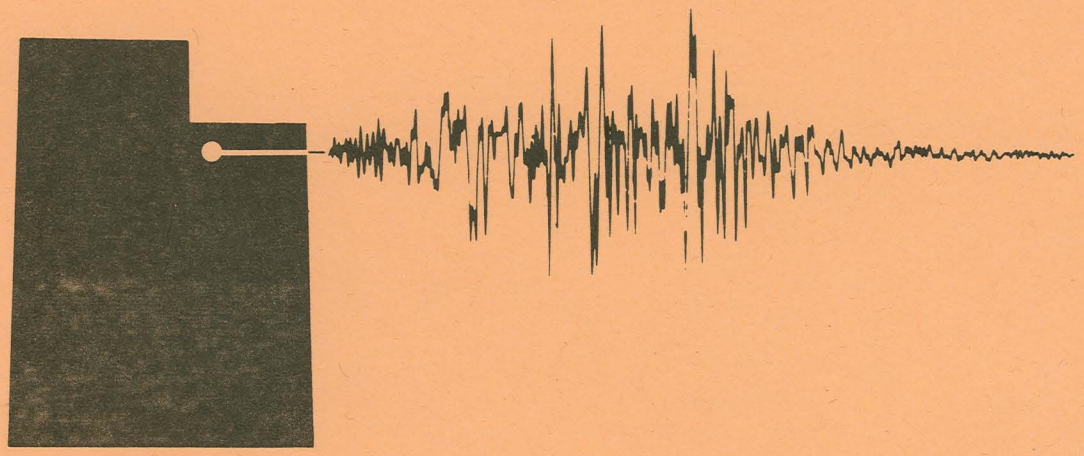

# Seismotectonic Study

## for
## Taskeech Dam and Reservoir Site
## and
## Upper Stillwater
## Dam and Reservoir Site
## Central Utah Project, Utah

U. S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
ENGINEERING AND RESEARCH CENTER
SEISMOTECTONIC SECTION
DENVER, COLORADO

# SEISMOTECTONIC STUDY FOR TASKEECH DAM AND RESERVOIR SITE UPALCO UNIT AND UPPER STILLWATER DAM AND RESERVOIR SITE BONNEVILLE UNIT CENTRAL UTAH PROJECT, UTAH

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Seismotectonic Section
Geologic Services Branch
Division of Geology
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## SUMMARY OF CONCLUSIONS

Taskeech and Upper Stillwater damsites are located along the south flank of the Uinta Mountains in north-eastern Utah on the Lake Fork River and Rock Creek, respectively. The proposed Taskeech Dam will be located about 40 km (25 mi) north of the city of Duchesne and is presently planned to be constructed of rolled earthfill to a height of about 68 m (223 ft). The proposed Upper Stillwater Dam will be located about 23 km (14 mi) west of Taskeech Dam and will be a gravity structure of roller-compacted concrete and be constructed to a height of 82 m (270 ft).

Taskeech and Upper Stillwater damsites lie within the eastern limits of the ISB (Intermountain seismic belt), a north-trending zone of diffuse but locally intense seismicity that extends for over 1300 km (800 mi) from southern Utah to northern Montana. The largest earthquake to have occurred within the ISB during historic times was the M 7.5 Heben Lake, Montana earthquake of 1959. Within Utah, earthquakes as large as M 6.6 have occurred since settlement in 1847. In the region of the damsites, two earthquakes in the magnitude range 4.5 to 5.0 have occurred within 7 km of Taskeech damsite, one in 1950 and another in 1977.

The ISB is also characterized by abundant geologic evidence for late Quaternary surface faulting. In central and northeastern Utah, this evidence can be found on the Wasatch, Strawberry, and Stinking Springs faults and on the faults on Towanta Flat near Taskeech damsite. The Wasatch, Strawberry, and Stinking Springs faults are believed to be capable of generating earthquakes in the 6.5 to 7.5 magnitude range with associated surface faulting. The faults on Towanta Flat are shown in this report to have long recurrence intervals of surface faulting; therefore, the liklihood of future surface faulting is judged to be sufficiently remote as to be of no consequence to the design of the dams.

Major geologic features in the vicinity of the damsites include the generally east-trending South Flank and Uinta Basin faults and a system of north-trending faults that are orthogonal to the east-west structural grain developed in the early Cenozoic. The north-trending faults are typically concealed features exhibiting little or no surface expression. Their existence, however, has been inferred from microseismic monitoring, as has been shown, for example, with the identification and delineation of the Bear Wallow fault during this study. The Bear Wallow fault is a north-trending blind structure that is believed to be the causative fault for the 1950 and 1977 earthquakes near Taskeech damsite. This fault, like the other north-trending faults, does not appear to have the capability to generate surface faulting earthquakes. However, because the dominant contemporary stress field in the ISB in Utah is east-west extension, faults with this orientation are likely candidates for future moderate-sized earthquakes. The Bear Wallow fault is assigned an MCE (maximum credible earthquake) of magnitude 6.0.

Based on geologic mapping described in this report, there has been no late Quaternary and probably no late Cenozoic surface displacement on the South Flank fault in the region near the damsites; therefore,

magnitude 6.5 to 7.5 earthquakes and associated surface faulting on the South Flank fault should not be considered credible. However, based on the occurrence of both historical felt earthquakes and continuing microearthquake activity in the region, an MCE of M 6.0 as a random earthquake is recommended. An epicentral distance of 2 km from Upper Stillwater Dam is assigned to this MCE to account for the possibility of a moderate-magnitude earthquake occurring on the South Flank fault. The Uinta Basin fault is completely buried and was not amenable to study. Its apparent structural relationship with the South Flank fault and its east-west strike indicate that as a preexisting zone of weakness it also has the capability to generate moderate-sized earthquakes under the current stress field.

Surface rupture has not been associated with earthquakes of magnitude 6.5 or less in Utah. Therefore, surface rupture or other significant topographic changes are not expected to accompany a magnitude 6.0 earthquake in the vicinity of either Taskeech or Upper Stillwater Dams.

# 1. Introduction

This report presents the results of a Bureau of Reclamation seismotectonic evaluation for the proposed Taskeech and Upper Stillwater Dams and Reservoir sites, Central Utah Project, Utah (fig. 1.1). A study was conducted by the Seismotectonic Section, Geologic Services Branch, for the specific purpose of assessing potential seismic hazards for consideration in the design of the subject dams.

## 1.1 Objectives

Study objectives included:

a. Outline the regional geology and tectonic setting of the project area

b. Evaluate the historic seismicity of the region

c. Assess the age and earthquake potential of: (1) the South Flank fault and related faults, (2) faults on Towanta Flat, and (3) other faults significant to Taskeech and Upper Stillwater damsites

d. Estimate the magnitudes, epicentral location, and recurrence intervals of earthquake sources for design purposes

e. Evaluate the potential for other seismically induced hazards

## 1.2 Scope

Our investigations included:

a. Review of existing geological and seismological literature

b. Interpretation of aerial photography

c. Field geologic mapping

d. Regional geologic investigations (including both aerial and ground reconnaissance surveys)

e. Topographic profiling of fault scarps

f. Subsurface investigations (including exploratory trenches and soil pits)

