28.0	20.0	20.0	0
31.w	28	0	1	1	0	35.9	0	52.0	24.0	0
32.w	25	3	1	0	1	36.6	30.3	33.0	0	31.0
33.m	25	0	0	3	2	43.6	0	0	35.0	28.5
35.m	26	1	0	3	0	42.2	34.0	0	33.6	0

Appendix B (cont.)

36.m	25	0	1	2	2	31.0	0	22.0	21.5	30.0
37.m	4	0	7	19	0	22.3	0	18.6	29.4	0
38.m	15	0	6	9	0	33.1	0	26.3	29.4	0
39.m	17	0	2	11	0	40.1	0	25.5	28.4	0
40.m	9	0	7	14	0	30.2	0	28.7	35.4	0
41.m	11	0	5	14	0	29.1	0	29.0	32.7	0
42.m	2	2	5	21	0	27.5	21.5	20.0	30.1	0
43.m	13	0	2	15	0	33.2	0	53.0	34.9	0
46.m	19	0	1	10	0	34.2	0	26.0	29.7	0
49.m	0	0	0	0	0	0	0	0	0	0

[1] Quartzofeldspathic gneiss
[2] Amphibolite
[3] Sedimentary lithologies
[4] Precambrian Stillwater Complex lithologies
[5] Other lithologies including: Precambrian mica schist, quartzite, and garnet bearing quartzofeldspathic gneiss
m-site located in the Main Boulder drainage
w-site located in the West Boulder drainage

APPENDIX C

Soil Data

McLeod Glaciation

Site #	A-Horizon							B-Horizon						
	TK[1]	STR[2]	TX[3]	pH[4]	CLR[5]	BD[6]	S/SI/C[7]	TK	STR	TX	pH	CLR	BD	S/SI/C
1s	9.5	101	022	6.0	132	10	0/ 0/0	7.9	101	022	6.0	153	00	63/28/9
3s	10.2	301	000	0.0	132	31	0/ 0/0	3.9	301	000	0.0	000	00	0/ 0/ 0
4s	7.9	301	022	6.5	133	31	54/36/10	7.9	000	002	6.0	153	00	49/37/14
6s	5.0	101	122	7.5	132	22	50/36/14	8.0	101	202	7.5	143	22	49/37/14
9s	6.0	101	002	7.8	142	22	51/31/18	14.0	121	002	8.3	172	00	43/36/21
11s	9.0	111	202	7.8	133	22	60/28/12	10.0	121	122	8.0	364	22	53/34/13
16s	6.0	201	202	7.3	143	22	53/28/19	7.0	121	202	7.5	154	32	49/28/23
21s	8.0	121	202	8.0	133	22	52/35/13	7.0	221	002	8.0	143	21	55/36/14
22s	6.0	221	202	7.8	133	21	67/24/ 9	5.0	221	202	8.0	154	21	57/27/16
23s	6.0	221	202	7.8	133	21	59/28/13	7.0	221	202	8.0	153	31	60/26/14
24s	5.0	221	202	7.8	133	22	48/34/18	7.0	221	212	7.3	154	22	30/36/34

Nurses Lakes Glaciation

2s	8.7	301	022	6.0	132	11	52/38/10	3.9	301	222	6.0	153	00	50/34/16
5s	8.0	001	232	8.0	132	22	53/39/ 8	4.0	001	222	8.0	172	22	42/44/14
7s	8.5	201	212	7.3	133	32	63/31/ 6	11.5	101	222	8.0	163	00	59/31/10
8s	6.0	201	202	7.3	132	22	55/36/ 9	15.0	201	202	7.3	154	00	52/38/10
10s	5.0	101	202	8.0	143	33	49/40/11	17.0	301	202	8.0	172	00	45/34/19
12s	6.0	121	202	7.0	132	22	58/29/13	3.0	123	212	7.8	154	00	55/23/22
13s	10.0	201	202	7.3	132	21	43/34/23	10.0	231	012	8.0	153	23	36/40/24
14s	5.0	000	222	7.0	133	32	58/27/15	11.0	202	000	7.5	154	21	51/29/20
15s	5.0	201	202	7.0	133	32	58/32/10	5.0	201	202	7.8	153	32	54/32/14
17s	5.0	201	202	6.5	133	31	60/25/15	10.0	201	202	7.0	154	31	56/25/19
18s	4.0	201	202	7.3	133	21	46/28/26	5.0	221	202	8.0	154	21	46/54/20
19s	3.5	201	202	7.0	133	21	47/31/22	4.0	121	202	7.8	143	21	43/33/24
20s	3.5	201	202	7.5	133	22	50/34/16	3.0	121	202	8.0	172	00	43/34/23
25s	8.0	221	212	8.0	143	22	36/36/28	13.0	221	212	8.0	162	00	38/38/24
26s	8.0	101	212	7.3	143	32	53/18/29	12.0	000	202	7.0	154	00	59/17/24
27s	8.0	101	202	7.0	133	21	55/26/19	9.0	121	002	7.0	256	21	56/27/17
28s	4.0	101	202	7.0	133	22	56/27/17	11.0	221	212	7.3	244	21	50/29/21
29s	7.0	000	202	8.0	132	31	52/30/18	3.0	000	222	8.0	234	22	54/30/16

