
by

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ABSTRACT

The Quaternary Geology of the Eastern Side of the
Greys River Valley and the Neotectonics of
the Greys River fault in Western Wyoming

by

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The Greys River fault is the easternmost active normal fault associated with Basin and Range extension in the Intermountain seismic belt. It is a north-south trending normal fault, located in the Sevier-age fold and thrust belt of western Wyoming, and bounds the west side of the Wyoming Range. The fault is at least 54 km long, and juxtaposes Permo-Pennsylvanian Wells Formation against various Triassic formations. Throw ranges from 100-1000 m. Seismic reflection data suggest that the Greys River fault is a listric normal fault that soles into the Darby thrust at depth. The fault offsets late Quaternary deposits on the west flank of the Wyoming Range. These deposits were mapped and differentiated on the basis of provenance and weathering characteristics. Four sets of moraines were identified in the study area. The moraines segregated into a local four-fold relative age sequence based on topographic position and relative dating parameters. The four-fold relative age sequence was correlated to Blackwelder's original Rocky Mountain glacial chronology. The most extensive glacial deposits were correlated to the late Pinedale glacial advance.
Alluvial deposits associated with the Pinedale glacial cycle also contain evidence for late Quaternary faulting on the Greys River fault.

Maximum vertical surface displacements of late Quaternary deposits range from 8.6 m in Blind Bull Creek to 8.3 m in Box Canyon, 25 kilometers to the south. Between these points, vertical surface offset ranges from 3 to 8.2 meters. Three trenches were excavated in a late Pinedale alluvial terrace complex in Sheep Creek across a 7.5-meter scarp, a 3.1-meter scarp, and a 7.5-meter scarp-graben. The trenches revealed evidence for two paleoseismic displacements, the ages of which were constrained by eight radiocarbon dates. The most recent event involved a maximum displacement of 4.5 meters and occurred between 2110 +/- 60 and 2910 +/- 60 14C years BP. The earlier event was associated with a maximum observed displacement of 3.2 meters and occurred between 5080 +/- 60 and 5310 +/- 60 14C years BP. The moment magnitudes for these events, calculated from displacement and surface rupture length, range from $M_w = 6.9$ to 7.4 for both events. Scarp heights indicate an uplift rate of 1.11 mm / year. If the late Pinedale alluvium is 14,000 years old, then it appears no events occurred between 14,000 yr BP and 5310 14C yr BP, and two events have occurred between 5310 14C yr BP and 2110 14C yr BP. Such irregular recurrence interval is typical for normal faults in the Basin and Range and makes long-term prediction difficult.
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INTRODUCTION

The Greys River fault is a listric normal fault located at the eastern edge of the Basin and Range province where extension is dismembering the Sevier fold and thrust belt. The fault is young in its state of development compared to other large normal faults in the region. The Greys River fault, which bounds a constricted, linear, stream valley, appears less evolved than larger normal faults farther west and south that bound larger tectonic depressions. The Greys River fault shows evidence for Holocene surface displacements generated during significant paleoseismic events. Study of this fault may yield important information about the growth of the Basin and Range province and its relationship to the Yellowstone hot spot (Pierce and Morgan, 1992).

Subsurface data suggest the Greys River fault is listric, which soles into a pre-existing thrust. This study may provide insight into the seismotectonics of low-angle and listric normal faults in the Basin and Range.

Objectives

The objectives of this study are to: (1) map at a scale of 1:24,000 the Greys River’s fault trace and the surficial deposits along the eastern side of the Greys River Valley, (2) establish a Quaternary chronology of the area by dating the surficial deposits of the eastern side of the Greys River Valley, and (3) determine the timing, magnitudes, offsets, and recurrence intervals of the latest Quaternary paleoearthquakes on the Greys River fault.

Location and Geomorphology of the Study Area

The Greys River Valley (Figure 1) is a narrow, north-trending structural/physiographic basin roughly 95 km south of Jackson, in western Wyoming. The
Greys River Valley is bordered by the Salt River Range to the west and the Wyoming Range to the east. The Greys River flows north from its headwaters along the base of the Wyoming Range for a distance of 64 km, after which it assumes a more northwest trend for 32 km to its confluence with the Snake River at Alpine, Wyoming.

The study area encompasses the Quaternary deposits on the eastern side of the Greys River Valley, and the Greys River fault trace on the west flank of the Wyoming Range. The western boundary of the study area is the Greys River, from the head waters, north to the confluence with Deadman Creek. The eastern boundary of the study area is the drainage divide of the Wyoming Range. Elevations in the study area range from 1,987 m where Deadman Creek enters the Greys River in the north, to 3,468 m at Wyoming Peak in the southern part of the area. Average climate conditions of 350 mm of annual precipitation and mean temperature of 3.3° C are approximated from averaging information from weather stations located nearby (Willmott and others, 1981).

**Previous Investigations**

The Greys River fault was originally mapped but not named by Rubey (1973). The Greys River fault also appears as a nameless fault on regional cross sections of the overthrust belt of western Wyoming (Dixon, 1982; Webel, 1987). Notably, the fault is absent from Witkind's (1975) "Preliminary Map Showing Known and Suspected Active Faults in Wyoming." The Greys River fault is an informal name, proposed for this fault by Jones and McCalpin (1992).

Rubey (1973) mapped bedrock, the surficial deposits, and the trace of the Greys River fault along the Greys River Valley on his 1: 62,500 scale geologic map of the Afton and part of the Big Piney Quadrangles. Rubey, without the aid of subsurface information, identified a steeply dipping, planar normal fault on
Figure 1. Location of the study area. (Adapted from Webel, 1987).
the west flank of the Wyoming Range, and interpreted it to displace the Darby thrust at depth (Rubey, 1973). Rubey’s main interest was mapping bedrock and structure. His classifications of surficial deposits were not sufficient for precise interpretation of the Quaternary deposits. The Greys River fault is shown on the west flank of the Wyoming Range on regional cross sections produced from seismic reflection profiles by Webel (1987) and Dixon (1982). These cross sections interpret the fault to be listric, steeply dipping (~60° west) at the surface and flattening out to ~45° west, where it soles into the Darby thrust at depth.

The major normal faults in western Wyoming were evaluated for their seismic potential for the seismotectonic evaluation of Palisades dam (Piety and others, 1986). The Greys River fault is within 60 km of the dam site. Piety and others (1986) were either unaware of the Greys River fault or they did not feel that it was a significant seismic source, when compared with the more prominent Teton and Star Valley faults.

**Geologic Setting**

**Stratigraphy.** Western Wyoming is composed of folded and faulted late Paleozoic-Mesozoic sedimentary rocks. The stratigraphy of the area consists of up to 15,000 m of marine limestones and dolostones deposited in large unrestricted basins in the Paleozoic, and up to 9,000 m of increasingly clastic material deposited in restricted basins during the Mesozoic (Armstrong and Oriel, 1965; Royse and others, 1975). Bedrock exposed in the study area (Figure 2) includes: the Mississippian Madison Formation; the Permian Wells Formation; the Permian Phosphoria Formation; the Triassic Dinwoody, Woodside, Thaynes, Ankareh and Nugget formations; the Jurassic Twin Creek Formation; the Cretaceous Gannet Group; and the Tertiary Wasatch Formation (Coogan and Royse, 1990).
Figure 2. Regional stratigraphic section for the Wyoming-Idaho-Utah thrust belt. (Adapted from Coogan and Royse, 1990).
Compressional Tectonics. Structural geology of the region is dominated by late Mesozoic, Sevier compressional features associated with the Utah-Idaho-Wyoming fold and thrust belt. The fold and thrust belt was formed during regional compression in late Jurassic to Eocene time (Armstrong and Oriel, 1965). The thrust belt consists of a series of north-striking, west-dipping, east-directed, eastward-younging thrust faults that merge westward into a master west-dipping decollement at depths of 8-12 km (Armstrong and Oriel, 1965; Dixon, 1982; Webel, 1987). The upper flats of these thrusts are typically preserved and uplifted in the normal-fault-bounded ranges to the west. Some of the major thrust faults in the Utah-Idaho-Wyoming fold and thrust belt are, from west to east, the Willard thrust, the Meade thrust, the Crawford thrust, the Absaroka thrust, the Darby thrust, and the Prospect thrust (Blackstone and De Bruin, 1987).

Tertiary clastic sediments shed off the thrust uplifts overlie the leading edge of the eastern most thrusts, in particularly the Prospect, Darby, and Absaroka thrusts (Webel, 1987; Dixon, 1982). The Greys River fault is located between the Darby thrust and the Absaroka thrust.

Extensional Tectonics. The Greys River fault is located at the northeast margin of the Basin and Range province (Figure 3). This margin contains numerous north-trending, down to the west, late Cenozoic normal faults superimposed on the compressional features of the fold and thrust belt (Smith and Sbar, 1974). The normal faults formed in response to east-west extension that began about 17 Ma (Stewart, 1971; Zoback and others, 1981; Eaton, 1982). Recurrent normal (down to the west) faulting has formed a northeast-trending zone of north-trending, right-stepping en-echelon horsts, graben, and tilted blocks between the Wasatch fault zone and the Teton fault (McCalpin, 1993).
Figure 3. Late Cenozoic normal faults and seismicity surrounding the Snake River Plain. Seismicity from historic earthquakes through 1988. (Adapted from Piety and others, 1992).
The Greys River fault is the easternmost expression of active (i.e. Holocene) Basin and Range extension (Gibbons and Dickey, 1983).

The Greys River Valley is near the southeastern edge of a north-trending parabolic distribution of seismicity surrounding the eastern Snake River plain. This seismic parabola is associated with a regional uplift and collapse caused by the migration of the Yellowstone hot spot (Anders and others, 1989). Based on seismic activity, Pierce and Morgan (1992) classified normal faults in this seismic parabola into four zones. The Greys River fault is located in the southern arm of zone 1 of this seismic parabola (Figure 4). Zone 1 is characterized by lesser and reactivated Holocene faults. Faults in this zone are considered active but are described as being early in their cycle of activity and have not accumulated large Quaternary offsets (less than 300 m) and bound small range fronts. Faults in zone 1 are considered waxing in their state of development when compared to the major Holocene faults of zone 2 (e.g. the Star Valley, Teton, and Wasatch faults), which are in a culminating state of activity and are characterized by high rates of slip and throws that exceed 1 km. Faults in zone 3 are major and lesser late Pleistocene normal faults characterized as waning in their cycle of activity (<0.1 mm/year). Faults in zone 4 are major and lesser Tertiary faults without evidence for Pleistocene offset. There has been little work done on faults in zone 1. The Rock Creek fault south of the Greys River fault is the only other fault that has been studied in zone 1 (McCalpin and Warren, 1992).

The seismic potential (i.e. capability of generating a large earthquake) of low-angle normal faults is a topic of on-going work. The distribution of aftershocks, and fault plane solutions on seismically active faults in the Basin and Range show that seismic events have occurred on steeply dipping, planar
Figure 4. The four zones of seismicity associated with the track of the Yellowstone hot spot. The four zones of seismicity, separated by dashed lines, are superimposed over an epicenter map showing locations of historic earthquakes. (Adapted from Pierce and Morgan, 1992).
faults. There is little evidence for seismic events on shallow dipping or listric faults (Arabasz and Julander, 1986; Jackson and White, 1989).

In contrast, seismic reflection studies suggest that some major normal faults in the Basin and Range province (the Star Valley, Bear Lake and East Cache faults) are listric in shape (Warren and McCalpin, 1992; Evans, 1991; Webel, 1987; Dixon, 1982). Studies of the East Cache fault, the East Bear Lake fault and the Star Valley fault suggest paleoseismic events have occurred on these faults (McCalpin, 1990; McCalpin and Forman, 1991; McCalpin and others, 1990a; McCalpin and others, 1990b; Warren, 1992). Work by Abers (1991), Wernicke (1981), and West (1993) also shows possible seismogenesis on shallow-dipping normal faults.

The two previous interpretations of the subsurface geometry of the Greys River fault differ. Rubey (1973) interpreted the Greys River fault as a steeply dipping, planar fault that offsets the Darby at depth. More recent seismic reflection studies suggest that the Greys River fault is listric, soling into a long, gentle ramp in the Darby thrust at depth (Webel, 1987; Dixon, 1982) (Figure 5). A new cross section across the Greys River Valley shows the Greys River fault as a listric normal fault soling into a steep ramp in the Darby thrust (Figure 6). This cross section was constructed using the simple balanced cross section techniques of Woodward and others (1985) and surface bedrock data from Rubey (1973).
Figure 5. Comparison of cross sections showing the interpreted subsurface geometry of the Greys River fault. The top cross section from Rubey (1973) interprets the Greys River fault to be planar and to offset the Darby Thrust. The bottom cross section from Webel (1987) is based on seismic data and interprets the Greys River fault to be listric and to sole into a gentle ramp in the Darby Thrust.
Figure 6. A cross section across the Greys River Valley. Note the listric geometry of the Greys River fault. This cross section crosses the Greys River Valley just north of Box Canyon Creek. The cross section was derived using a technique for balanced cross sections after Woodward and others (1985), and the surface bedrock data from Rubey (1973). Symbols are: C = Cambrian rocks, O = Ordovician rocks, M = Mississippian rocks, P = Pennsylvanian/Permian rocks, TR = Triassic/Jurassic rocks, K = Cretaceous rocks, T = Tertiary rocks, bold lines indicate faults, arrows indicate direction of movement.
METHODS

Aerial Photographic Mapping

Preliminary identification of surficial deposits and the fault trace were made from color aerial photographs. The photographs, flight number 56320, roll 1377, frames 40-80, and 170-208; roll 1477, frames 40-50, were taken on July 14, 1977, at a scale of 1:15,840. Deposit boundaries and locations were traced onto mylar from these photographs and assigned an initial interpretation. The interpreted mylar maps were checked and modified in the field.

Field Mapping

Field work was recorded on 1:24,000 topographic field maps. The study area is located in parts of Pickle Pass, Hoback Peak, Blind Bull Creek, Lookout Mountain, Park Creek, Triple Peak, Box Canyon Creek, Mount Schideler, Poison Meadows, and Wyoming Peak, Wyoming 7.5 minute quadrangles. Data from the field sheets were later transferred to a 1:48,000 scale mylar base map (Plate 1).

In addition to field checking, field studies were conducted to assess parameters that could not be identified from the aerial photographs. Parameters include: the morphology of each deposit, the degree of soil development, surface weathering characteristics, unit descriptions, stream terrace heights, and fault scarp characteristics. Deposit characteristics were recorded from 22 hand-dug soil pits. Surface characteristic measurements were collected from the area immediately surrounding the soil pit site.

Topographic profiles were measured across the fault to describe fault scarp morphology and calculate vertical surface offset. Profile sites were chosen in areas with little or no post-faulting disturbances or erosion.
profiles were measured using one of two methods: 1) the sighting method, using a Brunton compass or an Abney level to sight and pace up a scarp (Compton, 1985), and 2) the rod-leveling method, using a stadia rod and an Abney level (Bucknam and Anderson, 1979). The rod-leveling method begins at the base of the scarp with a rod of known length. The rod is laid perpendicular to the strike of the scarp, and the angle of the rod from horizontal is calculated using an Abney level and recorded. The rod is moved one length towards the top of the scarp and the process repeated until the top of the scarp is reached. The rod length and angle measurements were then entered into a spreadsheet. The spreadsheet graphically plotted cross sections of the surfaces. From these plots, surface offset, scarp height, and maximum slope angles were calculated for each of 30 profiles.

**Trenching**

The trenching techniques followed in this study are described by McCalpin (1989). Three trenches were excavated across the Greys River fault at Sheep Creek to reveal fault-related stratigraphy. The trenches were excavated perpendicular to the fault scarp with a large, tracked backhoe brought in by truck from Alpine, Wyoming. The trenches were fenced and hydraulic jacks (Shorealls) borrowed from the U.S. Bureau of Reclamation were installed to support the trench against collapse.

Preparation of the trench walls prior to mapping consisted of: 1) cleaning, using hoes and brooms to remove any loose material, and 2) constructing a reference grid on the south wall of each trench. The grid consisted of lines of nylon string, placed 1 m apart, stretched horizontally along the length of the trench and leveled with a line level. The level lines were then segmented into 1-m increments, along the length of the string.
Using the grid as reference, the stratigraphy exposed on the trench walls was mapped at a scale of 1 cm equals 20 cm. All depositional packages were drawn in stratigraphic order on the log. The log was used to determine the stratigraphic relationships between the depositional packages and the fault.

The trenches were left open for one month so that they could be reexamined after the preliminary interpretations were complete. The trenches were back filled with a bulldozer trucked in from Big Piney, Wyoming and restored to promote rapid recovery of the natural vegetation.

Relative Dating Methods

Relative dating techniques (Burke and Birkeland, 1979; Pierce, 1979; McCalpin, 1982; Meierding, 1984; Warren, 1992) were used to determine the temporal sequence of deposition of Quaternary deposits in the Greys River Valley.

A local four-fold relative-age subdivision of the glacial sequence was subdivided based on relative dating characteristics of moraines measured in the field. Relative dating parameters measured for moraines include: the stratigraphic and geomorphic position of the deposit within the drainage, frequency of boulders on the surface, extent of boulder burial, lithology, inner and outer slope angles, crest width, degree of soil development, and the thickness of loess cap. The four-fold subdivision of relative ages was correlated to Blackwelder's (1915) regional Rocky Mountain Chronology based on comparison of verbal descriptions of moraines, not by actual comparison of relative dating data. The relative dating measurements collected at the sample sites are given in Appendix A. For nonglacial deposits, relative dating parameters include: frequency of surface boulders, vegetation development, and stream incision.
The relative dating measurements were collected at sites that showed no signs of major postdepositional disturbance. Soil pits were dug at least 1 m deep at each site. A standard list of weathering characteristics was recorded to accurately describe the geology of each sample site. Descriptions of measurement techniques and definitions of the relative dating parameters are presented in Appendix A.

**Numerical Dating Methods**

The timing of paleoearthquakes on the Greys River fault is constrained by dates derived from $^{14}$C analysis of organic material within deposits exposed in the trenches. Organic material was collected from beds that when dated would constrain, through superposition and cross-cutting relationships, the timing of the paleoearthquake, as closely as possible.

The samples consisted of 1-2 kg of low-organic content material (weakly developed buried soils) taken from 10-15 cm of stratigraphic thickness. The samples were pretreated by wet-sieving through a 230 mesh and rinsed with HCl until all of the carbonates dissolved. The samples were not treated with NaOH. The samples were then sent to Beta Analytic Inc. for $^{14}$C analysis. The $^{14}$C analysis consisted of conventional gas counting $^{14}$C analysis.