g. Analysis of soil and fossil samples for dating

h. Electrical resistivity profiling

i. Microseismic monitoring and analysis

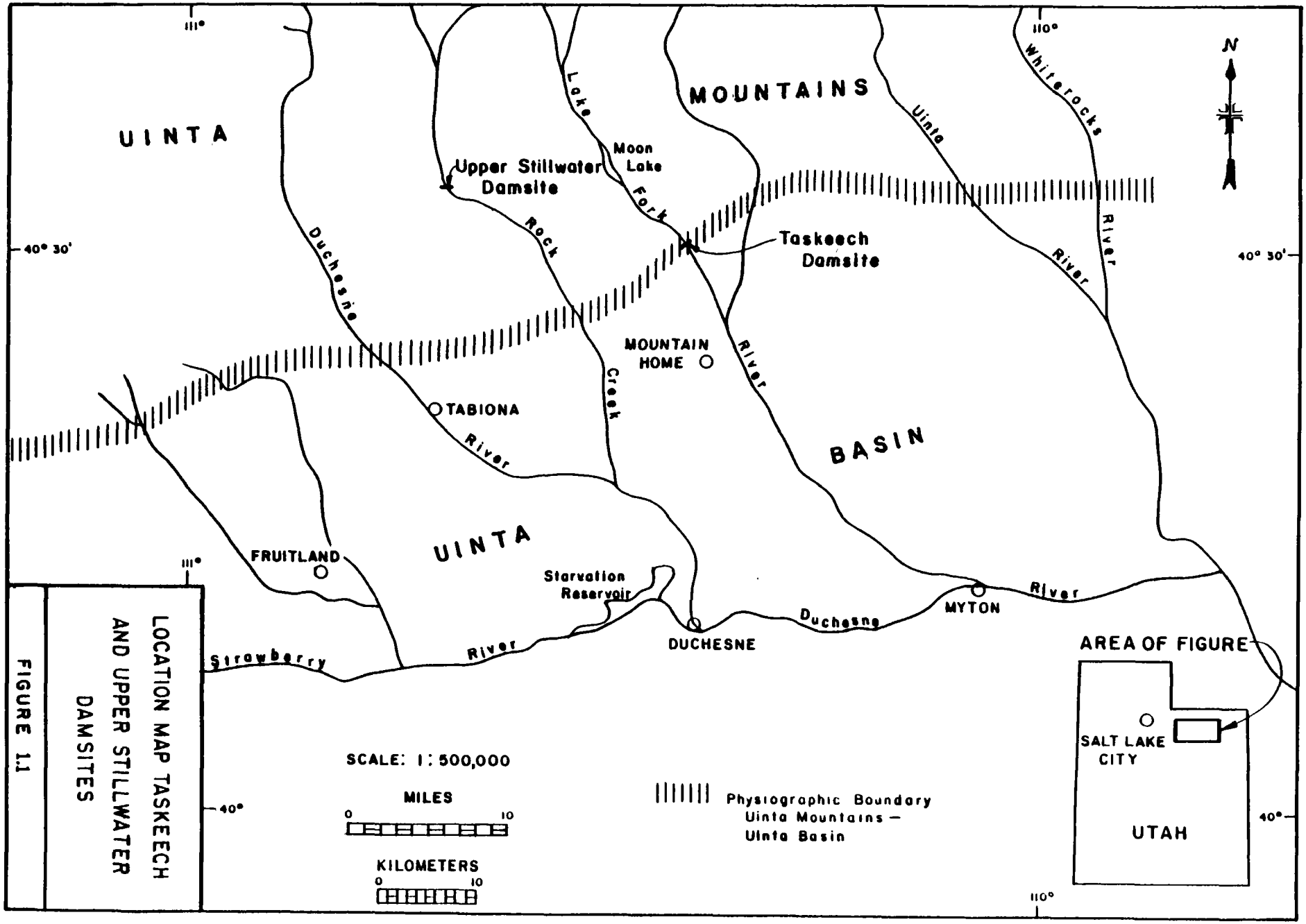



FIGURE 1.1 LOCATION MAP TASKEECH AND UPPER STILLWATER DAMSITES

j. Analysis of historic seismicity

## 1.3 Acknowledgments

This report was prepared by Rick Martin, Rod Weisser, Alan Nelson, and Tim Sullivan of the Seismotectonic Section, Geologic Services Branch, E&R Center. Although this report was edited and revised slightly during the second half of 1984 and early 1985, the main body of this report, analysis methods, and conclusions were developed and written during 1981 and 1982. Geologic fieldwork was completed by Rod Weisser (regional geology, mapping, and trench studies) and Alan Nelson (Quaternary geology) in 1980 with assistance from Bob Bridges and Dan Grundvig, Upper Colorado Region staff geologists; Jim Rogers and Steve Beason, Uinta Basin Construction Office staff geologists; and Jack Touseull, rotation engineer, E&R Center. The microseismic monitoring program was conducted in 1980 by Rick Martin with field and data processing assistance from John Michaels of the E&R Center and with field assistance from Russ Owens and Steve Oswill of the Uinta Basin Construction Office.

Arrangement of right-of-way, archeological and environmental clearances, trench and soil pit excavation, shoring and fencing operations, and provision of other necessary logistical support from Project Construction Engineer William White and Project Geologist Mike Deming were essential to the accomplishment of this effort. Sharing of data and ideas developed by other ongoing investigations at the Taskeech and Upper Stillwater damsites by Mike Deming and Jim Rogers are greatly appreciated.

Discussions with Howard Ritzma and Bruce Kaliser of the Utah Geological Survey and Bruce Bryant of the U.S. Geological Survey, Denver, were helpful. Mechanical and chemical analyses of soil samples were provided by Harold Furneaux, Head, Soil and Water Laboratory, Upper Colorado Region, Salt Lake City, and Rolf Khil, Sedimentology Laboratory, INSTAAR, University of Colorado. Some analyses at the university were done with a sedigraph supported by NSF Grant No. EAR-7823693. We also thank Richard Reynolds, Paleomagnetism Laboratory, USGS (U.S. Geological Survey), Denver, for free use of his facilities for paleomagnetic analyses.

Our appreciation is also extended to Charles Langer and David Carver, Branch of Engineering Geology and Tectonics, USGS, for the use of five portable seismographs and for helpful information regarding their previous monitoring effort in the study area.

## 2. Feature Description

### 2.1 Taskeech Dam and Reservoir

#### 2.1.1 Location and Physiography

The proposed Taskeech Dam is located in north-central Duchesne County about 40 km (25 mi) north of the city of Duchesne in northeastern Utah (fig. 1.1, pl. 1). The dam will be constructed across the Lake Fork River, a tributary to the Duchesne River. The damsite is situated within the Uintah and Ouray Indian Reservation and is located in the western half of sec. 1 and eastern half of sec. 2, T. 1 N., R. 5 W. (Uinta Special meridian) (approximate latitude 40.5° N. and longitude 110.4° W.). The dike, a secondary impoundment structure immediately northeast of the dam, will be located in the western half of sec. 1, T. 1 N., R. 5 W. (Uinta Special meridian). The dam and dike embankments will impound a reservoir extending to the northwest. The upper portion of the reservoir area will occupy Ashley National Forest land. The dam, dike, and reservoir sites are covered by the Lake Fork Mountain, Utah, USGS 7-1/2-minute topographic quadrangle.

#### 2.1.2 Proposed Construction

The Taskeech Reservoir will be impounded by the proposed Taskeech Dam and a small dike. The proposed dam is a rolled earthfill structure with a height of about 68 m (223 ft) above the streambed, a crest elevation of 2328 m (7638 ft) that will be 497 m (1630 ft) long and 9 m (30 ft) wide at the crest. The dike, located about 0.4 km (0.25 mi) north of the dam, will have a crest length of 165 m (540 ft) and will rise 19 m (61 ft) above the ground to a crest elevation of 2328 m (7638 ft). The dam and dike will contain about 3 088 800 $m^3$ (4 040 000 $yd^3$) of material, including 237 000 $m^3$ (310 000 $yd^3$) in the dike. A roller-compacted concrete dam is being considered as an alternate for the main dam and dike (USBR, 1984).

The outlet from Taskeech Reservoir to the Lake Fork River, to be located in the right abutment of the dam, will have a capacity of 23 $m^3/s$ (800 $ft^3/s$) when the reservoir is filled to the maximum water surface elevation 2326 m (7632.2 ft). The reservoir spillway, to be located on the left abutment of the dam, will have an uncontrolled side channel inlet with a crest elevation of 2324 m (7625 ft), and a design capacity of 300 $m^3/s$ (10 600 $ft^3/s$) at the maximum water surface elevation (USBR, 1984).

The dam and dike embankments will impound a reservoir of about 5.6 km (3.5 mi) in length extending generally to the northwest from the dam and will have a total capacity of approximately $9.7 \times 10^7$ $m^3$ (78 500 acre-ft). At normal water surface elevation 2324 m (7625 ft), the reservoir will cover an area of 4.9 $km^2$ (1210 acres), and the southwest shoreline will be less than 15 m (50 ft) from the existing Farnsworth Canal and Twin Pots Dam. A surcharge capacity of $9.5 \times 10^6$ $m^3$ (7700 acre-ft) will be provided (USBR, 1984).