1 thickness in inches

2 structure first number- 1=weak, 2=moderate, 3=strong; second number- 1=fine, 2=medium, 3=coarse; third number- 1=granular, 2=massive, 3=prismatic

3 texture first number- 1=clay, 2=gravel; second number- 1=clay, 2=sand, 3=silt; third number- 2=loam

4 pH in mol/dl

5 color (dry) of soil first, number- 1=10YR, 2=7.5YR, 3=2.5Y; second number- value, third number- chroma

6 boundary configuration, first number- 1=abrupt, 2=clear, 3=gradual, 4=diffuse; second number- 1=wavy, 2=smooth, 3=irregular, 4=broken

Appendix C (cont.)

[7] sand, clay, and silt percentages (Day, 1965)
Zero is a missing observation.

APPENDIX D

Locations of Soil and Relative Dating Sites

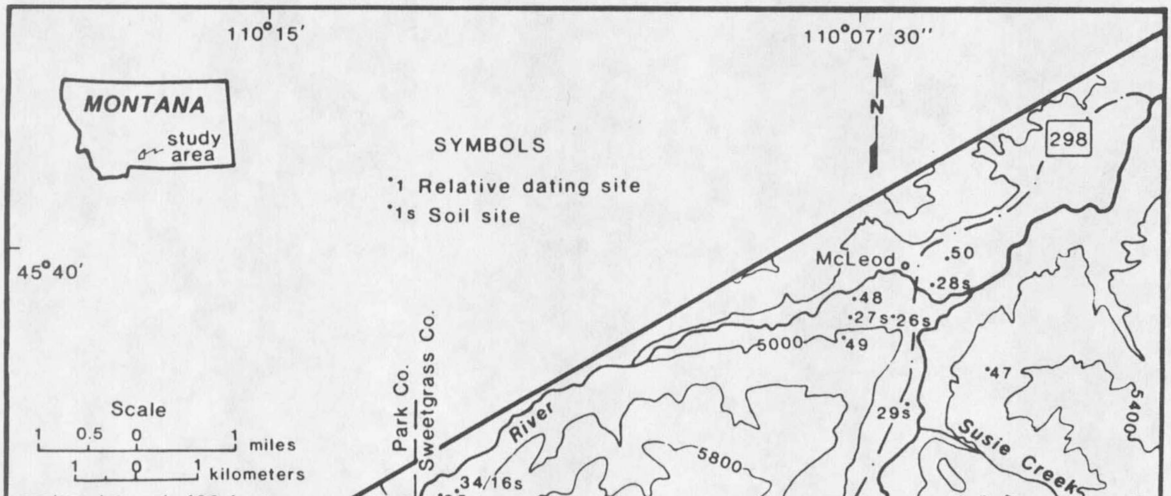
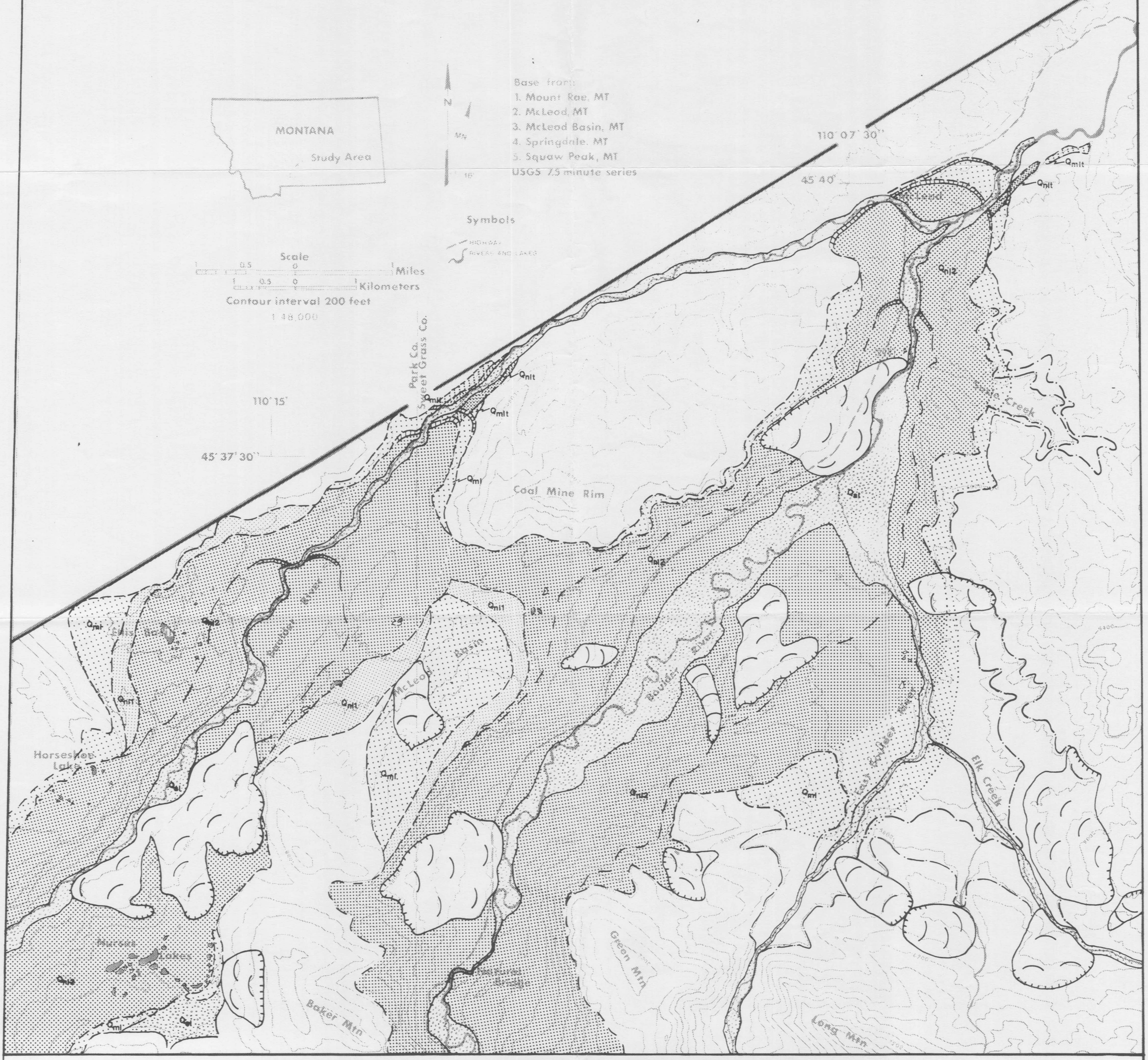


Figure 11. Relative dating and soil site locations

QUATERNARY DEPOSITS OF THE BOULDER RIVER AREA, SOUTHCENTRAL MONTANA

Plate 1



EXPLANATION

	mass movement	glacial	fluvial
QUATERNARY — HOLOCENE	LANDSLIDE		Qal ALLUVIUM
QUATERNARY — PLEISTOCENE		Qnl2 NURSES LAKES STADE 2	Qnlt NURSES LAKES TERRACE
		Qnl1 NURSES LAKES STADE 1	
		Qml McLEOD STAGE	Qmlt McLEOD TERRACE
	lithologies		
pre-Q	BEDROCK K-p€a		

SYMBOLS

- permanent lake-dashed if temporary
- terminal moraine
- modifed terminal moraine
- landslide-hachures on scarp face

CONTACTS

- certain
- approximate
- assumed
- probable ice dam boundary
- glacial lake shoreline