The laboratory dates were reported as radiocarbon years BP ($^{14}$C yr BP). The dates were then calendar corrected using a computer program (Stuiver and Reimer, 1993), to give a range of true calendar dates. The samples were not corrected for carbon age span or mean residence time (Machette and others, 1992, Appendix A).
Statistical Analysis

The Quaternary deposits of different age were differentiated using histograms of certain relative dating parameters, which include surface boulder frequency, boulder burial factor, and loess thickness. These parameters were found to be the best age discriminators in areas with mixed lithology based on a multivariate statistical analysis in works by Warren (1992), and Rice (1987). The development of weathering characteristics is dependent on age. Deposits that show similar degrees of weathering are similar in age. Due to incomplete occurrences of weathering characteristics and differences in lithology at sample sites throughout the study area, and differences in basin geometry, multivariate segregation of deposits in this study was not attempted. The histograms group deposits that show similar degrees of development of a certain weathering characteristic. The characteristics that were used for segregating deposits on the basis of age in this study were 1) geomorphic position, 2) thickness of loess, 3) surface boulder frequency, and 4) boulder burial factor. These characteristics are independent of the lithologic differences between drainages in the area.
QUATERNARY GEOLOGY

This thesis consists of three major parts: a description of the Quaternary geology, the detailed geology of selected drainages, and the neotectonics. The glacial sequence and the Quaternary deposits will be discussed in the following section. The detailed geology of selected drainages section describes the glacial sequence and Quaternary geology in the glaciated drainages along the Wyoming Range. The neotectonics section describes the geology of the Greys River fault, including its surface expression, fault scarp characteristics, and the results from the trenching investigation.

In constructing a temporal reference, only glacial deposits that have been numerically dated or are defined by specific, relative-dating techniques should be given stratigraphic names (Birkeland and others, 1979). The deposits contained in the Wyoming Range do not have numeric age control, and their high variability in relative age parameters (due to variable lithology) does not warrant local stratigraphic names. Correlating glacial deposits without numeric age control, as is the case in the Greys River Valley, must be done by defined relative dating techniques (Birkeland and others, 1979).

Correlation of glacial deposits in the Greys River Valley with those of regional studies proved very difficult. The weathering characteristics of sedimentary rocks in the Wyoming Range cannot be correlated with classic relative dating studies of Burke and Birkeland (1979), Porter and others (1983), or Pierce and others (1982). These studies examined weathering characteristics of basalt, granites, and crystalline bedrock, which weather differently than the sedimentary rocks in the Greys River Valley. Warren (1992) conducted a study similar to this one in the Salt River Range, of which the bedrock is very similar to that of the Wyoming Range. Warren (1992) used
weathering characteristics to relatively date deposits on the west flank of the Salt River Range.

Correlation of deposits within the study area was complicated by differences in bedrock. Unlike the Salt River Range, which is dominantly composed of Paleozoic and early Mesozoic rocks, there is Cretaceous bedrock underlying the upper Darby thrust flat that is exposed on the west side of the Wyoming Range. Moraine characteristics are strongly affected by bedrock lithology (Porter and others, 1983). Correlation of glacial deposits, within each drainage and to those in other drainages along the range, was complicated by the differences in bedrock within drainages and by lithologic differences and geometry differences of the source areas between drainages. The accumulation/source areas of these five drainages all differ in their physical as well as their lithologic settings.

The original Rocky Mountain glacial chronology established by Blackwelder (1915) recognized three glacial advances which are, from oldest to youngest, Buffalo, Bull Lake, and Pinedale. The Wyoming Range is within 100 km of type locations of the Bull Lake and Pinedale glacial advances, described by Blackwelder in 1915, in the Wind River Range. Although there is no actual data presented by Blackwelder (1915), he gives verbal descriptions of the glacial deposits. Deposits of Buffalo age were described as low shapeless moraines. Later work suggests that some of these deposits are Tertiary conglomerate exposed by erosion (Richmond, 1965). The Bull Lake moraines are described as having moderately weathered clasts at the surface, and smooth, pitless crests. The Pinedale moraines have sharp ridge crests and undrained depressions, and clasts show little to no weathering.
Glacial Moraine and Outwash Deposits

Five drainages in the study area contain evidence of glaciation; from north to south, these are Deadman Creek, Blind Bull Creek, Sheep Creek, Martin Creek, and Box Canyon Creek (Plates 2-4). On the basis of geomorphic position and relative dating characteristics (Appendix A; Figure 7), four different groups of moraines were differentiated in the study area. These four groups are informally described as "Bull Lake," "Early Pinedale," and "Late Pinedale" based on correlation to verbal descriptions of ages of moraines in Blackwelder's (1915) glacial sequence and "Neoglacial" to describe a group of moraines thought to postdate the Pinedale advance. Glacial deposits in the study area are not extensive. Moraines, ground moraine, and outwash that can be physically correlated with a specific moraine are classified together as "glacial deposits" in a single map unit, which is further segregated on the basis of age. General descriptions of morphology and weathering characteristics of each group of moraine are presented below. The detailed geology within each glaciated valley is described in the "Detailed Geology of Selected Drainages" section.

Bull Lake Glacial Deposits (map unit Bd). The most weathered glacial deposits in the study area form a set of broad lateral moraines in the valley bottom of Deadman Creek (Plate 2), a moraine and outwash deposit on the south side of Blind Bull Creek (Plate 2), and a lateral moraine on the south side of Martin Creek (Plate 4).

The moraines at Deadman Creek are large linear deposits with broad, >30-m wide crests about 75 m above the present stream. There is a dense, natural vegetation cover that consists of pines and firs with a thick grassy understory. The broad moraine crests are free of boulders. Boulders are
Figure 7. Histograms showing loess thickness and boulder burial. The top histogram shows the segregation of moraines into four relative-age groups based on loess thickness from soil pits. The bottom histogram shows segregation of moraines into relative-age groups based on the percentage of boulder burial at sample sites. The relative-age groups were then correlated with descriptions of moraines from Blackwelder (1915). Abbreviations are Nd = neoglacial age deposits (0-10 ka), LPd = late Pinedale age moraines (12-24 ka), EPd = early Pinedale moraines (24-35 ka), Bd = Bull Lake moraines (120-150 ka). Numbers are sample sites located on Plates 2-4.
present on the inner and outer slopes of the moraines where erosion has removed the fines and exposed the clasts. Most of the clasts on the moraine slopes are composed of Madison Limestone, a particularly competent rock in the study area.

Soil pits were dug on the crests of the paired set of moraines in Deadman Creek. These soil pits revealed over 2 m of clast-free silt (Figure 7). Loess thickness and character has been used in the dating of deposits in the northeast Basin and Range (Pierce and others, 1982; Lewis and Fosberg, 1982). No clasts were encountered in the soil pits, so a 12-cm diameter hand auger was used to penetrate the silt. The first clasts large enough to impede the auger in a series of holes augured at each site were composed of Cretaceous Blind Bull Formation (Kbb), at depths near 2 m. The silt is interpreted as loess.

The moraine and outwash deposit in Blind Bull Creek is on an upper level erosion surface identified by Rubey (1973). The deposit consists of a series of suspected, degraded lateral moraines about 80 m above Blind Bull Creek. The moraines grade into a large geomorphic surface that slopes to the southwest. Sampling this deposit revealed complete burial of surface boulders by 30 cm of clast-free loess. Road cuts across the outwash surface exhibit 1.5 m of loess on their surface.

Moraines in Martin Creek consist of a series of subdued linear deposits on the south side of the drainage, about 60 m above Martin Creek. The deposits were identified on the aerial photographs but not actually sampled. Based on relative position these moraines are correlated with the oldest moraines in Blind Bull and Deadman Creeks.

These deposits occupy the lowest or farthest down-valley geomorphic positions in the drainages that show clear evidence of glaciation. Their
morphology suggests correlation with verbal descriptions of the "type Bull Lake" glacial cycle (140 to 160 ka).

**Early Pinedale Glacial Deposits (map unit EPd).** A younger series of moraine remnants is located up to 2.4 km upstream from the Bull Lake moraines in Deadman and Blind Bull Creeks. Similar moraines are nested within the Bull Lake deposits in Martin Creek, and form the outermost moraines at the mouth of Box Canyon. The moraine remnants in Box Canyon are 85 m above Box Canyon Creek, and are butted up against the range front. Moraines form discontinuous ridges 50-60 m above the active stream in the Deadman Creek and Blind Bull Creek drainages, but cover the southern portion of the Martin Creek valley floor. The crests of these moraines are broad, averaging 20 m wide. These moraines, like the Bull Lake deposits, are covered with thick vegetation (dense tree cover with small shrubs and grasses as an understory) typical of the Greys River Valley.

The surfaces of most of the moraines are covered by loess. The loess, however, does not completely cover clasts on the surface. On average, boulders are buried 70-90 percent by loess (Figure 7). The lithology of the boulders in the moraines is dependent on the local bedrock of each drainage. In Deadman and Blind Bull Creeks the moraines contain mostly sandstone clasts derived from the Cretaceous Blind Bull Formation, which dominates the source area for the glaciers. In contrast, moraines in the three southern drainages are composed predominantly of limestones and sandstones derived from the older formations that dominate the upper accumulation areas of these drainages. Clasts of different lithologies weather differently. Since the lithology of each drainage is dominated by a different rock type, there are differences in
clast surface weathering rates, and weathering-rind thicknesses among deposits of the same age.

Soil pits in Deadman Creek, Martin Creek, and Box Canyon Creek revealed loess accumulations averaging 48 cm thick. These moraines were segregated on the basis of loess accumulation (Figure 7), morphology, and geomorphic position. There are correlated with verbal descriptions of the early Pinedale glacial cycle (18-35 ka),

**Late Pinedale Glacial Deposits (map unit LPd).** There are several fresh-appearing moraines that form large arcuate ridges 25-45 m above the creeks surrounding small ponds located 1.5 to 2 km upstream of the early Pinedale deposits in Deadman and Blind Bull Creeks (Figure 8). Similar moraines are nested inside the Early Pinedale moraines in the Sheep Creek and Box Canyon drainages. These moraines typically have sharp moraine crests (3-10 m wide) and a significantly higher surface boulder frequency than the moraines farther down-valley. Boulders on the surface of these moraines show burial up to 30 percent by loess compared to the 70 percent burial on the early Pinedale moraines. Soil pits in these deposits revealed loess thicknesses averaging less than 20 cm. The vegetation on the higher moraine surfaces is not as thick nor are the trees as large as on the moraine deposits down-valley, although the vegetation composition is identical to that of the surrounding terrain.

In Deadman, Blind Bull, and Sheep Creeks there are both drained and undrained depressions among the moraines. The undrained depressions typically have standing water and water-tolerant vegetation such as willows and cattails in them. The drained depressions were originally dammed by end moraines, which have been incised up to depths of 5 m by the creeks to
Figure 8. Photographs of Pinedale moraines. The top picture was taken from the upper cirque area of Blind Bull Creek looking south. The picture shows an early Pinedale moraine, composed of limestone clasts (older bedrock) derived from the hanging wall of the Darby Thrust, sitting on Cretaceous bedrock. The bottom picture was taken from the eastern drainage divide of Blind Bull Creek looking southwest. Arrows: A, marks the Darby Thrust; B, marks the early Pinedale moraine crests; C, marks the late Pinedale moraine crests surrounding a filled depression. The pine-forested slopes are composed of moraine; the aspens in the foreground are growing in alluvial/colluvial deposits derived from Cretaceous bedrock.
drain the depression. The areas behind the breach are swampy, and contain lacustrine silt and clay.

Segregated on the basis of weathering characteristics and morphology (Figure 7), these moraines are correlated with verbal descriptions of the late Pinedale glacial cycle (14-16 ka). The position of these moraines is consistent with the observation that late Pinedale deposits are usually located 25 to 75 percent up-valley from deposits attributed to the early Pinedale glaciation (Porter and others, 1983).

**Holocene Glacial Deposits (map unit Nd).** There are some small moraines in Deadman Creek, Blind Bull Creek, Sheep Creek, and Box Canyon Creek that consist of boulder-rich deposits no more than a few meters high and a few hundred meters from their cirque headwall. The surfaces of these moraines are composed predominantly of rock fragments and boulders, show no loess accumulation (Figure 7), and have little to no vegetation. These moraines are not very extensive and are confined to the high cirque areas. These deposits are assigned a Holocene age (0-10 ka). No attempt was made to correlate these moraines to specific Holocene advances, because the moraines do not approach the Greys River fault.

**Alluvial Deposits**

There are several types of alluvium in the study area. Alluvium is segregated into alluvium (map units ending in "al"), which includes stream alluvium and terrace deposits, alluvial fans (map units ending in "af"), lacustrine deposits (map unit HI), and mixed alluvium and colluvium (map units ending in "ac"). Glacial material eroded from moraines or outwash deposits that cannot be physically correlated to moraines are classified as alluvium. Alluvial deposits in the study area are segregated by age based on their morphology,
weathering characteristics, and, where possible, their geomorphic relationships with glacial deposits.

**Bull Lake Alluvium.** No alluvial deposits sampled during field mapping revealed weathering characteristics that could be correlated with the Bull Lake glacial cycle (140-160 ka).

**Early Pinedale Alluvium (map unit EPal).** There are discontinuous alluvial deposits in the Deadman and Blind Bull drainages (Plate 2) composed of fluvial gravels. Clasts vary in size and lithology according to the location within the drainages, and the lithology of the drainage. Typically there is thick vegetation covering these deposits. These alluvial remnants are located down-valley of early Pinedale moraines, perched on the side slopes 15-50 m above the present stream channel. Based on their geomorphic position these deposits are correlated with the early Pinedale glacial cycle (18-35 ka).

**Late Pinedale Alluvium (map unit LPal).** There are several large alluvial deposits located in the glaciated drainages, as well as in the main Greys River Valley, that form terraces from 5 to 15 m above the present stream. Terraces on the Greys River can be traced for some distances along the Wyoming Range. One alluvial deposit of significance is a terrace complex at Sheep Creek. The alluvium consists of multilithologic fluvial gravels, with loess accumulation limited to 20 cm. Some of the terraces at Sheep Creek and many of the alluvial deposits on the main Greys River are eroded up to 10 m by younger stream incision. Carbonate coatings on the carbonate clasts at Sheep Creek (discussed in the "Geology of the Trench Site" section of this thesis), loess accumulation, and physical continuity in the Blind Bull Creek and Deadman Creek drainages suggest correlation to the late Pinedale glacial cycle (14-16 ka).
Holocene Alluvium (map unit Hal). The most abundant alluvium in the study area occupies the lowest geomorphic positions in all the drainages along the Greys River. This alluvium forms small terraces up to 2 m above the stream in perennial stream drainages. In ephemeral stream valleys, alluvium covers the bottoms of the valleys forming broad flat floors 15 to 400 m wide. The floors range from smooth, planar grass-covered slopes as in South Twin Creek, to irregular, hummocky surfaces strewn with rock and avalanche debris such as in the Red Creek Drainage (Figure 9). The modern stream channel is usually incised less than 2 m into these deposits. Clasts 1.5 m in diameter are not uncommon in these deposits but the dominant clast size is less than 0.5 m in diameter.

Soil pits reveal that the gravel in some deposits is nearly matrix supported. Matrix in these deposits ranges from well-sorted sands to poorly sorted fine-sand to granules. There is no evidence for loess accumulation on the youngest terraces. The drainage floors are covered with thick grasses and some small willows. These alluvial deposits are assigned to the Holocene (10-0 ka), based on geomorphic position, loess accumulation, and morphology.

Alluvial Fan Deposits. Alluvial fans are segregated into two ages based primarily on their morphology and relation to the present streams. Older deposits (map unit Paf) consist of large fan deposits that are no longer active and are graded to a base level 8-15 m above the present stream level. They have numerous angular boulders at the surface, ranging in size from 1 cm to well over 1 meter in diameter. The lithology of boulders depends on the bedrock of the drainage basin. The toes of these fans are incised 15 m in the Sheep Creek drainage.
Figure 9. Photographs of Holocene alluvium. The top picture shows the broad, flat valley bottom of South Twin Creek, looking east. Arrow shows the location of the Greys River fault marked by the line of aspens. The fault scarp across this valley bottom is covered with alluvium. The bottom picture shows alluvium in Red Creek. The valley floor is hummocky and irregular with numerous piles of rock and avalanche debris. As in South Twin Creek the fault scarp across the Red Creek Valley bottom is concealed.
The older fans are inferred to be post late Pinedale to early Holocene in age. Fans started forming on the over-steepened, valley walls following the last major glaciation, and were graded to stream channels that were filling their floors with alluvium, see Church and Ryder (1972) or Bull (1991).

Younger alluvial fans (map unit Haf) are incised below and in some cases overlap the older fan surfaces. Younger fans are graded to within 1-2 m of the modern stream. The toes of these fans show incision of less than 1 m by the modern stream. The composition of clasts on the younger fan surfaces is similar to that of clasts on the older fans. However, clasts on the older fans have a greater degree of weathering (Appendix A). Clasts on the younger fans consist of very angular gravel, 0.1-2 m in diameter, have fresh surfaces with a poorly sorted coarse matrix. Younger fans are assumed to be middle to late Holocene in age.

Lacustrine Deposits (map unit HI). Deposits of silt and clay form large flat bottoms in depressions constrained by end moraines in Deadman Creek, Blind Bull Creek, and Sheep Creek. These deposits formed as glacial depressions gradually filled with fine-grained material, blown in by the wind or washed in from the stream and the surrounding slopes. These deposits exceed 5 m of thickness in places and are composed of massively bedded, well-sorted silt and clay. A 5-m deep hand auger hole in the Sheep Creek drainage (Plate 3) revealed layers of charcoal at 8-24 cm intervals in a dark, massive grey clay.

Vegetation on the lacustrine deposits is composed of willows and poplars intermixed with reeds and marsh grasses, indicating a high local water table. Lacustrine deposits are most commonly associated with moraines from the late Pinedale cycle, but there are some associated with early Pinedale moraines in the Blind Bull Creek drainage.
Alluvial/Colluvial Deposits

Hill-slope deposits, composed of soil and rock fragments that have varying degrees of soil development, cover most of the slopes in the Greys River Valley. Soil pits in hill-slope deposits in the study area revealed upwards of 1 m of unconsolidated material covering bedrock. Hill-slope processes are a combination of gravity fall and fluvial transport, spread out over a long period of time. Because hill-slope depositional processes are slow and continuous, hill-slope deposits in this study are not segregated on the basis of age.

Colluvial Deposits

Colluvial deposits in the study area are segregated into talus deposits (map units ending in "ct"), mass-wasting (landslide) deposits (map unit Hs), and rock glaciers (map unit Hcr).

Talus Deposits. Talus deposits in the field area are cone-shaped concentrations of rock debris in which clast sizes vary from 10 cm to 2 m in diameter. Talus deposits are more abundant in the southern part of the study area where they form at the base of cliffs and on glacial over-steepened valley walls. Talus, mapped in this study, is divided into active and inactive talus based on its geomorphic position, morphology, and vegetation cover.

