Quaternary Geology and Neotectonics of Southern Star Valley and the Southwest Flank of the Salt River Range, Western Wyoming

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QUATERNARY GEOLOGY AND NEOTECTONICS OF SOUTHERN
STAR VALLEY AND THE SOUTHWEST FLANK
OF THE SALT RIVER RANGE,
WESTERN WYOMING

by

Gregory A. Warren

A thesis submitted in partial fulfillment of
the requirements for the degree
of
MASTER OF SCIENCE
in
Geology

Approved:

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1992
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Greg Warren
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ABSTRACT

Quaternary geology and neotectonics of southern Star Valley
and the southwest flank of the Salt River Range,
western Wyoming

by

Gregory A. Warren, Master of Science
Utah State University, 1992

Major Professor: Dr. James P. McCalpin
Department: Geology

Southern Star Valley is a structural and physiographic basin bounded on the
east by the southern Star Valley fault, an active normal fault associated with Basin and
Range extension. The southern Star Valley fault separates southern Star Valley from
the Salt River Range and forms a dramatic north-south trending topographic
escarpment. Statistical analysis of relative-age dating (RD) parameters taken from
glacial deposits in the Salt River Range defined distinctive age groups for the deposits,
and comparison of RD data allowed correlations with late Pleistocene and Holocene
glacial deposits elsewhere in the Rocky Mountains. However, the sedimentary
lithologies in the glacial deposits in the study area and inherent variability of RD data
limited definitive regional correlations.

The southern Star Valley fault (SSVF) lies in a parabola-shaped zone of large,
seismogenic normal faults. The zone trails to the west of the eastward-migrating
Yellowstone hot spot. Basin-facing fault scarps up to 11 meters high created by
recurrent late Quaternary faulting along the southern Star Valley fault are preserved in
late-Pleistocene and Holocene alluvial fans along the Salt River Range front.
Radiocarbon ages from faulted deposits exposed in a trench provide age estimates of ca. 8,090 ± 80 and 5,540 ± 70 yrs. B. P. for the two most recent paleoeartuquakes. The magnitudes of the paleoearthquakes, based on surface rupture height and length and estimates, were between M₆.9 and M₇.1. The tectonic geomorphology of river alluvium and alluvial fans near the SSVF suggests that recurrent faulting has down-dropped the northern end of southern Star Valley more in relationship to the southern part of the valley and created a deep depocenter in the northern part.
INTRODUCTION

Due to the two-part nature of this study, this thesis is divided into two discrete parts. The first part (Chapter 1) will address the chronology and age estimates of late Quaternary glacial and alluvial deposits in the study area. The second part (Chapter 2) will address the sequence and magnitude of faulting on the southern Star Valley fault. Chapter 1 introduces the and ages and types of surficial deposits in the study area, which have been affected by recurrent faulting by the southern Star Valley fault. Determining the ages of the surficial deposits in southern Star Valley allowed assessment of the recurrence intervals and late Quaternary activity of the southern Star Valley fault. The recurrence of faulting and effects of faulting on the surficial deposits are discussed in Chapter 2.
CHAPTER 1
ABSTRACT

Glacial deposits, of sedimentary provenance in the southwest Salt River Range of western Wyoming, were mapped and subdivided using relative-age dating (RD) methods. Large moraines located up to 4 km from cirque headwalls and nested cirque moraines were identified and, based on RD values and topographic position, tentatively correlated with late Pinedale and Neoglacial ice advances, respectively, as defined in the standard Rocky Mountain glacial chronology. No deposits older than late Pinedale were positively identified, possibly because late Pinedale glaciers were more extensive and thus overrode and reworked older deposits. Broad, coalescing, slightly dissected alluvial fans at the Salt River Range front could not be directly correlated upvalley to glacial deposits, but are inferred to be a late Pleistocene age based on their soil development.

Cluster analysis of RD data produced a dendrogram which subdivided the glacial deposits into distinctive age groups. Moraines inferred to be late Pinedale in age clustered in a different group than did moraines of inferred Neoglacial age, which suggests that cluster analysis can distinguish Holocene and late Pleistocene-age deposits. The cluster analysis also appeared to distinguish early- from late- Neoglacial deposits whose age differences coincide with morphologic relationships mapped in the field. However, excessive subdivision of the cluster groupings may yield groups that are non-age dependent. Despite success in local age subdivision, the cluster analysis was less useful in regional correlations due to differences between RD values from the sedimentary rocks of the Salt River Range and values from other RD-generated chronologies that used crystalline rocks in the Rocky Mountains.
INTRODUCTION

Objectives

The objectives of this study are to: (1) differentiate and map at 1:24,000 scale the surficial deposits of the west flank of the Salt River Range and southern Star Valley; and (2) date the surficial deposits and establish a late Quaternary chronology. The ages of the faulted alluvial deposits are needed to establish the timing and magnitude of latest Quaternary faulting along the southern segment of the Star Valley fault.

Location and Physiography

Southern Star Valley is a structural and physiographic basin 22 km long and 2 to 8 km wide covered with late Quaternary alluvial deposits. It lies about 100 km south of Jackson, Wyoming (Figure 1.1). The Salt River flows northward through the valley, and exits through a bedrock constriction known as "The Narrows" into northern Star Valley. The southern Star Valley fault, a west-dipping Neogene normal fault along the eastern margin of southern Star Valley, forms a dramatic north-trending topographic escarpment that separates the valley from the Salt River Range. Elevations range from 1830 m at the north end of the valley to 3282 m in the Salt River Range.

Geologic Setting

Pre-Quaternary Stratigraphy of Study Area

The geologic setting of the study area is dominated by Cenozoic normal faults superimposed on late Mesozoic Sevier thrust faults and folded sedimentary rocks of the Idaho-Wyoming thrust belt. The stratigraphic record within the mapped study area consists of up to 15,000 meters of marine limestones and dolostones deposited during
Figure 1.1. Location of study area.
the Paleozoic Era in large geosynclinal basins in what is now western Wyoming, eastern Idaho, western Utah, and much of Nevada (Armstrong and Oriel, 1965). During Mesozoic time, 4,500 to 9,000 meters of increasingly elastic sediments were deposited in regional basins (Armstrong and Oriel, 1965). Pre-Tertiary sedimentary rocks exposed in the study area include the Permo-Pennsylvanian Wells; Permian Phosphoria; Triassic Dinwoody, Woodside, Thaynes, Ankareh and Nugget; and Jurassic Twin Creek formations (Figure 1.2). Glacial deposits in the study area consist primarily of clasts derived from thin-bedded limestones of the Thaynes Formation, red siltstones of the Ankareh Formation, and quartzarenite of the Nugget Formation.

**Quaternary Stratigraphic Nomenclature**

Blackwelder (1915) established the original Rocky Mountain glacial chronology of three glacial advances, from oldest to youngest the Buffalo, Bull Lake and Pinedale glaciations. In previous investigations in the Rocky Mountain region, local RD-generated relative glacial chronologies have been correlated with the regional Bull Lake - Pinedale chronology. However, assignment of these correlative ages in the absence of numerical ages is subjective (Pierce, 1979). For example, if the outermost moraines in a valley are Pinedale but are erroneously assigned a Bull Lake age, the entire local sequence may be dated incorrectly based on the relative chronology. Furthermore, in many valleys Pinedale glaciers completely overrode and removed or covered Bull Lake deposits, so that only end moraines of Pinedale age remain (Madole, 1976; Miller, 1979; Pierce, 1979; Huber and Grogger, 1985; Pierce and Morgan, 1990). Birkeland et al. (1979, p. 533) stated: "...only those glacial deposits that are numerically dated or that are defined and characterized by adequate RD data are worthy of stratigraphic names and type localities."

In this report, the poorly preserved sequence of glacial deposits, lack of numerical ages, and high variability of the RD parameters make a local stratigraphic
Figure 1.2. Regional stratigraphic section. Glacial deposits are composed of the Thaynes, Ankareh, Nugget, and Twin Creek formations (adapted from Coogan and Royse, 1990).
name unjustified. Therefore, the Salt River Range sequence will be correlated with the latest Quaternary regional glacial chronology (Figure 1.3), and deposits will be referred to as pre-Pinedale, Pinedale, early Holocene, and Neoglacial for that purpose. Deposits of probable latest Pleistocene age were tentatively correlated with deposits previously labeled "early Holocene" age, which recently have been redated as latest Pleistocene, i.e., type Temple Lake (Davis and Osborn, 1987). Due to the age uncertainty and closeness of inferred age to the Pleistocene/Holocene boundary, these deposits are herein referred to as "early Holocene" deposits, mainly to distinguish them from deposits of late Pinedale age.

Methods

Field Mapping

The surficial geologic deposits were initially mapped onto 1:15,840 color aerial photographs covering the range front and mountains, and 1:20,000 black and white aerial photographs covering southern Star Valley. Extensive field checking followed to differentiate surficial deposits that could not be accurately mapped from the aerial photographs. Heights above the streams of glacial-outwash terraces downstream from the glacial deposits to the outwash fans at the range front, and depths of channel incisions in the broad alluvial-fan surfaces at the range front were measured in an attempt to establish correlation. Mapping was transferred from the aerial photographs onto a 1:24,000 Mylar topographic base map.

Relative-Age Dating (RD) Measurements and Definitions

RD data were collected to subdivide glacial deposits by age and provide a means of statistical comparison of weathering of the deposits. The RD technique involves measuring morphologic and weathering characteristics of a given sequence of deposits in order to assign relative ages to them. Ten RD parameters were collected and then
Figure 1.3. Late Quaternary Rocky Mountain chronology of glacial deposits showing possible correlations of Salt River Range deposits.
analyzed using a multivariate-statistical clustering program. Because all of the surficial deposits in the study area are composed of sedimentary rocks, chiefly gray limestones, tan sandstones and red siltstones, problems were encountered during collection and analysis of RD data. In most previous studies using the RD technique (e.g. Benedict, 1973; Currey, 1974; Burke and Birkeland, 1979; Hall and Heiny, 1983), the deposits sampled were composed of crystalline rock clasts. Crystalline rocks are advantageous for RD techniques because they are often homogenous and weather more or less uniformly. Sedimentary rocks, however, weather much differently even within a single formation. Glacial deposits within a given valley may be equivalent in position and age, yet exhibit different weathering characteristics due to different clast composition.

RD sampling stations were chosen on moraine crests undisturbed by roads, logging, or erosion. RD data also were collected in glaciated valleys on hummocky, valley-bottom debris-avalanche (?) deposits that strongly resemble ground moraine. Up to ten RD parameters were obtained (where collectable) from 25 sampling sites:

1. MPD: Maximum Pit Depth - solution pits in limestone were measured by inserting a pencil into the pit and measuring pit depth in millimeters.
2. RIH: Resistate Inclusion Height - resistant inclusions in limestones, most often chert nodules, stand out in relief on weathered rocks. The heights of these outstanding cherts were measured relative to the limestone to the nearest millimeter with a plastic ruler.
3. SBF: Surface Boulder Frequency - the number of boulders over 30 cm in length visible on the surface in a 20 meter by 6 meter area along the crest of the deposit were counted.
4. BBF: Boulder Burial Factor - twenty-five boulders were visually examined to determine the percent depth to which their surface had been buried by loess and organic
duff since deposition. The BBF is computed by multiplying the estimated percent of boulders at least partially buried by the averaged percent burial of each boulder.

5. SPD: Soil Profile Development - at each station a soil pit 60-100 cm deep was dug to determine the degree of soil development in the deposit. The SPD is a number ranging from 0 to 20, assigned according to the degree of soil development in a given deposit:

   0 - No soil.
   5 - Windblown loess cap, weak O or A horizon in deposit.
   10 - Moderate A horizon formation, evidence of slight horizonation, Cox horizon present.
   15 - Developed horizons, moderate weathering of subsurface clasts, no Bt horizon.
   20 - Thick A horizon, weathering rinds on subsurface clasts, Bt or Bk horizon

6 and 7. MIA/MOA: Maximum Inner and Outer slope Angles - the steepest slope angles of lateral moraines were measured to the nearest degree with a rod and a Brunton compass used as a clinometer.

8. RCW: Ridge Crest Width - the average width of the crest of the ridge of a moraine was measured with a rod and Brunton compass to the nearest 0.5 meter. The crest was considered the part of the top of the moraine which slopes less than 5 degrees.

9. ART: Average Rind Thickness - twenty-five rocks on the crest of the deposit were broken, and weathering rinds were measured to the nearest 0.5 millimeter with a plastic ruler.

10. MLD: Maximum Lichen Diameter - the thallus diameter of circular *Rhizocarbon geographicum* lichens on sandstone boulders in cirque moraines was measured to the nearest millimeter with a plastic ruler.

All RD data collection is subject to an investigator's personal techniques of data collection. Therefore correlating RD-generated glacial sequences with results of other workers is risky due to operator bias and natural variabilities in RD values. Birkeland
et al. (1979, p. 534) stated: "... no subdivision of deposits should be more detailed than the resolution of the RD methods upon which it is based." In other words, the RD technique may be useful for subdividing glacial deposits with large age differences, but not deposits of similar ages from minor glacial fluctuations. Division of deposits is also subject to the investigator's judgment.

**Statistical Analysis of RD Parameters**

The methods of statistical analysis employed to analyze the RD data were a Q-mode cluster analysis to analyze the objects in the data set (RD stations) and an R-mode Principal Component Analysis (PCA) to analyze the variables (RD parameters). Miller (1979) and Dowdeswell and Morris (1982) used cluster analyses to divide local glacial deposits in the Rocky Mountains and correlate them with regional chronologies. Unfortunately, direct comparison of cluster analyses in this report with those of previous workers is complicated by differences in lithologies and general variability of RD values among the Salt River Range and other areas in the Rocky Mountains. However, cluster analysis proved useful in determining relative age groups for the local deposits.

Cluster analysis produces a dendrogram that groups objects with like similarities; in this case similar RD parameters collected from sampled deposits. The Euclidean distance, a quantitative dissimilarity coefficient, was used to calculate the spatial separation of pairs and groups of objects in the data set. According to the Euclidean method, the distance between points i and j is:

$$d_{ij} = \left[ \sum_{n=1}^{k} (X_{ik} - X_{jk})^2 \right]^{1/2}$$

where $d_{ij}$ is the Euclidean distance, $X_{ik}$ is the kth variable for the ith object and $X_{jk}$ is the kth variable for the jth object (Everitt, 1974). In other words, the larger the Euclidean distance, the more dissimilar the ith and jth objects are. The Euclidean
distance was used because it is not substantially affected by large differences which can exist between the individual data points.

For the cluster analysis, six of the ten RD parameters were used: SBF, BBF, SPD, MOA, MIA, and RCW (Table 1.1). The RIH and MPD data were not used due to a large number of missing RD values because of lithologic constraints (i.e., sandstone did not pit or contain inclusions). The ART was also not used because of many missing RD values (rind thicknesses were measured only in sandstone); however, the ART was used in regional correlations. The MLD was not used because lichens are only useful for RD dating above timberline (Meierding, 1984), so the lichen measurements (when obtainable) were confined to the cirque moraines only.

The data were standardized using the formula \[ A = \frac{a}{\text{max}} \], where \( A \) is the standardized value, \( a \) is the original RD value, and max is the maximum value of a particular RD parameter. Standardization reduced extreme RD values and made the parameters of the different measurements more comparable. For example, the surface boulder frequency represents a count of objects which ranged from 12 to 245, whereas the slope measurements were angular measurements ranging from 5° to 36°. The standardization procedure enabled the computer to compare the RD values with variable ranges, while ignoring differences in measurement units.