### 2.1.3 Hazard Classification

No downstream flood inundation map has been prepared to reflect the effects of a sudden failure of Taskeech Dam. Ranches and homes are scattered along the Lake Fork River south of the damsite, and the community of Myton, Utah, immediately downstream of the confluence of the Lake Fork River with the Duchesne River, lies about 47 km (29 mi) downstream of the damsite (fig. 1.1 and pl. 1). Improved and unimproved roads and transmission and telephone lines cross the Lake Fork River and the Duchesne River, downstream of the confluence. U.S. Highway No. 40, a major transportation route across northeastern Utah, crosses the Duchesne River at Myton. Pasture and croplands lie within the flood plains of the Lake Fork and Duchesne Rivers and irrigation canals which are located along both rivers divert and convey water. In the event of failure of Taskeech Dam, these probably would be the primary areas and features affected by floodwater downstream of the dam.

## 2.2 Upper Stillwater Dam and Reservoir

### 2.2.1 Location and Physiography

The proposed Upper Stillwater Dam is located in northwestern Duchesne County about 50 km (30 mi) northwest of the city of Duchesne in northeastern Utah (fig. 1.1, pl. 1). The dam will be constructed across the glaciated valley of Rock Creek, a tributary to the Duchesne River, in the Ashley National Forest. Although this area has not been surveyed and divided into sections, by projecting section lines from the surrounding area the damsite is tentatively located in sec. 20 and 21, T. 2 N., R. 7 W. (Uinta Special meridian) (approximate latitude 40.6° N. and longitude 110.7° W.). The dam will impound a reservoir extending 3.2 km (2 mi) to the north. The dam and reservoir sites are covered by the Tworoose Pass, Utah, USGS 7-1/2-minute topographic quadrangle.

### 2.2.2 Proposed Construction

The proposed Upper Stillwater Dam will be a gravity structure of roller-compacted concrete with conventional concrete facing. The dam would have a maximum structural height of 82 m (270 ft) above the foundation. The crest of the dam, at an elevation of 2492 m (8176 ft) would have a total length of 812 m (2664 ft) and a crest width of 9 m (30 ft). The dam will have a vertical upstream face and a variable (0.32:1 to 0.6:1) sloping downstream face. An overflow spillway to be located near the middle of the dam will have a capacity similar to the inflow design flood of about 425 $m^3/s$ (15 000 $ft^3/s$) (USBR, 1982).

The dam will impound a reservoir of about 3.2 km (2 mi) in length extending to the north which would have a storage capacity of approximately $3.7 \times 10^7$ $m^3$ (30 000 acre-ft) at a water surface elevation of about 2490 m (8170 ft).

### 2.2.3 Hazard Classification

No downstream flood inundation map has been prepared to reflect the effects of a sudden failure of Upper Stillwater Dam. Ranches and homes are scattered along Rock Creek immediately downstream of the damsite and downstream of the confluence of Rock Creek and the Duchesne River. The city of Duchesne, Utah (population 3,200), lies about 57 km (35 mi) downstream of the damsite (fig. 1.1 and pl. 1). Campground facilities are located immediately downstream of the damsite. Improved and unimproved roads, transmission and telephone lines, and pipelines parallel and/or cross Rock Creek and the Duchesne River downstream of the damsite. U.S. Highway No. 40, a major transportation route across northeastern Utah, crosses the Duchesne River at Duchesne. Pasture and croplands lie within the flood plains of Rock Creek and the Duchesne River. In the event of failure of Upper Stillwater Dam, these probably would be the primary areas and features affected by floodwater downstream of the dam.

# 3. Geologic, Seismologic, and Tectonic Setting

## 3.1 Regional Geology

### 3.1.1 Physiography

The Uinta Mountains are an east-west-trending, 240-km (150-mi) long, 60-km (35-mi) wide range situated in northeastern Utah and northwestern Colorado (fig. 3.1). This range comprises part of the Middle Rocky Mountains physiographic province and is bounded on the south by the Uinta Basin portion of the Colorado Plateau province.

The present landscape of the Uinta Mountains consists of a broad, plateau-like summit area that has been incised as much as 600 m (2000 ft) by many of the larger drainages. During the Pleistocene, glaciers modified preexisting drainages forming broad U-shaped glacial valley landscapes (Atwood, 1909). Headward erosion by valley glaciers has carved large coalescing cirques with sharp aretes in the high country. Glacial erosion in the Uintas was accompanied by deposition of moraines at the mountain front. Outwash sediments were deposited on outwash plains and in melt water channels far out into the adjacent basins to the north and south.

The overall drainage pattern of the Uinta Mountains and northern Uinta Basin is radially dendritic. However, along the flanks of the range, some of the drainages have developed along the general east-west strike of more resistant strata to produce a local trellis drainage pattern. Drainages of both the north and south flanks, with the exception of the extreme western portion, are tributary to the Green River.

### 3.1.2 Stratigraphy

Bedrock stratigraphy exposed in the Uinta Mountains and Basin is comprised almost entirely of sedimentary formations of marine and continental origin (figs. 3.2 and 3.3). The core of the Uintas consists primarily of Precambrian sedimentary rocks. Successively younger Paleozoic and Mesozoic rocks are principally confined to and form the flanks of the range. However, Tertiary formations which onlap the flanks of the mountains conceal this pre-Tertiary succession in some areas.

The Uinta Mountains area was formerly a broad, elongated geosynclinal trough. The Uinta trough is believed to have been an east-west embayment of the roughly north-south-trending Wasatch trough located to the west (Untermann and Untermann, 1969; Hansen, 1969b). Deposition in the trough was progressive, though intermittent, from Precambrian through the late Cretaceous. Total known thickness of deposits ranging from Precambrian to Tertiary age in the Uinta Mountains varies from 13 700 m (45 000 ft) in the eastern portion to 19 200 m (63 000 ft) in the western portion (Untermann and Untermann, 1969).