Inactive talus (map unit Pct) is typified by fragmented rock debris that has a weathered, stable appearance. The surface clasts on these deposits contain large lichen colonies of various types and sizes. Benedict (1985) and Porter (1981) used lichen to correlate deposits of differing ages. There is little fine-grained material on the surface of these deposits, but vegetation grows in the interstices between the boulders, with population densities increasing toward the edges of the deposit, especially on the down-slope edge. Vegetation
consists of small bushes and grasses, which are most prevalent in lower valley wall positions. The inactive talus is inferred to postdate the late Pinedale glaciation. Talus began to accumulate at the base of slopes denuded during the latest glacial advance.

Active talus (map unit Hct) deposits are unstable in appearance. The surfaces of the active talus deposits are irregular and approach the angle of repose. Clasts have a fresh appearance. There is very little lichen growth on the clasts. On clasts that do have lichen, the lichen seems to be battered, showing signs of recent transport.

In the Sheep Creek, Martin Creek, and Box Canyon Creek drainages there are many fresh talus deposits prograding out over inactive talus deposits. The fresh talus is usually present higher on the valley walls than the inactive talus. It dominantly occurs in the upper cirques in the southern part of the field area, where it forms at the base of cliffs. Active talus deposits are inferred to be Holocene in age and have active deposition.

**Mass-Wasting Deposits.** There are two main types of mass movements evident in the field area: landslides and debris-flows. Landslide deposits are slumps and slides that have morphologies that consist of lobate toes and arcuate head scarps. Debris-flow deposits are thick packages of matrix-rich, angular rock debris covering the bottoms of many of the drainages of the Wyoming Range.

Landslide deposits (map unit Hs) have a wide range of characteristics. They range from slumps and small-scale rotational features to large-scale slides hundreds of meters across. The composition of landslide deposits consists of everything from large blocks of intact bedrock complete with intact vegetation to angular poorly sorted piles of rock debris. Landslide deposits are
present throughout the field area, but are dominant in the high elevation
drainages that are composed of fine-grained Cretaceous sedimentary rocks.
The Deadman Creek, Blind Bull Creek (Plate 2), and Sheep Creek drainages
(Plate 3) exhibit extensive slope failure in the Cretaceous sections.

Landslide deposits mapped in this study are obvious large-scale features
or small-scale features that have some physical relation (i.e. are offset by the
fault, cover the fault trace, or cover deposits offset by the fault) to the Greys River
fault. The majority of landslide deposits in this study have an easily identifiable
head scarp and lobate toes, and some landslides have moved in historic time.
Two large mass-movement deposits in the Sheep Creek drainage, observed in
1991, do not appear on the 1977 aerial photographs. There are landslide
deposits throughout the Wyoming Range but most are concentrated in the
glaciated drainages. Many of the landslides overlap glacial deposits of a late
Pinedale age. Accurately mapping all of the small-scale landslides throughout
the area was beyond the scope of this project.

Debris-flow deposits (map unit Hal) composed of matrix-rich, poorly
sorted, angular gravel are intermixed with alluvial material in many drainages.
The texture of these deposits suggests mass movement as the transport
mechanism, but the source area is uncertain because definable detachment
scarps could not be found. These deposits are assumed to have resulted from
large sediment discharges from a higher elevation in the drainages. The
debris-flow material is combined with other debris such as avalanche debris
and alluvial material during deposition and is subsequently reworked and
redistributed across the valley floors. The debris-flow material is nearly
impossible to distinguish from alluvium in the field. As a result, debris-flow
deposits that do not have a definable detachment scarp are classified as alluvium.

**Rock Glaciers (map unit Hcr).** The Martin Creek and Box Canyon drainages contain large, rock debris deposits that appear to have been, or are presently, prograding down-valley. These deposits are composed of large, angular boulders. The surface of the deposit can be segregated into three zones: 1) the upper surface, 2) the lower surface, and 3) the leading edge (Figure 10). On the upper surface of this deposit the boulders appear in arcuate ridges, indicating down-valley movement. The lower surface is an older talus deposit. Both the upper and lower surfaces have a weathered appearance. The surface boulders have discolored surfaces and lichen cover. The leading edge, the steep transition from upper to lower surface, has a very fresh appearance. These deposits are interpreted to be rock glaciers. These deposits are positioned in the uppermost protected glaciated cirques, and their active appearance indicates that they are Holocene in age.

**Quaternary/Tertiary Deposits**

Older alluvial, colluvial, and glacial material, composed of unconsolidated to consolidated matrix-rich, poorly sorted, subangular to rounded rock debris, is present on a discontinuous high-level erosion surface roughly 200 m above the Greys River along the length of the field area. The source of these deposits is not clear. They may be older glacial drift, or exposures of a Tertiary conglomerate. Rubey (1973) interpreted these deposits to be associated with a fanglomerate sequence shed off the Salt River Range and draped over the Greys River Valley in late Tertiary or early Quaternary time.
Figure 10. Photograph of a rock glacier in the Box Canyon Drainage. The picture was taken from the eastern headwall looking west. The rock glacier, moving toward the photographer, is protected from the sun by the unnamed peak in the center of the picture. The weathered upper-surface, the fresh leading edge, and the weathered lower-surface are indicated A, B, and C respectively.
Bedrock

The bedrock in the study area is grouped into two units: older bedrock (map unit bo) and younger bedrock (map unit by). Older bedrock consists of Mississippian through Jurassic limestones and sandstones. Older bedrock makes up the hanging wall of the Darby thrust. Younger bedrock is composed of Cretaceous shales. The Tertiary Wasatch Formation, overlaying the Cretaceous rocks exposed along the leading edge of the Darby Thrust, is included with the younger bedrock. Younger bedrock composes the footwall of the Darby thrust.
DETAILED GEOLOGY OF SELECTED DRAINAGES

Portions of the 1:48,000 base map (Plate 1), were enlarged to show in more detail the relationships between Quaternary deposits, in particular the glacial deposits in the major side canyons (Figure 11). Blowup maps of Deadman Creek and Blind Bull Creek (Plate 2), Sheep Creek (Plate 3), and Martin Creek and Box Canyon Creek (Plate 4) were traced from the aerial photographs onto 7.5 minute quadrangles enlarged to a scale of 1:15,840. The blowup maps also show the locations of the relative dating sample sites. The following sections will describe the geology of the glaciated drainages (Plates 2-4).

Deadman Creek

The Deadman Creek drainage (Plate 2) is the northern-most valley in the field area that contains evidence of glaciation. The Deadman Creek drainage trends east to west and is roughly 8 km long. The western 4.75 km of the valley is composed of older bedrock of the hanging wall of the Darby thrust. East of the Darby thrust trace, bedrock lithology is composed of fine-grained sandstone of the Cretaceous age Gannet Group.

The accumulation area for glaciers in this drainage is a broad, west-facing slope whose divide is at an elevation of 2890 m. Four age groups of moraines, segregated based on geomorphic position and weathering characteristics, are located in the Deadman Creek drainage. Moraines contain clasts of fine-grained sandstones from the Cretaceous section. The absence of clasts of older, Mississippian Madison Formation and Pennsylvanian Amsden Formation in the moraines is consistent with the estimated equilibrium line altitude for the glaciers. The equilibrium line, estimated using techniques
Figure 11. Map showing the location of the plates and drainages mentioned in the text.
described by Meierding (1982), for the glaciers is east of the Darby thrust trace.

The lowest moraines are a pair of lateral moraines 2.5 km west of the trace of Darby thrust. The moraines have smooth, pitless crests with no boulders present at the surface. They are covered with up to 2 m of clast-free loess. Four auger holes showed that the loess averages 198 cm thick. The broad crests of the moraines, the lack of surface boulders, and a thick loess cap suggests correlation to the Bull Lake glacial cycle.

Two kilometers upstream from the older moraines is a group of moraines consisting of a small, discontinuous, left-lateral moraine and an end moraine enclosing a small, filled depression. Sampling here revealed surface boulders that were buried up to 90 percent by loess. Loess accumulated in the spaces between the boulders is 32 cm thick. The loess is much thinner than on the older moraines. On the basis of boulder burial and loess accumulation these deposits correlate to the early Pinedale glacial cycle.

Upstream 3 km from the early Pinedale moraines, and 1.5 km down-valley from the cirque is a group of nested moraines. In the center of the moraines an end moraine encloses a depression. A small pond in the depression drains through an incision in the end moraine that is roughly 5-7 m deep. This depression contains very fine-grained deposits of lacustrine origin, indicating that the creek was dammed. There are numerous closed depressions located outside of the innermost moraine crest.

The nested moraines surrounding the depression are hummocky with surface boulders that show up to 25 percent burial by loess. The innermost moraine crest averages 3 m wide. Moraine crests outside of the innermost crest are only slightly wider, ranging 3-5 m across. These moraines are assigned to the late Pinedale glacial cycle based on their appearance and their geomorphic
position, 40 percent upstream (i.e. total length of the glacier is 25-75 percent as long as early Pinedale glaciers), from deposits assigned to the early Pinedale glacial cycle.

A small depression is located in the center of the Deadman drainage at the base of the head-wall slope. The depression is interpreted to be a glacial accumulation center (cirque). The depression is enclosed by a pair of end moraines that dam a small lake. The moraines are partly obscured by some landslide deposits on the south side of the creek and a tailings pile from the Vail mine on the north side of the creek. Deadman Creek has breached and incised the moraine 3 m, where it originates from this lake. The moraines are fresh in appearance. The surfaces are covered with boulders without much fine accumulation. Vegetation is limited to small grasses and very small shrubs. The fresh appearance, absence of loess, and up-valley position suggest a Holocene age.

The entire Cretaceous section in the Deadman Creek drainage shows extensive slope failure. There are several landslides in the broad west-facing head-wall slope, composed of west-dipping bedrock. The mass movement deposits overlap glacial deposits and are difficult to differentiate in some areas. Landslide deposits originate primarily from failures of dip-slopes. Some of the landslide deposits overlap ground moraine.

**Blind Bull Creek**

The geography of the Blind Bull Creek drainage (Plate 2) is similar to that of the Deadman Creek drainage. The Blind Bull drainage borders the Deadman Creek drainage to the south and has roughly the same shape. Like the Deadman Creek drainage, the large west-facing headwall slope is composed of Cretaceous rocks. Unlike the Deadman Creek drainage, the
topographic upper portion of southern ridge divide in the Blind Bull Creek drainage is composed of older bedrock, Mississippian through Triassic limestones that compose the hanging wall of the Darby Trust.

Glacial ice accumulated in an north-northwest facing bowl at the head of the valley. Moraines in this valley contain differing percentages of rock types, depending on their location in the drainage. They are composed dominantly of Cretaceous sandstones, but the moraines on the south ridge contain more older bedrock near the drainage divide. The percentage of more competent clasts in the moraines is a function of their distance from the trace of the Darby thrust, on the south ridge. Concentrations of clasts of older bedrock in the moraines decrease away from the southern ridge. Clasts of Cretaceous rocks dominate because most of the accumulation zone is composed of Cretaceous shales and mudstones.

The Blind Bull drainage contains evidence for five glacial advances. Evidence for the Bull Lake glacial advance is limited to a high trim line 200 m above the stream, subdued moraines, and an outwash deposit overlaying the upper erosion surface of Rubey (1973), 8.7 km down-valley. The moraines are composed dominantly of clasts of Cretaceous Blind Bull Formation intermixed with clasts of Mississippian Madison Formation. The surfaces are subdued and degraded, show no sharp crests or depressions, and are boulder free.

There are two sets of moraines 1 km up-valley from the Bull Lake moraines. The lower of these sets of moraines consists of a small lateral moraine on the north side of the creek and a series of nested lateral moraine ridges to the south. The moraine crests are distinguishable and traceable for several hundred meters upstream. Blind Bull Creek has incised over 10 m through the end moraines. Surface boulders are composed of 80 percent
younger bedrock and 20 percent of older bedrock, and show a high boulder burial factor. The vegetation consists of dense forest. The higher moraine set appears to be a recessional moraine enclosing a small depression. Its morphology is similar to those of the lower moraines.

There is a lateral moraine deposited on Cretaceous bedrock, near the western edge of a broad cirque high up on the south wall. It is composed exclusively of pre-Cretaceous limestone clasts, and has weathering characteristics similar to the two sets of moraines down-valley. This moraine marks the trim line for the advance. From the amount of loess accumulation and boulder burial, this moraine is assigned to the early Pinedale glacial cycle.

Moraines 3 km down-valley from the headwall record the last major advance of glaciers in this drainage (map unit LPd). These glaciers deposited a complex of nested moraines in the center of the valley. These moraines have sharp crests and contain numerous closed undrained depressions. Surface boulders are composed of younger bedrock and show a low burial factor. There is ground moraine in the high bowls on the south wall of the drainage. Ground moraine was deposited following retreat of this last major glacial advance. Surface boulders here are composed more dominantly of older limestone clasts.

Evidence for Holocene glaciation is limited to a series of discontinuous boulder ridges no more than a hundred meters from some small cirques high on the southern headwall. These moraines are composed of the competent older bedrock of the Darby thrust.

As in the Deadman Creek drainage, there is evidence for extensive slope failures in the upper part of this drainage. The deposits range from rotational slump deposits to deposits from mobilized flows. The Cretaceous section dips
25-35° west. Dip-slope failures in these fine-grained sedimentary rocks are the most common.

Sheep Creek

The geography of the Sheep Creek drainage (Plate 3) is unique in the Grey River Valley due to several aspects. The Sheep Creek drainage is the largest drainage on the east side of the Greys River Valley. The headwaters of Sheep Creek consist of a series of four northeast-trending linear valleys that drain into a large depression at the base of the eastern flank of the Wyoming Range. From this depression Sheep Creek assumes a west trend, flowing though McDougal Gap, a sharp canyon cut in through Wyoming Range to its confluence with the Greys River 18 km to the west.

Most of the evidence for glaciers in the Sheep Creek drainage is on the east side of the Wyoming Range where two sets of moraines are identified. The bedrock in the accumulation area consists of the older limestones and sandstones from the hanging wall of the Darby thrust. Cretaceous rocks underlie the leading edge of the Darby thrust. Cretaceous bedrock makes up the east border of the large depression at the base of the range. Tertiary clastic rocks (in particular the Tertiary Wasatch Formation) were shed off the rising thrust and cover the Cretaceous rocks at the leading edge of the thrust. The Wasatch Formation is a light grey to red, poorly sorted, variably cemented conglomerate. Isolated outcrops of Tertiary Wasatch Formation, which appear on the north side of the drainage on the east flank of the Wyoming Range, may have been confused with glacial material by Rubey (1973).

A series of moraines overlies Cretaceous bedrock. The moraine crests are 120 m above the floor of the large depression on the east side of Sheep Creek and mark the divide between Sheep Creek and a large low-angle
surface that drains water east to the Green River. The moraine crests consist of 2-5 linear ridges, whose crests average 9-12 m wide. Moraines here have a high surface boulder frequency and show high boulder burial factors. Clasts are composed of older bedrock from the Wyoming Range. Loess 20 cm thick covers the surface of the moraines. Based on loess thickness and the degree of boulder burial, these moraines are assigned to the early Pinedale glacial cycle.

The northernmost portion of the large depression floor (Plate 3) is covered with lacustrine silt and clay deposits. Hand auguring revealed over 5 m of massively bedded silty-clay near the northern edge of the depression. The southern portion of the large depression is covered with ground moraine. The ground moraine consists of discontinuous boulder-rich ridges, closed depressions are interspersed throughout. There are also discontinuous traces of lateral moraines near the southeast side of the depression and in the canyon that drains the upper Sheep Creek into the drainage. The moraines in the depression interfinger with talus being shed off Triple Peak. Moraines in the upper Sheep Creek area are lateral moraine deposited at canyon confluences. These moraines are associated with the late Pinedale glacial advance.

Ice accumulated in northeast-facing bedrock cirques and flowed to the northeast past the leading edge of the Darby thrust and into the depression. Confined within the depression, the glacier deposited a large moraine complex on Cretaceous bedrock. On the west side of the depression Sheep Creek drains through McDougal Gap, a sharp gap in the Wyoming Range. Any evidence of ice moving through or into this gap from the depression has been destroyed by subsequent fluvial erosion and colluvial processes. Two large historic landslide deposits occupy the northeast corner of the depression at the north edge of the gap in the range.
The North Fork of Sheep Creek (Plate 3) is a south-trending strike valley that joins Sheep Creek on the west side of the range. Moraines in this valley were deposited by glaciers that accumulated in a narrow south-facing cirque. The divide at the top of the North Fork of Sheep Creek borders the cirque accumulation zone of Blind Bull Creek drainage. The moraines are discontinuously nested, morainal ridges and recessional deposits. They are composed of clasts of older bedrock. Cretaceous rocks are not present on the west side of the range in this drainage. The moraines are assigned a late Pinedale age.

Small, fresh-appearing moraines are present in the high, northeast-facing valleys of Sheep Creek and the North Fork of Sheep Creek, 10-450 m down-valley from the headwall. The bare, rocky moraines are assigned a Holocene age.

There are large alluvial deposits in the Sheep Creek drainage down-valley from the gap in the range. Sheep Creek filled the lower portions of its valley with over 10 m of alluvium in some places. The alluvial deposits in the lower portions of the Sheep Creek drainage are described in detail in the geology of the trench site section.

**Martin Creek**

The Martin Creek drainage (Plate 4) shows less extensive evidence of glaciation compared to the other drainages in the study area. Martin Creek is a deep northwest-trending valley approximately 5 km long. There is no definable west-draining cirque here. The accumulation area is composed of two high cirques that drain to the east. The two large cirques border the head of the Martin Creek drainage on the north and south sides. The less extensive glacial features down-valley result from the lack of a west-facing cirque. Spill-over ice
from two large east-facing cirques on the east side of the Range produced glaciers that flowed down Martin Creek. Only the most extensive glacial advances had enough ice in the cirques to spill ice over the divide into the Martin Creek drainage.

There are two groups of moraines in Martin Creek. The moraines 4.7 km down-valley are very low, shapeless, smoothed undulating surfaces outlined by lineations on the aerial photographs. These deposits (map unit Bd) occupy the lowest position of glacial material in the Martin Creek drainage. They are plastered high on the south ridge, and probably correlate with the Bull Lake glacial cycle. Clasts are derived exclusively from older bedrock. Cretaceous rocks are not present in this part of the Wyoming Range.

A second group of moraines is located 4.6 km down-valley from the range divide. The moraines consist of two to three low linear ridges on either side of the creek. Results from sampling these moraines suggest the weathering characteristics correlate to the early Pinedale glacial cycle.

The Martin Creek drainage contains two generations of talus deposits. The side slopes of the Martin Creek drainage are very steep. Cliffs formed in the Wells and Nugget formations rim the upper edge of the canyon. Talus deposits form at the base of the cliffs all the way around the drainage. Younger talus deposits are prograding out over the older talus deposits.