An R-mode Principal Component Analysis (PCA) performed on the data set determined which variables (RD parameters) in the data set were highly correlated and useful for differentiation of objects. A PCA generates linear composites of the original variables (principal components) which account (in decreasing order) for variation in the data set. Variables in the data set that correlate with a high principal component, which accounts for most of the variability of the data set, are more useful to differentiate objects in the data set. Thus, correlation of variables to the various principal components assists in identification of RD variables that would be most useful
Table 1.1

RD values obtained from deposits in study area

<table>
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<th>RD station</th>
<th>Deposit</th>
<th>Elev. (m)</th>
<th>Lith.</th>
<th>SBF³ (#)</th>
<th>BBF³ (%)</th>
<th>SPD³ (#)</th>
<th>MOA³ (deg)</th>
<th>MIA³ (deg)</th>
<th>RCW³ (m)</th>
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</table>

1 The first two letters indicate inferred age of deposit (NT = Neoglacial, EH = early Holocene/latest Pleistocene, PT = late Pinedale, QD = late Pleistocene (?) non-glacial deposits). Numbers refer to station numbers on Figs. 1.5 and 1.6.

2 ss = quartzarenite sandstone
ls = thin-bedded, sandy, limestone

3 See text for abbreviations and definitions of RD parameters.
in age differentiation of the deposits. The program used for cluster analysis and PCA was MVSP 87 by Warren L. Kovach.

Previous Investigations

Rubey (1973) mapped the bedrock geology of the Salt River and Wyoming ranges from 1931-1939 in search of phosphate deposits. The floor of southern Star Valley was mapped as undifferentiated Qal. Although Rubey erroneously mapped many landslides and thick colluvial deposits as moraines in the Salt River Range, his accurate bedrock mapping proved invaluable for determining the provenance of Quaternary deposits. Piety et al. (1986) described soils and assigned ages to the faulted alluvial-fan surfaces in southern Star Valley. Rice (1987) used RD techniques and cluster analysis to date relatively and to assign age classifications to landslides in the Salt River Range. Rice (1987) included RD data on moraines to which he assigned a late Pinedale age.

GLACIAL DEPOSITS

The southwest flank of the Salt River Range contains evidence for one major late Pleistocene glaciation, a possible early Holocene/latest Pleistocene advance, and several late Holocene glacial advances. Glaciers originated in cirques at elevations 2800 m to 3000 m and flowed as much as 4 km downvalley in three drainages to elevations near 2200 m (Figure 1.4). Glacial deposits in Cottonwood and Dry Creeks consist of four large, well-preserved lateral moraines 2-4 km downvalley from cirque headwalls, ridge-like morainal deposits slightly upvalley from the lateral moraines, and nested moraines in several cirques. A third glaciated drainage, Swift Creek, exhibits weak glacial erosional features (U-shaped valley, talus aprons along oversteepened walls), but does not contain well-preserved glacial deposits. Small glaciers occupied
Figure 1.4. Generalized surficial map of southern Star Valley which shows limits of late Pinedale glaciation of west flank of Salt River Range. See Figures 1.5 and 1.6 for detailed glacial geology.
tributaries of Cottonwood Creek and the right fork of Dry Creek, but were not sampled for RD data. No glaciers reached the range front, so all glacial deposits are confined to stream valleys in the mountains more than 5 km east of southern Star Valley.

The drainages in the Salt River Range follow bands of folded sedimentary rocks that comprise the range. The headwaters of most drainages occupy north- or south-trending strike valleys. Thus, cirques in Cottonwood and Dry creeks face either north or south. North-facing cirques are well developed, and south-facing cirques are poorly developed. North-facing cirques accumulated much more ice during glacial periods, and during the Neoglacial only the north-facing cirques generated active ice bodies.

In addition to structurally controlled cirque orientation, the folded sedimentary rocks of the range create lithologic differences in the glacial deposits that affect data collection and analysis. Moraines in Cottonwood Creek contain limestone boulders because the cirque headwall is composed of limestone of the Thaynes Formation, whereas moraines in Dry Creek contain boulders of quartzarenite sandstone and red siltstone derived from the Nugget and Ankareh formations.

Pre-Pinedale Deposits

In the valley walls along the North Fork of Cottonwood Creek (Bt? on Figure 1.5) a large-bouldered, carbonate-cemented, limestone conglomerate is exposed. A stream-cut ridge of the conglomerate is overlain by uncemented Pinedale till, which indicates the conglomerate is older. Richmond (1965) noted that occasionally Bull Lake till becomes so enriched in carbonate that the boulders become cemented. Such an origin could explain the conglomerate in the valley of Cottonwood Creek. Because the conglomerate was cemented, the sides were stream-cut, and no boulders were present on the surface, no RD data were collected. However, if the conglomerate represents till, its cementation, dissection, and position slightly past the limits of Pinedale glaciation suggests deposition during an older (Bull Lake?) major glaciation.
GLACIAL GEOLOGY, COTTONWOOD CREEK

Hal - Holocene alluvium
Hat - Holocene alluvial fan
Nt - Neoglacial till, undifferentiated
Na - active talus
Nt - talus cone
Npr - Protalus rampart
Pt - Pinedale till
Bt - older (possible Bull Lake?) till
Od - debris avalanche (various ages)
Lc - lacustrine silt and clay
s - slide, undifferentiated
PMB - bedrock

> - glacial limit
- - contact
- - - - moraine crest
PT4 - sampling station

Figure 1.5. Glacial geology of Cottonwood Creek.
Figure 1.6. Glacial geology of Dry Creek.
Late Pinedale Deposits

RD data were collected from four large, single-crested lateral moraines that lie 2-4 km downvalley from cirque headwalls in Cottonwood and Dry creeks. The lateral moraines in Dry Creek are 2 km long, and the terminal moraine has been eroded by Dry Creek (Figure 1.6). The Pinedale ice thickness in Dry Creek (Figure 1.7) was reconstructed using a graph of valley gradient versus ice thickness (Porter et al., 1983).

![Graph of valley gradient versus ice thickness](image)

Figure 1.7: Reconstruction of late Pinedale ice thickness in Dry Creek, calculated from valley gradient vs. ice thickness (Porter et al., 1983). Assume 1 bar basal shear stress. PT2, PT5, PT6, and PT8 are topographic positions and heights of RD stations on moraines.

The lateral moraines in Cottonwood Creek are about 1 km long and the distal ends are difficult to distinguish from the valley-bottom deposits of debris avalanches (Figure 1.5). Small, linear to arcuate ridges on the inner flanks of the moraines suggest the glaciers made minor fluctuations during their overall retreat. The moraines are slightly bouldery, forested, have crest heights of about 30 meters above the modern stream, and exhibit soils containing a thin Bt or Bk horizon. A Bt horizon is rare for Pinedale deposits (Shroba and Birkeland, 1983), but most descriptions of Pinedale soils come from moraines containing crystalline rock clasts. Because the deposits in
the Salt River Range contain shaly and calcium-carbonate lithologies, they had an initially higher content of clay and carbonate that could facilitate Bt and Bk horizon development. The morphologic and weathering characteristics of the moraines are similar to those of late Pinedale moraines described by Madole (1976). The lack of large moraines preserved upvalley suggests the Dry Creek and Cottonwood Creek moraines were deposited during the last major glacial advance.

Early Holocene/latest Pleistocene Deposits

Ridge-like deposits in the main fork and right-hand fork of Dry Creek that appear to be moraines lie 0.5-1.0 km upvalley from the late Pinedale moraines, but are well outside the limits of cirque moraines (Figure 1.6). There are no equivalent deposits elsewhere in the study area. The deposits contain boulders of Thaynes Limestone derived from the valley wall east of the cirques, which is a large, west-facing dipslope. There are two likely origins of the moraine-like deposits: (1) they may represent a latest Pleistocene / early Holocene glacial advance (equivalent to the type Temple Lake or Santanta Peak) or (2) they may have been dipslope-slides which fell onto a glacier and were deposited as the glacier melted. RD characteristics of the deposits include low boulder frequency, moderate to steep slope angles, and moderate soil development including a weak B horizon (Table 1.1). The relative position of the ridge-like deposits suggests an age younger than late Pinedale but older than the cirque moraines. Therefore, they are tentatively labeled an Early Holocene age to distinguish them from late Pinedale deposits.

Neoglacial Deposits

Cirque moraines present in north-facing cirques of Dry Creek, Cottonwood Creek, and cirques in tributaries of Cottonwood Creek are assigned a Neoglacial age based on topographic position and RD values. Neoglacial deposits in the Dry Creek cirque are bouldery, slightly to moderately vegetated, arcuate, single-crested moraines
containing quartzarenite boulders. In cirques of Cottonwood Creek, Neoglacial deposits are hummocky, bouldery, slightly vegetated, and contain boulders of thin-bedded limestone. The Cottonwood Creek cirque deposits are hummocky because many of the limestone boulders split into very thin sheets, probably during deposition. RD values for the Neoglacial deposits include steep slope angles, high boulder frequencies, low boulder-burial values, and weak soil development without B horizons (Table 1.1). The ridge crests of the limestone-dominated cirque moraines are wider than the those of sandstone-dominated moraines, probably due to the spalling of the limestone clasts.

NON-GLACIAL ALPINE DEPOSITS

Non-glacial alpine deposits in the study area include talus and rockfall deposits, landslides, and valley-bottom debris avalanches. Talus and rockfall deposits exist mainly in cirques and along valley walls that were oversteepened by glacial erosion. Talus was subdivided into two types, active and inactive, based on morphology and vegetation. Inactive talus is stabilized, vegetated, and present dominantly in south-facing cirques that were not glaciated during the Holocene. Active talus is blocky and unvegetated, and present mainly in north-facing cirques that contain Holocene glacial deposits. In some areas talus cones have formed by a combination of gravity fall from oversteepened slopes and alluvial action, evidenced by the presence of debris-flow levees and channels.

Several landslides are present in the study area, most of which were mapped by Rice (1987). In the present study, only major slides in or near glacial deposits were mapped. The most common types of slides are slumps and dipslope block-slides, some of which mobilized into debris avalanches. The valley-bottom deposits of debris avalanches strongly resemble ground moraine (Figure 1.8), and in places are intermixed with glacial till. These deposits, mostly in Cottonwood Creek, are
hummocky, bouldery, well vegetated, and consist mainly of Thaynes Limestone (Table 1.1 - QD stations). The source areas of the debris avalanches are obscure, but seem to be where failures on steeply-dipping bedding mobilized into debris avalanches. These deposits exist up to 2 km beyond the outer limits of Pinedale glaciation. Less-weathered, more bouldery areas within the debris-avalanche deposits indicate several generations of mass movements. Relative-age assignments based on RD values suggest the debris-avalanche deposits (see Results of Cluster Analysis) are mostly late Pleistocene in age.

Figure 1.8. Valley-bottom debris avalanche in Cottonwood Creek that resembles ground moraine (site of RD station QD5 on Figure 2.4, see Table 1.2 for RD values). This deposit clustered in a group with Neoglacial till, which suggests it is late Holocene in age.
ALLUVIAL DEPOSITS

Upper Quaternary alluvial deposits cover the surface of southern Star Valley (Figure 1.4). Holocene alluvium from the northward-flowing Salt River dominates the western half of the valley, and large, coalescing late Pleistocene (Pinedale) alluvial fans deposited from glaciated drainages of the Salt River Range dominate the eastern portion.

Pre-Pinedale Alluvium

The only alluvium in the study area that appears to be pre-Pinedale in age constitutes eroded remnants of fan surfaces present only on the Cottonwood Creek fan (pPf on Figure 1.4). These surfaces are topographically higher (up to 6 meters) than Pinedale fan surfaces and have loess caps at least two meters thick. This evidence suggests these remnants are considerably older than the surrounding Pinedale fan surfaces. The older fan remnants are assigned a pre-Pinedale age, and may have been deposited in response to an older glaciation (Pierce and Scott, 1982).

Pinedale Alluvium

Broad, coalescing alluvial fans inferred to be Late Pinedale in age are present at the mouths of Cottonwood, Dry, and Swift creeks (Figure 1.4). A smaller fan deposited by intermittent Phillips Creek and its adjacent drainages is present north of the Swift Creek fan. The alluvial fans are characterized by large, aggradational surfaces (Pf1 on Figure 1.4) dissected by younger channels of variable widths and depths, and one modern (active) stream channel. Younger distributary channels (Pf2 on Figure 1.4) are eroded into the Pf1 surface, probably during the late-glacial period when snowmelts were high and sediment yield was low (Schumm, 1965). On the Phillips Creek and Dry Creek fans, younger fan surfaces are given a Pf2 age assignment based
on the presence of fault scarps 5 meters high, which contrast the fault scarps 11 meters high on the Pf1 surfaces.

The Phillips Creek alluvial fan is 9.1 km$^2$ in area and has two ages of alluvium present, Pf1 and Pf2, based on their faulted relationships. A fault scarp 9 meters high offsets the Pf1 surface, and a fault scarp 5.3 meters high offsets the Pf2 surface (Piety et al., 1986). The Swift Creek alluvial fan is 15.5 km$^2$ in area and extends about 4.5 km from the range front. A fault scarp 11 meters high offsets the Pf1 surface. Discontinuous surfaces about 1.5 meters below the Pf1 surface have been eroded by post-Pinedale stream activity, and tentatively have been assigned a Pf2 age. The modern Swift Creek channel is inset as much as 4 meters into Pf1 and extends northwest from the range front. Other young channels diverge near the fault zone and trend northwest. Some of these have eroded laterally and cut scarps into smaller range-front fans. The Dry Creek alluvial fan is about 10.5 km$^2$ in area, and extends 4.5 km from the range front. The fan is asymmetric, with about 70% of its area north of where Dry Creek exits the range front. The Pf1 surface on the Dry Creek fan is offset 11.3 meters by faulting, whereas the Pf2 surface is only offset 5 meters by faulting. The Cottonwood Creek fan is highly asymmetric, 20 km$^2$ in area, and extends northwest up to 6.5 km from the mountain front. In contrast to the other three fans, it has not been offset by late Quaternary faulting. The Cottonwood Creek fan consists of a large Pf1 surface, inset channels assigned to Pf2, and eroded pPf remnants. The modern channel, inset 4 meters into the Pf1 surface, exits the range front and trends about N40°W. The asymmetry of the alluvial fans is the result of greater fault offset in the northern part of southern Star Valley, where alluvial deposition from the mountain front was directed northwesterly into the deepest part of the basin. See Chapter 2 for more discussion on tectonic geomorphology.
Post-Pinedale Alluvium

At smaller, intermittent stream valleys at the range front between Phillips and Dry creeks, remnants of alluvial surfaces in the canyon mouths have been tectonically uplifted by faulting along the range front. The fault scarps are up to 11 meters high, which implies that these deposits have been offset the same amount by recurrent faulting, and are therefore similar in age to the Pfl surfaces. Smaller, undissected, unfaulted post-Pinedale alluvial fans have been deposited from these canyons subsequent to uplift of the Pfl remnants, and are graded to the downthrown Pfl fan surfaces of Dry, Swift, and Phillips creeks. Elsewhere along the range front, small, steep alluvial fans and cones, and occasional landslides of post-Pinedale age have been deposited out of steep range-front drainages onto Pfl and the younger alluvial fans just described.