Marine conditions in the Uinta trough commenced in Precambrian time and

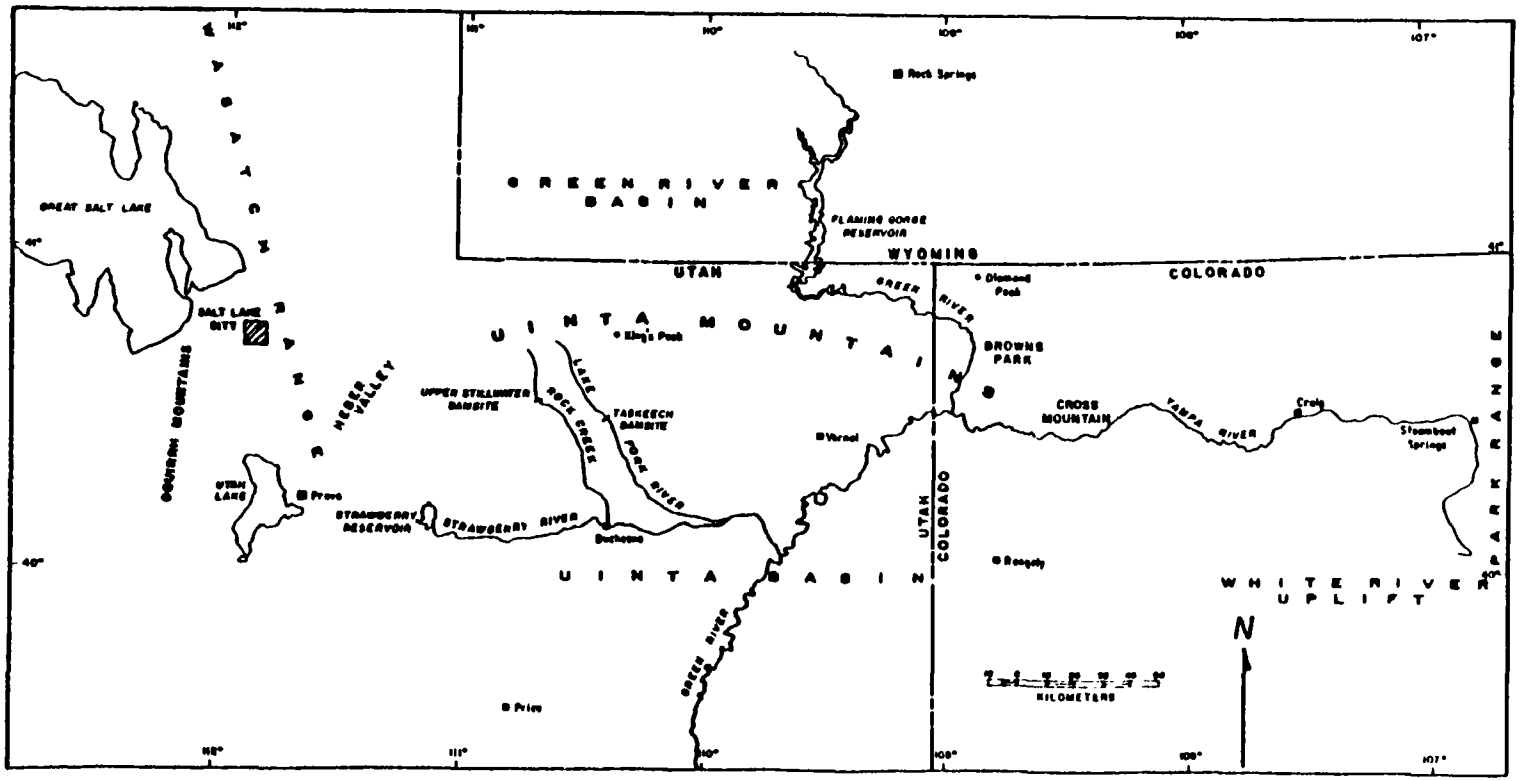



Figure 3.1. Geographic map of the Uinta Mountains and Uinta Basin.

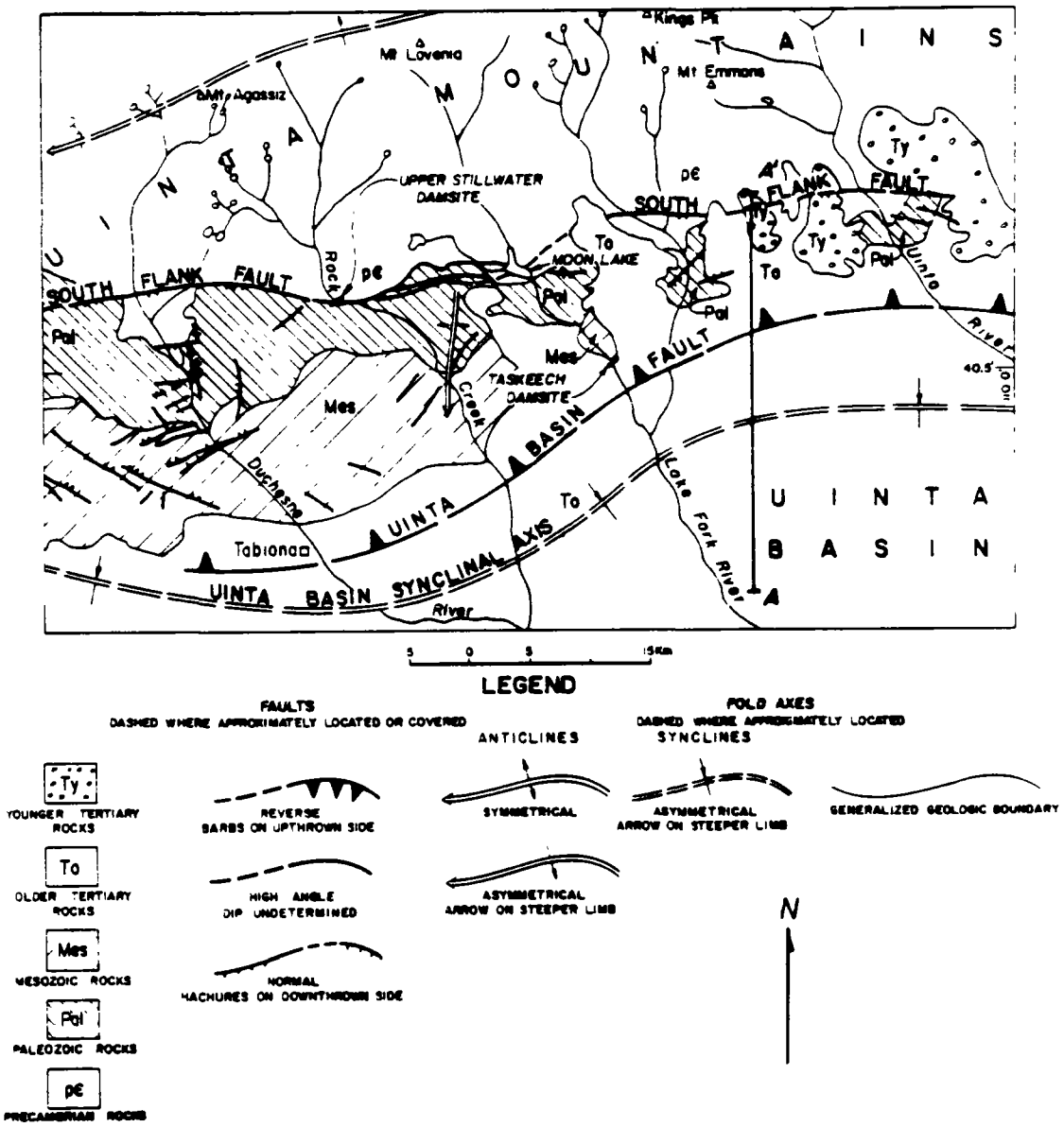



Figure 3.2. Generalized geologic map of the Uinta Mountains and Uinta Basin in the vicinity of Taskeech and Upper Stillwater damsites (modified from Campbell, 1975).