**Box Canyon Creek**

The Box Canyon drainage (Plate 4) is a narrow, deep canyon that drains two large cirques high in the Wyoming Range. The cirques are hanging valley cirques, of which one faces south and the other faces north. The cirques have several levels of large, gently sloping shelves, that are strewn with rock debris, composed of the older rocks in the hanging wall of the Darby thrust.
There are three sets of moraines in this drainage. Glaciers flowed out of the steep confines of Box Canyon into a very narrow section of the Greys River Valley, which is bordered on the west by a bedrock ridge. This bedrock ridge blocked the west-flowing glaciers and resulted in a large deposit of till at the mouth of Box Canyon. Consequently, each successive advance bulldozed and reworked the till from the previous advance. Deposits of Bull Lake advances were over-run, reworked, or buried by subsequent glacial advances.

The large, moraine complex at the mouth of Box Canyon Creek has forced the Greys River to the west. There is evidence for two major glacial advances, of Pinedale age, in the complex. The moraines at Box Canyon are nested moraines indicating there were several fluctuations in ice advance during the glacial cycles. The two outermost, lateral moraines on the north edge side of the complex butt up against the range front. Weathering characteristics from sampling these moraines suggest correlation to the early Pinedale advance.

Inside the two outermost moraines is a group of large linear moraines that nest inside one another. The moraines on the north side of the creek, for the most part, have pairs on the south side of the creek. The three to five nested moraines suggest several advances and retreats during each glacial cycle. Each advance restricted the drainage channel by lining it with till. The surface of these deposits is covered with boulders and contains very little loess. A forest fire in 1989 may have affected the surface morphology of the moraines. These moraines are assigned to the late Pinedale glacial cycle.

Rock debris covers the cirque areas of Box Canyon. It is difficult to differentiate between talus deposits and glacial deposits. Rock slides (map unit Hs) composed of very fresh-appearing clasts compose a large colluvial apron at
the base of the constraining wall of the cirque areas. There is a series of small moraines that correlate with Holocene age advances in several parts of the upper cirques.

A large deposit of rock debris (Figure 10) at the base of an east-facing cliff. Situated in the shade for most of the day, it has a very fresh-appearing, leading escarpment compared to its upper and lower surfaces. It is interpreted to be a rock glacier whose active appearance indicates a Holocene age.
NEOTECTONICS

One of the main objectives of this study is to describe the neotectonics and the paleoseismology of the Greys River fault. To characterize the surface expression of the Greys River fault, the fault trace was mapped and profiled throughout its length. Three trenches were excavated at Sheep Creek to determine the timing and displacements of latest Quaternary faulting on the Greys River fault. The following sections describe the geometry of the Greys River fault and the morphology of fault scarps in the Greys River Valley. The geology and sequence of events in the three trenches and the timing and magnitudes of paleoseismic events calculated from the trenches follow.

Greys River Fault

The initial interpretation of the subsurface geometry of the Greys River fault is that of Rubey (1973). Rubey, without the aid of subsurface information, interpreted the Greys River fault as a steeply dipping (60° to the west), planar normal fault that offsets the Darby thrust at a depth of approximately 1,220 m and displaces the underlying Cretaceous bedrock (Figure 5). Subsequent seismic reflection studies of the Wyoming overthrust belt indicate that in the subsurface, the Greys River fault has a listric geometry (Webel, 1987; Dixon, 1982). The dip of the fault at the surface is 56°, and flattens out at depth to less than 30° where it soles into the Darby thrust, a major west-dipping decollement, at a depths of 2-4 km. The Darby thrust joins a larger decollement to the west at a depth around 8.2 km (Webel, 1987; Dixon, 1982).

Bedrock of the Wyoming Range is composed of hanging-wall rocks above the Darby thrust. The strike of bedrock is roughly north and dips 30-50° west in the center of the valley. The dip, however, flattens to the east to 0-20° in
a syncline. The Darby thrust places older Mississippian through Jurassic limestones and sandstones on top of Cretaceous mudstones and shales. The underlying Cretaceous rocks dip 15-35° west and flatten out to the east. The trace of the Darby thrust is very sinuous. The Darby thrust trace is on the east side of the Wyoming Range south of Sheep Creek, where the trace is linear, striking north. North of Sheep Creek, the thrust trace trends west, where the trace crosses the Wyoming Range at the ridge that separates the head of North Fork of Sheep Creek from Blind Bull Creek. To the north, the fault trace maintains a roughly north trend on the west side of the Wyoming Range.

The interpreted trend and dip of the Greys River fault from field mapping is 356° and 56° west. The trend was calculated from a map, using two points on the fault at the northern and southern ends and measuring their trend. The surface dip of the fault was calculated using simple three-point calculations. In the northern part of the study area the strike and dip of the fault are nearly the same as that of bedrock. In the south, in the Box Canyon area, the fault trace separates horizontal rocks to the east in the hangingwall flat of the Darby thrust from west-dipping rocks to the west in a hanging wall ramp of the Darby thrust. The Box Canyon area is also a region of the Wyoming Range that has a clearly defined range front with the Greys River fault trace, appearing near the base of the range.

The Greys River fault is located high on the west flank of the Wyoming Range, from 100 to 800 m in elevation above the Greys River. This is unusual for large normal faults in the Basin and Range Province. Most of the large, normal faults in the Basin and Range Province are situated at the base of the range fronts. These large faults mark the border of broad flat-bottomed valleys and the adjacent ranges. Examples include the Star Valley fault (Warren, 1992;
Piety and others, 1986), the East-Bear Lake fault (McCalpin and others, 1990b), the East-Cache fault (McCalpin and Forman, 1991), and the Wasatch fault (Personius, 1991). The location of the Greys River fault high on the range is similar to the Hebgen Lake fault and parts of Lost River and Lemhi faults (Crone and Haller, 1991; Myers and Hamilton, 1964). However, these fault also border broad flat valleys. The Greys River Valley is very narrow and lacks a large flat valley bottom. The valley floor is at most 2 km wide. There is no clearly defined range front along the northern half of the Wyoming Range. Here, the fault bounds a series of large bedrock hills west of the main range front. The Rock Creek fault south of the Greys River fault resembles the Greys River fault in both basin shape and location of the fault high on the range (McCalpin and Warren, 1992). Both these faults are young zone 1 normal faults (Pierce and Morgan, 1992).

Displacement on the Greys River fault ranges from 0 to 1000 m (Rubey, 1973; Webel, 1987), based on offsets in bedrock exposed along the range front. Rubey's estimates of slip range from 0 m north of Sheep Creek to 800 m just south of Sheep Creek. Rubey's map clearly shows fault scarps in Quaternary deposits in several drainages along the Wyoming Range. Webel (1987) suggests displacement up to 1000 m at Blind Bull Creek based on seismic reflection data.

The late Quaternary surface trace of the Greys River fault is very poorly expressed. There are some well-preserved fault scarps in the valley bottoms of Blind Bull Creek, Sheep Creek, and Box Canyon Creek, as well, as some in the smaller drainages along the range. For the most part, the fault trace is high on the range front. Side slopes along the range and in many of the drainages
exceed 40° and have thick forest cover, which make identification of fault scarps difficult.

The Greys River fault has a trace length of 54 km. The fault trace is sinuous at a small scale and trends can range from 310° to 50°. The average orientation of traces of the fault on north-facing slopes ranges from 0° to 345°. The fault trace on the south-facing slopes ranges from 0° to 55°. The fault trace in valley bottoms and west-facing slopes ranges from 310° to 55°.

Typically, large normal faults in the Basin and Range are composed of segments 20-30 km long. The segments are bounded by features such as bedrock salients, gaps in surface faulting, and fault step-overs (Crone and Haller, 1991; DePolo and others, 1991; Machette and others, 1989). Rubey (1973) showed a gap in the surface expression of the Greys River fault that could indicate a segment boundary between Sheep Creek and Deadman Creek. My mapping, however, shows that fault scarps are continuous across this area (Plate 1). Rubey may have missed these fault scarps because the fault trace is covered by alluvium in the drainage bottoms and is very difficult to see on the steep side slopes. In this area there are several kilometers of densely forested slopes between the Greys River and the fault.

The fault splits into two strands for a length of 5 km, from just south of Box Canyon to just south of Kinney Creek (Plate 1). One strand is low on the range 20-30 m above the river. The other strand gains elevation and appears at the base of a cliff section near the top of the range. The split is not a fault step-over because the two strands appear to rejoin in the Kinney Creek drainage. There are no fault step-overs or bedrock salients to indicate a segment boundary along the Greys River fault. The Greys River fault maintains a general north-south trend throughout its length and shows no clear evidence of segmentation.
It is assumed that the entire Greys River fault ruptured during each paleoseismic event.

**Fault Scarps**

Profiles across fault scarps can be used to estimate the vertical surface offset incurred during recent faulting events. Fault scarps are formed with initial, near vertical, free faces and immediately begin to degrade. Material eroded from the free face is deposited at the base of the scarp forming a colluvial wedge (Wallace, 1977; Schwartz and Coppersmith, 1984; McCalpin and others, 1991). The colluvial wedge buries the fault and part of the hanging wall. Trenching the fault will expose the colluvial wedge, which can also be used to estimate displacement. The thickness of the colluvial wedge is roughly 1/2 the height of the free face from which it was derived (Ostenaa, 1984). Several factors can effect this relationship, in particular, rupture features, such as basal tension cracks, so this relationship only holds true for colluvial wedges deposited on nearly flat surfaces.

Fault scarps along the Greys River fault were profiled and the measurements were plotted using a graphics program to produce a cross-sectional view of the scarp (Figure 12). The upthrown surface was projected out over the downthrown surface. The vertical distance between a point on the projected surface and a point on the down-slope surface, beyond the colluvial wedge, is the vertical surface offset. The calculated scarp height is not that of Bucknam and Anderson (1979) but a leveled scarp height. A leveled scarp height is the vertical distance between the toe of the scarp and the top of the scarp (Figure 12).

When calculating surface offset and scarp height, the gradient of the upthrown surface, defined as the far-field slope, is often not the same as the
Figure 12. Diagram illustrating the method for calculating vertical surface offset and scarp height from a fault scarp.
downthrown surface gradient. Typically, in the study area, the downthrown surface gradient is usually less than that of the upthrown surface gradient. Any difference in surface slope on either side of the fault, will introduce an error in the surface offset calculations. Differences in surface slope on either side of the fault can be a result of a variety of conditions. The prefaulting slope angle could have decreased down-slope naturally, or one or both sides of the fault could have experienced rotation during faulting. The profile sites were chosen to minimize the chance of the slope-angle decreasing down-slope due to surficial processes. It is difficult to ascertain the amount of rotation incurred for either of the surfaces without knowing the original slope of the surface. In this study the upthrown surface was projected over the downthrown surface. The closest profile segment, on the downthrown surface, to the fault, whose slope-angle most closely resembles the upthrown slope angle that shows no evidence of postfaulting deposition, was used for the surface offset calculation. Because the surfaces are usually projected only a few tens of meters and the difference in slope-angle is only 1°, the error is small. As a result, calculations give a reasonable estimation of surface offset (Table 1) without having to produce long detailed profiles to identify rotated fault blocks.

Identifying the fault scarps in the Greys River Valley is complicated by thick vegetation, steep slopes, gully formation and distributed faulting, and multiple scarps rather than a single fault scarp. There are many seeps and springs along the base of the Wyoming Range. In many locations the springs are located near the fault trace. In Deadman Creek, small-scale mass movements have sloughed sections of the downthrown block down to the south. In Blind Bull Creek, upthrown block material has slumped out over the fault scarp. Fault scarps consist mainly of west-facing linear escarpments, formed in
**TABLE 1. CHARACTERISTICS OF FAULT SCARPS ALONG THE GREYS RIVER FAULT**

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* Profile sites numbered from north (1) to south (28) are listed on Plate 1.

EP = Early Pinedale.

LP = Late Pinedale.

H = Holocene.

SO = Surface offset (m).

SH = Scarp height (m).

MSA = Maximum slope angle (degrees).

LSA = Lower slope angle (degrees).

USA = Upper slope angle (degrees).

All profiles trend west to east.

Negative slopes indicate the surface slopes east.
late Pleistocene glacial features in Blind Bull and Box Canyon Creeks, and late Pleistocene through Holocene alluvium and colluvial deposits throughout the rest of the range. The best preserved scarps are in a late Pinedale terrace complex in Sheep Creek (Figure 13). These scarps are described in the geology of the trench site section. Characteristics of fault scarps at profile sites (Plate 1) are given in Table 1.

Fault scarps range from single scarps to more complex zones of deformation. In zones of deformation, parallel to subparallel scarps are spaced 10 to 30 m apart. Multiple scarps sometimes have similar displacements on each scarp, but sometimes displacement varies. In areas of multiple scarps the underlying bedrock is above a ramp in the Darby thrust (Rubey, 1973), and strikes north and dips steeply west. The multiple scarps may be a result of the fault plane breaking into the bedding planes as it approaches the surface. This suggests that some of the displacement is accommodated through bedding plane slip near the surface. Bedding appears to control the geometry of the Greys River fault in the Trail Creek drainage where the fault trace deviates from its north-south trend and appears as a series of low scarps along the axis of a northwest trending ridge that follows the strike of bedrock. The fault trace is barely perceptible on the ground, but can be seen on the aerial photographs.

**Fault Scarps in Glacial Deposits.** The trace of the Greys River fault is evident as west-facing linear escarpments across glacial deposits in three of the five glaciated drainages. The fault offsets moraines in the Blind Bull Creek, Martin Creek, and Box Canyon Creek drainages. There are no glacial deposits present where the fault trace crosses the Deadman Creek and the Sheep Creek drainages.

At Blind Bull Creek the fault scarps cross a series of early Pinedale,
Figure 13. Photograph of the fault scarp at Sheep Creek. The picture was taken from the Sheep Creek road, looking to the northeast. The Sheep Creek road follows the t1l terrace to the fault where it crosses the fault onto the t2u terrace and continues up the drainage to the divide (McDougal Gap) 13 km to the east then into the Green River Drainage farther to the east. Labels are: A, the t1u terrace surface (offset 7.2m from the t1l terrace surface by the Greys River fault); B, the t1l terrace surface; C, the t2u terrace surface; D, a small landslide on the downthrown block; N, the location of the north trench; M, the location of the middle trench.
lateral moraines. The trends of the fault trace range from $330^\circ$ to $10^\circ$ and vary in height from 4.3 m to 9.2 m high with surface offsets ranging from 4.3 m to 7 m (Table 1). The maximum slope angle is $34^\circ$. The 4-m scarp in the early Pinedale moraine is within 100 m of scarps that exhibit 7-8 m of surface offset. Initially, this scarp was thought to be the result of fewer events, but a large swampy area below the scarp may be a section of the upthrown surface that sloughed out over the downthrown surface. Because the scarp does not offset any younger deposits, there is no clear geomorphic evidence of multiple events here. Towards the southern edge of the moraine complex the fault trace bifurcates. The fault trace splits into multiple scarps 3-10 m apart. The fault trace grades into a wide zone of deformation on the ridge to the south of Blind Bull Creek.

The fault scarp in Martin Creek is located in an early Pinedale lateral moraine and outwash surface. The scarp on the south side of the creek is 4.2 m high with a surface offset of $-4$ m, a maximum slope angle of $33^\circ$, and a trend of $0^\circ$. The fault trace again splits in two as it trends up the ridge to the south of Martin Creek. The fault trace is expressed as two 3-m-high, west-facing lineaments that trend $0^\circ$ to $5^\circ$. Again, only a single-age deposit is offset, so there is no geomorphic evidence of repeated faulting in Martin Creek.

At Box Canyon the fault offsets late Pinedale lateral moraines on the north and south sides of the creek. The trend of the scarps is $350^\circ$ and scarps range from 6-14 m high and have offsets ranging from 5-8 m. The maximum slope angles are $32-34^\circ$. The early Pinedale moraines are located just downstream of the fault trace on the north side of the creek and were not offset.

**Fault Scarps in Alluvium.** The Greys River fault forms scarps in several alluviated valley bottoms along the length of the range. In a majority of
the drainages, the fault scarps have been covered by late-Holocene alluvium. The fault is usually traceable on the steep side-slopes on the sides of a drainage, but evidence of the fault trace across the valley floors is limited to slight steepened areas in some of the drainages. Most of the small-scale drainages along the range do not show evidence for the fault.

Fault scarps appear in alluvium on the valley floors of Trail Creek, Bug Creek, Buck Creek, North Twin Creek, and Slate Creek. The trend of the fault trace ranges from 310° to 55° and averages 350°. Scarp heights loosely cluster around 4 and 8 m (Figure 14). Surface offsets on the 4 m scarps range from 3-4 m, whereas offset on the 8-m scarps ranges from 6-7 m.

**Fault Scarps on Side-Slopes.** Fault scarps are difficult to identify or follow on the steep slopes of the Greys River Valley. The fault scarps are most recognizable on the north-facing slopes where the tree cover is the most dense. The scarps appear as linear ridges that trend 320°-350°. Profiles were taken from scarps that trend perpendicular to the slope. Often, on the north-facing slopes, bedrock may be exposed on the upthrown side of the fault. Small gullies are eroded along the axis of many scarps, which make it difficult to distinguish between scarps and ordinary gullies.

On south-facing slopes the scarps are much more subdued and degraded. These scarps are usually defined by a slight swale and a vegetation lineament trending 50°-20°.

Erosion of fault scarps on steep slopes is rapid enough to completely obliterate any trace after 5-7 ka (Andrews and Hanks, 1985). When the fault trace parallels a contour on a steep slope, the surface slope angle of a colluvial wedge may approximate the initial slope angle. In these cases, the fault trace appears as a vegetation or slope lineament on the aerial photographs and may
or may not be visible on the ground as a small swale or shelf trending perpendicular to slope. Fault scarps on steep side-slopes range from 10-28 m high and show offsets of 4-7 m (Table 1). A scarp just north of Buck Creek is typical of fault scarps on side-slopes. It is 27.9 m high but has a surface offset of only 4.6 m with a maximum slope angle of 44°. The unusually high scarp height is due to the steepness of the initial slope (23°).

Discussion of Fault Scarps

Recurrent normal faulting should produce a relationship between displacement and age of displaced deposits. Typically, younger deposits should have lower scarps and older deposits should have higher scarps. In the Greys River Valley, there does not seem to be a good correlation between the age of faulted deposits and the amount of surface offset. Moraines of early Pinedale age contain 4- to 5-m scarps as well as 6- to 9-m scarps (Figure 14). Postglacial alluvium also contains scarps 6-9 m high. Fault scarps of 1-3 m offset postglacial alluvium, but do not occur in glacial deposits. This would suggest that the smaller scarps, which are all in Holocene alluvium, are a result of one faulting event and the higher scarps in older glacial deposits are a result of the sum of more than one faulting event.