Salt River Alluvium

The Salt River enters southern Star Valley from the south and maintains a rather straight course north to the latitude of Afton, where the channel changes to a very sinuous, meandering pattern (Figure 1.4). Near this same point several small tributary creeks rise from springs in the valley floor, flow northward in meandering channels, and merge with the Salt River. Alluvium from the Salt River grades from dominantly gravelly in the southern half of the valley to sandy and silty in the northern half of the valley. Several small terrace risers and abandoned stream channels are present south of Afton, and north of Afton a very low-gradient, marshy floodplain with several active river channels dominates the valley. The headwaters of the Salt River are south of the study area, so that part of its drainage basin and alluvial deposits were not studied in detail.

The inferred age of the alluvium of the Salt River is based on its contacts with the Pinedale alluvial fans along the range front. In the southern end of the valley, the
Salt River has cut a scarp up to 6 meters high into the distal portion of the Cottonwood Creek and southwest part of Dry Creek Pinedale fans, and in the northern end of the valley the Salt River has cut a sinuous scarp into the distal portion of the Phillips Creek Pinedale fan. Consequently, the alluvium deposited by the Salt River, in erosional contact with the distal fans, is probably late Pinedale or post-Pinedale in age.

Age Criteria for Pinedale Alluvium

Numerical ages could not obtained to date the alluvial fans directly, nor could the outwash fans be physically correlated to the moraines. Therefore, we attempted to infer the ages of the fans based on the following criteria:

**Criterion 1:** Comparison of soil development on fans: Piety et al. (1986) assigned a late Pleistocene age (10-15 ka) to the southern Star Valley alluvial fans based on comparison of soil development and carbonate-rind thicknesses with soil development in Pinedale outwash terraces along the Snake River 45 km north of the study area, near Alpine, Wyoming. The soil development of the fans in southern Star Valley is slightly less than the Snake River terraces, which were deposited in response to the latest Pinedale glaciation of the Yellowstone area ca. 15-20 ka (Walker, 1964).

**Criterion 2:** Relative timing of glacial vs. fluvial deposition: Previous studies have shown that deposition of glacial outwash is contemporaneous with full glaciation in mountain valleys (Schumm, 1965; Pierce and Scott, 1982; McCalpin, 1983) or occurs at the onset of deglaciation (Church and Ryder, 1972). Comparisons of the weathering and soil development between the fans and the moraines show moderately similar characteristics (Figure 1.9), but definitive comparisons of soils are complicated due to climate and parent-material differences between alluvial fans and moraines. The Pf1 fan surfaces have a thin loess cap about 40 cm thick, the subsurface clasts are virtually unweathered, and soils contain a very thick (over 100 cm) Bk horizon with stage I, II, and II+ carbonate coatings (Piety et al., 1986). The soils in the moraines of Dry Creek
Figure 1.9. Soil chronosequence of alluvial fans of southern Star Valley and of glacial deposits of the Salt River Range. Locations of profiles: Pf1 profile (Piety et al., 1986, p. C39) is located at the head of the Swift Creek fan, pPf (?) profile (Ravenholt et al., 1976, p. 21) is located in northern Star Valley, from the same soil series as the pPf fan surface. The following profiles are from RD stations on Figure 1.6: Pt at PT8, EHt at EH1, Nt1-2 at NT9, Nt3 at NT6, Nt4 at NT7.
and Cottonwood Creek have slightly weathered subsurface clasts with stage I and II carbonate coatings and a Bt or Bk horizon. Carbonate coatings are better developed in the Cottonwood Creek moraines because all of the clasts are limestone.

The alluvial fans are at elevations near 2000 m, and consist of clasts of limestone, sandstone, and red siltstone. The Pinedale moraines are at elevations near 2500 m, and consist of limestone or sandstone and red siltstone. Thus, the soils in the moraines inherently show different characteristics due to lithology and climatic influences.

By comparison, the older fan surfaces present on the Cottonwood Creek fan (pPf) have a loess cap more than two meters thick with no clasts, and contain a fine silt loam soil with a Bt horizon 80 cm thick (Ravenholt et al., 1976). It was impossible to determine the degree of clast weathering of the older fan surfaces without a backhoe because the clasts were buried too deeply by loess and none were found during excavations.

**Criterion 3:** Amount of tectonic deformation of fans by recurrent late Quaternary faulting: If the alluvial fans in southern Star Valley were much older than 20 ka, they would be appreciably downfaulted into the basin. The late Quaternary slip rate of the SSVF is determined to be between 0.73 mm/yr and 0.91 mm/yr (see *Radiocarbon Ages and Numerical Chronology of Paleoseismic Events*). If the fans were older, such as a Bull Lake age (140-150 ka), they probably would have been downfaulted into the basin in the 120 ka between Bull Lake and late Pinedale time (ca. 15-20 ka), and most certainly covered by younger alluvial deposits. In addition, the only older fan remnants (pPf) in southern Star Valley are present on the Cottonwood Creek fan, south of an inferred "hinge point" on the SSVF. The hinge point separates rapid subsidence in the northern part of the valley from slower subsidence in the southern part of the valley (see Chapter 2). Thus, the only older fans are present where there is decreased fault activity. No remnants of older alluvial fans are preserved east of the fault.
Using the above criteria, the major alluvial fan surfaces in question are assigned a late Pinedale age, probably coincident with the latest major glaciation in the mountains, and are inferred to have been deposited chiefly in response to glacial erosion upvalley in the Salt River Range, transportation by meltwater, and deposition in southern Star Valley.

CORRELATIONS AND CHRONOLOGY OF QUATERNARY DEPOSITS

A major goal of this study was to subdivide the local glacial deposits and correlate them with established regional chronologies. The local glacial sequence was divided initially from air-photo and field mapping based on topographic position of the deposits. Cluster analysis and a Principal Component Analysis (PCA) performed on the RD data set provided distinctive age groups for the deposits, and determined which RD parameters were most useful for age differentiation.

Local Subdivision of Glacial Deposits

Since only two valleys (Dry Creek and Cottonwood Creek) have well preserved glacial deposits, local subdivision was not extremely difficult and RD data collection was concentrated there. Two major groups of deposits are present: large, forested, weathered and slightly eroded lateral moraines (Pinedale age) up to 4 km from the cirque headwalls, and smaller, bouldery, slightly vegetated nested moraines (Neoglacial age) within the cirques. The cirque moraines are cross-cutting and overlapping in places, which suggests that several minor glacial advances occurred during the Neoglacial period. In the main artery and the right fork of Dry Creek, moraine-like deposits assigned an early-Holocene (?) age are preserved upvalley from the Pinedale deposits, but outside the limits of the cirque moraines.
Results of Statistical Analysis

Limitations of the RD method

In the Salt River Range, several limitations exist for relative-age dating of the glacial deposits because they are composed of sedimentary rocks (refer to Relative-Age Dating (RD) Measurements and Definitions). Only one unit of the Thaynes Limestone contained solution pits, and the other common sandstone and siltstone lithologies did not pit at all. Resistate inclusions existed in only one member of Thaynes Limestone. The resultant lack of data forced the omission of the MPD and RIH from the statistical analyses. The SBF was affected by boulder spalling (especially in thin-bedded siltstones and limestones), which reduced or increased the boulder count on certain deposits. The BBF is a visual estimate of the degree of boulder implantation, and is highly subject to the investigator's judgment. The SPD on moraine soils is strongly dependent on the parent material and climatic factors of soil formation (Shroba and Birkeland, 1983, p. 149). Moraines formed of mudstone will have an initially higher clay content than those formed of limestone, so the soil will more readily develop a Bt horizon, compared to development of a Bk horizon in a contemporaneous moraine composed of limestone. Also, cirque moraines in the study area are at an elevation of roughly 2800 meters, compared to the downvalley moraines at 2300 meters in elevation. Pedogenesis is typically more rapid at higher elevations than in lower-elevation, forested moraines (Shroba and Birkeland, 1983).

Post-depositional modifications such as slumping or stream incision affected the MIA, and the MOA was sometimes unobtainable due to the deposit being plastered against a valley wall. The RCW was variable along the >1 km lengths of moraine crests, and areas of slumping or human interaction (logging roads) were present. Weathering-rind data were variable due to different rind formation on different lithologies, asymmetric rinds, presence of multiple, concentric rinds in a single clast,
and slope aspect and vegetational cover. In the Thaynes limestone, carbonate dissolution formed a leached, sandy rind, but these "rinds" were highly variable even within a single deposit, and were not used for comparison. For consistency, only rind thicknesses in Nugget Sandstone (Table 1.1) were used. The commonly measured lichen, Rhizocarbon geographicum, could be measured only on deposits containing abundant non-carbonate clasts, which included only 5 of 9 cirque moraines sampled. Other problems include the ineffectiveness of lichenometry below treeline (Meierding, 1984), inability to find the largest lichen on a given deposit, and the possibility of a lichen growing on a rock before it was deposited in the moraine.

Results of Principal Component Analysis

The PCA shows high correlations between related time-dependent variables (Correlation matrix, Table 1.2). High negative correlations exist between the BBF and SBF, and the SPD and SBF, which is reasonable because a high surface boulder frequency suggests a young, bouldery deposit without boulder implantation or substantial soil development. The surface boulder frequency should decrease with time, while soil development and burial of boulders should increase with time. High direct correlations are found between the SPD and BBF, and RCW and BBF. These correlations are reasonable because boulder burial by loess and organic matter, soil development, and ridge crest width should all increase with time as deposits weather chemically and physically.

In correlations with the principal components, the first, second and third principal components account for 81.75% of the variability of the data set (Component matrix, Table 1.2). The BBF and SPD are most highly correlated with the first principal component, which accounts for 46.16% of the variability of the data set.
Table 1.2

Results of principal component analysis\textsuperscript{a}

<table>
<thead>
<tr>
<th>RD parameter</th>
<th>SBF</th>
<th>BBF</th>
<th>SPD</th>
<th>MOA</th>
<th>MIA</th>
<th>RCW</th>
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<tr>
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<th>PC2</th>
<th>PC3</th>
</tr>
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<tbody>
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<tr>
<td>RCW</td>
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<td>-0.422</td>
<td>0.195</td>
</tr>
</tbody>
</table>

% variation of components 46.16% 21.08% 14.51%
Cumulative % of variation 46.16% 67.24% 81.75%

\textsuperscript{a}See Table 1.1 for definition of RD parameters. PC1, PC2, and PC3 are the first, second, and third principal components. Values >0.5000 are considered highly correlated and are highlighted by boxes.
Thus, the BBF and SPD are the RD parameters most useful in age determination. The SBF and RCW correlate almost as highly as the BBF and SPD, and are also useful in age determination. The MIA and MOA are very highly correlated with the second and third principal components, respectively, which account for 35.59% of the variability of the data set. Therefore, all six RD parameters used in the statistical analysis are useful in age differentiation of the deposits. The PCA results imply that because the BBF, SPD, SBF, and RCW all correlate almost equally with the first principal component, they have equal influence on the variability in the data set and are useful for age differentiation of deposits. In future research using the RD technique, knowing which variables are more useful for age differentiation will facilitate data collection and provide more meaningful analyses.

Results of Cluster Analysis

One of the limitations of cluster analysis is the subjectivity in subdividing a dendrogram. In this instance, where the main purpose of the dendrogram is to provide age groups of deposits, subdividing the tree too finely would not be useful if many non age-dependent groups were defined. The initial age split occurs at a very high dissimilarity (i.e., high Euclidean distance), and creates Holocene-age (Neoglacial, group A) and late Pleistocene-age (late Pinedale, group B) groups (Figure 1.10). This initial split coincides with groups of deposits whose ages are known to be different, i.e., downvalley and cirque moraines. The EH deposits (group B1) are separated from the two groups by a large Euclidean distance, which suggests that they were highly dissimilar to groups A and B. Figure 1.11 shows the topographic positions of the deposits, which aids in assessing how the deposits should be grouped.

Group A includes all Neoglacial-age deposits and two debris-flow deposits. RD stations NT3, NT4, and NT7 could be separated into a high-dissimilarity subgroup (A1) which appears dependent on very high SBF. The position of these deposits
Figure 1.11. Topographic positions of RD stations, glacial deposits, and mass movements in Dry and Cottonwood creeks.

closest to the cirque headwall indicates they represent the youngest Neoglacial deposits. Subgroup A2 includes RD stations NT1, NT2, NT5, NT6, NT8, and NT9. NT1, NT6, NT8, and NT9 are cirque moraines in the Dry Creek cirque that lie outside NT7 of subgroup A1. Thus, group A2 deposits must be older based on their topographic position. QD3 and QD5 are grouped with the Neoglacial deposits because they are very fresh, bouldery deposits which represent Holocene-age mass movements (non-glacially related) whose down-valley positions are not age related or topographically constrained, such as the glacial deposits (Figure 1.11).

Group B includes late-Pleistocene deposits that can be split at a moderately high dissimilarity into three subgroups that are dependent on age and lithology. Subgroup B2, which consists of RD stations PT1, PT3, and PT4 in Cottonwood Creek, are moraines containing limestone clasts. Subgroup B3, which consists of RD stations
PT2, PT5, PT6, and PT8 in Dry Creek, are moraines containing sandstone clasts. PT7, composed of limestone clasts, is grouped within the sandstone group but lies in Slide Canyon, a tributary of Cottonwood Creek. All of the above-mentioned late-Pinedale moraines are inferred to be the same age based on their topographic positions 2-4 km from the cirque headwalls. It appears that lithologic differences create enough differential-weathering characteristics to group deposits of similar age into different provenance subgroups. QD1, QD2, and QD4 are valley-bottom debris-avalanche deposits composed of limestone clasts that lie near the outermost Pinedale-age deposits in Cottonwood Creek. They clustered with the Pinedale-age groups (B2 and B3), which suggests that they are late Pleistocene in age. A cooler, possibly wetter climate at that time would be conducive to large numbers of mass movements.

The EH deposits (subgroup B1) have a very high dissimilarity from the main groups, A and B, which was expected because spatially they occur midway between the other two groups. The RD data and topographic position both suggest they are younger than the Pinedale deposits and older than the Neoglacial deposits.

Euclidean distances over about 0.6 define age-diagnostic groups in Figure 1.10. Groups separated by a Euclidean distance less than about 0.6 are dependent on lithologic weathering differences or outstanding RD values. The initial division of groups A and B occurs at a Euclidean distance of near 1.0, or total dissimilarity between the two. Subgroup B1 is separated from subgroups B2 and B3 by Euclidean distances of 0.84 and 0.86. The EH deposits are inferred to be younger than the PT deposits based on their topographic positions. Subgroup A1 is separated from subgroup A2 by a Euclidean distance of 0.8. A1 deposits are inferred to be younger than A2 deposits based on their near-cirque positions. Subgroups B2 and B3 are inferred to be the same age (late Pinedale), and are split at a Euclidean distance of 0.58. RD stations NT1 and NT6 of subgroup A2 lie on cirque moraines of similar
topographic position, but are split at a Euclidean distance of about 0.59, therefore this division must not be age-related.

Conclusions of Statistical Analysis

The main usefulness of the cluster dendrograms is to provide distinctive relative age groups for moraines, especially for deposits in different valleys which may be of the same age. However, the resolution of the cluster analysis appears sensitive enough to distinguish subgroups of deposits the same age dependent on extreme RD values, and possibly variations in weathering due to lithologic differences. The problem that the clusters did not solve is the absolute ages of the deposits, nor do the dendrograms provide a continuous chronosequence, i.e., the clusters group the deposits together, but do not give an age sequence to the deposits. In other words, the dendrogram does not show that group B deposits are older than group A deposits. However, if the field relationships of the deposits are known (from field mapping), the cluster tree can be "rotated" about its nodes to provide an age progression, as in Figure 1.10.