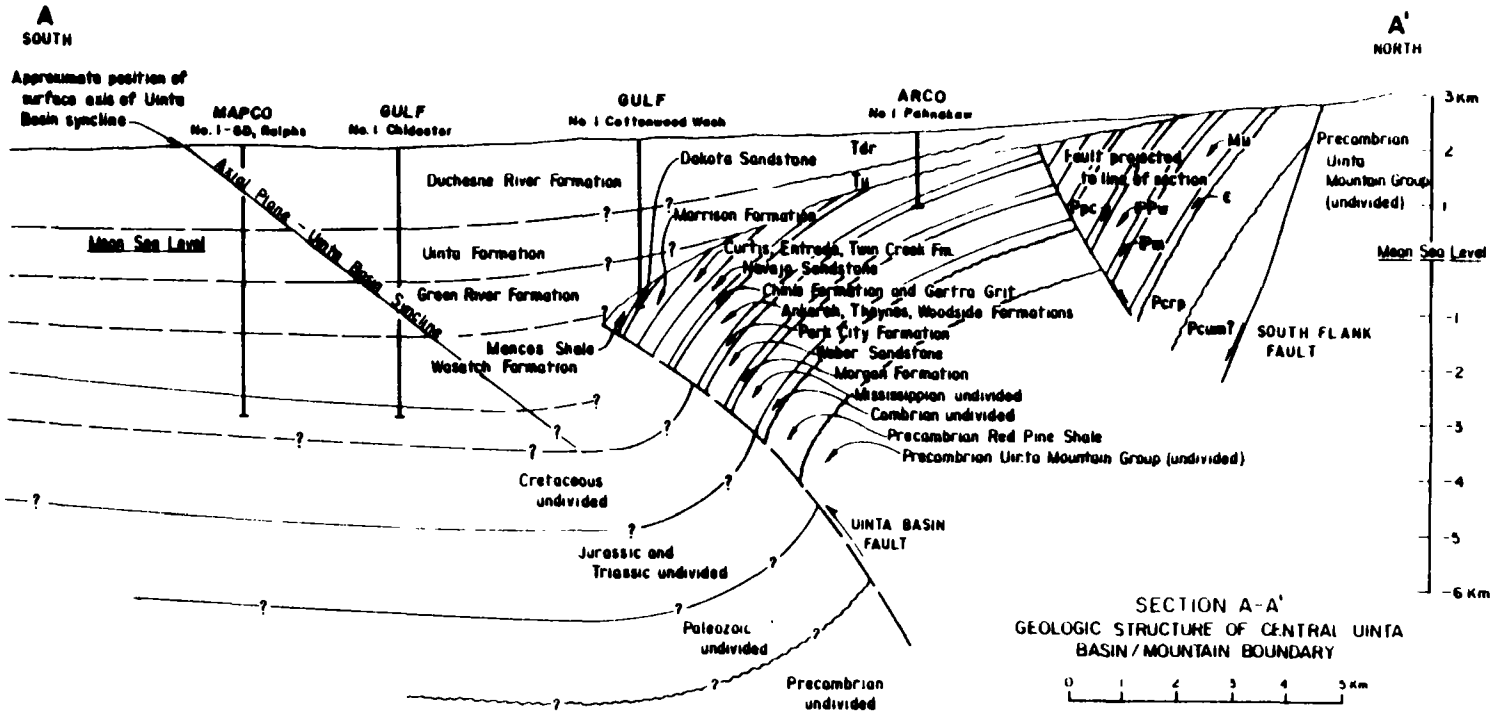



Figure 3.3. Geologic cross section (A-A'; fig. 3.2) of the south flank of the Uinta Mountains and northern Uinta Basin (modified from Campbell, 1975).

continued throughout much of the Paleozoic and Mesozoic. However, marine deposition in the trough was interrupted at various times by gradual epeirogenic uplifts. The absence of Ordovician, Silurian, and Devonian rocks in the Uinta Mountain region is believed to indicate such an uplift, although the range probably was not greatly elevated as no coarse clastics were derived from this region (Osmond, 1964; Untermann and Untermann, 1969).

Throughout much of its geologic history, subsidence in the Uinta trough is inferred to have been more rapid in the western portion. Consequently, marine waters in response to isostatic adjustments transgressed the trough area from the west. Therefore, onshore subaerial deposits in the eastern portion of the trough grade laterally into marine facies which thicken to the west. Mesozoic sediments show lateral facies changes shifted repeatedly back and forth across the Uinta trough during this period. These conditions were reversed during the Cretaceous due to uplifts to the west. Then, subsidence was greater in the eastern portion of the trough and marine waters transgressed from the east (Hansen, 1969b).

Immediately to the south of the Uinta Mountains, a thick section of Paleogene fluvial and lacustrine sediments were deposited in the Uinta Basin. The basal Wasatch Formation is overlain by Eocene lacustrine shales and marginal facies of the Green River Formation which were deposited in Lake Uinta and presently outcrop in the southern margin of the basin. The overlying sandstones and shales of the Uinta Formation are exposed in the central part of the basin. The Oligocene-age sandstones of Duchesne River Formation are exposed along the northern margin of the basin where they overlap the tilted Paleozoic and Mesozoic rocks along the south limb of the Uinta anticline (Stokes and Madsen, 1961).

### 3.1.3 Structure

#### 3.1.3.1 Overthrust Belt

The Sevier and Laramide orogenies in the Overthrust Belt in Idaho, Wyoming, and Utah are characterized by low-angle, east-directed, "thin-skinned," imbricate thrust faulting involving Precambrian to Mesozoic-age sedimentary rocks that began during the Jurassic and ended in the Eocene (Armstrong, 1968). In contrast, the Laramide-age block uplifts further east in Wyoming, Utah, and Colorado are bounded by both high-angle and low-angle thrust faults that involve crystalline basement rocks.

Early interpretations of the structure of the Uinta Mountains suggested they were a Laramide-age block uplift bounded by high-angle, mountainward dipping reverse faults (Sales, 1969; Campbell, 1975). Beutner (1977) concludes that the west end of the Uinta uplift is a structural reentrant within the overthrust belt implying that the development of the Uinta uplift is not related to overthrusting. Bruhn and others (1983) conclude, however, that the Uinta Mountains are underlain by a low-angle thrust fault and suggest that the Uinta uplift results from ramp folding above a low-angle, east-directed thrust fault.

### 3.1.3.2 Uinta Anticline

The Uinta Mountains consist of an asymmetrical doubly plunging, east-west-trending, compound, anticlinal fold (fig. 3.4). The Uinta anticlinal arch, somewhat convex to the north, reaches maximum convexity near the Utah-Colorado state line; here, the axis bends sharply to the southeast. This structural trend conforms with the northwest-southeast-trending White River Uplift and Park Range of northwestern Colorado. The fold axis, roughly coinciding with the crest of the mountains, lies closer to the north side of the range. Near the crest, the strata gradually dip away from the axis, although on the flanks of the fold the dip of the strata abruptly steepen. On the south flank of the Uintas, this change in dip generally occurs along or near the South Flank fault.

This compound anticline consists of an eastern and western dome aligned on an east-west axis (Hansen 1965). Subsidiary anticlines increase the structural complexity of the east dome (fig. 3.4).

### 3.1.3.3 Uinta Basin

The Uinta Basin is a topographic as well as structural low which includes an area of over 24 000 $km^2$ (9 300 $mi^2$). Late Cretaceous and early Tertiary uplift of the Uinta Mountains was accompanied by subsidence of the adjacent Uinta Basin. Thick deposits of Paleocene to Oligocene age clastic sediments derived from the Uinta Mountain region accumulated in the basin and facilitated downwarping of this area (Untermann and Untermann, 1969; Hansen, 1969b). Subsidence of the Uinta Basin syncline appears to have been greatest adjacent to the south flank of the mountains; consequently, the syncline exhibits an asymmetrical configuration with the axis located near the northern margin of the basin. Strata on the north limb of the axis dip more steeply than in the broad area to the south. The synclinal axis trends generally east-west, convex to the north, and roughly parallels the Uinta anticlinal axis. The axial plane has been reported by Childs (1950) to dip to the north suggesting a structural boundary (Uinta Basin fault) that also dips to the north (Campbell, 1975).

### 3.1.3.4 Mountain Flank Faulting

Based on structural and stratigraphic relationships, pronounced uplift of the Uinta Mountains occurred in the early Eocene and continued up to the middle Eocene (Tweto, 1975). This uplift was accommodated by large displacements on reverse faults which bound the range; the south dipping North Flank reverse fault on the north, and a north dipping Uinta Basin reverse fault on the south. In addition, a major normal fault, the South Flank fault, bounds the southern margin of the range.

#### Uinta Basin Fault

Garvin (1969), based on surface and subsurface data, suggested the existence of a concealed fault in the western Uinta Basin which he named