A technique to determine the number of displacements on strike-slip faults is to make a histogram of displacement across a fault scarp, at sites along the length of the fault (Wallace, 1968). This technique has never been applied to normal faults. The fault scarp profiles plotted from scarps along the Greys River give a good estimate of vertical surface offset (Table 1). Vertical surface offsets on fault scarps along the Greys River fault were plotted (Figure 14). The fault scarps chosen for this technique were single fault scarps or multiple fault scarps of which the profiles included all of the displacement.
Figure 14. Histogram showing the distribution of offset along the Greys River fault. The small displacement scenario is derived from a unimodal interpretation of distribution of slip along the fault, which supports four faulting events with 2 m of offset during each event. The large displacement scenario is derived from a bimodal interpretation of the distribution of offset along the fault, which supports two faulting events with 4 m of offset during each event. Ages of faulted deposits are given: EPd = early Pinedale moraine, LPd = late Pinedale moraine, Hae = Holocene hill-slope deposits, Hal = Holocene alluvium.
There is currently a controversy over how to interpret such histograms. McGill and Sieh (1991) suggest the displacements along a fault will form a single peak on a histogram. Histograms that include multiple-event scarps, each peak will indicate a separate earthquake. Weldon and others (in press) suggest that displacements during a single event may have more than one peak. Data from the Landers earthquake support a bimodal distribution of slip along a fault (McGill and Rubin, 1994).

There are peaks on the histogram (Figure 14) at 2, 4, 6, and 8 m. A unimodal interpretation would suggest small-displacement during each earthquake (i.e. three to four faulting events, each of which incurred 2-3 meters of displacement could be interpreted from this data). In contrast a bimodal distribution interpretation of the histogram would suggest a large displacement scenario. The peaks at 2-3 m and the 4-5 m were produced during one event. The peaks at 6-7, 7-8, and 8-9 m were produced by two earthquakes, each with a displacement over 4 m. In the central portion of the study area the 1- to 4-m high scarps would represent single event fault scarps in young deposits or may be a result of partial displacement occurring on splay faults not identified. The 6- to 8-m fault scarps represent two event fault scarps. At the distal ends, in particular to the south, displacement during faulting could be diminishing. The smaller scarps could represent two events where the displacement was diminished from that revealed at the Sheep Creek trenches.

**Geology of the Trench Site**

The following section describes the geology associated with the trench site at Sheep Creek (Figure 15). Paleoearthquake characteristics of the Greys River fault were determined from these trenches.
Figure 15. Map showing the Sheep Creek terrace complex. Terraces (t) are numbered from oldest (1) to youngest (4) and are labeled (u) for upthrown and (l) for downthrown; numbers in parentheses indicate the height above the modern stream (in meters). Terrace t1 is equivalent to LPd and terraces t2 - t4 correspond to Hal of maps and text. Deposits: afu = Haf, af0 = Paf, Is = landslide, b = bedrock.
Three trenches were excavated in an alluvial terrace complex at Sheep Creek (Figure 15). This site was chosen for trenching because: 1) there is a well-preserved scarp in a large terrace complex, 2) there is a fault-bounded graben that could trap dateable organic material, and 3) there was good access for the backhoe.

The terrace complex consists of four terrace levels. The trace of the Greys River fault crosses the terrace complex and appears to offset various terrace surfaces differing amounts. The terraces are numbered from oldest (t1) to youngest (t4), and labeled "u" for upthrown side of the fault, and "l" for downthrown side of the fault.

Material in the terrace complex at the trench site is composed of alluvium deposited from Sheep Creek. The origin of the material is a combination of debris eroded from mass movement and glacial deposits upstream. The head of Sheep Creek contains several moraines of early and late Pinedale that interfinger with colluvial deposits. Large sections of till and colluvial deposits have been eroded from the upper areas of the drainage (Plate 3). The material removed in this breech has been deposited downstream in the main valley of Sheep Creek. The landslides have moved in historic time. There is evidence that Sheep Creek may have been dammed by a landslide deposit just east of the terrace complex.

The highest terrace, t1_u, is 10.7 m above the stream on the upthrown block compared to the corresponding t1_l surface 4.2 m above the stream on the downthrown block (Figure 15). The t1_l surface is the only faulted terrace present on the downthrown side of the fault. A Forest Service gravel pit in the t1_u terrace does not appear to have altered the morphology of the scarp face at the middle trench site. The t1_u terrace is in contact with an older alluvial fan (af_0) at
its northern edge. The fan on the upthrown side is incised 3 m. Material from
the incision is contained in a younger fan (afy) prograding out over the T11
surface. The two fans are issuing from a small gully at the north edge of the
terrace complex (Figure 15).

The t2 surface, 5.5-5.8 m above the stream, is present only on the
upthrown side of the fault. A gravel road crosses the fault scarp where the t2
surface is 5.5 m above the stream. Alteration to the fault scarp in construction of
the road destroyed any geomorphic features.

The t3 surface also appears only on the upthrown block. The t3 consists
of two parts: a small channel, t3ua, and the surface into which it was cut, t3ub.
The t3ua is 4.1 m and t3ub is 3.1 m above the stream.

The t1-t3 surfaces have all been faulted. The t4 surface, which is
associated with the modern stream flood channel, is not faulted. The t4 surface
maintains a height of 0.8 m above the stream across the fault. The t4 surface is
covered by a small alluvial fan issuing from a gully to the south. This fan is
limited to the downthrown side of the fault.

The t1 terrace level is assigned a late Pinedale age based on weathering
characteristics. In particular, stage 1 carbonate rinds, averaging 1.15 mm thick
(n=17) on limestone clasts exposed in the trenches (Pierce, personal
communication) support a late Pinedale age assignment (Pierce and Scott,
1982). The t2-t3 terraces were formed either from post-glacial incision (Bull,
1991) or from fault induced incision. Either interpretation indicates a Holocene
age. The t4 surface is considered modern Holocene alluvium.

**Trench Work**

The following section will discuss the stratigraphy, structure, and
sequence of events recorded from the three trenches. Stratigraphic evidence
exposed during trenching revealed two paleoseismic events at Sheep Creek. These events are referred to in this report as the first (older) event and the second (younger) event. Portions of some units exposed in the trench were dated through radiocarbon analysis. Dates discussed in this section are laboratory dates reported in radiocarbon years BP ($^{14}$C yr BP).

**Southern Trench**

Figure 16 shows a simplified log of the south wall of the southern trench at Sheep Creek. A detailed log of the south wall is shown in Plate 5. Units are numbered from oldest (1) to youngest (5). The southern trench was excavated at the 2.7 m fault scarp which separates the t3$_b$ terrace on the upthrown side of the fault from an alluvial fan surface (af$_v$) on the downthrown side of the fault. The t3$_b$ terrace on the south side of Sheep Creek stands 3.1 m above the present stream at this site. The trench was 21 m long and 3 m deep. Five units were identified in the trench based on their lithology. The following section briefly describes the stratigraphy of the southern trench. Full lithologic descriptions appear in Appendix B. Two faulting events are recorded in this trench. Four samples were taken from this trench, of which one was sent to the laboratory for radiocarbon dating.

**Stratigraphy of the South Trench.** The stratigraphy of the southern trench is dominated by fluvial gravel from Sheep Creek, from which two major lithologic units were distinguished. Unit 1 is a package of fluvial gravel subdivided into 11 subunits, (a through l). These gravels are composed of poorly sorted, rounded gravel with a coarse sand to granule matrix, imbricated clasts, interspersed clean sand and matrix free gravel lenses. Unit 1 is probable Pinedale and post-Pinedale alluvium deposited from Sheep Creek following the end of the late Pinedale advance.
Figure 16. Simplified version of the log of the south trench at Sheep Creek. Logged in July of 1991, by L.C. Allen Jones, Greg Warren, James McCalpin and Darin Hinton.
Unit 2 is composed of two subunits. Unit 2 is the only unit exposed on both sides of the fault in this trench. The lower subunit 2a occupies a scour in unit 1 on the upthrown side of the fault. Subunit 2a is a brown sandy fluvial gravel that exhibits very-weak soil development. The upper subunit 2b is a well-sorted brown silt which is interpreted as a loess cap. Unit 2 has been down-dropped 4.2 m during faulting, and tilted 5-8° west. The loess cap (subunit 2b) on the downthrown block is thinner and slightly more coarse than the loess on the upthrown side.

Unit 3 is composed of three subunits, (a through c). Subunits (3a-3c) consist of moderately to poorly sorted, matrix-rich, brown gravels that exhibit a down-slope (10-30°) fabric, and are faulted down to the west. Unit 3 is interpreted to be scarp-derived colluvium. The three subunits interfinger with each other and subunits of unit 4, suggesting fluvial-colluvial interaction during deposition.

Unit 4 is a package of poorly to well-sorted gravel subdivided into eight subunits (a through h). They are composed of interfingering coarse and medium gravel with lenses of well-sorted sand. Unit 4 is interpreted as fluvial gravel deposited in a low formed in the hanging wall during the first event. The uppermost subunits, 4f-4h, appear to be scoured and are overlain by unit 5. Subunit 4e is one of the few units than contains layers of organic material rich enough for dating. A sample (SC-S4) of detrital organic material was collected from subunit 4e and dated through radiocarbon, at 5080 +/- 60 14C yr BP. Unit 4 is interpreted as having accumulated contemporaneously with the unit 3 scarp-derived colluvium. This means that the date from subunit 4e postdates the rupture by the length of time it took for unit 3, and subunits 4a through e to be deposited.
Unit 5 is composed of four subunits (a through d). Subunit 5a is a matrix-rich gravel that shows a fabric inclined 30° to the west, and is nearly indistinguishable from subunit 3c. Subunit 5a is interpreted as scarp-derived colluvium from the second event. Subunit 5b is composed of a matrix-rich small gravel that grades to the west and interfingers with subunit 5c. It is interpreted as slope colluvium. Subunit 5c is a matrix-rich angular gravel. There is a dark organic layer that appears along the base of subunit 5c. Unit 5c is interpreted as an alluvial fan gravel that was discharged from a small drainage to the south of the trench. Incorporated in unit 5 are some small lenses of poorly sorted angular gravel, subunits 5d, which are interpreted as fluvial gravels.

**Structure of the South Trench.** The dominant structure exposed in the south trench is a single normal fault near the center of the trench. The fault trace is near vertical to within 2 m of the surface where it decreases to 50-60° west dip within 1.2 m of the surface. The fault separates horizontally bedded fluvial units on the upthrown side from faulted fluvial units and scarp-derived colluvial units on the downthrown block. The faulted fluvial unit (unit 2a) is tilted to the west 5-8° relative to the correlative unit on the upthrown block. Scarp-derived colluvium from the second faulting event, covers the erosionally truncated beds above the fault on the upthrown side, the fault plane and faulted scarp-derived colluvium from the first faulting event.

The height of the fault scarp does not accurately reflect the displacement accommodated by the fault at this site. There is 4.2 m of net slip whereas the scarp-height is only 2 m where trenched. Ordinary surface-offset calculations would indicate only 2.7 m of offset. The depression formed in the hanging wall during faulting was filled with fluvial and alluvial gravel from Sheep Creek and a
small gully to the south following faulting. All of the displacement was accommodated on a single fault plane.

**Sequence of Events for the South Trench.** The first event recorded in the south trench is the deposition of late Pleistocene fluvial material. Fluvial gravels were deposited by Sheep Creek as it aggraded its valley bottom with over 10 m of gravel. In the early-Holocene, Sheep Creek cut in to its alluvium forming a series of terraces. The t3 level, which is 4.1 m above the modern stream, was exposed long enough for a weak soil to develop and 20 cm of loess to accumulate. Some time prior to 5080 +/- 60 \(^{14}\)C yr BP, that is, before the unit 4e was deposited, the first faulting event occurred.

The faulting event formed a vertical free face approximately 2 m high across the t3 terrace. Immediately following faulting, the scarp-derived colluvium of unit 3 from the degradation of the free face begins to accumulate. Unit 3 interfingers with the unit 4a fluvial gravel unit and suggests that the low formed in the hanging wall during faulting was filled in by fine alluvium of Sheep Creek.

The second event happened some time after 5080 +/- 60 yr BP and another free face was generated. Unit 5 was deposited after this second event. Unit 5a is scarp-derived colluvium shed from the free face, as it began to degrade. Unit 5b was deposited through slope wash processes. Unit 5c is an alluvial fan deposit whose origin was a small ephemeral stream that flows down a small valley to the south. This small valley was formed when the footwall dropped in the first event.

**Middle Trench**

Figure 17 shows a simplified log of the south wall of the middle trench at Sheep Creek. A detailed log of the trench is shown in Plate 6. Units are...
Figure 17. Simplified version of the log of the middle trench at Sheep Creek. Logged in July of 1991, by L.C. Allen Jones, James McCalpin, Witold Zuchiewicz and Kelly Davis.
numbered oldest (1) to youngest (15). The middle trench was excavated across a fault-bounded graben on the t1 terrace. The t1 terrace is 10.7 m above the present stream at this location (Figure 15). The scarp height is 11.7 m from the floor of the graben. The trench was 50 m long and 5.5 m deep. Fifteen units were identified in the trench based on their lithology. The following section briefly describes the stratigraphy of the middle trench, and full lithologic descriptions are given in Appendix C. Two faulting events are recorded in this trench. Four samples collected from this trench, three of which were radiocarbon dated.

**Stratigraphy of the Middle Trench.** The stratigraphy in the middle trench is dominated by fluvial gravel deposited by Sheep Creek, from which 10 distinct units were identified on the up-throw side of the fault. Units 1 through 10 are packages of coarse multilithologic gravel with subrounded to rounded, poorly sorted clasts ranging in size from 2 to 40 cm, and a matrix ranging from absent to fine sand. The gravel beds range in thickness form 0.5 to 1.5 meters. The 1.15 mm average thickness of carbonate coats n=25 on carbonate clasts indicate a late Pleistocene age (Pierce, personal communication; Pierce and Scott, 1982).

Unit 11 overlies the unit 10 fluvial gravel and underlies the modern soil. Unit 11 is a poorly sorted silt with loose single grain structure that grades into the modern soil (subunit 15g) exposed at the top of the trench.

Units 8a, 9a, 10a, and 11a on the downthrown side of the fault are interpreted, to correlate with units 8, 9, 10, and 11, respectively, on the upthrown side of the fault. They cannot be physically traced across the fault but are correlated on the basis of their composition.
Unit 11a is transitional between a fluvial gravel and a fine-grained graben-fill. Unit 11a is interpreted to be the prefaulting surface of the terrace. Unit 11a contained enough organic soil material to sample (SC-M2) for a radiocarbon date. The unit was dated at 5310 +/-60 $^{14}$C yr BP and predates the first event.

Unit 12a is a gravelly, very-fine sand to silt unit, showing stratification. The grain size indicates deposition in a low energy environment. Unit 12a is interpreted as a graben-fill deposit that formed following the first faulting event. The fineness and stratification of this unit are evidence for the formation of the graben during the first faulting event.

Unit 13 was subdivided into 4 subunits (a-d). Subunits 13a-d are poorly sorted gravel with a silty-sand matrix. Subunits 13a and 13c have a down-slope fabric that dips as much as 30° w. Subunit 13b has a random fabric and subunit 3d has a horizontal fabric. Subunits 13a-d are interpreted as scarp-derived colluvium shed from the scarp following the first faulting event.

Unit 14 is subdivided into three subunits (a-c). Subunit 14a is a well-sorted, subangular to subrounded gravel with no matrix and shows a strong down-slope dipping fabric. Subunit 14b is moderately sorted gravel with a down-slope fabric similar to that of unit 14a but has a silt to fine sand matrix. A sample of detrital organic material (SC-M1) was collected from the toe of subunit 14a. The sample was dated at 2110 +/- 60 $^{14}$C yr BP. Subunits 14a and 14b are interpreted as scarp-derived colluvium shed from the free face following the second faulting event. Unit 14c is a subrounded poorly sorted gravel with a fine-sand to granule matrix. It has a weak east-dipping fabric. Subunit 14c is interpreted as scarp-derived colluvium shed from the antithetic free face formed during the second faulting event.
Unit 15 was subdivided into seven subunits (a-g). Subunits 15a, 15b, 15e, and 15f are composed of laminated fine sands and silt. A series of organic rich horizons occurs within these units. These subunits are interpreted as fine-grained graben-fill material that settled out of ponded water within the graben, following the second faulting event. Subunit 15a was sampled (SC-M3) and dated at 540 +/-50 $^{14}$C yr BP. Subunit 15c consists of open work cobbles 6-12 cm in size. The cobbles are thought to have rolled off the scarp, or may have been pushed over the scarp during gravel operations in the U. S. Forest Service gravel pit on the upthrown surface, and accumulated at the base of the scarp. Subunit 15d is a moderately sorted, matrix-rich gravel with a down-slope fabric. It is interpreted as slope colluvium. Subunit 15g is a sandy-loam with weak granular structure interpreted as the modern soil.

**Structure of the Middle Trench.** The structure of the middle trench is dominated by a fault-bounded graben 25 m wide. The graben is bounded on the east by the main 10.2-m high fault scarp and to the west by an antithetic fault scarp that is 3 m high. The antithetic faults accommodate 2.9 m of net slip. Most of the 2.9 m of displacement is spread over a zone 5 m wide, with 0.5 m taken up on a larger fault at the base of the antithetic scarp. The faults in this zone are vertical to dipping steeply to the east. There is scarp-derived colluvium that lapped up against each small antithetic free face.

The main fault trace is in the east side of the trench. The fault dips 85° west to within 2.5 m of the surface. All of the 10.2 m of displacement across the main fault scarp is accommodated by this single fault strand. The main fault separates flat to gently west-dipping fluvial units on the upthrown side of the fault from the somewhat distorted faulted units on the downthrown graben floor. Scarp-derived colluvium from the second event covers the fault and scarp-
derived colluvium from the first event. The first faulting event down-dropped units 8a, 9a, 10a, and 11a roughly 3.2 m, whereas 4 m of displacement occurred during the second faulting event. Net displacement of 7.2 was calculated by projecting the ground-surface of the upthrown block at 0° over the downthrown surface beyond the antithetic fault scarp.

**Sequence of Events for the Middle Trench.** The oldest event recorded in this trench is the deposition of the fluvial gravel units 1 through 10, probably during the late Pinedale glacial advance. The t1 terrace was abandoned by Sheep Creek as the river formed the lower terraces in either deglacial (10-14 ka) or early Holocene time. Following formation of the terrace complex the first event displaced the fluvial gravel an estimated 4 m forming a 4-m high free face and a graben at the base of the scarp. Constraint on the age of the first faulting event in this trench comes from a date of 5310 +/- 60 14C yr BP, from subunit 11a. Unit 11a is thought to be the original terrace surface displaced in the first event.

After the first event the graben was flooded or ponded and fine-grained material accumulated in the bottom of the graben. The coarse material incorporated into the silt comes from small gravel being transported from north to south down the axis of the graben depositing unit 12a. The graben-fill was contemporaneous with the deposition of the scarp-derived colluvium (unit 13) shed from the free face.