Correlations With Standard Rocky Mountain Glacial Chronology

The correlation of glacial deposits on the west flank of the Salt River Range with latest Pinedale, early Holocene, and Neoglacial moraines was based on the topographic positions of the moraines and comparison with RD values obtained from other works. Comparison of RD values obtained from deposits in the study area and other mountain ranges is hampered due to several factors which influence RD values such as lithology, climate, and elevation. As noted previously, most glacial chronologies using RD methods were constructed in areas composed of crystalline rocks, and only few publications could be found which successfully divided glacial deposits of sedimentary rock provenance with RD values (Anderson and Anderson, 1981; McCalpin, 1983).
However, because only two major sets of glacial deposits are present in the study area, with deposits of a possible intermediate advance between them, regional correlations were somewhat simplified. Because major sets of deposits exist as large downvalley moraines, smaller moraines outside the limits of cirque moraines, and nested cirque moraines, they are assigned late Pinedale, early Holocene, and Neoglacial ages, respectively, in keeping with regional Quaternary stratigraphic nomenclature discussed in the Introduction.

**Pre-Pinedale Deposits**

No pre-Pinedale age deposits were positively identified in the study area. Older moraines (i.e., Bull Lake age) are not always present in a glaciated valley for several reasons: the mountains were not as extensively glaciated during older glaciations due to climatic factors or tectonically lower mountains (Pierce and Morgan, 1990), or the older moraines were removed by erosion or subsequent glaciations. A possible pre-Pinedale, cemented till is present in Cottonwood Creek, so the study area may have been glaciated during older glaciations, but those deposits now are covered or are non-recognizable. Rice (1987) noted that in other parts of the Salt River Range moraines possibly Bull Lake in age were composed of soft, sedimentary rocks and were eroded nearly to non-recognition.

**Late Pinedale Deposits**

The lack of multiple sequences of large, down-valley lateral and terminal moraines in the study area suggests that the single set of lateral moraines present is a result of the most recent major glacial advance, the latest Pinedale (Porter et al., 1983). If the moraines in Dry Creek and Cottonwood Creek are the result of early Pinedale or Bull Lake glaciation, large moraines of late Pinedale age should be preserved upvalley, but no such moraines exist.
A reliable RD parameter for correlation for this study seems to be weathering-rind thicknesses. Anderson and Anderson (1981) used average weathering-rind thicknesses in calcareous quartzarenite to distinguish moraines of pre-Altithermal (early Holocene), early Neoglacial, and late Neoglacial ages. Average rind thicknesses in the Nugget sandstone taken from late Pinedale, early Neoglacial, and late Neoglacial moraines in Dry Creek were compared to rind measurements from Anderson and Anderson (1981) (Figure 1.12). Anderson and Anderson's (1981) average rind thicknesses were similar, in size and magnitude of difference in Neoglacial and pre-Altithermal deposits, to the rinds in Neoglacial and late Pinedale deposits in this study. Rind thicknesses are similar in early and late Neoglacial deposits, as are rind thicknesses in late Pinedale and pre-Altithermal deposits. However, a large difference exists between Neoglacial and late Pinedale/pre-Altithermal deposits, which suggests that the resolution of average rind thicknesses is only adequate to subdivide major glacial events, and not minor glacial advances.

Morphologic measurements on late Pinedale moraines in the study area (maximum inner and outer slope angles) were compared to data from late Pinedale moraines of sandstone provenance in the northern Sangre de Cristo Mountains (McCalpin, 1983). Data from McCalpin (1983) were chosen because of their abundance and similar methods of collection. Other workers have assembled moraine-morphology data, but their data is based largely on proximal and distal slope-angle measurements on terminal moraines. Meierding (1984) suggested morphologic measurements be taken from lateral moraines because they are less variable in their initial deposition, and change more in time due to weathering than terminal moraines. Maximum outer and inner slope angles were 26.1° and 29.4°, respectively, for late Pinedale moraines in the present study, and 26° and 29° for late Pinedale moraines in the northern Sangre de Cristo Mountains. Thus, the moraines in the two areas have
Figure 1.12. Comparison of weathering rind thicknesses in quartzarenite clasts from Salt River Range (this study) and Mount Timpanogos, Utah (Anderson and Anderson, 1981).
been subjected to roughly the same amount of weathering, and likely were deposited at similar times.

*Early Holocene Deposits*

The moraine-like deposits upvalley from the late Pinedale moraines in the main fork and right fork of Dry Creek may represent the latest Pleistocene (ca. 10-12 ka) glacial advance. RD measurements were taken for the ridge-like deposits, but because they were composed of limestone clasts, no comparable RD values exist in literature. However, a soil profile was similar to soils in type Temple Lake deposits (Miller and Birkeland, 1974) and Santanta Peak deposits (Benedict, 1973). The ridge-like deposits exhibit moderate soil development that includes a weak, textural B horizon. Based on topographic position and soil development, the deposits (if they truly represent a glacial advance) may correlate with type Temple Lake and Santanta Peak deposits.

A radiocarbon age of $3800 \pm 70$ yr B. P. dated a buried peat layer from an auger hole near Dry Creek Lake (Figure 1.6). Dry Creek Lake is impounded by a possible early Holocene moraine. Such a date is quite young for a possible early Holocene deposit, but it only provides a minimum age for the moraine-like deposit. The auger hole, near the shore of the lake and only 220 cm deep, probably does not represent the oldest organics in the Dry Creek Lake sediments.

*Neoglacial Deposits*

The Neoglacial advances preserved in Dry Creek are correlated largely on position of deposits in and near the cirques, and some RD value comparisons. The cluster dendrogram split the Neoglacial dendrograms into two groups based on RD values, but the cluster may not have been sensitive enough to distinguish multiple Neoglacial advances. Correlations using diameters of *Rhizocarbon geographicum*, often used in Neoglacial correlations, were attempted. However, lichen measurements are inconsistent in the study area because larger lichens are present on smaller moraines
nearer to the cirque headwall than on the obviously older moraines farther out of the cirque. Reasons for inconsistency may be due to the cirque moraines lying below treeline in the study area, incorporation of rocks with lichens already growing on them into the youngest deposits, or inconsistent lichen growth due to lingering snowcover.

The cirque moraines in Dry Creek were chosen for regional correlation because of the apparent completeness of the Neoglacial record and excellent moraine morphology preserved there. Problems with regionally correlating the Dry Creek chronology are: (1) the moraines are all made of quartzarenite clasts compared to crystalline rocks of the Front Range and the Wind River Range; (2) the moraines are so closely nested it is difficult to recognize discrete advances, and (3) in general there is poor control of ages and correlations of Neoglacial deposits. Field mapping revealed three possible glacial advances confined to the cirque (Nt1-2, Nt3, and Nt4 on Figure 1.5). The cirque moraines are progressively larger and more weathered farther from the cirque. The actual subdivision of the cirque moraines is subjective, as nested moraines may not represent a discrete readvance but only a minor fluctuation within an overall retreat. Nt1 and Nt2 were grouped together because they are very similar in size and morphology, and show no significant cross-cutting relationship. Nt3 cross-cuts Nt1-2, and Nt4 cross-cuts Nt3, so they may represent discrete advances.

Benedict (1973) described in detail the deposits and ages of the three Neoglacial stades recognized in the Front Range: the Triple Lakes (ca. 3-5 ka), which has minor fluctuations, the Audubon (ca. 1-2 ka) and the Arapaho Peak (ca. 0.1-0.3 ka). Miller and Birkeland (1974) also suggested three Neoglacial advances for the Wind River Mountains: an early Neoglacial advance (Triple Lakes equivalent), a possible Audubon equivalent, and the Gannett Peak (Arapaho Peak equivalent) advance. The characteristics of the deposits of each stade, such as vegetation, loess thickness, and soil development described by Benedict (1973), are somewhat comparable with the field characteristics of the Dry Creek deposits (Figure 1.13).
<table>
<thead>
<tr>
<th>Vegetation</th>
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<th>Late Neoglacial</th>
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<tr>
<td></td>
<td>Nt 1-2 Triple Lakes/E. Neoglacial</td>
<td>Nt 3 Audubon</td>
</tr>
<tr>
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<td>Krummholz spruce, shrubs</td>
<td>Sparse spruce, shrubs</td>
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<td>O-Cox A=3-15 cm</td>
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<tr>
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1- Deposits in Salt River Range lie below treeline at elev. 2800 m.; deposits in Wind River and Front Ranges lie near or above treeline at elev. >3200 m
2- Soil development varies considerably; generally the Nt soils more closely resemble weaker soils from deposits in other areas
3- Boulder percentage is strongly influenced by lithology; in general, sedimentary rocks produce lower boulder percent due to splitting and rapid weathering

Figure 1.13. Comparison of characteristics of Neoglacial deposits in Salt River Range with characteristics of Neoglacial till in the Front Range (Benedict, 1973) and Wind River Mountains (Currey, 1974; Miller and Birkeland, 1974).
Boulder frequency and soil development in the Front Range cirque moraines varies considerably even within moraines of a given age (Benedict, 1973), so correlations by use of RD data are not definitive. However, the weaker soils in the Front Range deposits are similar to the soils in the Dry Creek cirque moraines despite inherent differences due to altitude, latitude, and lithologies. It was virtually useless to compare other RD data from the Salt River Range with other RD data from Neoglacial deposits in the Wind River Mountains by Miller and Birkeland (1974) and Currey (1974) because of different methods of data collection and different parameters collected, in addition to the aforementioned limitations. Due to the lack of firm RD correlations, the variability and limitations of the RD method, and the lack of radiocarbon age control, moraines of the Dry Creek cirque are only tentatively correlated with the Neoglacial advances in other areas.

CONCLUSIONS

Late Pinedale and Neoglacial moraines, present in two valleys in the southwest Salt River Range, are assigned relative ages based on topographic positions and comparison of RD values with other works. The RD techniques proved useful in subdivision of local deposits into age groups using statistical analysis. In long-distance regional correlation, the RD techniques were not as successful because weathering processes and the range of RD values are quite different for sedimentary lithologies in our study area compared to those encountered in more extensively studied deposits of crystalline-rock provenance. With cluster analysis, the magnitude of differences of RD values was sufficient to distinguish late Pinedale, early Holocene (latest Pleistocene?), and Neoglacial deposits. Some subgroups on the cluster dendrogram appeared lithologically dependent (sandstone compared to limestone), which suggests that lithologic differences create substantial weathering differences among deposits of the same age. Some RD values gave counter-intuitive results, such as inner slope angles,
which were found on average to be steeper on Pinedale moraines than on Neoglacial moraines. However, this anomaly probably was due to post-depositional modification of older moraines such as stream incision.

Weathering-rind thicknesses in quartzarenite clasts, when correlated with measurements from a single previous study of sedimentary lithologies, suggested that rinds may be useful in establishing long-distance correlations among glacial deposits composed of similar sedimentary lithologies. Rind thicknesses were sufficiently different to distinguish between Neoglacial and late Pinedale deposits, but not to subdivide Neoglacial deposits. Finally, it was somewhat disappointing to discover that only very limited work on sedimentary rocks is available for comparisons with RD data collected in the present study.
REFERENCES CITED


CHAPTER 2

Abstract. The southern Star Valley fault (SSVF) is an active, west-dipping Neogene normal fault at the southern end of the Grand Valley - Star Valley (GV-SV) fault system of western Wyoming and eastern Idaho. The GV-SV system is in the center of a major system of large, en-echelon normal faults between the northern Wasatch and Teton faults. These faults mark the northeastern margin of Basin and Range normal faulting.

To determine the magnitude and recurrence of paleoseismic events generated on the SSVF, a trench was excavated across a fault scarp 11 meters high in a late Pleistocene alluvial fan. The trench stratigraphy revealed three distinct paleoseismic surface ruptures since ca. 15,000 yr B. P. Radiocarbon ages from faulted deposits in the trench date the two most recent events at about $8,090 \pm 80$ yr B. P. and about $5,540 \pm 70$ yr B. P. The surface displacements during prehistoric surface ruptures, determined from scarp heights and faulted stratigraphic units in the trench, were four meters for the earliest event (estimated at ca. 12-15 ka based on soil development), four meters for the 8,090 yr B. P. event, and three meters for the 5,540 yr B. P. event. The along-strike distribution of fault scarps indicates that late Quaternary faulting was limited to the northern 21 km of the SSVF and the southern 3 km of the northern Star Valley fault. This distribution suggests that the surface rupture spanned a 4-km en-echelon right-stepover between the two faults. Based on estimates of surface displacements and rupture lengths, magnitudes of the paleoearthquakes generated by the SSVF were between $M_s 6.9$ and $M_s 7.1$. The recurrence intervals for the paleoseismic events are somewhat irregular, and range from about 4,000 - 7,000 years between the first and second events, about 2,500 years between the second and third events, and at least 5,500 years since the third event.
INTRODUCTION

Objectives

The objectives of the study were to determine the temporal sequence of late Quaternary faulting on the southern Star Valley fault (SSVF), to determine the magnitude of paleoearthquakes generated on the SSVF, and to analyze the tectonic geomorphology of southern Star Valley to determine the effects of recurrent faulting on the surficial deposits.

Location and Physiography

The SSVF is a north-trending normal fault 24 km long that separates southern Star Valley in the west from the Salt River Range in the east. The SSVF is within the Northern Wasatch to Teton Corridor (NWTC), a series of large, right-stepping en echelon Quaternary normal faults that extends from the Wasatch fault zone in Utah to the Teton fault in northwestern Wyoming [McCalpin, 1990a]. Major normal faults included in the NWTC are the Brigham City segment of the Wasatch fault, the East Cache fault, the Bear Lake faults, the Grand Valley-Star Valley fault system, and the Teton fault. The NWTC is part of a larger parabola-shaped system of major Quaternary faults that trails to the west of the northeastward-migrating Yellowstone hot spot (Figure 2.1).

The Grand Valley - Star Valley (GV-SV) fault system is 100-km long (Figure 2.2) and consists of late Cenozoic normal faults that bound the western margins of the Snake River Range and Salt River Range [Piety et al., 1986; Anders et al., 1990]. The SSVF is at the southernmost segment of the GV-SV system, separated from the northern Star Valley fault (NSVF) by a 4 km right en echelon stepover. Southern Star Valley is a half-graben containing 2-3 km of upper Tertiary and Quaternary basin fill [Dixon, 1982] bounded on the east by the SSVF, which has a total estimated net slip of
Fig. 2.1. Distribution of Holocene faults in the "seismic parabola" around the Yellowstone hot spot [adapted from Pierce and Morgan, 1990]. Pierce and Morgan [1990] divided faults in the seismic parabola into four zones; the faults shown here are in Zone II, which includes the most active Quaternary structures. Major normal faults of the Northern Wasatch to Teton Corridor (NWTC) are the Wasatch fault, the East Cache fault, the Bear Lake fault, the southern Star Valley fault, and the Teton fault.
Fig. 2.2. The Grand Valley - Star Valley fault system. SSVF = southern Star Valley fault, NSVF = northern Star Valley fault, GVF = Grand Valley fault. Hachures indicate distribution of latest Quaternary faulting. Study area (Figure 2.4) is outlined.
5.5 km [Coogan and Royse, 1990]. Together with the southernmost 16 km of the NSVF, the SSVF is the only segment of the GV-SV system with clear evidence of late Quaternary displacement. The evidence includes a linear, faceted mountain front and fault scarps preserved in late Pleistocene and Holocene alluvium [Piety et al., 1986; McCalpin et al., 1990a].