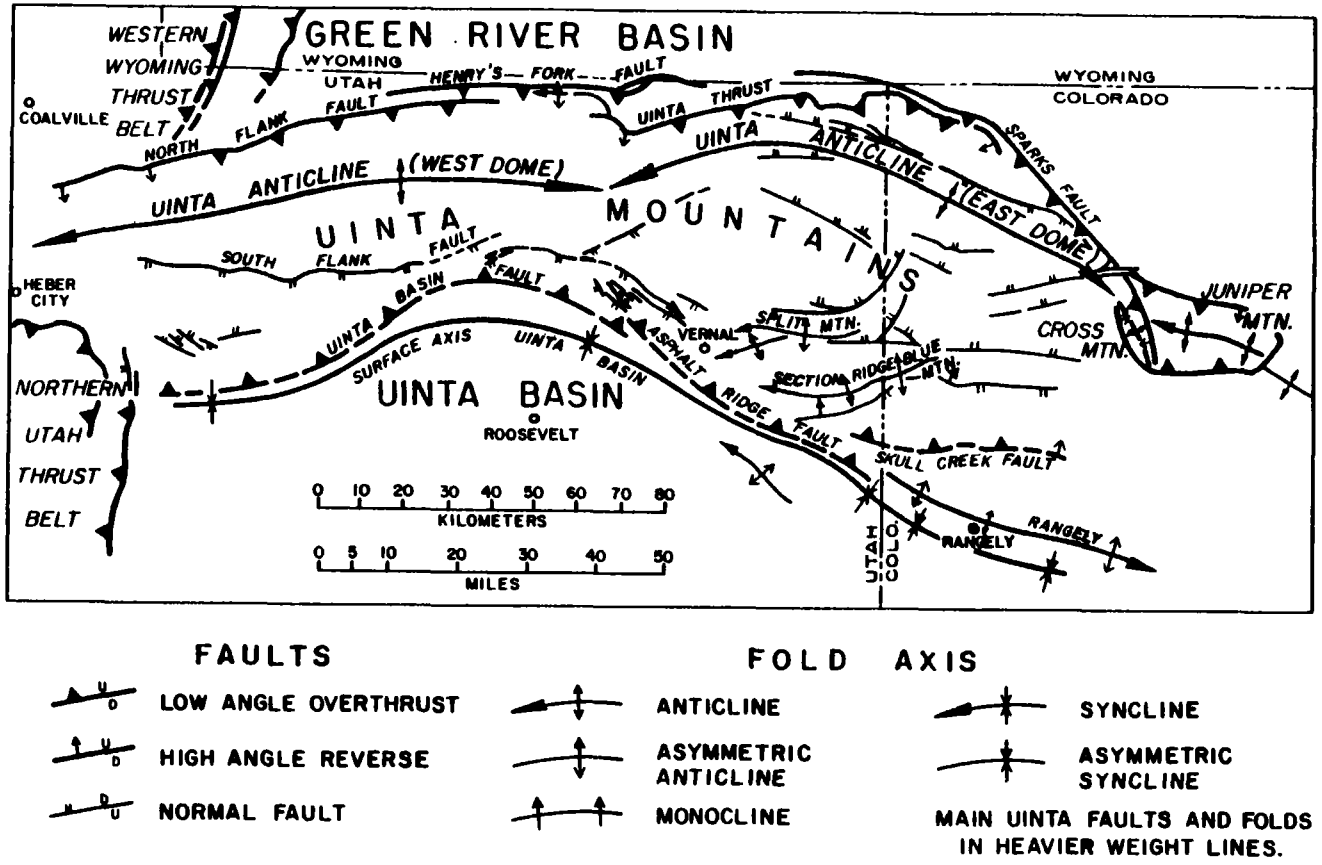



Figure 3.4. Generalized tectonic map of the Uinta Mountains (modified from Ritzma, 1969).

the Uinta Basin fault (figs. 3.2, 3.4). [Note: This fault was also named the Basin-Mountain Boundary fault by Ritzma (1969) and Campbell (1975), but will be referred to as the Uinta Basin fault in this report.] Subsequent investigations have inferred this fault as a steeply dipping reverse fault that is concealed by overlying Tertiary deposits (fig. 3.3). This fault generally parallels and roughly coincides with the axis of the Uinta Basin syncline which is located in the extreme northern portion of the Uinta Basin.

Geophysical and drill hole data have also established the presence of a major thrust fault in the vicinity of Asphalt Ridge immediately southwest of Vernal, Utah (fig. 3.4). Campbell (1975) suggests this fault, which he refers to as the Asphalt Ridge fault, and the Uinta Basin fault are laterally continuous; however, he notes available data are insufficient to conclusively make this correlation. Although these faults cannot unequivocally be demonstrated to be physically continuous, they represent a major structural discontinuity along the south flank of the Uinta Mountains.

Displacement on the Uinta Basin fault diminishes to the west where it appears to join the generally east-west-trending fold axis of the Uinta Basin syncline in eastern Wasatch County, Utah. Garvin (1969) offers evidence for at least 300 m (1000 ft) of displacement along a segment of the Uinta Basin fault in western Duchesne County, Utah. Eastward, the fault is inferred to extend through the Starr Flat oilfield in northeastern Duchesne County (pl. 1) where Goodwin (1961) has mapped a fault of similar trend with about 60 to 150 m (200 to 500 ft) of displacement. Further to the east, provided the Asphalt Ridge and Uinta Basin faults form a continuous structure, this fault deviates to a N. 70° W. trend and parallels Asphalt Ridge (fig. 3.4). The Uinta Basin/Asphalt Ridge fault probably reaches its maximum displacement in the Asphalt Ridge area. Along this segment of the fault, 2400 to 2700 m (8000 to 9000 ft) of vertical stratigraphic displacement has been reported (Campbell, 1975). Lucas and Drexler (1975) report that little or no fault displacement is recognized in deposits younger than middle Green River time which overlie the Uinta Basin fault.

Uplift-bounding faults have been described throughout the southern and middle Rocky Mountains and have been interpreted as vertical faults at depth that become drape folds in the overlying sediments and ultimately reverse faults such as the Uinta Basin fault if displacement is great enough (Matthews, 1978). Laboratory experiments conducted by Stearns and others (1978) tend to support this structural style of faulting. Their experiments have consistently reproduced a similar sequence and orientation of fractures as those noted along the south flank of the Uinta Mountains by pushing a piston vertically upward in a layered sandbox. However, recent interpretations suggest that the Uinta Basin fault could be considered a back thrust that joins the low-angle decollement inferred below the Uinta Mountains (Bruhn and others, 1983).

South Flank Fault

The South Flank fault, as well as other normal faults exposed in the western Uinta Mountains, appear to be related to early Tertiary uplift of the Uinta Mountains. Uplift and thrusting along the thrust faults bounding the Uintas on both the north and south margins resulted in tension across the Uinta Mountain block (Campbell, 1975).

Published maps depict the South Flank fault as a high-angle normal fault that dips between 60° to 80° to the south at the surface (Campbell, 1975), typically juxtaposing Paleozoic limestones in the hanging wall against Precambrian quartzite in the foot wall as shown on figure 3.3. The South Flank fault has generally been shown to extend from the North Fork of the Provo River to the Ashley Creek area, a distance of about 130 km (80 mi) (pl. 1). Maximum displacement on this fault is believed to be greater than 1220 m (4000 ft) in the Duchesne River area (Huddle and others, 1951). A lack of correlative stratigraphy prevents measurement of the total displacement as Paleozoic rocks have been removed on the upthrown block from the Duschesne River to the Uinta River.

The trend of the South Flank fault is generally along the margin of the west dome of the Uinta Mountains and in many areas consists of a single well-defined fault trace, although it deviates to a northeast strike in the Miners Gulch and Fish Creek areas. A complex pattern of faulting is associated with the northeast bend in the Miners Gulch area, and numerous branch and splay faults have been mapped along this portion of the South Flank fault by Huddle and others (1951). The fault does not display this complexity where it bends to the northeast in the Fish Creek area. Huddle and others (1951) noted faults both east of Moon Lake and in the Lower Stillwater area (pl. 2), and suggested that these faults are structurally related to the South Flank fault and its deviation to a northeasterly trend in these areas.

The mapped extent of the South Flank fault is about 25 km (15 mi) east of the Whiterocks River (pl. 1), but it does not appear to continue along the south flank of the east dome of the Uinta Mountains. Rather, a more complex pattern of northeast and northwest trending faults accommodated displacement.

3.1.3.5 Neogene Fault Reactivation

Hansen (1983) summarizes the Laramide structural development of the Uinta Mountains and discusses the Neogene reactivation of mountain flank faults bounding the east dome of the Uinta anticline. The evidence for Neogene reactivation is the tilting and displacement of the Oligocene-age Gilbert Peak erosion surface and overlying Bishop conglomerate, first recognized by Bradley (1936). Hansen (1983, p. 18) concludes that the crest of the east dome has subsided 1570 m (5150 ft) during the late Cenozoic. This subsidence was accommodated on the north flank of the east dome by reactivation of the Uinta and Dutch John faults with a sense of displacement opposite to that of Laramide reverse faulting (Hansen, 1983, fig. 14). This crestal subsidence is manifested as

northerly rotation of the Gilbert Peak erosion surface on the south flank of the east dome and was accommodated by rotational fault slippage and monoclinal flexing over the Uinta Basin fault (Hansen, 1983, p. 16), as well as Neogene and Quaternary displacements on reactivated faults.

## 3.2 Site Geology

### 3.2.1 Taskeech Dam and Reservoir

The damsite is located on the south-flowing Lake Fork River about 10 km downstream of Moon Lake (fig. 3.2) near the physiographic boundary between the Uinta Mountains and Uinta Basin (fig. 1.1).