The second event ruptured prior to 2110 +/- 60 14C yr BP creating another free face approximately 3.2 m high. The dated subunit postdates the second event by the length of time for a colluvial wedge (subunit 14) to be deposited. The graben was not immediately flooded because subunit 14a overlays the fine-grained graben-fill (subunit 12a) that was deposited after the
first event. Subunit 14c forms at this time as it is scarp-derived colluvium from the antithetic fault scarps. A period of increased slope degradation occurs at this time as subunit 14b is draped over the fault and half way across the graben floor. Fine-grained graben-fill dated at 540 +/- 50 \(^{14}\)C yr BP overlies subunit 14b. Subunit 15g and 15f are modern soils.

Northern Trench

Figure 18 shows a simplified log of the south wall of the northern trench at Sheep Creek. A detailed log of the trench is given in Plate 7. Units are numbered from oldest (1) to youngest (8). The northern trench was dug across a 9.3 meter fault scarp on the eastern edge of a small alluvial fan associated with a small gully to the northeast. The trench was 32 m long and 4.5 m deep. There were 9 units identified in the trench based on their lithology. The following section briefly describes the stratigraphy of the northern trench. Full lithologic descriptions are given in Appendix D. Two faulting events are recorded in this trench. Seven samples were collected in this trench, of which four were sent to the laboratory for radiocarbon dating.

Stratigraphy of the North Trench. The stratigraphy of the northern trench is dominated by a thick package of alluvial fan material. The alluvial fan gravels are underlain by fluvial gravel from Sheep Creek and overlain by a debris-flow deposit on the upthrown side of the fault.

Unit 1 is a coarse multi-lithologic fluvial gravel, whose composition resembles units exposed in the footwall of the middle trench. Unit 1 is interpreted as fluvial gravel deposited by Sheep Creek following the late Pinedale glacial advance.

Unit 2 is subdivided into 13 subunits (a-m). Subunits 2a-2l are a series of coarse, angular, multilithologic gravels. Clasts are moderately sorted, with
Figure 18. Simplified version of the log of the north trench at Sheep Creek. Logged in July of 1991, by L.C. Allen Jones, James McCalpin and Matthew Novak.
angular clasts ranging in size from 1-14 cm, with little to no matrix. Subunits 2a-2l are interpreted as alluvial fan material derived from a small gully to the northeast. Subunit 2m is an angular, poorly sorted matrix-rich gravel with a hard, massive structure and random fabric. Subunit 2m is interpreted as a debris-flow unit. There are two landslide scarps near the trench that represent likely sources for the material.

Unit 3 was divided into four subunits (a-d). Subunits 3a and 3b are weakly organic and matrix-supported, which differs greatly with the alluvial fan and the debris-flow material below them. They are interpreted as scarp-derived colluvium. Subunit 3c is fine-grained material with few clasts. Unit 3d has the same lithology as that of subunit 2m and is interpreted as a debris-flow unit. Subunit 3b was sampled (SC-N4) and dated at 1810 +/- 60 14C yr BP. This section of the trench contains evidence of animal burrows so the validity of this date is questionable.

Unit 4 is divided into four subunits (a-e). Units 4a, 4c, and 4d are poorly sorted, angular gravel with a strong down-slope fabric. Unit 4a has clasts dipping 60-70° to the west and shows evidence of shear on the east edge. This shows that unit 4a has been faulted. Subunit 4b is a suspected chunk of subunit 2i, and subunits 4d is a suspected block of subunit 2l. Unit 4 is interpreted as scarp-derived colluvium shed from the scarp following the first faulting event.

Unit 5 is a subrounded gravel with a comparatively organic rich silty-sand matrix. Bedding in this unit dips 12-15° to the west, with weak fabric that parallels bedding. Unit 5 is interpreted as alluvial gravel that accumulated as the small stream to the north incised down through the fault scarp. The concentration of organic content may be associated with a small slump to the
north of the trench. The upper contact of unit 5 (SC-N1) was dated at 840 +/- 50 14C yr BP. The lower contact of unit 5 (SC-N4) was dated at 1910 +/- 60 14C yr BP. Unit 3b is stratigraphically lower than that of unit 5 but is dated as younger in age. The dates from unit 5 do not bracket the age of the second faulting event, but date the deposition of unit 5.

Unit 6 is a poorly sorted, subangular gravel with a soft silty-sand matrix. It is weakly organic throughout. Unit 6 is interpreted as distal scarp-derived colluvium.

Unit 7 is a poorly sorted angular gravel imbricated 25-35° to the west and contains pockets of detrital organic matter throughout. Unit 7 is interpreted as scarp-derived colluvium from the second faulting event. A sample of organic soil from unit 7 (SC-N7) was sampled at the fault and yielded at date of 2910 +/-70 14C yr BP. The dated material is thought to be a piece of pre-second event soil that fell into basal tension crack that opened during the second faulting event; if so, the date should slightly predate the second event. However, if the soil piece carried a mean Residence Age of several hundred years at the time it fell into the crack (see Machette and others 1992, Appendix A), then the 2110 +/- 70 yr date may be several hundred years older than the true time of faulting.

Unit 8 is poorly sorted angular gravel that is interpreted as alluvial fan material deposited after the second faulting event. Unit 9 is the modern soil.

Structure of the North Trench. The main fault trace exposed in this trench dips 60° west, and accommodates 8.2 m of displacement based on the offset of the unit 3/unit 2 contact. There is a small shear zone 3 m to the east of the main fault which is nearly vertical. The displacement in this zone is only 25 cm. There is no datable material that can be correlated to this zone. Doubling
the thickness of the colluvial wedges suggests 4.5 m of displacement during the first faulting event and 3.2 m of displacement during the second faulting event. There is no evidence for the existence of the graben in this trench.

The fault separates alluvial fan gravels on the upthrown side of the fault from faulted alluvial fan gravels and first event scarp-derived colluvium on the downthrown side of the fault. The upper portion of the fault scarp at the north trench shows a creep zone near the surface where material is transported down the scarp by means of small-scale mass movement. The scarp-derived colluvium for the second event is draped up against the eroded free face exposed during the second event. The modern soil covers both the creep zone on the upthrown block and the scarp-derived colluvium from the second event.

**Sequence of Events for the North Trench.** Unit 1 is the oldest deposit exposed in the north trench, and it is the fluvial gravel deposited by Sheep Creek following Pinedale glaciation. As the terraces were formed a thick alluvial fan package prograded out over the t1 surface from a small gully to the northeast. Evidence from the trench indicates there was a mass movement event, consisting of a small-scale debris-flow.

The first event is not tightly constrained in this trench by radiocarbon dates. The event occurred prior to 2910 +/- 70 ¹⁴C yr BP, based on dated organic material that fell into a tension crack on top of the first event scarp-derived colluvium. Following the deposition of the first colluvial wedge, alluvial fan material started accumulating on the downthrown block as the small ephemeral stream cut down through the fault scarp. The alluvial fan deposited material over the colluvial units at the base of the scarp. Slope colluvium interfingered with the fan material.
The second faulting event occurred after deposition of unit 5. The timing of the second faulting event is also constrained in this trench by the 2910 +/- 70 14C yr BP date from material at the base of the second colluvial wedge. The second event formed a free face that degrades to form the scarp-derived colluvium (unit 6 and unit 7) that covers the colluvium from the first event. Unit 8 is the most recent alluvial fan material, which was deposited as the small stream begins to cut down through the fault scarp. Unit 9 is the modern soil, currently undergoing formation.

Sequence of Events at the Sheep Creek Terrace Complex

The lack of suitable radiocarbon dating material made it difficult to tightly bracket the timing of each paleorupture in each of the trenches. However, the first and second faulting events should correlate among trenches, so it is possible to determine the timing of faulting at Sheep Creek using data from all three trenches.

The oldest sediments in the trenches are a thick package of stream gravel that was deposited following the last major deglaciation, approximately 15,000 yr BP. The formation of this alluvial fan and debris-flow package at the northern trench site occurred after the fluvial gravel reached its maximum fill depth. The alluvial fan was formed during paraglacial fan depositions as described by Church and Ryder (1972). As the alluvial fan prograded out over the fluvial gravel, Sheep Creek was cutting down to form the terrace complex in the late Pleistocene or early Holocene time. The lowest terrace was stable for enough time for a loess cap to develop as shown in the southern trench. The first faulting event is bracketed between a 5310 +/- 60 14C yr BP date from the middle trench and 5080 +/- 60 14C yr BP date from the south trench. Following
the first event, free face and scarp degradation was the dominant process. Sheep Creek flooded the downthrown side of the t3 terrace, depositing material (afy) concurrently with the first colluvial wedge.

The second event is constrained by the dates of 2910 +/- 60 yr BP from the top the north trench and 2110 +/- 60 yr BP from the middle trench. The later date from the middle trench postdates the event by the amount of time it takes for the colluvial wedge to build out that far. The earlier date may be 150-300 years older than the second event if mean residence effects are operating. Following rupture, scarp-degradational processes dominate and colluvial and alluvial material was deposited across the downthrown surfaces on both sides of Sheep Creek. At the north edge of the terrace complex, material eroded from the fault scarp as a small gully cuts down through the fault scarp is transported south down the axis of the graben. At the south edge of the terrace complex material is being deposited on the downthrown block from the hill slope to the south. The gully is forming as material is eroded from the base of the fault scarp on the south slope. The scarp degradation rates level off and the modern soil begins and continues to develop.

The t2 and t3 terrace surfaces (Figure 15) were formed before the first faulting event observed in the trenches. They are not tectonic terraces, even though they look like it. The t2 terrace is 5.5-5.8 m above the present stream on the upthrown block. The displacement of stratigraphic units observed in the middle trench indicates the downthrown block has been down-dropped 7.2 m. The corresponding t2 and t3 terraces on the downthrown block were down-dropped below the present stream level and were subsequently buried by alluvium from Sheep Creek after faulting.
Paleomagnitudes of Earthquakes

The magnitudes of paleoearthquakes on the Greys River fault were estimated using three different methods: 1) surface rupture length, 2) average surface displacement, and 3) seismic moment. Previous work has shown that earthquake magnitude is related to fault characteristics such as surface rupture length, rupture width, rupture area, and displacement (Khromovskikh, 1989; Bonilla and others, 1984; Slemmons, 1982). An empirical relationship between surface rupture length, displacement, and moment-magnitude ($M_w$) is described by earthquake-magnitude regression equations calculated from historic earthquake data (Wells and Coppersmith, 1994). Paleomagnitudes were estimated from surface rupture length and displacement using moment-magnitude equations from Wells and Coppersmith (1994) (Table 2). Paleomagnitudes were also estimated using the moment-magnitude equations of Hanks and Kanamori (1979) (Table 2).

Two rupture lengths were used for calculating paleomagnitude. It is unclear whether the entire fault ruptured during both events because the only subsurface control is at Sheep Creek. Trenching the southern end of the fault would constrain the minimum rupture distance further. The minimum rupture length (30 km) is the maximum length along the fault that shows surface offsets similar to those at Sheep Creek, which are roughly 7 m. North of Blind Bull and south of Box Canyon the fault scarps decrease in height. Because the Greys River fault does not show any signs of segmentation, the maximum probable rupture length is the total length of the Greys River fault that shows clear evidence of Holocene faulting, or 54 km. The estimates of moment-magnitudes using the surface rupture length equations from Wells and Coppersmith (1994) are $M_w = 6.8$ for the minimum rupture length and $M_w = 7.1$ for the maximum
TABLE 2. EQUATIONS FOR CALCULATING MOMENT-MAGNITUDES FOR PALEOEARTHQUAKES

1. \( M = a + b \log(X) \) (Wells and Coppersmith, 1993).

- \( M \) = moment magnitude.
- \( a, b \) = from table below.
- \( X \) = from field mapping.

<table>
<thead>
<tr>
<th>( X )</th>
<th>Type</th>
<th>n</th>
<th>( a ) (sa)</th>
<th>( b ) (sb)</th>
<th>s</th>
<th>( r )</th>
<th>Magnitude Range</th>
<th>Length/ Distance Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLR (km)</td>
<td>N</td>
<td>15</td>
<td>4.86 (0.34)</td>
<td>1.32 (0.26)</td>
<td>0.34</td>
<td>0.81</td>
<td>5.2 - 7.3</td>
<td>2.5 - 41 (km)</td>
</tr>
<tr>
<td>SLR (km)</td>
<td>All</td>
<td>77</td>
<td>5.08 (0.10)</td>
<td>1.16 (0.07)</td>
<td>0.28</td>
<td>0.89</td>
<td>5.2 - 8.1</td>
<td>1.3 - 432 (km)</td>
</tr>
<tr>
<td>AD (m)</td>
<td>N</td>
<td>12</td>
<td>6.78 (0.12)</td>
<td>0.65 (0.025)</td>
<td>0.33</td>
<td>0.64</td>
<td>6.0 - 7.3</td>
<td>0.08 - 2.1 (m)</td>
</tr>
<tr>
<td>AD (m)</td>
<td>All</td>
<td>56</td>
<td>6.93 (0.05)</td>
<td>0.82 (0.10)</td>
<td>0.39</td>
<td>0.75</td>
<td>5.6 - 8.1</td>
<td>0.05 - 8.0 (m)</td>
</tr>
</tbody>
</table>

- SLR = surface rupture length.
- MD = maximum displacement.

Type = (N = normal fault data), (All = data from strike-slip, reverse and normal faults).

- \( n \) = number of faults in data set.
- \( a(sa), b(sb) \) = coefficient (standard error).
- \( s \) = standard deviation.
- \( r \) = correlation coefficient.

2. \( M = 2/3 \log(M_o) - 10.7 \) (Hanks and Kanamori, 1979).

\[ M_o = \mu a d \]

- \( \mu = \) elastic modulus, \( 3 \times 10^{11} \) dynes/cm\(^2\) (Arabasz, 1979)
- \( a = ((\text{Length} \times (\sin 45° \times \text{Depth} \ (\text{km}))) \times \text{Depth}) \) is the assumed average dip of the fault
- \( d = \) displacement (m)
- Length = length of the surface rupture
- Depth = depth of the rupture
probable rupture length. Since the only variable in the equations is surface rupture length, and the rupture lengths are assumed the same for both Holocene paleoseismic events, the estimates for the moment-magnitude are the same for both the first and second paleoseismic events.

Displacements used in the displacement-magnitude equations from Wells and Coppersmith (1994) were determined in the trenches at Sheep Creek. Since maximum slip occurs only in one narrow spike, displacement measurements from randomly located trenches along a fault scarp should be assumed to be closer to the mean rather than the maximum displacement incurred during faulting (Mason, 1992). Moment-magnitudes calculated based on average displacements measured from trenching are summarized in Table 3. The maximum displacement for each of the two events is 4.5 m for the first event and 3.2 m for the second event. By using the displacement from the trenches as the average displacement in the average displacement equation (Wells and Coppersmith, 1994), the 4.5 m displacement yields a Mw = 7.4 and a Mw = 7.1 for the 3.2 m displacement using the normal fault data, and Mw = 7.4 for the 4.5 m displacement and Mw = 7.3 using all fault-type data.

Moment-magnitudes are also estimated based on seismic moment. Calculations relate the seismic moment to the area of the fault plane and the displacement. The seismic moment is the product of the elastic modulus (µ), the fault plane area (a), and the average displacement (d) (Hanks and Kanamori, 1979). The elastic modulus for sedimentary rocks in the Basin and Range province was estimated to be 3 x 10^{11} dynes/cm^2 (Arabasz and others, 1979). The fault plane area (a) is the product of the surface rupture length and the depth of rupture, divided by the sin of the dip. To calculate the area I assumed the fault plane to be rectangular and have a uniform dip. The Greys River fault
### Table 3. Calculated Moment-Magnitudes for Paleoearthquakes on the Greys River Fault

1. Results from paleomagnitude calculations using equations from Wells and Coppersmith (1993).

<table>
<thead>
<tr>
<th>Event</th>
<th>Trench</th>
<th>Net Slip</th>
<th>Rupture Length</th>
<th>Moment Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>South</td>
<td>2.0 m</td>
<td></td>
<td>7.0 N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.1 N</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>4.0 m</td>
<td>30 km *</td>
<td>6.8 N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>54 km †</td>
<td>6.8 N</td>
</tr>
<tr>
<td></td>
<td>North</td>
<td>4.5 m</td>
<td>54 km</td>
<td>7.1 N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>71 N</td>
<td>7.1 N</td>
</tr>
</tbody>
</table>

2nd Event

<table>
<thead>
<tr>
<th>Event</th>
<th>Trench</th>
<th>Net Slip</th>
<th>Rupture Length</th>
<th>Moment Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>South</td>
<td>2.2 m</td>
<td></td>
<td>30 km</td>
<td>6.8</td>
</tr>
<tr>
<td>Middle</td>
<td>3.2 m</td>
<td></td>
<td></td>
<td>7.1 N</td>
</tr>
<tr>
<td>North</td>
<td>3.2 m</td>
<td></td>
<td></td>
<td>7.1 All</td>
</tr>
</tbody>
</table>

2). Results of paleomagnitude calculations using the equations from Hanks and Kanamori (1979).

<table>
<thead>
<tr>
<th>Event</th>
<th>Trench</th>
<th>Net Slip</th>
<th>Rupture Length</th>
<th>Moment Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>South</td>
<td>2.0 m</td>
<td>30 km *</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>54 km †</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>4.0 m</td>
<td>30 km</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>54 km</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>North</td>
<td>4.5 m</td>
<td>30 km</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>54 km</td>
<td>7.3</td>
</tr>
</tbody>
</table>

2nd Event

<table>
<thead>
<tr>
<th>Event</th>
<th>Trench</th>
<th>Net Slip</th>
<th>Rupture Length</th>
<th>Moment Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>South</td>
<td>2.2 m</td>
<td></td>
<td>30 km</td>
<td>6.9</td>
</tr>
<tr>
<td>Middle</td>
<td>3.2 m</td>
<td></td>
<td>30 km</td>
<td>6.9</td>
</tr>
<tr>
<td>North</td>
<td>3.2 m</td>
<td></td>
<td>30 km</td>
<td>6.9</td>
</tr>
</tbody>
</table>

* = Minimum rupture length
† = Maximum rupture length
§ = (N = normal fault regression), (All = all fault type regression).
dips $56^\circ$ at the surface and $30^\circ$ at depth where it soles into the Darby thrust (Webel, 1987). The average dip of the fault plane is assumed to be $45^\circ$. The Greys River fault soles into the Darby thrust at depth. The Darby Thrust merges with a larger decollement to the west at depths near 8.2 km. The depth of fault rupture is unknown, so the depth is assumed to be the major subsurface decollment in which the Darby soles (8.2 km). The depth of displacement divided by the sin of the average dip of the fault ($8.2 \text{ km} / \sin 45^\circ$) multiplied by the minimum and maximum probable rupture lengths gives the area of the fault plane. The average displacement used in this equation comes from evidence exposed in the trenches. Estimates for moment-magnitude using the equation of Hanks and Kanamori (1979) are $M_W = 6.9$ to 7.2. The magnitudes calculated using this method generally agree with those calculated using the displacement and rupture length methods from Wells and Coppersmith (1994).