Previous Investigations

Rubey [1973] mapped fault scarps in Quaternary deposits along the SSVF. Piety et al. [1986] constructed detailed profiles of late Quaternary fault scarps, analyzed the geomorphology of the Salt River Range front, and mapped surficial deposits in southern Star Valley. Regional studies by Anders et al. [1989], Westaway [1989], and Pierce and Morgan [1990] described normal faulting and seismicity in the "seismic parabola" associated with the migration of the Yellowstone hot spot. The seismic parabola was divided into four different zones of seismicity and faulting activity by Pierce and Morgan [1990], who placed the SSVF in Zone II (Figure 2.1), characterized by major Holocene faults (the most active Quaternary structures).

Regional Geologic Setting

The geologic setting of the region is dominated by Cenozoic normal faults superimposed on late Mesozoic Sevier thrusts and folded sedimentary rocks. Regional compression of Paleozoic and Mesozoic sedimentary rocks from late Jurassic into Eocene time created the Idaho-Wyoming thrust belt. The thrust belt is a zone 320 km long and 100 km wide that contains north-trending, west-dipping, eastward-younging thrust faults and eastward-overturned folds associated with hanging-wall deformation [Armstrong and Oriel, 1965]. Normal faulting in response to east-west extension that began ca. 17 million yr B. P. created the Basin and Range province [Stewart, 1972; Zoback et al., 1981; Eaton, 1982]. Anders et al. [1989] suggested that extension in the GV - SV fault system began about 10 million yr B. P.
Normal-Fault Geometry

The subsurface geometry and related seismicity of large normal faults in the eastern Basin and Range province is the subject of an ongoing discussion. Studies of focal mechanisms and aftershocks on seismically active faults support the theory that large normal faults in the eastern Basin and Range province have a planar geometry, and that seismic slip occurs only on moderate- to high-angle planar faults [Jackson and White, 1989; Arabasz and Julander, 1986]. Aftershock data [Richins et al., 1987] and geodetic observations [Stein and Barrientos, 1985] from the 1983 Borah Peak (Ms 7.3), Idaho, earthquake suggest that slip on the Lost River fault was planar and that the fault plane dips uniformly at 40°-50° to a depth of about 16 km. Fault-plane solutions and spatial patterns of earthquake foci in the eastern Basin and Range province indicate that seismic slip occurs on planar faults that dip 30°-60°, and no instances of clustered earthquake foci demonstrate seismic slip on low-angle (< 30°) or listric faults [Arabasz and Julander, 1986; Jackson and White, 1989].

In contrast, seismic-reflection profiles suggest that major normal faults in the eastern Basin and Range (especially in the Wyoming-Idaho thrust belt) are listric, and merge into ramps in Sevier thrust faults at depth [Royse et al., 1975; Dixon, 1982; Webel, 1987; Evans, 1991]. A cross section based on a seismic-reflection profile across the SSVF at Afton, Wyoming (Figure 2.3) shows the SSVF merging westward into the Absaroka thrust at depth. Webel [1987] interpreted the SSVF from the seismic-reflection profile as dipping about 70° near the surface and flattening downward to a dip of less than 10° at a depth of about 12 km.

The geometry of the SSVF has implications for future earthquake potential. No evidence exists for seismic slip on listric faults in the eastern Basin and Range [Arabasz and Julander, 1986; Jackson and White, 1989]. If the SSVF is indeed listric and listric faults slip by aseismic creep, the SSVF may not generate large earthquakes.
Fig. 2.3. Cross section from seismic-reflection data across the southern Star Valley fault near Afton showing inferred listric geometry of SSVF [adapted from Webel, 1987]. No vertical exaggeration.
However, stratigraphic evidence in a trench across the SSVF shows that individual surface ruptures up to 4 meters high have occurred, which suggests that seismic slip is the dominant mechanism for movement on the SSVF. Similar surface ruptures have accompanied all large-magnitude earthquakes in the Basin and Range [Bucknam et al., 1980]. Despite the uncertainty as to the subsurface geometry of the SSVF, field evidence clearly indicates that the fault has experienced large instantaneous fault rupture.

Methods

A backhoe trench 20 meters long and up to 4.5 meters deep in a fault scarp in a late-Pleistocene alluvial fan exposed faulted stratigraphy, enabled face-mapping of faulted deposits, and allowed sample collection of organic material to numerically (14C) date paleoearthquakes. Detailed descriptions of the trenching techniques used were described by McCalpin [1989].

LATE QUATERNARY FAULT SCARPS

Linear, basin-facing fault scarps from recurrent late Quaternary faulting on the SSVF are preserved in late Pleistocene and Holocene alluvium in southern Star Valley [Piety et al., 1986] (Figure 2.4). Two late Pleistocene fan surfaces are typically faulted, and are correlated as late Pinedale (Pf1) and younger (Pf2, early Holocene?) ages.

Fault-scarp data from southern Star Valley were taken from Piety et al. [1986]. Figure 2.4 shows locations of fault scarps, and Table 2.1 gives scarp characteristics. At Phillips Creek, a fault scarp 9.0 meters high in the Pf1 surface has a maximum scarp angle of 25°, and a fault scarp 5.3 meters high is present in Pf2. At Swift Creek, a single fault scarp 11.0 meters high in the Pf1 surface has a maximum scarp angle of 34°. An alluvial fan from a small, unnamed tributary just south of Swift Creek is graded to the Pf1 surface, and is offset 7.0 meters by the SSVF. On the north
Fig. 2.4. Generalized surficial geologic map of southern Star Valley. Hachures along SSVF show locations of late Quaternary fault scarps, numbers show amounts of surface displacements (in meters) of the fault scarps.

Hal = Holocene alluvium of Salt River
Pf1 = Late Pleistocene Pinedale outwash fan
Pf2 = Late Pleistocene/early Holocene (?) alluvium
B = Paleozoic and Mesozoic bedrock
SSVF = southern Star Valley fault

W. C. = Willow Creek, P. C. = Phillips Creek, D. C. = Dry Creek,
S. C. = Swift Creek, C. C. = Cottonwood Creek.
TABLE 2.1. Characteristics of fault scarps along the southern Star Valley fault [adapted from Piety et al., 1986]

<table>
<thead>
<tr>
<th>Profile location</th>
<th>Vertical surface displacement (m)</th>
<th>Scarp height (m)</th>
<th>Maximum slope angle (degrees)</th>
<th>Slope of upper surface (degrees)</th>
<th>Slope of lower surface (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Willow Creek</td>
<td>8.3</td>
<td>9.3</td>
<td>31.5</td>
<td>1.5 - 3.5</td>
<td>3.0 - 3.5</td>
</tr>
<tr>
<td>Willow Creek</td>
<td>3.3</td>
<td>4.0</td>
<td>16.5</td>
<td>3.0 - 3.5</td>
<td>2.5 - 3.0</td>
</tr>
<tr>
<td>Phillips Creek</td>
<td>9.0</td>
<td>10.0</td>
<td>25</td>
<td>2 - 5</td>
<td>0 - 2</td>
</tr>
<tr>
<td>Swift Creek</td>
<td>11.0</td>
<td>12.0</td>
<td>34</td>
<td>1 - 3</td>
<td>2 - 4</td>
</tr>
<tr>
<td>Swift Creek</td>
<td>7.0</td>
<td>11.3</td>
<td>25</td>
<td>9 - 12</td>
<td>2 - 8</td>
</tr>
<tr>
<td>Dry Creek</td>
<td>11.3</td>
<td>12.3</td>
<td>27</td>
<td>0 - 1.5</td>
<td>0 - 1</td>
</tr>
<tr>
<td>Dry Creek</td>
<td>5.0</td>
<td>5.3</td>
<td>28</td>
<td>0</td>
<td>&lt;2</td>
</tr>
</tbody>
</table>

side of Dry Creek, a fault scarp 11.3 meters high in the Pf1 surface has a maximum scarp angle of 27°. On the south side of Dry Creek, the Pf2 surface is offset by a fault scarp 5.0 meters high with a maximum scarp angle of 28°. No fault scarps are present in the Pf1 surface at Cottonwood Creek, which suggests that late Quaternary faulting dies out southward somewhere along the fault trace between Dry and Cottonwood creeks.

Scarps up to 11.0 meters high are preserved at the mouths of small, unglaciated drainages between Phillips and Dry Creeks [Piety et al., 1986]. The faulted alluvium is preserved as small, eroded remnants of Pf1 on the upthrown block in the mouths of these drainages. These uplifted fan surfaces have since been eroded, and are partially covered by younger unfaulted alluvial fans which are graded onto downthrown Pf1
surfaces. Because fault-scarp heights are similar to the fault scarps in the Pf1 surfaces, the remnants of alluvium are inferred to be of similar age.

No fault scarps are present along the SSVF between the aforementioned major drainages, either in colluvium, across small, Holocene, range-front alluvial fans, or at the bases of the faceted spurs. The lack of continuous fault scarps implies that either (1) all colluvium and younger fans post-date the latest faulting event, or (2) scarps were formed across these steeper geomorphic surfaces, but have since been destroyed by erosion or flowage. According to Pierce and Colman [1986], the maximum slope angle of a fault scarp 5.0 meters high and 5,000 years old is about 25°. The most recent paleoearthquake along the SSVF, ca. 5,540 yr B. P., was accompanied by a surface displacement 3.0 meters high, so the present maximum scarp angle from that event should be roughly 25°. (Pierce and Colman [1986] had no data for 5,000 year-old fault scarp 3.0 meters high, but presumably a scarp 3.0 meters high would erode as fast as a fault scarp 5.0 meters high.) The colluvium, faceted spurs, and Holocene fans have slopes between 20° and 25°, therefore no recognizable fault scarps are present at the range front except in the large, low-gradient alluvial fans at the mouths of larger drainages. In addition, McCalpin [1983] noted a similar lack of fault scarps between faulted drainage mouths along the Sangre de Cristo fault, where the latest surface rupture was dated at ca. 7.7 ka. Presumably, erosion of fault scarps across steeper slopes is rapid enough to obliterate traces of surface rupture in ca. 5-7 ka [Andrews and Hanks, 1985].

AFTON TRENCH SITE

Site Geology

A backhoe trench was excavated across the fault scarp on the Swift Creek alluvial fan in the town of Afton, Wyoming. The surficial geology of the trench site is dominated by the Pf1 surface, which is underlain by dominantly rounded, sandy,
Fig. 2.5. Surficial geologic map of alluvial deposits and fault scarp profiles near the Afton trench site [adapted from Piety et al., 1986].

- Hal: Holocene alluvium
- Hal1: Holocene alluvial fan
- Hal1-2: Holocene tectonic terraces
- Pi1: Pinedale outwash fan
- Co: Older, loess-covered alluvium, tectonically uplifted
- B: Paleozoic/Mesozoic bedrock

P1: Profile with 11.0 m surface displacement
P2: Profile with 7.0 m surface displacement
stream gravels (Figure 2.5). An alluvial fan (Haf on Figure 2.5) from a small tributary southeast of the fault is graded onto the Swift Creek fan and is displaced where it crosses the scarp. Small, tectonic, strath terraces were cut by Swift Creek into the upthrown block of alluvium east of the SSVF between periods of faulting (Hat, Figure 2.5).

Due to restrictive property access, the trench had to be placed at the extreme distal portion of the tributary fan where it contacts the fault scarp (Figure 2.5). This trench placement resulted in a unique geomorphic setting for the trench that affected the trench stratigraphy and scarp height at the trench location. The stratigraphy of the trench included not only faulted stratigraphy of the Swift Creek alluvial fan (Pf1 surface), but distal sediments from the small tributary fan (Haf on Figure 2.5). In addition, the surface offset shown on a scarp profile (constructed using a rod and Abney level) where the trench was dug (Figure 2.6) was 9.6 meters, intermediate between the 11.0 meters of total surface offset of Pf1 and the 7.0 meters of offset of the axis of the tributary fan. The 9.6 meters of surface offset is less than the 11.0 meters of maximum surface displacement of the Pf1 fan surface because material of the tributary fan is only present on the downthrown block (lower part of the scarp).

Age of Faulted Deposits

The age of the faulted Pf1 fan surface was estimated to be late Pleistocene by Piety et al. [1986]. They based this correlation on the similarity of soil-development indices from the Pf1 surfaces to those of late Pinedale outwash terraces along the Snake River 45 km north of the site. A soil profile from a pit in the upthrown block of the scarp about 300 meters NW of the trench site shows a Bk horizon with a maximum carbonate-stage development of II+ [Piety et al., 1986]. The soil development of the Swift Creek fan is similar to, but slightly weaker than, those on the Snake River terraces, which were deposited during latest Pinedale glaciation of the Yellowstone area.
Fig. 2.6. Scarp profile along the line of the Afton trench which shows the estimated position (prior to trenching) and the actual position of the fault trace in the scarp and the outline of the trench. The surface offset (SO) is 9.6 meters.
ca. 15-20 ka [Walker, 1964]. Piety et al. [1986] therefore concluded that the Swift Creek fan is ca. 10-15 ka in age. In addition, the alluvial fans are inferred to be young because they have not been appreciably downfaulted into the basin, as would older fans, such as those of Bull Lake-age (ca. 140-150 ka) (see Age Criteria for Pinedale Alluvium).

**Fault-Scarp Development**

A generalized evolution of the fault scarp in the Pf1 surface in the Swift Creek fan was diagrammed prior to trench excavation (Figure 2.7) to determine what stratigraphic relationships probably existed between Pf1 and the tributary fan. Because the tributary fan was displaced 4 meters less than the Pf1 surface, which suggested it had been faulted fewer times than the Pf1 surface, we believed the tributary fan was deposited between faulting events. Although the surface displacement at the trench is 9.6 meters, the scarp evolution model is based on the total surface offset of the Pf1 surface, which is 11.0 meters (see above discussion under Site Geology).

The evolutionary model begins with deposition of the Pf1 fan surface, and initial fault rupture (and free-face erosion?) before the tributary fan (Haf) was deposited (Figure 2.7, A and B). The tributary fan was deposited across the scarp before the next fault offset, then truncated by it (Figure 2.7, C and D). The axis of the tributary fan is offset 7.0 meters (Table 2.1), but a fault scarp 7.0 meters high is unlikely the result of a single event, based on worldwide surface displacement data [Bonilla et al., 1984]. The 7.0 meters of displacement in the fan was therefore hypothesized to be the result of two ruptures, on the order of 3-4 meters each, shown in the evolutionary diagram. The free face from the second rupture would erode into a second colluvial wedge, and then the third rupture would occur and the free face would erode into a third colluvial wedge (Figure 2.7, E and F). This model is fairly typical of
Fig. 2.7. Conceptual diagram of inferred evolution of fault scarp in Afton that shows deposition and interaction of tributary fan with fault scarp (see text for discussion). The total surface displacement of the Pf1 surface is 11 meters, however, because the scarp profile in Figure 2.6 includes the toe of the tributary fan (Haf on Figure 2.5) on the downthrown block, its surface offset (SO) is 9.6 meters here.
multiple-event fault-scarp evolution [Hanson et al., 1982; McCalpin, 1987], the only difference being the deposition of the tributary fan between the first two fault ruptures.