#### 3.2.1.1 Geologic Setting

The Lake Fork River has incised moderately south-dipping, successively younger Paleozoic and Mesozoic rocks downstream of Moon Lake. In the vicinity of the damsite, gently south-dipping Tertiary fluvial deposits of the Duchesne River Formation are exposed unconformably overlying older rocks. The present channel of the river was formed by melt water during the later stages of the last glaciation, but the river also formerly occupied now-abandoned channels to the east and west (app. A).

The foundation and abutments of the dam and dike will be located entirely in the 8° to 10° southeast dipping, northeast striking Duchesne River Formation, an alternating sequence of sandstone, conglomerate, mudstone and claystone. The surficial deposits presently overlying the foundation consist of alluvium, colluvium, and outwash deposits ranging from 0 to over 30 m (100 ft) in thickness. Drilling on the dam axis and exposures immediately upstream show that the Duchesne River Formation overlies the Morrison or Dakota Formations of Mesozoic age with angular unconformity. This erosional unconformity rises upstream in the canyon walls, but appears extremely irregular with numerous cut and fill channels along the contact (USBR, 1964).

Mesozoic rocks striking north 75° to 80° east, generally dipping 25° to 35° south, but locally 50°, are exposed in the lower portions of the canyon walls upstream of the damsite. Drift (outwash and till), alluvium, and colluvium will underlie the major portion of the reservoir.

#### 3.2.1.2 Faulting

Geologic mapping and a thorough review of aerial photography revealed no evidence of faulting in Bull Lake to Pinedale age (RAG 5-7; app. A) moraines and outwash deposits surrounding Taskeech damsite, and strongly suggest faults of this age related to the Towanta flats faults (sec. 4.2.4.) do not extend into the vicinity of the damsite. Available subsurface data have revealed no evidence of faulting in the dam foundation. If north-trending faults do exist in the foundation, stratigraphic projection of correlative beds within the Curtis Formation across the valley immediately upstream of the dam axis precludes bedrock displacements of 50 m (160 ft) or more. About 600 m upstream, a high-

angle east- or northeast-trending contact between Morrison Formation and Duchesne River Formation, defined by drilling and outcrops, is suspected to be a fault. Further investigation of this feature is planned for spring 1985. The Design Data Report for Taskeech Dam and Reservoir, scheduled for completion early in 1985, should provide more definitive data about faulting in the damsite and reservoir.

#### 3.2.1.3 Landslides

Several Quaternary landslides have been mapped on the northeast side of the Lake Fork River valley in the vicinity of the proposed reservoir site. In addition to these landslide masses, an area of slope failure along the northeast margin of the reservoir is believed to have moved during the earthquake sequence of September 30 through October 11, 1977 (discussed in section 4.2.6.4).

### 3.2.2 Upper Stillwater Dam and Reservoir

Upper Stillwater Dam and Reservoir will occupy the glaciated valley of south-flowing Rock Creek in the Uinta Mountains (fig. 1.1). The valley at the damsite is approximately 0.8-km (0.5-mi) wide and incised more than 600 m (2000 ft) into bedrock.

#### 3.2.2.1 Geologic Setting

The Upper Stillwater damsite is situated on the south margin of the wide crest of the Uinta anticlinal arch near the South Flank fault. Bedrock at the damsite is the 1° to 3° northwest dipping Uinta Mountain Group consisting of quartzose sandstones interbedded with varying lesser amounts of argillite of upper Precambrian age. This alternating sequence of sandstone and argillite underlies the dam foundation, and is exposed along the upper portions of both abutments. Quaternary deposits overlie the bedrock on the floor of the Rock Creek valley; isolated bedrock exposures crop out across the valley floor near the dam axis.

Quaternary deposits at the Upper Stillwater damsite have an average thickness of 12 m (40 ft) with a maximum thickness of at least 35.7 m (117 ft), as indicated in drill hole DH-102 (USBR, 1978). These deposits consist of glacial drift, talus, stream fill, alluvial fan deposits, and colluvium. Talus deposits have accumulated along the toe of both valley walls. Glacial, stream, and alluvial fan deposits, extending across the valley floor, will underlie the major portion of the reservoir.

#### 3.2.2.2 Faulting

The South Flank fault, a major structural feature that extends along much of the south flank of the Uintas, subparallels and passes within approximately 370 m (1200 ft) of the dam axis (fig. 3.2, pl. 1, 2).

This fault is a generally east-west-trending, high-angle normal fault dipping to the south. The damsite and reservoir area are located on the upthrown block to the north. A detailed evaluation of this fault is presented in section 4.2.3.1.

The Design Data Report for Upper Stillwater Dam and Reservoir discusses additional faults in the vicinity of the damsite and reservoir consisting of two sets: a generally north-south-trending set oriented between N. 5° W. to N. 10° E., and a second set trending N. 30° to 35° E. (USBR, 1978). Preliminary geologic maps of the excavated dam foundation identify six high-angle, north- and northeast-trending faults in the bedrock in addition to a low-angle bedding plane fault. Further detailed discussion of these faults is presently available only in biweekly construction geology reports. Further excavation and detailed mapping of these faults is planned for summer 1985.

3.2.2.3 Landslides

No major landslides have been mapped at the damsite or in the reservoir.

3.3 Historical Seismicity

The historic record of earthquake occurrence in Utah dates back to about 1847 when Mormon settlers first moved to the Salt Lake City area. Prior to the installation of a seismograph station at the University of Utah in 1907, the only locatable earthquakes were those occurring near populated areas, primarily along the Wasatch Range front. Instrumental epicenter determinations for earthquakes occurring in Utah after 1907 were not very accurate, however, and felt reports of ground shaking were relied on heavily through 1949 (Arabasz, 1979).

In 1950, the U.S. Coast and Geodetic Survey initiated routine epicentral determinations for moderate-size earthquakes (Richter magnitude, $M_L$, greater than 3) in the Intermountain area using data from widely spaced regional seismographs. A skeletal statewide network of nine stations was installed in 1962 and considerably improved the earthquake location capability in Utah. Instrumental coverage along the now densely populated Wasatch Front was further augmented in 1974 when a telemetered network of high-gain seismograph stations was put into operation.

The following section will discuss the occurrence of earthquakes for the past 130 years in Utah on a regional scale. This is followed by a more detailed discussion of the historical seismicity local to the Taskeech and Upper Stillwater damsites. Finally, available data on focal depths and focal mechanisms for Utah earthquakes will be discussed. A discussion on earthquake recurrence is deferred until section 5.6. All reported magnitudes are considered Richter magnitudes unless specified otherwise.

### 3.3.1 Regional Seismicity

It was not until about 8 to 10 years after the installation of the statewide seismograph network in 1962, that a noticeable pattern of earthquake occurrence could be identified from the apparently random distribution of epicenters in Utah. A sufficient set of well-located epicenters existed by 1972 to define a prominent zone of diffuse, but locally intense seismicity, at least 100 km (62 mi) wide, roughly centered along the major north-south-trending Wasatch fault zone (Smith and Sbar, 1974).

The ISB (Intermountain seismic belt), the adopted name of this zone of intraplate seismicity, has subsequently been shown to approach 200 km (124 mi) in width and over 1300 km (800 mi) in length. It extends from the Arizona-Nevada border through Utah, Idaho, and Wyoming into Montana (Arabasz and others, 1979). It is considered to have one of the highest levels of earthquake risk in the contiguous United States outside California and Nevada (Arabasz and Smith, 1979). More than 15 events with magnitudes greater than or equal to 6 have occurred within the ISB since the mid-1800's, the largest being the 1959 Hebgen Lake earthquake of magnitude 7.5 (Smith and Richins, 1984). Eight of the magnitude 6+ earthquakes occurred in Utah, and include the 1901 magnitude 6.5 Richfield and 1934 magnitude 6.6 Hansel Valley earthquakes. Table 3.1 lists the pertinent data for the 15 historic Utah earthquakes that have magnitudes greater than or equal to 5.5. The Hansel Valley event is the only earthquake in Utah that has produced surface displacement (0.5 m; Shenon, 1936) during historic times.