Differences in geologic conditions at the surface cause uncertain variations in the surface expression. Inherent difference in surface expression and errors in field measurements overwhelm the error specific to the equations. The values from the equations are an expected value. Over all the error in the magnitudes are $+/- 0.3$ magnitude units.

**Recurrence Intervals**

To calculate the recurrence interval of earthquakes on the Greys River fault, the radiocarbon dates were calendar corrected using a program by Stuiver and Reimer (1993) (Table 4). There are three intervals recorded in the terrace complex at Sheep Creek. The terrace complex is estimated to be late Pinedale in age (~14 ka). The first event occurred between 5830 $+/- 80$ and 6110 $+/- 150$ cal. yr BP, and the second event occurred sometime after 3030 $+/- 130$ cal. yr BP. The first recurrence interval, not a true recurrence interval
TABLE 4. RADIOCARBON AGES AND CALENDAR CORRECTED DATES

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Location</th>
<th>Material</th>
<th>laboratory date (^{14}\text{C yr BP})</th>
<th>Calendar corrected ages (cal. yr BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lab number</td>
<td></td>
</tr>
<tr>
<td>SC-S4</td>
<td>South Trench</td>
<td>Detrital organics</td>
<td>5080 +/- 60</td>
<td>5830 +/- 80</td>
</tr>
<tr>
<td></td>
<td>Unit - 4e</td>
<td></td>
<td>8-48132</td>
<td></td>
</tr>
<tr>
<td>SC-M1</td>
<td>Middle Trench</td>
<td>Weakly organic soil</td>
<td>2110 +/- 60</td>
<td>2050 +/- 100</td>
</tr>
<tr>
<td></td>
<td>Unit- 14a, toe</td>
<td></td>
<td>8-48125</td>
<td></td>
</tr>
<tr>
<td>SC-M2</td>
<td>Middle Trench</td>
<td>Weakly organic soil</td>
<td>5310 +/- 60</td>
<td>6110 +/- 150</td>
</tr>
<tr>
<td></td>
<td>Unit- 11a, top</td>
<td></td>
<td>8-48126</td>
<td></td>
</tr>
<tr>
<td>SC-M3</td>
<td>Middle Trench</td>
<td>Weakly organic graben-fill</td>
<td>540 +/- 50</td>
<td>390 +/- 80</td>
</tr>
<tr>
<td></td>
<td>Unit- 15a</td>
<td></td>
<td>8-48127</td>
<td></td>
</tr>
<tr>
<td>SC-N1</td>
<td>North Trench</td>
<td>Detrital organics</td>
<td>840 +/- 50</td>
<td>730 +/- 50</td>
</tr>
<tr>
<td></td>
<td>Unit- 5, top</td>
<td></td>
<td>8-48128</td>
<td></td>
</tr>
<tr>
<td>SC-N4</td>
<td>North Trench</td>
<td>Weakly organic colluvium</td>
<td>1810 +/- 60</td>
<td>1710 +/- 100</td>
</tr>
<tr>
<td></td>
<td>Unit- 3b, base</td>
<td></td>
<td>8-48129</td>
<td></td>
</tr>
<tr>
<td>SC-N5</td>
<td>North Trench</td>
<td>Detrital organics</td>
<td>1910 +/- 60</td>
<td>1830 +/- 100</td>
</tr>
<tr>
<td></td>
<td>Unit- 5, base</td>
<td></td>
<td>8-48130</td>
<td></td>
</tr>
<tr>
<td>SC-N7</td>
<td>North Trench</td>
<td>Weakly organic soil</td>
<td>2910 +/- 70</td>
<td>3030 +/- 130</td>
</tr>
<tr>
<td></td>
<td>Unit- 7b, base</td>
<td></td>
<td>8-48131</td>
<td></td>
</tr>
</tbody>
</table>

* Calendar corrected ages from (CALIB 3.0) (Stuiver and Reimer, 1993).

† Calibration data set (Stuiver and Becker, 1993).
because it is not bounded at the older bend is >8 ka and the second recurrence interval is ~3 ka. The elapsed time is also ~3 ka. This recurrence pattern is typical for faults in the northeastern Basin and Range, and makes long-term prediction difficult. The next earthquake on the Greys River fault may occur in the near future or over 10,000 years from now.

The penultimate event on the Greys River Fault (Figure 19) is only a little bit younger (5080-5310 $^{14}$C yr BP) than the latest event on the Star Valley fault (5540 $^{14}$C yr BP; Warren, 1992). The Star Valley fault and the Greys River fault sole into the same detachment at depth. Slip on the Star Valley fault could have triggered later slip on the Greys River fault, but at 8 ka the Star Valley fault ruptured and the Greys River fault did not. The Greys River fault ruptured near the time (2-3 ka) of an event on the east Bear Lake fault 80 km to the southwest (McCcalpin, 1990).

**Fault Segmentation**

The Greys River fault does not show any distinct signs for segmentation. There does not seem to be any preexisting structures that influence the surface geometry of the Greys River fault. Many large faults in the Basin and Range Province are composed of multiple segments (Crone and Haller, 1991; Machette and others, 1989; DePolo and others, 1991). Typically long faults are made up of long segments and short faults are composed of short segments (Machette and others, 1989). The segment boundaries are usually indicated by; geometric, structural and behavioral discontinuities (DePolo and others, 1991). The Greys River fault does not show any geometric or structural discontinuities such as fault step-overs separations or gaps in the fault zone or footwall salients. The only evidence for a segment boundary is in area along the fault near the Martin Creek drainage. The fault to the south is located at the
Figure 19. Temporal distribution of paleoseismic events in the northeast Basin and Range Province. Shaded boxes show inferred time periods for paleoearthquakes as bracketed by radiocarbon dates (black dots). Horizontal lines with hatchers indicates oldest Quaternary stratigraphic unit investigated. The timing for the paleoseismic events come from: Teton fault (Byrd and Smith, 1990); Greys River fault (Jones and McCalpin, 1992); Star Valley fault (Warren, 1992); Bear Lake faults (McCalpin and others, 1990b); Rock Creek fault (McCalpin and Warren, 1992); East Cache fault (McCalpin and Forman, 1991); Wasatch fault, Brigham City segment (Personius, 1991). (Adapted from McCalpin, 1993).
base of the clearly defined Range front. To the north of Martin Creek the fault separates the Range on the east from some large bedrock ridges to the west. This suggests that the north end of the valley may not have as much overall displacement as that of the southern part of the valley, or the overall displacement is occurring in a wide zone in the north compared to the south.

**Short-Term Versus Long-Term Slip Rates**

The long-term slip rate of the Greys River fault is not very well constrained. There is no information on the timing or magnitudes for paleoearthquakes on the Greys River fault prior to 15 ka. Pierce and Morgan (1992) suggest that faults in zone 1 show million-year time scale slip rates of <0.03 mm/year, whereas offset in the last 15 ka suggests there may be an increase in activity in the last 15 ka or that offset on faults with very long recurrence intervals just happens to have ruptured in the last 15 ka. Displacements observed at the Sheep Creek terrace complex indicate 7.2 m of offset since 15 ka. This gives a slip rate of 1.11 mm/year. However, this slip rate is calculated using only two earthquakes since 15 ka. Offsets across fault scarps in older glacial deposits (<35 ka) similar in height to those at Sheep Creek in Blind Bull Creek suggest there may have been a long state of quiescence on the Greys River fault prior to 15 ka. The apparent increase in activity of the Greys River fault may be in response to the approaching "bow wave" of the migrating Yellowstone hot spot described by Pierce and Morgan (1992) and Anders and others (1989).

Assuming a 1.11 mm/year slip rate and 1 km of offset the Greys River fault is roughly 1 million years old, but if a more "typical" slip rate for Basin and Range normal faults of 0.5 mm/year is assumed, the Greys River fault is closer
to 2 million years old. Slip rates are difficult to assess without a long-term record of timing and offsets of paleoearthquakes on a fault (Machette, 1987). Apparent changes in activity could be a result of a random distribution of faulting events on regional fault. Changes in long-term versus short-term slip rates on the Greys River fault would reveal relations of regional response to the migration of the Yellowstone hot spot. However, there is little evidence for either the offsets or the timing of paleoearthquakes on the Greys River fault prior to 15 ka.
CONCLUSIONS AND FUTURE WORK

The Greys River Valley contains evidence for four glacial advances. Glacial deposits in the study area were sampled and correlated to Blackwelder's (1915) Rocky Mountain glacial sequence on the basis of weathering characteristics. The oldest advance is the Bull Lake advance, which deposited moraines 9 km down-valley in the Blind Bull Creek and the Deadman Creek drainages. Bull Lake deposits in the study area are characterized as subdued moraines with eroded crests and a thick loess cap. During the early Pinedale advance, glaciers flowed 7 km down-valley in these same two drainages as well as depositing moraines in the Martin Creek drainage and at the mouth of the Box Canyon Creek drainage. Early Pinedale moraines have discontinuous degraded crests with a loess cap thick enough to bury the surface boulders 75-90 percent. Late Pinedale glaciers formed a series of nested moraines in all of the glaciated drainages except Martin Creek. Late Pinedale moraines have sharp crests and numerous boulders at the surface showing little burial. The most recent advance is the Neoglacial advance. The Neoglacial moraines consist of small ridges of rock fragments located in the upper elevations of the glaciated drainages.

The Greys River fault has a surface trace of 54 km, forming west-facing fault scarps from 2-10 m high along the west flank of the Wyoming Range. The subsurface fault geometry is suggested to be listric, dipping 56° at the surface and flattening to a dip ~30° where it soles into the Darby thrust at depth. Faulting on the Greys River fault has produced fault scarps 4-9 m high in glacial deposits and 1- to 10-m high fault scarps in postglacial deposits. Analysis of the distribution of displacement along the Greys River fault suggests a bimodal distribution of displacement, which is supported by trenching investigations.
Evidence exposed during trenching revealed evidence for two paleoseismic ruptures on the Greys River fault with displacements of 4 m. The evidence for the oldest event observed in the trenches indicated that the Greys River fault ruptured between 5830 and 6110 cal yr BP, having a maximum observed vertical surface displacement of 3.3 m and producing an earthquake with a moment-magnitude between 6.8 and 7.4. The more recent event observed in the trenches occurred some time after 3030 cal yr BP with 4.5 m of maximum observed vertical surface displacement and a moment magnitude between 6.8 and 7.3. The recurrence intervals for earthquakes on the Greys River fault are sporadic. The Greys River fault has recurrence interval as low as 3,000 years.

Future work could involve study of the distal ends of the Greys River fault. More detailed study of the distal ends of the fault may more tightly constrain the length of fault that is capable of rupturing during a single event. This would include other possible trench sites at Blind Bull Creek, Box Canyon Creek, or near Slate Creek. To the south of the study area there is a series of normal faults (Rubey, 1973) that may be related to the Greys River fault. The western side of the Greys River Valley is also in need of detailed geologic mapping. There is evidence for extensive glacial deposits coming from the Salt River Range.
REFERENCES CITED


Burke, R. M., and Birkeland, P. W., 1979, Reevaluation of the multiparameter relative dating techniques and their application to the glacial sequence along the eastern escarpment of the Sierra Nevada, California: Quaternary Research, v. 11, p. 21-51.


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APPENDICES
Appendix A

Definitions and Measurement Techniques for Relative Dating Parameters (adapted from Burke and Birkeland, 1979).

1. SFB - Surface boulder frequency. The number of clasts bigger than 30 cm in diameter exposed at or on the surface in a 20 m by 30 m area. Areas were chosen which seemed to represent the moraine crest.

2. BBF - Boulder burial factor. The average of visual estimates of the percentage of the volume of the boulders that are beneath the surface.

3. MCW - Moraine crest width. The horizontal width of the moraine crest as measured by rod to the nearest 0.5 meter. The crest was considered the top of a moraine that has a slope less than 5°.

4. MOSA - Maximum outer slope angle. The maximum measured outer slope of the moraine. Measurements were made using a rod Brunton compass as a clinometer.

5. MISA - Maximum inner slope angle. The maximum measured inner slope of the moraine. Measured using a rod and compass.

6. MCA - Moraine crest angle. The gradient of the crest of the moraine.

7. MRT - Maximum rind thickness. The maximum weathering rind thickness in mm, measured from 50 clasts at or on the surface of the moraine crest.

8. ART - Average rind thickness. The average weathering rind thickness in mm measured from 50 clasts at or on the surface of the moraine crest.

9. VCF - Vegetation cover factor. The visual estimate of the percentage of vegetation cover. Values range from 0 for no vegetation to 100 for organic duff.

10. LCT - Loess cap thickness. The thickness in cm of loess measured from soil pits dug into the crests of the moraine.
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* Sites locations are indicated on Plate 2-4
* Valley position of moraine compared to other moraines in the drainage, numbered from upvalley (1) to downvalley (4)
nc = no data collected
Appendix B

Unit Descriptions, Southern Trench at Sheep Creek, Wyoming.

Unit 1a - Pinkish-tan (7.5YR4/4) gravel; clasts: 20 cm max., 5-10 cm avg., subrounded, poorly sorted, clay coatings, slight upstream imbrication; coarse sand to clay matrix; fluvial gravel.

Unit 1b - Pinkish-tan (7.5YR5/4) gravel; clasts: 12 cm max., 2-4 cm avg., subangular to subrounded, well sorted, very coarse sand to clay matrix, slight stratification; fluvial gravel.

Unit 1c - Light grey (5YR7/1) gravel; clasts: 4 cm max., 1-2 cm avg., subrounded, well sorted; no matrix; fluvial gravel.

Unit 1d - Pinkish-grey (5YR7/3) sand; well sorted; no matrix; tabular lens of fluvial gravel.

Unit 1e - Pinkish-grey (5YR6/3) gravel; clasts: 10 cm max., 2-4 cm avg., subrounded to well rounded, well sorted; clay coatings on a pebble matrix, fluvial gravel.

Unit 1f - Pink (5YR7/3) gravelly-sand; clasts: 7 cm max., 3-5 cm avg., subrounded to rounded; very coarse to medium sand matrix; fluvial gravel.

Unit 1g - Pink (5YR7/3) gravel; clasts: 11 cm max., 3-5 cm avg., rounded to well rounded, well sorted; clay coatings on a pebble matrix; fluvial gravel.

Unit 1h - Greyish-brown (5YR4/2) gravel; clasts: 8 cm max., 3-5 cm avg., subrounded, moderately sorted; no matrix; fluvial gravel.

Unit 1j - Greyish-brown (5YR4/2) sandy-gravel; clasts: 30 cm max., 8-12 cm avg., subrounded, moderately sorted; medium to coarse sand matrix; fluvial gravel.

Unit 1k - Pale orangish-brown (10YR7/3) gravel; clasts: 10 cm max., 3-5 cm avg., subrounded; medium to coarse sand matrix; fluvial gravel.

Unit 1l - Pea gravel; 8 cm max., 1-3 cm avg., subrounded to rounded; no matrix; lens of fluvial gravel.

Unit 2a - Brown (10YR4/4) sandy-gravel; clasts: 40 cm max., 10-14 cm avg., subrounded, moderately sorted; very coarse to coarse sand matrix; iron stains and weak soil development, a/c ox horizon; fluvial gravel.

Unit 2b - Brown (10YR5/3) silt; occasional rounded clasts; very well sorted; fine silt to fine sand matrix; massively bedded; loess cap.
Unit 3a - Pinkish-brown (7.5YR5/4) gravel; clasts: 22 cm max., 3-5 cm avg., subrounded, moderately sorted; occasional medium to fine sand stratification; down slope fabric 10-20 degrees to the west; scarp-derived colluvium from the earlier event.

Unit 3b - Tan (10YR5/3) sand; clasts: 17 cm max., 2-4 cm avg., subrounded, imbrication 20 degrees to the west; coarse sand to granule matrix; minor stratification; scarp-derived colluvium from the earlier event.

Unit 3c - Dark yellowish-brown (10YR3/4) gravel; clasts: 31 cm max., 10-15 cm avg., subrounded, moderately sorted, make up 30 percent of volume, imbrication 30 degrees to the west; fine to medium sand matrix; scarp-derived colluvium from the earlier event.

Unit 4a - Light pinkish-grey (5YR6/2) sandy-gravel; clasts: 15 cm max., 4-6 cm avg., subangular to subrounded, poorly sorted; coarse to very coarse sand matrix; horizontal stratification; contains 2-3 cm thick layer of well-stratified gravel; extremely friable; fluvial gravel.

Unit 4b - Pinkish-grey (7.5YR6/2) sand; clasts: 11 cm max., 3-6 cm avg., subangular, moderate to well sorted; no matrix; inter fingering gravel tongues from the west; fluvial gravel.

Unit 4c - Grey (5YR5/2) gravel; clasts: 11 cm max., 3-6 cm avg., subrounded to subangular, moderately sorted; discontinuous layers of coarse sand to granule; fluvial gravel.

Unit 4d - Brown (10YR3/3) gravelly-sand; clasts: 8 cm max., 2-4 cm avg., 60 percent of volume, subangular to subrounded, poorly sorted; horizontal beds that cut into colluvial wedge to the east; fluvial gravel.

Unit 4e - Brown (10YR3/3) sand; clasts: pebbles in places, well sorted; medium to fine sand matrix; dark (10YR3/2) continuous organic layer 2-3 cm thick; low energy fluvial sand. This unit was dated to be 5080 $^{14}$C yr BP.

Unit 4f - Pinkish-grey (7.5YR7/2) sandy-gravel; clasts: 11 cm max., 3-5 cm avg., subangular to subrounded, moderately sorted, some upstream imbrication; medium sand matrix; layer of iron stains between 5 and 6 meters horizontal; fluvial gravel.

Unit 4g - Light brown (10YR5/3) gravelly-sand; clasts: 13 cm max., 3-5 cm avg., subangular to subrounded, moderately sorted; fine sand matrix; fluvial sand.

Unit 4h - Grey (5YR5/2) and Tan (10YR5/3) gravel; clasts: 7 cm max., 1-2 cm avg., well rounded to subangular, moderately sorted with lenses of well-sorted pea gravel; discontinuous coarse sand matrix; fluvial gravel.
Unit 5a - Dark yellowish-brown (10YR3/4) gravel; clasts: 31 cm max., 10-15 cm avg., subrounded, moderately sorted, make up 30 percent of volume, imbrication 30 degrees to the west; fine to medium sand matrix; scarp-derived colluvium from the latter event.

Unit 5b - Dark greyish-brown (10YR4/2) gravelly-organic-sand; clasts: 5 cm max., 2-3 cm avg., 5-10 percent of volume, angular to subangular, well sorted; fine sand matrix; massively bedded; some iron stains; burrows between 9 and 10 meters horizontal; light grey mottling; grades laterally into unit 5c; cummlic slope-wash.