RESULTS OF FAULT-SCARP TRENCHING

Trench Stratigraphy and Structure

The stratigraphy of the trench is dominated by stream gravels and scarp-derived colluvium (Figure 2.8, Appendix B). Unit 1, the Swift Creek fan alluvium, is a cobble stream gravel in a pink sandy matrix. Because the trench did not go to the top of the scarp, Unit 1 could not be directly correlated with the Pf1 surface, but is assumed to represent late Pinedale aggradational gravels. Unit 2, a very loose, cobbly gravel in a coarse sandy matrix, is the uppermost portion of the colluvial wedge deposited after the first surface rupture. Unit 3 is slightly gravelly, pink sand and silt with soil A, Bk, and C horizons that constitutes the distal portion of the tributary fan. The contact between the Unit 2 colluvium and the Unit 3 fan sediments was not exposed in the trench, but it was assumed that they interfingered under the trench floor because they were both deposited subsequent to the first fault rupture. Unit 4 is sheared sandy gravel and tension crack fill in a tectonic shear zone one meter wide between the main fault and a small synthetic fault. Many of the pebbles in Unit 4 are oriented with their long axes dipping between 40° and vertical, an indication they have been rotated and/or fell into an open void. Unit 5 is a well preserved, gravelly and sandy colluvial wedge 2 meters thick deposited after the penultimate surface rupture. A soil A horizon 20-40 cm thick is developed in the upper part of the colluvium. Unit 6 is a sandy gravel lens 20-30 cm thick which was probably deposited as a debris-flow along the base of the scarp. Unit 7 is a tabular, sandy gravel body of scarp-derived colluvium. It is more elongate than underlying colluvial wedges because it was deposited on the sloping surface of a wedge. A soil A horizon is developed in the upper part of Unit 7, which thickens considerably into a cumulic A horizon near the bottom of the scarp.
Stratigraphic Units:

Unit 7: Colluvium of latest event
- 7b - cumulic A horizon
- 7a - stony colluvium

Unit 6: Gravelly debris flow

Unit 5: Colluvium of penultimate event
- 5d - soil A horizon
- 5c - sandy colluvium
- 5a - stony colluvium

Unit 4: Gravelly tension-fissure fill

Unit 3: Tributary fan material
- 3f - soil A horizon
- 3e - soil Bk horizon
- 3b - soil C horizon
- 3a - silty sag-pond deposit

Unit 2: Gravelly colluvium of earliest event

Unit 1: Pre-faulting alluvium of Swift Creek (Pf1 fan surface)

5,540 ± 70 yr B.P.

8,090 ± 80 yr B.P.
The structure of the trench was dominated by one major fault strand, on which almost all of the stratigraphic displacement occurred (Figure 2.8, 13-17 m on log). A small synthetic fault displaces Unit 3 about 1.5 meters west of the main fault near the bottom of the trench. A wedge-shaped tension fissure containing vertically oriented rocks (Unit 4) is adjacent to the main fault plane 15-16 m from the west end of the trench. Sheared gravels and the unusually steep top of the Unit 2 colluvium suggest hanging-wall drag during a faulting event. A graben-like tension crack 0.5 meter wide about 7 meters east of the fault plane offsets Units 3 through 6, and thereby indicates extension in the trench during the latest event. Unit 1 dips into the fault plane and appears to be backtilted due to hanging-wall flexure. This argument is supported by the silty nature of the lowermost part of Unit 3 directly above it, which we interpret as a fine-grained sag-pond deposit.

Sequence of Faulting Events Interpreted from the Trench

Stratigraphic evidence from the trench confirmed that three distinct surface ruptures displaced the Swift Creek fan. The sequence of events begins with deposition of the Swift Creek fan gravels, which were displaced by the first surface rupture soon after deposition, before a soil formed. The height of the surface displacement of 4 meters was estimated by subtracting the 7 meters of surface displacement of the tributary fan (sum of the latest two events) from the 11 meters of total displacement (sum of the latest three events) of the Swift Creek fan. The Unit 2 colluvium was subsequently deposited from the receding scarp free face, and the lowermost Unit 3 silt was deposited into the sag created by backtilting of Unit 1. The Unit 3 alluvial fan (the tributary fan) next was deposited against the scarp. The fan surface then was stable long enough to develop a 50-cm-thick Bk horizon. The second rupture followed, and Unit 5 colluvium was deposited from the degrading free face. A surface offset of 4 meters for the second rupture was estimated by assuming that the height of the free face
was twice the thickness of the colluvial wedge [Ostenaa, 1984]. During the second rupture, the top of Unit 3 was faulted by the synthetic fault, the footwall block was eroded level with the hanging wall, and both were buried by the Unit 5 colluvial wedge. After Unit 5 stabilized, a soil A horizon formed prior to the deposition of Unit 6 and the final faulting event. The third rupture created a free face 3 meters high. This displacement was estimated by subtracting the surface displacement from the first two events, 8 meters, from the 11 meters of total surface offset of the Pf1 fan. Unit 7, scarp-derived colluvium, was deposited on the scarp surface by erosion of the free face, and has subsequently stabilized sufficiently that a cumulic A horizon could form.

Radiocarbon Ages and Numerical Chronology of Paleoseismic Events

Radiocarbon samples were taken from the A horizons of Units 3f and 5d to date the two most recent faulting events. Unit 3f is an organic horizon buried by the colluvial wedge of the second event, and Unit 5d is an organic horizon buried by scarp-derived colluvium of the third event. A radiocarbon age of 8,090 ± 80 (B-39700) yr B. P. post-dates the second event, and a radiocarbon age of 5,540 ± 70 (B-39701) yr B. P. post-dates the third event. These radiocarbon ages are raw ages, uncorrected for mean residence time or calendar years.

The timing of the earliest event could not be dated by radiocarbon material, but is based on the estimated age of the faulted Swift Creek fan and two factors of soil development:

(1) No soil developed in the Unit 1 gravel of the Swift Creek fan before it was faulted and buried by colluvium from the earliest fault scarp. To estimate rates of soil development, the elapsed time between the deposition of Unit 5 (from the second rupture) and the next (third) rupture was considered. A soil A horizon 20-40 cm thick formed in Unit 5 before being buried no more than 2,500 years later by colluvium from
the third rupture. The absence of an A horizon in Unit 1 suggests that considerably less than 2,500 years elapsed between deposition of Unit 1 and the first fault rupture.

(2) Unit 3 was deposited subsequent to the first event. Its degree of soil development (A, Bk, and C horizons) indicates that it was stable for a protracted time before burial after the second faulting event. Therefore, a much longer time span probably occurred between the first and second ruptures than the second and third ruptures. This analysis suggests that the first rupture was soon after deposition of the Pf1 surface of the Swift Creek fan. The Swift Creek fan surface is estimated to be late Pleistocene (ca. 10-15 ka) in age [Chapter 1 of this thesis; Piety et al., 1986]. Because the second event occurred ca. 8,100 ka, the first event must have occurred considerably before 10.6 ka (8,100 years + 2,500 years minimum), and probably closer to 12-15 ka. (Figure 2.9).

The late Quaternary slip rate of the SSVF can be calculated by dividing the net slip of the fault by the estimated age of the faulted deposits. The Pf1 fan surface has been offset 11 meters in ca. 12-15 ka, which yields slip rates between 0.73 mm/yr and 0.91 mm/yr. These rates are consistent with other active normal faults in the NWTC [McCalpin, 1990a, 1990b; McCalpin et al., 1990b; McCalpin and Forman, 1991].

Long-term slip rates for the SSVF were calculated by dividing the total net slip of 5.5 km of the SSVF [Coogan and Royse, 1990] by the minimum and maximum estimated ages of onset of extension in the northern Basin and Range, and more specifically the GV - SV fault system. If extension in the GV - SV fault system began at 10 Ma [Anders et al., 1989], the maximum long-term slip rate of the SSVF is 0.55 mm/yr. If the GV - SV system began to form contemporaneously with the northeastern Basin and Range at about 17 Ma [Stewart, 1972; Zoback et al, 1981; Eaton, 1982], a minimum slip rate of 0.32 mm/yr is estimated for the SSVF. The late Quaternary slip rates for the SSVF are about twice the long-term slip rates for the GV - SV system as a whole. Anders et al. [1989] concluded that a "collapse shadow" from the passing
Yellowstone hot spot is responsible for fault quiescence near the Snake River Plain, and that late Quaternary fault activity (e.g., the SSVF) increases progressively away from the plain.

Fig. 2.9. Temporal relations of paleoearthquakes along the SSVF.
Magnitudes of Paleoearthquakes

Previous work by Hanks and Kanamori [1979], Slemmons [1982] and Bonilla et al. [1984] contains earthquake-magnitude regression equations derived from historic earthquake data. These equations were used to estimate the magnitudes of prehistoric earthquakes generated by the SSVF. Parameters such as fault-rupture lengths and fault-scarp heights are entered into these equations (Table 2.2) to calculate magnitudes of prehistoric earthquakes.

Equations 1 and 2 in Table 2.2 relate the amount of surface displacement during an earthquake to its surface-wave magnitude. The amount of displacement for each prehistoric rupture on the SSVF was determined from trench stratigraphy and geomorphic relations of the scarp (see Sequence of Faulting Events Interpreted from the Trench).

TABLE 2.2. Equations used in calculations of Paleoearthquake magnitudes

<table>
<thead>
<tr>
<th>Equation</th>
<th>Expression</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>( M_s = 6.71 + 0.741 \log d ) (m)</td>
<td>Bonilla et al., 1984</td>
</tr>
<tr>
<td>2.</td>
<td>( M_s = 6.668 + 0.75 \log d ) (m)</td>
<td>Slemmons, 1982</td>
</tr>
<tr>
<td>3.</td>
<td>( M_s = 6.02 + 0.729 \log L ) (km)</td>
<td>Bonilla et al., 1984</td>
</tr>
<tr>
<td>4.</td>
<td>( M_s = 0.809 + 1.341 \log L ) (m)</td>
<td>Slemmons, 1982</td>
</tr>
<tr>
<td>5.</td>
<td>( M_w = 2/3 \log M_o - 10.7 ); ( M_o = M_{Ad} )</td>
<td>Hanks and Kanamori, 1979</td>
</tr>
</tbody>
</table>

Definitions:
- \( M_s \) = surface-wave magnitude
- \( M_w \) = seismic-moment magnitude
- \( d \) = vertical surface displacement in meters
- \( L \) = rupture length in meters or kilometers
- \( M_o \) = seismic moment
- \( M \) is the elastic modulus (\( 3 \times 10^{11} \) dynes/cm²) (Arabasz et al., 1979)
- \( A \) is the area of the fault plane (focal depth assumed 12 km, average dip of fault plane assumed 45°; see Figure 2.3)

Equations 3 and 4 relate the length of the fault's surface rupture with the magnitude of the surface waves. The minimum length of surface ruptures was
determined by examining the spatial distribution of late Quaternary fault scarps (which offset the Pf1 and Pf2 fan surfaces) along the SSVF. The northernmost fault scarp that offsets late Quaternary deposits is actually at the extreme southern end of the northern Star Valley fault (NSVF), at the mouth of Willow Creek (Figure 2.4), where 11.6 meters of offset are present on a length of the fault 3 km long. Along the SSVF late Quaternary fault scarps 9.0 to 11.3 meters high are present from Phillips Creek to Dry Creek, a distance of 14 km. The Willow Creek section of the fault is 3 km long, and included in the total Holocene rupture length because it is assumed that this part of the fault ruptured contemporaneously with the SSVF, and not independently. This assumption of synchronicity is based on two premises: (1) 11.6 meters of surface displacement on a 3 km long fault segment is highly inconsistent with worldwide surface-displacement data [Bonilla et al., 1984], and (2) although the 4-km, en-echelon stepover between the SSVF and the NSVF could be a segment boundary, across which a surface rupture would not propagate, De Polo et al. [1991] showed that about half of the historic surface ruptures in the western U.S. actually spanned what were previously considered segment boundaries. A comparison of the surface-rupture style of the SSVF-NSVF system with the 1983 Borah Peak earthquake surface ruptures [De Polo et al., 1991; Bruhn et al., 1991] showed close similarities (Figure 2.10). The Borah Peak surface ruptures are present north and south of a "segment boundary" 4 km wide, but are discontinous across that boundary. A similar geometry exists between the SSVF and NSVF, so it is reasonable that a rupture could indeed span this "boundary." Therefore, the minimum length of surface rupture was calculated to be 17 km, between Willow Creek and Dry Creek.

No late Quaternary fault scarps are present south of Dry Creek, possibly because no low-angle Pinedale fan surfaces cross the fault. The lack of fault scarps in the Cottonwood Creek Pf1 surface and the increasingly sinuous range front south of Dry Creek suggest that recent activity of the SSVF was limited to an area north of
Cottonwood Creek. Choosing a point to call the fault "inactive," i.e., the southern limit of late Quaternary activity, was somewhat arbitrary, but a point where the strike of the fault changes and the range-front sinuosity increases was chosen (Figure 2.4). This point yields a maximum offset length of 24 km.

Fig. 2.10. Comparison of SSVF late Quaternary fault scarps with surface ruptures of the Lost River fault during the 1983 Borah Peak (Ms7.3) earthquake [after DePolo et al., 1991]. Surface rupturing during the Borah Peak earthquake spanned a previously designated fault-segment boundary (TS = Thousand Springs segment, WS = Warm Springs segment).
Equation 5 of Table 2.2 combines the area of the fault plane, the surface displacement, and the seismic moment to give the seismic-moment magnitude ($M_w$), which is a direct representation of the radiated energy of an earthquake [Hanks and Kanamori, 1979]. The seismic moment ($M_o$) is calculated by multiplying the elastic modulus ($M$) by the area of the fault plane ($A$), and the amount of surface displacement ($d$). The elastic modulus of sedimentary rocks in the eastern Basin and Range region has been estimated as ca. $3 \times 10^{11}$ dynes/cm$^2$ [Arabasz et al., 1979]. To calculate the area of the fault plane, the minimum and maximum lengths of surface offset were used for the lengths of the fault plane (assumed rectangular), and the width was calculated by the formula $w = 12 \text{ km} / \sin 45^\circ$, where 12 km is the focal depth (i.e., bottom of the fault plane) and $45^\circ$ is the average dip (Figure 2.3).

Calculations of paleoearthquake magnitudes are shown in Table 2.3. Because the first two events had the same amount of surface displacement, their calculated magnitudes are similar. Separate calculations were made to include minimum and maximum rupture lengths, since it is unknown whether or not the entire SSVF ruptured during each event. Equations of surface displacement, from Bonilla et al. [1984] and Slemmons [1982], yielded estimated magnitudes of 7.2 and 7.1, respectively, for the first two events, and magnitudes of 7.1 and 7.0 for the third event. Equations of surface-rupture length, by Bonilla et al. [1984] and Slemmons [1982], yielded magnitudes of 6.9 and 6.5, respectively, for minimum rupture length, and 7.0 and 6.7 for maximum rupture length. The seismic-moment magnitudes were calculated for surface displacements of 4 and 3 meters along 17 and 24 kilometer rupture lengths. Moment magnitudes ranged from 6.9 for a displacement of 3 meters along a 17 km rupture to 7.1 for a displacement of 4 meters along a 24 km rupture.
<table>
<thead>
<tr>
<th>NET SLIP</th>
<th>RUPTURE LENGTH</th>
<th>ESTIMATED SEISMIC MOMENT Mo (dyne-cm)</th>
<th>ESTIMATED MOMENT MAGNITUDE Mw</th>
<th>ESTIMATED MAGNITUDE Ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVENTS 1, 2 4 m</td>
<td>17 km$^4$</td>
<td>3.50 x 10$^{26}$</td>
<td>7.0</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>24 km$^5$</td>
<td>4.99 x 10$^{26}$</td>
<td>7.1</td>
<td>7.0</td>
</tr>
<tr>
<td>EVENT 3 3 m</td>
<td>17 km$^4$</td>
<td>2.65 x 10$^{26}$</td>
<td>6.9</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>24 km$^5$</td>
<td>3.74 x 10$^{26}$</td>
<td>7.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

1from Hanks and Kanamori [1979]
2from Bonilla et al. [1984]
3from Slemmons [1982]
4minimum rupture length
5probable rupture length
The effects of active tectonism on the surficial deposits of southern Star Valley were analyzed through three questions:

1. Do the alluvial fans have normal areas and gradients compared with their basin sizes relative to data from previous works?

2. Do faulted fan surfaces have gradients steeper than, flatter than, or similar to those of the younger, unfaulted fan channels?

3. How has the course and gradient of the Salt River and its relationship with the southern Star Valley alluvial fans been affected by active tectonics?

Sizes of Alluvial Fans

Data from the southern Star Valley alluvial fans were compared with data for alluvial fans in California composed of sandstone and shale [Bull, 1964]. The southern Star Valley alluvial fans consist of 40-50% limestone, 40-70% sandstone, and <10% siltstone [Piety et al., 1986]. The alluvial fans of Cottonwood, Swift, and Dry creeks plotted smaller than, and the Phillips Creek fan similar, in sizes compared to basin areas of the data set of Bull [1964](Figure 2.11).

Gradients of Alluvial Fans

The gradients of the southern Star Valley alluvial fans plotted similar to the gradients of shaly alluvial fans of Bull [1964], despite dominantly sandstone and limestone compositions. The alluvial-fan gradients in this study were calculated by dividing the elevation change from the head to the toe of the fan, taken from contours with intervals of 20 feet, by the fan radius. Errors introduced during gradient calculations include toes of fans being removed or covered (i.e., incorrect radius) and
Fig. 2.11. Comparison of areas and gradients of southern Star Valley alluvial fans with alluvial-fan data of Bull [1964]. Dots represent fans of shaly lithologies; circles represent fans with sandstone lithologies. Clasts of southern Star Valley alluvial fans are 40-50% limestone, 40-70% sandstone, and <10% shale and siltstone. PC = Phillips Creek fan, SC = Swift Creek fan, DC = Dry Creek fan, CC = Cottonwood Creek fan.
subjective error from the large contour interval. However, the gradients of the southern Star Valley alluvial fans were within the range of scatter in the data set of Bull [1964].

*Faulted Versus Unfaulted Fan Gradients*

The gradient of the faulted fan surface (Pf1) was compared to the gradient of the unfaulted fan-channel alluvium. A profile was plotted along the unfaulted Holocene alluvial channel in the Swift Creek fan, then the heights of the faulted Pf1 surface above the channel were plotted on the profile (Figure 2.12) to determine whether the faulted and unfaulted surfaces converge, diverge, or are parallel. The transect from the distal to proximal ends of the fan (i.e., toward the fault zone) shows that the Pf1 surface diverges for 1.5 km, then converges with the Holocene channel for about 1 km, and then stays between 2 and 2.5 meters above the channel east to the fault.

*Tectonic Effects on the Salt River Alluvium*

The alluvium of the Salt River is in erosional and gradational contact with the distal margins of the range-front alluvial fans in southern Star Valley (Figure 2.4). The Salt River characteristics vary considerably from the southern to the northern ends of southern Star Valley. The Salt River is sinuous with a gradient of about 2.3% in the southern part of the valley, and slower and meandering with a gradient of about 0.7% in the northern part of the valley (Figure 2.13). Consequently, alluvium of the Salt River is cobbly and sandy in the south, and grades northward into pebbly, sandy, and silty alluvium.

A river-cut scarp 5 km long is present in the distal portion of the Cottonwood Creek fan from incision by the Salt River. The scarp is 5-6 meters high and fairly linear. In contrast, a 4-km long river-cut scarp in the distal Phillips Creek fan is 2-3 meters high and very sinuous from cutting by the meandering Salt River. A faint river-cut scarp is present in the southwest part of the Dry Creek fan, but none is present elsewhere in the Dry Creek or Swift Creek fans. The distal parts of the Dry and Swift
Fig. 2.12. Transect of Swift Creek alluvial fan at Afton, Wyoming, that shows differing heights between faulted fan surface (Pf1) and unfaulted (Holocene channel) parts of the fan. Backtilting of stratigraphic units was observed in a trench near the line of this transect. The transect follows the modern channel in the Swift Creek fan from west to east (Figure 2.4).
Fig. 2.13. Diagram which shows the relationship between the regimen of the Salt River and longitudinal extent of late Quaternary faulting in southern Star Valley. See text for discussion.
creek fans are located where the Salt River makes the transition from sinuous to meandering, and appear to be in equilibrium with the alluvium of the Salt River.

DISCUSSION OF TECTONIC GEOMORPHOLOGY

*Sizes of Alluvial Fans*

The smaller sizes compared to basin areas of the alluvial fans of Swift, Dry, and Cottonwood creeks may result from several influences. Recurrent faulting and down-dropping of the valley floor may cause the volume of the alluvial fans to be distributed more vertically instead of laterally, which would result in the alluvial fans being thicker with smaller areas. However, fault offset is not apparent in the Cottonwood Creek fan, and fans from Bull’s [1964] data set were also in a subsiding basin.

Another possibility for reduced fan size is that the distal parts of the fans have been covered by alluvium from the Salt River, or removed by erosion, which would reduce the areas of the fans. Erosion of the distal parts of the Cottonwood and Phillips creeks fans is evidenced by river-cut scarps, but the Phillips Creek fan plotted consistently with Bull’s [1964] data (Figure 2.11). The distal parts of the Swift and Dry creeks fans may be covered by alluvium of the Salt River, again reducing the fan area. Additional influences in alluvial fan size include error in determination of fan areas, and climatic and vegetational differences between the more humid Salt River Range and the study area in California of Bull [1964]. The sediment supply of the basins of the Salt River Range may be lower due to increased vegetational cover or lower peak storm runoff, which would result in less transportable material and smaller fans.

In addition to the southern Star Valley alluvial fans being somewhat small in size, the Cottonwood and Dry creek fans are asymmetric. Most of the areas of these fans are distributed north of the respective canyon mouths, and the Holocene channels in the fans trend northwest (Figure 2.4). The asymmetry is likely due to increased late
Quaternary fault offset on the SSVF from Dry Creek northward, and no observable Quaternary offset at the south end of the fault. The increased subsidence of the north end of southern Star Valley caused the deposition from the mouths of Dry and Cottonwood Creeks to be directed northwesterly into the deepest (most subsided) part of the basin.

**Gradients of Alluvial Fans**

The gradients of the southern Star Valley alluvial fans were comparable to gradients of shaly alluvial fans in California, but lower than the gradients of sandstone fans [Bull 1964]. This comparison is anomalous because the southern Star Valley fans are dominantly sandstone and limestone. The fan gradients were calculated by dividing the fan height by fan radius, yet the radius may have been reduced by removal or burial of the distal portion of the fan. However, such error should result in increased gradients for the southern Star Valley fans. The low gradient of the southern Star Valley alluvial fans may be explained by rotation into the plane of the SSVF; however, this hypothesis does not explain the low gradient of the Pf1 surface of the Cottonwood Creek fan, which has not been faulted.

**Faulted Versus Unfaulted Fan Gradients**

In the Afton trench, backtilted stratigraphy near the fault zone (Figure 2.8) supports the hypothesis of local backtilting of the fan surface due to hanging-wall flexure. The comparison of the faulted Pf1 surface and the unfaulted Holocene channel does not show substantial convergence near the fault, which suggests that hanging-wall flexure has not been substantial farther away (up to 1.5 km or so) from the fault. The Holocene channel, although unfaulted, may be influenced by fluctuations in its local base level (the Salt River alluvium), which would result in different depths of incision into the Pf1 surface.
**Tectonic Effects on the Salt River Alluvium**

The changes in stream regimen of the Salt River can be related to the amount and spatial distribution of late Quaternary offset along the SSVF. Late Quaternary fault scarps are present in southern Star Valley from Phillips Creek southward to Dry Creek (Figure 2.13). The fault scarps suggest that the northern part of southern Star Valley has subsided more in relation to the extreme southern part, due to no late Quaternary offset on the SSVF south of Dry Creek. In addition, no fault scarps are present north of Willow Creek in northern Star Valley, which suggests a lack of late Quaternary faulting there. The overall geometry of southern Star Valley may then be thought of as a tectonic basin created by differential fault offset, with the deepest parts between Phillips and Dry creeks.

Two hypotheses were proposed to explain the meandering-river pattern associated with a low gradient, apparent aggradation, and near-surface water table at the northern end of the valley: (1) the rate of downcutting of the Salt River through the limestone and sandstone of "The Narrows" at the north end of the valley is less than the rate of valley subsidence; or (2) the increased subsidence of the north end of the valley has caused the river to slow considerably as it flows through the deepest part, or "bottom" of the basin.

To determine which hypothesis is more favorable, the position of The Narrows was examined in relation to the fault scarps to determine if it is also undergoing subsidence along the active part of the SSVF (Figure 2.13). The Narrows is near the active part of the SSVF and south end of the NSVF, about 5 km east of Willow Creek (Figure 2.4). This position suggests that the narrows is subsiding along with the valley, therefore the Salt River is not necessarily constricted trying to cut through The Narrows. Instead, the Salt River is entering the deepest part of southern Star Valley. Consequently its gradient is lowered, its alluvium is sandy and silty, and its channel pattern becomes meandering.
The different styles of the river-cut scarps in the Phillips and Cottonwood creeks fans can be related to the different stream regimens of the Salt River. The river-cut scarp in the Cottonwood Creek fan appears to have resulted from downcutting by the Salt River as it flows into the down-dropping north end of the valley. In contrast, the river-cut scarp in the Phillips Creek fan appears to be laterally cut by the slow, meandering Salt River in the "bottom" of the basin.

CONCLUSIONS

Fault scarps in late Pleistocene and Holocene alluvium in southern Star Valley yield evidence for late Quaternary movement along the southern segment of the Star Valley fault. A trench across a late Quaternary fault scarp along the SSVF revealed three distinct surface ruptures associated with paleoearthquakes since late Pleistocene time (ca. 15 ka). Radiocarbon ages constrained the two latest events at ca. 8,090 ± 80 yr B. P. and 5,540 ± 70 yr B. P., respectively. The earliest event was estimated at ca. 12-15 ka from lack of soil formation in the faulted and buried late-Pleistocene alluvial fan (Pfl) surface. A well-developed soil in a deposit which formed during a period of fault quiescence between the earliest and second events also indicates that the earliest event happened soon after deposition of the late-Pleistocene fan. The late Quaternary slip rate of the SSVF was calculated to be between 0.73 mm/yr and 0.91 mm/yr, about twice as great as the long-term slip rate calculated for the GV - SV fault system. Estimated heights and lengths of surface ruptures yielded calculated magnitudes generally between 6.9 and 7.1 of paleoearthquakes generated by the SSVF, from regression equations derived from worldwide data.

Alluvial-fan areas and gradients plotted fairly consistently with data from previous studies, which suggests that late Quaternary faulting has not substantially affected fan geometry. The asymmetry of the alluvial fans and analysis of the alluvium and stream characteristics of the Salt River suggest that more fault offset between Dry
and Phillips creeks has resulted in the north end of southern Star Valley being deepest and acting as a depocenter. Consequently, the Salt River has a lower gradient, meandering channel, and fine-grained alluvium there.

A controversy exists over the subsurface geometry and seismicity of extensional faults in the Wyoming-Idaho thrust belt, and the subsurface geometry of the SSVF remains unresolved. Stratigraphic evidence in the Afton trench showed that individual surface ruptures of the SSVF were up to 4 meters high. Therefore, it is presumed that the movement along the southern Star Valley fault occurs dominantly as seismic slip, and the fault is capable of generating large-magnitude earthquakes.
REFERENCES


McCalpin, J. P., Quaternary geology and neotectonics of the west flank of the northern Sangre de Cristo Mountains, south-central Colorado, Colorado School of Mines Quarterly 77, 97 pp., 1983.


CHAPTER 3

Late Pinedale and Neoglacial moraines, present in two valleys in the southwest Salt River Range, are assigned relative ages based on topographic positions and comparison of RD values with other works. The RD technique proved useful in subdivision of local deposits into age groups using statistical analysis. In long-distance regional correlation, the RD technique was not as successful because weathering processes and the range of RD values are quite different for sedimentary lithologies in our study area compared to those encountered in more commonly studied deposits of crystalline-rock provenance. With cluster analysis, the magnitude of differences of RD values was sufficient to distinguish late Pinedale from Neoglacial deposits, and early Neoglacial from late Neoglacial deposits. Some subgroups on the dendrogram appeared lithologically dependent (sandstone compared to limestone), which suggests that lithologic differences create substantial weathering differences among deposits of the same age. Some RD values gave counter-intuitive results, such as inner slope angles, which were found on average to be higher on Pinedale moraines than on Neoglacial moraines. However, this anomaly is probably due to post-depositional modification of older moraines by such processes as stream incision.

Weathering-rind thicknesses from quartzarenite clasts, when correlated with measurements from a single previous study in sedimentary lithologies, suggested that rinds may be useful in establishing long-distance correlations between glacial deposits composed of similar sedimentary lithologies. Rind thicknesses were sufficiently different to distinguish between Neoglacial and late Pinedale deposits, but not to subdivide Neoglacial deposits.

It was necessary to establish the late Quaternary chronology to determine the sequence of late Quaternary faulting that offsets the surficial deposits of southern Star Valley. Fault scarps in the late Pleistocene and Holocene alluvium in southern Star
Valley yield evidence for late Quaternary movement along the southern segment of the Star Valley fault (SSVF). A trench across a late Quaternary fault scarp along the SSVF revealed three distinct surface ruptures associated with paleoearthquakes since late Pleistocene time (ca. 15 ka). Radiocarbon ages constrained the two latest events at ca. 8,090 ± 80 yr B. P. and 5,540 ± 70 yr B. P., respectively. The earliest event was estimated at ca. 12-15 ka from lack of soil formation in the faulted and buried late Pleistocene alluvial-fan surface. A well-developed soil in a deposit which formed during a period of fault quiescence between the earliest and second events also suggests that the earliest event happened soon after deposition of the late-Pleistocene fan. The late Quaternary slip rate of the SSVF was calculated to be between 0.73 mm/yr and 0.91 mm/yr, about two orders of magnitude greater than the long-term slip rate calculated for the GV - SV fault system. Estimated heights and lengths of surface ruptures yielded calculated magnitudes between 6.9 and 7.1 of paleoearthquakes generated by the SSVF, from regression equations derived from worldwide data.

Alluvial-fan areas and gradients plotted fairly consistently with data from previous studies, which suggests that late Quaternary faulting has not substantially affected fan geometry. Analysis of the alluvium and stream characteristics of the Salt River suggests that distribution of faulting has created a small "tectonic basin" in the north end of southern Star Valley. Consequently, the Salt River has a lower gradient, meandering channel, and fine-grained alluvium there.

A controversy exists over the subsurface geometry and seismicity of extensional faults in the Wyoming-Idaho thrust belt, and the subsurface geometry of the SSVF remains unresolved. Stratigraphic evidence in the Afton trench showed that individual surface ruptures of the SSVF were up to 4 meters high. Therefore, it is presumed that the movement along the southern Star Valley fault occurs dominantly as seismic slip, and the fault is capable of generating large-magnitude earthquakes.
APPENDICES
Appendix A:

Description of Map Units

Valley deposits:

Hal - Gray, tan, pink, and red sandy gravel; clasts: 40 cm max, 5-15 cm avg., round-subround, poorly sorted; discontinuous very coarse sand matrix; very loose, some upstream imbrication; in channels incised up to 4 meters into Pf1 surface.