Unit 5c - Dark greyish-brown (10YR4/2) organic-sandy-gravel; clasts: 9 cm max., 2-4 cm avg., angular to subangular, moderately well sorted; very fine sand matrix; dark organic layer from 0 to 5 meters horizontal, near the bottom of the unit; alluvial fan and slope-wash material from the slope to the south.

Unit 5d - Brown (10YR4/2) sandy-gravel; clasts: 12 cm max., 5 cm avg., angular, poorly sorted; fine to medium sand matrix; iron stains; fluvial gravel.
Appendix C

Unit Descriptions, Middle Trench at Sheep Creek, Wyoming.

Unit 1 - Pale yellowish-brown (7.5YR6/2) gravel; clasts: 17 cm max., 5 cm avg., subangular to rounded, poorly sorted; fine sand to granule matrix; clast supported; weakly bedded; fluvial gravel.

Unit 2 - Pale yellowish-brown (7.5YR6/2) gravel; clasts: 8 cm max., 4 cm avg., subangular to subrounded, poor to moderately sorted, horizontal imbrication; fine sand to granule matrix; clast supported; moderately bedded with beds 12 cm thick; fluvial gravel.

Unit 3 - Yellowish-orange (7.5YR7/4) cobbles; clasts: 25 cm max., 10 cm avg., subangular to subrounded, weak imbrication to the west; silty-sand matrix; moderately cemented; clast supported; weakly bedded; Pinedale(?) outwash gravel.

Unit 4 - Pale yellowish-brown (7.5YR6/2) gravel; clasts: 20 cm max., 7 cm avg., subrounded to rounded, imbrication to the west; fine sand to granule matrix; weakly cemented; weakly bedded; clast supported; Pinedale(?) outwash gravel.

Unit 5 - Pale brown (7.5YR7/2) gravel; clasts: 15 cm max., 4 cm avg., subrounded, poorly sorted, horizontal imbrication; fine sand to silt matrix; moderately bedded with beds 8-10 cm thick; well cemented; Pinedale(?) outwash gravel.

Unit 6 - Pale Brown (7.5YR7/2) sandy-gravel; clasts: 25 cm max., 5-6 cm avg., poorly sorted, moderate imbrication to the west; fine to coarse sand matrix; moderately bedded with beds 10 cm thick; weakly cemented; clast supported; Pinedale(?) outwash gravel.

Unit 7 - Pale orangish-brown (10YR7/2) sandy-gravel; clasts: 20 cm max., 8 cm avg., subrounded to subangular, poorly sorted, moderate imbrication to the west; fine sand matrix; weakly bedded; well cemented; clast supported; Pinedale(?) outwash gravel.

Unit 8 - Pale yellowish-brown (10YR6/2) sandy-gravel; clasts: 20 cm max., 10 cm avg., subangular to subrounded, poorly sorted; fine sand and silt matrix; uncemented; weakly bedded; clast supported; Pinedale(?) outwash gravel.

Unit 8a - Yellowish-brown (7.5YR5/4) gravel; clasts: 16 cm max., 4 cm avg., subrounded to rounded, poorly sorted, imbrication 5-7 degrees to the east; silty-sand to granule matrix; matrix supported; moderately cemented; Pinedale(?) outwash gravel. Correlates with unit 8.
Unit 9 - Pale orangish-brown (10YR6/2) sandy-gravel; clasts: 23 cm max., 5-7 cm avg., subangular to subrounded, poorly sorted, very weakly imbricated to the west; fine sand and silt matrix; thin inter-bedded lenses of pea gravel; well cemented; Pinedale(?) outwash gravel.

Unit 9a - Pale yellowish-brown (10YR7/3) gravel; clasts: 19 cm max., 5 cm avg., subrounded to rounded, poorly sorted, weakly imbricated to the east; fine sand to granule matrix; alternately bedded gravel and pea gravel, with beds 8-10 cm thick; minor angular unconformity at the top. boundary between units 10b and 10c: matrix supported gravel; clasts 2-6 cm; fine to coarse sand matrix; lignite clasts; weak horizontal imbrication; Pinedale(?) outwash gravel. Correlates with unit 9.

Unit 10 - Pale orangish-brown (10YR7/2) sandy-gravel; clasts: 15 cm max., 5 cm avg., subangular to subrounded, poorly sorted, weakly imbricated to the west; silt matrix; clast supported; massively bedded; weakly cemented; Pinedale(?) outwash gravel.

Unit 10a - Pale yellowish-brown (10YR6/3) gravel; clasts: 25 cm max., 7-8 cm avg., subrounded to rounded, poorly sorted; fine sand to pea gravel matrix; weakly bedded; weak horizontal lineation; weakly cemented; inter-bedded pea gravel lenses: clasts 1-5 cm, rounded to subrounded, horizontal bedded, no cementation; Pinedale(?) outwash gravel. Correlates with unit 10.

Unit 10b - Moderate brown (5YR4/3) gravel; clasts: 11 cm max., 4 cm avg., subrounded to rounded, poorly sorted; silt to granule, predominantly sand matrix; matrix supported; random fabric; weakly cemented; Pinedale(?) outwash gravel.

Unit 11 - Moderate yellowish-brown (10YR5/4) gravelly-silt; clasts: 15 cm max., 5-8 cm avg., subangular to subrounded, poorly sorted; matrix supported; loose single grain structure; Transition to from Pinedale(?) outwash gravel to a soil horizon.

Unit 11a - Moderate yellowish-brown (7.5YR4/4) gravel; clasts: 13 cm max., 2 cm avg., subrounded, poorly sorted; fine sand to granule matrix; random fabric; weakly cemented; Pinedale(?) outwash gravel. This unit was dated at 5310 +/- 60 yr BP (B-48126).

Unit 12a - Moderate yellowish-brown (7.5YR3/4) gravelly-silt; clasts: 8 cm max., 2 cm avg., subrounded to rounded, poorly sorted, imbricated 20-30 degrees to the west; sandy-silt matrix; matrix supported; weakly cemented; weakly organic; graben-fill.

Unit 13a - Dark yellowish-brown (7.5YR4/6) gravel; clasts: 28 cm max., 7-9 cm avg., subrounded to rounded, poorly sorted, imbricated 20-30 degrees to the west; sandy-silt matrix; red sandstone clasts; sand lenses; scarp-derived colluvium associated with the first event.
Unit 13b - Dark yellowish-brown (10YR4/4) gravel; clasts: 26 cm max., 5-8 cm avg., rounded to subrounded, poorly sorted; silt to sand matrix; random fabric; weakly cemented; scarp-derived colluvium associated with the first event.

Unit 13c - Moderately yellowish-brown (7.5YR4/4) gravel; clasts: 12 cm max., 2-5 cm avg., subrounded to rounded, poorly, imbricated 15-20 degrees to the west; silt to sand matrix; clast supported; Scarp-derived colluvium associated with the first event.

Unit 13d - Dark yellowish-brown (10YR4/3) gravel; clasts: 20 cm max., 3-5 cm avg., rounded to subrounded, poorly sorted; silt to granule matrix; weakly horizontally bedded; horizontal fabric; scarp-derived colluvium associated with the first event.

Unit 14a - Dark yellowish-brown (10YR4/4) gravel; clasts: 28 cm max., 6-9 cm avg., subangular to subrounded, well sorted, carbonate pendants; no matrix; down-slope fabric; scarp-derived colluvium associated with the second event. This unit was dated at 2110 +/- 60 yr BP (B-48125).

Unit 14b - Dark yellowish-brown (10YR4/3) sandy-gravel; clasts: 11 cm max., 0.5-2 cm avg., subangular to subrounded, moderately sorted; silt to fine sand matrix; down-slope fabric; scarp-derived colluvium associated with the second event.

Unit 14c - Moderate yellowish-brown (7.5YR5/4) gravel; clasts: 12 cm max., 1-2 cm avg., subrounded, poorly sorted; fine sand to granule matrix; very faint down-slope fabric, to the east; scarp-derived gravel from the antithetic scarp associated with the second event.

Unit 15a - Dark yellowish-brown (10YR3/2) silt; alternating light and dark layers; very well sorted; graben-fill. This unit was dated at 540 +/- 50 yr BP (B-48127).

Unit 15b - Moderate yellowish-brown (10YR5/3) sandy-silt; well sorted; layers 3-6 cm thick; alternating sand and silt layers; silt is laminated; graben-fill.

Unit 15c - Moderate yellowish-brown (10YR5/3) silty-gravel; clasts: 16 cm max., 6-9 cm avg., subrounded to subangular, well sorted; fine sand to granule matrix; weak down-slope fabric, coarsening to the west; scarp-derived gravels in graben-fill.

Unit 15d - Dark yellowish-brown (10YR4/2) silty-gravel; clasts: 21 cm max., 2-5 cm avg., subangular to subrounded, moderately sorted, platy clasts oriented down-slope; fine sand matrix; organic rich; slope colluvium.

Unit 15e - Yellowish-brown (7.5YR5/4) silt; well sorted; fining upwards; finely laminated; lower portion has iron stains; fall-out in ponded graben.
Unit 15f - Pale brown (5YR5/2) silt; well sorted; weak soil development; many roots; fall-out in ponded graben.

Unit 15g - Brown (10YR3/3 moist), (10YR2/2 dry) soil; gravelly-silt; clasts: 5 cm max., 1-2 cm avg., subangular, poorly sorted, matrix supported; weak granular structure, friable; consistence dry; slightly hard; s.o., p.o., sandy-loam; modern soil.
Appendix D

Unit Descriptions, Northern Trench at Sheep Creek, Wyoming.

Unit 1 - Dark yellowish-brown (10YR4/2) gravel; clasts: 13 cm max., 2 cm avg., subrounded to rounded, well sorted, exotic lithologies, horizontal lineation; coarse sand to granule matrix; soft horizontal beds 5-10 cm thick; upper 20 cm has a silty matrix, loess cap; Pinedale(?) outwash gravel.

Unit 2a - Pale brown (7.56/2) gravel; clasts: 12 cm max., 2-3 cm avg., angular, moderate to well sorted; coarse sand to granule matrix; some open-work lenses; alluvial fan gravel.

Unit 2b - Pale brown (7.5YR6/2) gravel; clasts: 8 cm max., 1-2 cm avg., angular, well sorted; no matrix; some open-work layers; alluvial fan gravel.

Unit 2c - Pale brown (7.5YR6/2) gravel; clasts: 13 cm max., 4 cm avg., angular, moderately sorted, horizontal imbrication; medium to fine sand matrix; clast supported; alluvial fan gravel.

Unit 2d - Pale brown (7.5YR6/2) gravel; clasts: 8 cm max., 1-2 cm avg., angular, well sorted; no matrix; alluvial fan gravel.

Unit 2e - Pale brown (7.5YR6/2) gravel; clasts: 13 cm max., 3-5 cm avg., angular, moderately sorted, horizontal imbrication; fine sand matrix; clast supported; alluvial fan gravel.

Unit 2f - Light brown (7.5YR7/4) gravel; clasts: 10 cm max., 2-3 cm avg., subangular, well sorted, weak horizontal lineation; granule matrix; non cohesive; bedding 8-10 cm thick; alluvial fan gravel.

Unit 2g - Light brown (7.5YR7/4) gravel; clasts: 12 cm max., 4 cm avg., angular, moderately sorted, horizontal imbrication; fine to medium sand matrix; clast supported; alluvial fan gravel.

Unit 2h - Pale brown (7.5YR6/2) gravel; clasts: 14 cm max., 3-5 cm avg., angular, moderately sorted, horizontal imbrication; granule matrix; clast supported; alluvial fan gravel.

Unit 2i - Pale brown (7.5YR6/2) gravel; clasts: 13 cm max., 4 cm avg., angular, moderately sorted, horizontal imbrication; medium to fine sand matrix; vague 15-20 cm thick beds; clast supported; alluvial fan gravel.

Unit 2j - Pale brown (7.5YR6/2) gravel; clasts: 12 cm max., 4 cm avg., angular, moderately sorted, horizontal imbrication; medium to fine sand matrix; open-work layers; stratified; alluvial fan gravel.
Unity 2k - Pale brown (7.5YR6/2) gravel; clasts: 8 cm max., 1-2 cm avg., angular, well sorted; no matrix; loose and soft; horizontal beds 10 cm thick; alluvial fan gravel.

Unit 2l - Pale yellowish-brown (10YR6/3) gravel; clasts: 12 cm max., 2-3 cm avg., angular, moderate to well sorted; coarse sand to granule matrix; horizontal beds 10 cm thick; some open-work layers; alluvial fan gravel.

Unit 2m - Light brown (7.5YR7/4) gravel; clasts: 15 cm max., 2 cm avg., angular, poorly sorted; silty-sand matrix; hard; massive; random fabric; weak A horizon; clay cementation; debris-flow.

Unit 3a - Moderate brown (10YR3/3) gravel; clasts: 11 cm max., 3 cm avg., angular, poorly sorted; silty-sand matrix; soft, weak fabric 15-20 degrees to the west; weakly organic in matrix; wash facies colluvium.

Unit 3b - Moderate brown (10YR3/3) gravelly-sand; clasts: 4 cm max., 1 cm avg.; silty-sand matrix; soft; matrix supported; weakly organic in matrix; wash-facies colluvium. The lower contact of this unit was dated at 1810 +/- 60 yr BP (B-48129).

Unit 3c - Light brown (7.5YR5/2) sandy-gravel; clasts: 35 cm max., 2-3 cm avg., angular to subangular, moderately sorted, weak imbrication to the west; fine sand to granule matrix; weak horizontal beds; weak A horizon; alluvial fan gravel.

Unit 3d - Yellowish-brown (10YR6/4) silty-gravel; clasts: 7 cm max., 4 cm avg., angular to subangular, poorly sorted; silty-sand matrix; soft; matrix supported; weakly organic in matrix; debris-flow.

Unit 4a - Pale brown (7.5YR6/2) gravel; clasts: 12 cm max., 3 cm avg., angular, poorly sorted; weakly stratified with orientations of 65-70 degrees to the west; left contact looks sheared; crack fill associated with the first event.

Unit 4b - Yellowish-brown (7.5YR6/2) gravel; clasts: 10 cm max., 3 cm avg., angular, poorly sorted, clasts on the east margin imbricated 60 degrees to the west; variable hardness; voids on both east and west margins; soft organic pockets throughout; crack fill associated with the second event.

Unit 4c - Dark yellowish-brown (10YR4/4) gravel; clasts: 10 cm max., 3 cm avg., angular, poorly sorted, imbrication 25-30 degrees to the west; silty-sand matrix; variable hardness; pockets of weak organics; scarp-derived colluvium associated with the first event.

Unit 4d - Pale brown (7.5YR6/2) gravel; suspected chunk of unit 2l shed off the scarp, associated with the first event.
Unit 5 - Dark yellowish-brown (10YR4/2) gravel; clasts: 4 cm max., 2 cm avg., subangular to subrounded, poorly sorted; organic rich silty-sand matrix; very soft; bedding 12-15 degrees to the east; weak imbrication parallels bedding; nearly matrix supported; does not resemble any of the unit 2's; alluvial fan gravel. This unit was dated at the lower contact at 1910 +/- 60 yr BP (B-48130), and the upper contact was dated at 840 +/- 50 yr BP (B-48128).

Unit 6 - Dark yellowish-brown (10YR4/2) gravel; clasts: 4 cm max., 2 cm avg., subangular to subrounded, poorly sorted; silty-sand matrix; very soft; weakly organic throughout; nearly matrix supported; wash-facies colluvium.

Unit 7a - Yellowish-brown (10YR6/3) gravel; suspected chunk of unit 2i, shed off the scarp, associated with the first event.

Unit 7b - Moderate yellowish-brown (10YR5/3) gravel; clasts: 10 cm max., 4 cm avg., angular, poorly sorted, imbricated 25-35 degrees to the west; silty-sand matrix; soft; richly organic throughout; matrix supported; scarp-derived colluvium associated with the second event. This unit was dated at 2910 +/- 70 yr BP (B-48131).

Unit 7c - Pale brown (7.5YR6/2) gravel; clasts: 10 cm max., 3 cm avg., angular, poorly sorted, imbricated 25-30 degrees to the west; silty-sand matrix; variable hardness; pockets of weak organics; scarp-derived colluvium associated with the first event.

Unit 8 - Dark yellowish-brown (10YR4/4) gravel; clasts: 5 cm max., 2 cm avg., angular, poorly sorted, horizontal imbrication; sandy-silt matrix; very soft; very weak bedding; basal 2 cm, laminated fine sand, sag pond deposit; alluvial fan gravel.

Unit A1 - Dark yellowish-brown (10YR3/1) soil; very dark A horizon; 1 cm thick reddish brown peat layer at the top, color may be due to disseminated coal or a fire; A horizon.
Plate 1.
Fault Trace Map of the Greys River Fault, Scale 1:48,000.
Plate 2.

Quaternary Geologic Map of the Deadman Creek and the Blind Bull Creek Drainages, Scale 1:15,840.
Plate 3.
Quaternary Geologic Map of the Sheep Creek Drainage, Scale 1:15,840.
Plate 4.

4a. Quaternary Geologic Map of the Martin Creek Drainage, Scale 1:15,840.

4b. Quaternary Geologic Map of the Box Canyon Creek Drainage, Scale 1:15,840.
Plate 5.
Detailed Trench Log of the South Trench at Sheep Creek.

LOG OF THE SOUTHERN TRENCH AT SHEEP CREEK,
LINCOLN COUNTY, WYOMING.
Logged in July of 1991,

Explanation

<table>
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</tr>
<tr>
<td>Samples</td>
<td>Gravel with sand matrix, 15-20 degree fabric</td>
</tr>
</tbody>
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Stratigraphic Units

1. Fluvial Gravels
   a. Fluvial Gravel from Sheep Creek
   b. Fluvial gravel very coarse sand matrix
   c. Fluvial gravel coarse sand matrix
   d. Fluvial gravel medium sand matrix
   e. Fluvial gravel fine sandy matrix
   f. Fluvial gravel
   g. Fluvial gravel clay in coating in the matrix
   h. Fluvial gravel clay coating on a pebble matrix
   i. Fluvial gravel clay coating
   j. Fluvial gravel
   k. Fluvial gravel sand to clay matrix
   l. Fluvial gravel sand to clay matrix

2. Loess Cap
   a. Fluvial Gravel
   b. Fluvial Gravel

3. Scarp-Derived Colluvium
   a. Gravel with sand matrix, 15-20 degree fabric
   b. Gravel with sand matrix
Plate 6.
Detailed Trench Log of the Middle Trench at Sheep Creek.

LOG OF THE MIDDLE TRENCH AT SHEEP CREEK,
LINCOLN COUNTY, WYOMING.
Logged in July of 1991,
by L.C. Allen Jones, Kelly Davis, Witold Zuchiewicz, James McGeehan.
Plate 7.

Detailed Trench Log of the North Trench at Sheep Creek.