Hal of Salt River:
south end of valley - Sandy gravel; clasts: 30 cm max, 10-20 cm avg., well rounded to subround, poorly sorted; medium to very coarse sand matrix, clast-dominated; alluvium of Salt River, some terraces.
north end of valley - Gravel, sand, and silt; clasts: 30 cm max, 5-10 avg., round to subround, moderately sorted; sandy and silt matrix; clay layer one meter below floodplain; alluvium varies considerably between pools and riffles; alluvium of Salt River.

Haf2-4 - Reddish brown (10YR4/4) gravel, sand, and silt; clasts: 18 max, 3-5 avg., poorly sorted, angular-subangular; very coarse to fine sand matrix; friable, oxidized; steep alluvial cones from range-front drainages, relatively numbered.

Haf1 - Moderate brown (5YR4/4) gravel, sand, and silt; clasts: 20 cm max, 3-8 avg., angular-subangular, very poorly sorted; fine to coarse sand matrix; friable, oxidized, CaCO₃ stringers, thin loess cap; alluvial fans from smaller, non-glaciated drainages graded to Pf1.

Pf2 - Dark, yellowish brown (10YR4/2) to pale red (10YR6/2) sandy gravel; clasts: 60 cm max, 5-15 avg., well-rounded to subround, poorly sorted; sandy, silty matrix; friable, some upstream imbrication, A horizon development; alluvial distributary channels incised 1.5 - 2.0 meters into Pf1.

Pf1 - Brownish gray (10YR4/2) gravel, sand, and silt; clasts: 35 cm max, 5-15 avg., well rounded to subrounded, poorly sorted; medium to very coarse sand matrix; friable, some upstream imbrication, 40 cm thick loess cap; forms broad, flat fan surfaces.

pPf - Brownish gray (10YR4/2) sand and silt; 2-4 cm rounded clasts below 2 meters; upper 2 meters is sand and silt; friable; eroded fan remnants 3-5 meters above Pf1 on Cottonwood Creek fan.

Mountain deposits:

Nrg - Gray quartzite boulders; clasts: 150 cm max, 10-30 cm avg., angular, very poorly sorted; no matrix; tongue-shaped rock glaciers.

Npr - Pink (5R6/2) sandy gravel, clasts: 210 cm max., 40-60 cm avg., angular to subangular, poorly sorted; very fine to coarse sand matrix; friable, weak soil; linear protalus ramparts below walls of talus.
Appendix A cont.

Nta - Pink, gray, red, buff, and pink gravel; clasts: 300 cm max, 10-100 avg., angular to subangular, very poorly sorted; no matrix; some wind-blown sand and silt; non-vegetated; talus lining north-facing cirque headwalls.

Ntc - same as Nta, but cone-shaped with occasional debris-flow levees and channels present.

Nt4 - Pink, gray, and buff gravel and windblown silt; clasts: 200 cm max, 10-30 cm avg., angular-subangular, very poorly sorted; some fine sandy and silty matrix; friable, slight loess cap; ridges closest to cirque headwall, maybe very young protalus ramparts.

Nt3 - Pink and tan (5YR6/2) gravel, sand, and silt; clasts: 130 cm max., 10-30 cm avg., angular-subangular, very poorly sorted; coarse to fine sand matrix; friable, slight soil development, curvelinear moraines in cirques.

Nt1-2 - Moderate reddish-brown (10YR4/6) gravel, sand, and silt; clasts: 120 cm max, 20-40 avg., subangular, poorly sorted; very fine to coarse sandy matrix; friable, curvelinear moraines in cirques.

Pta - Gray, red, buff, and pink gravel and sand; clasts: 150 cm max, 10-50 cm avg., angular, very poorly sorted; sandy matrix; friable; vegetated with grass and trees; talus in south-facing cirques that did not contain Holocene ice bodies.

Po - Gray, pink, red gravel and sand; clasts: 80 cm max, 10-15 cm avg., well-rounded to subrounded, moderately sorted; sandy matrix; friable, some upstream imbrication; outwash terraces 1-2 meters above active stream channels in valleys below glacial limits.

Ppr - Brownish gray (10YR5/2) gravel, sand, and silt; clasts: 150 cm max, 15-50 cm avg., subangular, poorly sorted; sandy matrix; friable, moderate soil development, vegetated; linear ridges at base of older taluse deposits.

Pt - Brownish gray (10YR5/2) gravel, sand, and silt; clasts: 180 cm max, 10-30 cm avg., subrounded, poorly sorted; sandy and silty matrix; friable, moderate soil development with Bt or Bk horizons, large moraines up to 2 km long.

Bt (?) - Gray and buff gravel; clasts: 80 cm max, 10-20 avg., subrounded to subangular, poorly sorted; matrix is carbonate cement; non-friable, loess cap; possible older cemented till or debris flows.

S - Gray, pink, buff, and red gravel, sand, and silt; clasts vary greatly between deposits, up to 150 cm max, usually average about 15-30 cm, angular to subrounded, very poorly sorted; sandy to silty to matrix, some young deposits have no matrix; friable, various degrees of soil development due to time-transgressive deposits; slump type landslides of various ages and morphologies.
Appendix A cont.

Qda - Brownish gray (10YR4/2) gravelly sand; clasts: >200 cm max, 20-40 cm avg., subround to subangular, poorly sorted; sandy and silty matrix; friable, various degrees of soil development due to time-transgressive deposits, unstratified; multiple generations of hummocky, valley-bottom debris avalanches.

Qlc - Brown to tan pebble-gravel, sand, silt, and clay; stratified layers, some organic muck, some peat; lacustrine sediments.

Qac - Red, buff, or gray gravel and sand; clasts: 30 cm max, 2-5 avg., angular to subangular, moderately sorted; fine to coarse sand matrix; friable, various soil development; alluvial/colluvial aprons of slpewash material often on dipslopes.

Tsl - Salt Lake Formation; tuff and tuffaceous conglomerates

PMb - Paleozoic and Mesozoic bedrock; chiefly limestones, sandstones, and siltstones
Appendix B

Description of Afton Trench Units

Unit 1a and b - Pinkish tan sandy gravel; clasts: 55 cm max, 15-20 cm avg., well rounded, poorly sorted; coarse sand to pebble matrix; very friable to slightly friable, no imbrication or structure, clay coatings on gravel; Alluvium of Swift Creek.

Unit 1c - Pink, gravelly, sandy, and silty transition zone between 1b and 3a in lower part of trench.

Unit 2 - Pink, gravelly, clast-rich colluvium in pink sandy matrix; very friable; only extreme upper part exposed in bottom of trench; Scarp-derived colluvium of second rupture.

Unit 3a - Tan silt; well-sorted, moderately friable, massive; Sag-pond deposit.

Unit 3b - Soil Ck horizon developed in sandy gravel; clasts: 20 cm max, 10 cm avg., well rounded and moderately sorted; sandy matrix, clasts west-dipping; Distal tributary fan material in part mixed with scarp-derived colluvium.

Unit 3c - Stony soil similar to Unit 3b, but clast-rich.

Unit 3d - Pinkish-tan sandy gravel; clasts: 25 cm max, 5-8 avg., well rounded, poorly sorted; very coarse sand to silt matrix; moderately friable; Small locally derived debris-flow.

Unit 3e and 3f - Soil Bk and A horizons developed in upper sandy and silty tributary fan material.

Unit 4a - Very coarse pebbly, sand with pink clay coatings; friable, platy pebbles 40° 50° west-dipping; sheared pebble-gravel near fault zone.

Unit 4b - Pink, clay-coated sandy gravel; clasts: 32 cm max, 5-8 cm avg., rounded, poorly sorted; very coarse sand and granule matrix; very friable, clasts steeply dipping; Gravelly tension-crack fill.

Unit 5a - Pinkish-tan sandy and pebbly gravel; clasts: 50 cm max, 10-20 cm avg., well rounded, poorly sorted; very coarse sand and granule discontinous matrix; friable, platy clasts 20° west-dipping; Scarp-derived colluvium from causative free face.

Unit 5b - Cobbly gravel; clasts: 26 max, 5-8 avg., well rounded, moderately sorted; no matrix; carbonate coatings on clasts; Open-work colluvium.

Unit 5c - Pinkish-tan, granular coarse sand, with minor fine sand and silt; moderately friable, moderately organic in upper part; some pebble layers dipping 20° west, Sandy scarp-derived colluvium.

Unit 5d - Sandy and silty soil A horizon developed in colluvium.
Appendix B cont.

Unit 6 - Light-brown, friable, sandy gravel; Locally derived debris flow deposited on base of scarp.

Unit 7a - Gray gravelly sand; clasts:18 cm max, 5-10 avg., rounded, poorly sorted, 30-50% clasts; very fine to coarse sandy matrix; friable, mildly organic; Stony scarp-derived colluvium of latest rupture.

Unit 7b - Sandy and silty, cumulic, soil A horizon developed in colluvium.

Unit 7c - Gravelly, sandy, organic slopewash along scarp face, grades downslope into Unit 7a.

Unit 7d - Sandy and silty soil A horizon that grades laterally into Unit 7b.

Soil Descriptions:

Unit 7d - Dark brown (10YR3/4 moist color) loam, very weak fine granular, very friable, slightly sticky and slightly plastic, no effervescence, 5-10% pebbly clasts.

Unit 7b - Very dark brown (10YR2/1 moist color) loam, weak medium to coarse granular, friable, slightly sticky and slightly plastic, no effervescence, < 5% clasts.

Unit 5d - Very dark brown (10YR2/1 moist color) loam, weak very fine granular, loose, friable, slightly sticky and slightly plastic, effervesces slightly, 80% gravelly clasts.

Unit 3f - Dark brown (10YR3/3 moist color) loam, massive, hard, firm, slightly sticky and slightly plastic, slight effervescence, 5% angular pebbles.

Unit 3e - Yellowish brown (5YR4/6 moist color) sandy loam, massive, hard, firm, sticky and non-plastic, effervesces strongly, CaCO₃ stringers, 10% angular pebbles.

Unit 3b - Yellowish brown (5YR4/6 moist color) sandy loam, massive, slightly hard, firm, slightly sticky and non-plastic, effervesces strongly, no CaCO₃ stringers, 5% angular clasts.
SURFICIAL GEOLOGIC MAP OF SOUTHERN STAR VALLEY
LINCOLN CO., WYOMING
by
GREG WARREN
1991
**PLATE 1.2**

**EXPLANATION**

NORMAL FAULT: DASHED WHERE INFERRED, DOTTED WHERE CONCEALED; HACHURES REPRESENT LATE QUATERNARY SCARPS (TEETH ON DOWNTHROWN SIDE) U = UPTHROWN SIDE, D = DOWNTHROWN SIDE

CONTACT BETWEEN STRATIGRAPHIC UNITS; DASHED WHERE INFERRED, DOTTED WHERE CONCEALED

LIMITS OF GLACIATION, TEETH ON UNGLACIATED SIDE

MORaine CREST OR RIDGE

BOG OR LAKE

RIVER-CUT SCARP; HACHURES ON UPHILL SIDE

TRENCH SITE

**MAP UNITS**

- **Nrg** - Neoglaciar rock glacier - tongue-shaped deposits of angular boulders
- **Npr** - Neoglaciar protalus rampart - ridges of boulders, gravel, and sand at the bases of talus slopes
- **Nta** - Neoglaciar-age talus - angular boulders mantling steep cirque walls
- **Ntc** - Neoglaciar talus cone - steep, alluvial cones formed by combination rockfall/alluvial processes
- **Hal** - Neoglaciar till - hummocky, arcuate ridges of subangular boulders, sand, and silt confined to cirques; relatively numbered according to topographic positions; 1 is oldest and 4 is youngest
- **Haf** - Holocene alluvium - rounded gravel and sand in incised alluvial-fan channels (Pf1-2) and in stream valleys incised into Po
- **Haf-1** - Holocene alluvial fan - angular and subangular gravel, sand, and silt deposited from steep tributary drainages; higher subscripts represent relatively younger fans
- **Qda** - Debris-avalanche deposits - hummocky, slightly weathered, subangular to angular boulders, sand, and silt in valley bottoms
- **Qac** - Alluvial/colluvial slopewash - angular gravel, sand, and silt mantling hillslopes, especially large dipslopes
- **Qlc** - Lacustrine deposits - silt and clay in ponded areas and kettles
- **EHt** - Early Holocene/latest Pleistocene till-like deposits - ridge-like deposits of subangular boulders, sand, and silt
- **Ppr** - Pinedale protalus rampart - ridges of slightly weathered subangular boulders and sand
- **Pta** - Pinedale-age talus - vegetated, stabilized, subangular boulders, sand, and silt mantling cirque walls that contained Pinedale glaciers
- **Pt** - Pinedale till - large, forested, lateral and ground moraines of slightly weathered, subround boulders, sand, and silt
- **Po** - Pinedale outwash - terraces of rounded gravel and sand in stream valleys below glacial limits
- **Pf1** - Pinedale alluvium - large alluvial fans of round gravel and sand, surfaces relatively dated by heights above modern channel (Hal); Pf1 is larger, older surface, Pf2 are younger channels incised into Pf1
- **Pt?** - Pre-Pinedale (Bull Lake?) till - carbonate-cemented, subround, boulders underlying Pinedale till in the canyon walls of Cottonwood Creek
- **pPr** - Pre-Pinedale alluvial fan - topographically higher, loess-covered, dissected fan remnants on the Cottonwood Creek Pf1 surface
- **S** - Slide - undifferentiated slumps and blockslides of subangular to angular boulders and sand
- **Tsl** - Salt Lake and Long Springs formations - tuff and tuffaceous conglomerates
- **Pmb** - Paleozoic and Mesozoic bedrock - limestones, sandstones, and siltstones

**CORRELATION OF MAP UNITS**

<table>
<thead>
<tr>
<th>BEDROCK</th>
<th>GLACIAL DEPOSITS</th>
<th>ALLUVIAL DEPOSITS</th>
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**BEDROCK**

**GLACIAL DEPOSITS**

**ALLUVIAL DEPOSITS**

**LACUSTRINE DEPOSITS**

**MASS MOVEMENTS**
Plate 2.1

Explanatory legend:

- Symbols:
  - Fault
  - Fracture
  - Contact
  - Rock
  - Sample
  - Bottom of Bk horizon

- Lithologic symbols:
  - Very coarse sand and gravel
  - Stony colluvium
  - Sandy colluvium
  - Pebbly sand
  - Silt
  - A horizon

- Stratigraphic units:
  - Colluvium from latest event:
    - Soil A horizon
    - Slope colluvium
    - Cumulic A horizon
  - Colluvium from penultimate event:
    - Soil A horizon
    - Sandy colluvium
    - Matrixless stony colluvium
  - Colluvium from earliest event:
    - Soil A horizon
  - Locally derived debris flow
  - Alluvial fan of small tributary:
    - Soil A horizon
    - Soil B horizon
    - Debris flow lens
    - Stony soil
    - Soil C horizon
  - Pre-faulting alluvium of Swift Creek:
    - Transition zone to overlying silt
    - Cobble stream gravel (upper)
    - Cobble stream gravel (lower)

Log of trench at Swift Creek, Afton, Wyoming
Logged in May, 1990
By Greg Warren, James McCalpin, and Allen Jones
Department of Geology Utah State University
Funded by USGS-NEHRP Contract 14-08-0001-G1396