Table 3.1. - Largest earthquakes in the Utah region, 1850 - 1981*

| Local date | Lat. (°N.) | Long. (°W.) | $I_0$ | Magnitude $M_L$ | Location |
|---|---|---|---|---|---|
| 1884 Nov. 10 | 42.0 | 111.3 | 8 | (6) | Bear Lake Valley |
| 1887 Dec. 05 | 37.1 | 112.5 | 7 | (5-1/2) | Kanab |
| 1900 Aug. 01 | 40.0 | 112.1 | 7 | (5-1/2) | Eureka |
| 1901 Nov. 13 | 38.8 | 112.1 | 9 | (6-1/2+) | Richfield |
| 1902 Nov. 17 | 37.4 | 113.5 | 8 | (6) | Pine Valley |
| 1909 Oct. 05 | 41.8 | 112.7 | 8 | (6) | Hansel Valley |
| 1910 May 22 | 40.8 | 111.9 | 7 | (5-1/2) | Salt Lake City |
| 1914 May 13 | 41.2 | 112.0 | 7 | (5-1/2) | Ogden |
| 1921 Sep. 29 | 38.7 | 112.2 | 8 | (6) | Elsinore |
| 1921 Oct. 01 | 38.7 | 112.2 | 8 | (6) | Elsinore |
| 1934 Mar. 12 | 41.7 | 112.8 | 9 | 6.6 | Hansel Valley (Kosmo) |
| 1959 Jul. 21 | 37.0 | 112.5 | 6 | 5.5+ | Utah-Arizona border (Kanab) |
| 1962 Aug. 30 | 42.0 | 111.7 | 7 | 5.7 | Cache Valley (Logan) |
| 1966 Aug. 16 | 37.5 | 114.2 | 6 | 5.6 | Nevada-Utah border |
| 1975 Mar. 27 | 42.1 | 112.5 | 8 | 6.0 | Idaho-Utah border (Pocatello Valley) |

* Modified from Arabasz and Smith, 1979. Table includes earthquakes of maximum Modified Mercalli intensity ($I_0$) of VII or greater, or Richter magnitude 5.5 or greater. Magnitudes in parenthesis are estimated from $I_0$. Aftershocks excluded.

Epicenters of the largest earthquakes ($M \geq 4$) occurring in Utah since 1850 are shown together with zones of major faulting in figure 3.5. The distribution of epicenters and faulting indicates there is a broad, north-south zone of ongoing crustal deformation in Utah, that coincides with the transition between the Basin and Range physiographic province to the west, and the Colorado Plateau and Middle Rocky Mountains provinces to the east. The most prominent feature within this zone in central and northern Utah is the 370-km-long (230-mi) Wasatch fault, a segmented geologic break along which young mountain blocks have been uplifted to form a steep, west-facing scarp (Arabasz and Smith, 1979).

Only two of the historic earthquakes of magnitude greater than 4 are suspected of occurring directly on the Wasatch fault, the 1910 earthquake (M 5.5) near Salt Lake City, and the 1914 event (M 5.5) near Ogden (Arabasz and Smith, 1979). There has been, however, abundant and persistent small magnitude activity associated with the Wasatch fault. This seismicity has been mainly concentrated along specific sections of the fault that are separated from each other by segments of nonactivity (i.e., seismic gaps). The great majority of historic earthquake activity within the ISB in central and northern Utah has been east and west of the Wasatch fault, and, in general, does not coincide with known late Cenozoic faulting.

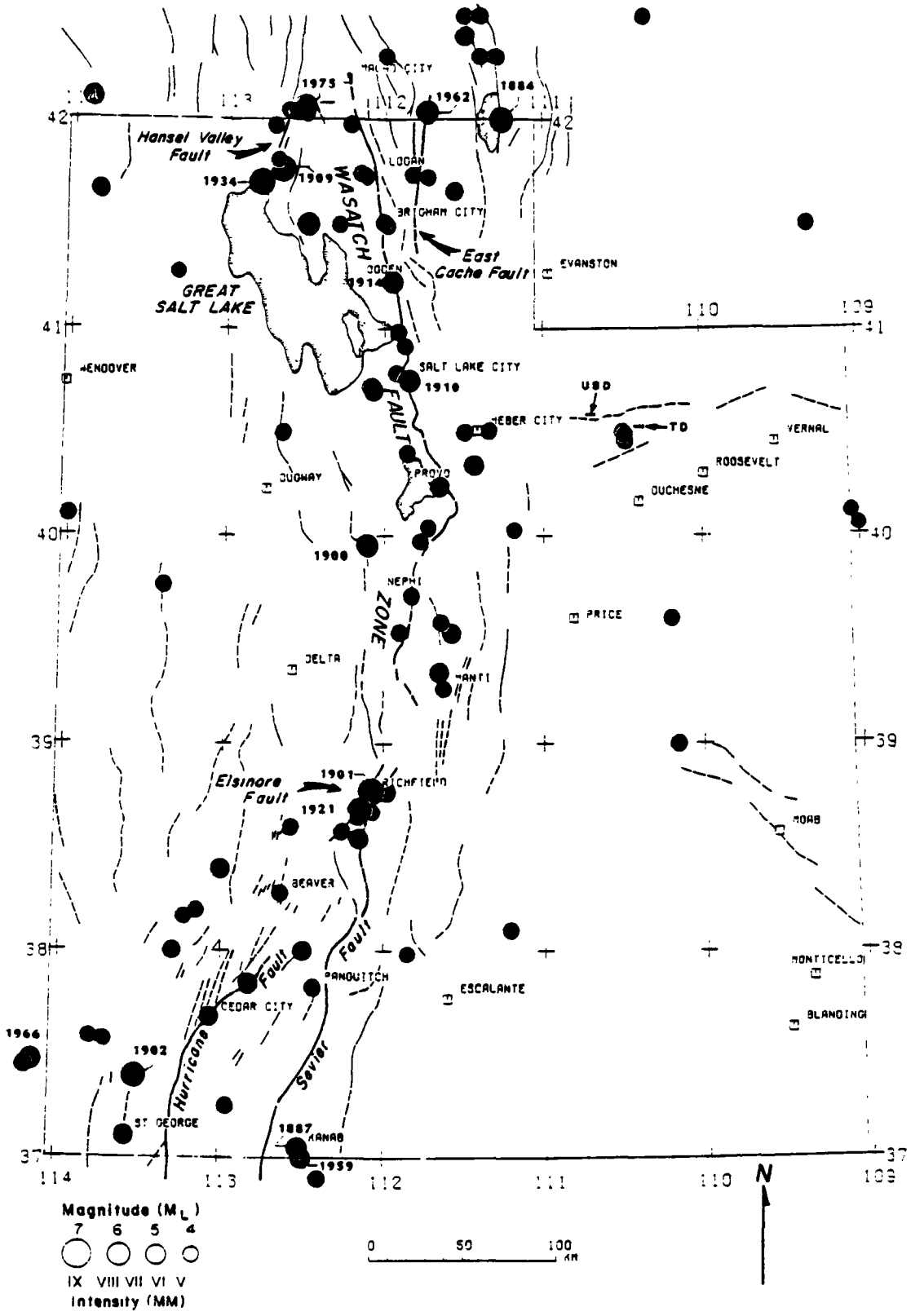



Figure 3.5. Epicenter map of the largest historical earthquakes in the Utah region, 1850-1978. For coincident epicenters, only the largest event is shown. Earthquakes of magnitude 5.5 or greater are dated by year. Cenozoic faults shown for reference. Taskeech and Upper Stillwater damsites are indicated by TD and USD, respectively (modified from Arabasz and Smith, 1979).

Since October 1974, regional arrays of relatively dense, high-gain, telemetry seismograph stations have been installed and operated by the University of Utah for the purpose of studying seismicity and associated hazards along the Wasatch fault. The distribution of these short period, predominately vertical component seismograph stations, as of June 1979, is illustrated on figure 3.6. The dashed line encloses the area covered on figure 3.7, an epicentral map of earthquakes recorded by the telemetered network through June 1978. The occurrence of earthquake activity east and west of the Wasatch fault is well illustrated on figure 3.7, as is the lack of activity within the seismic gaps along the Wasatch fault, here indicated by the dashed lines north and south of Salt Lake City. Although concentrated along the Wasatch Front, the seismic network is demonstrating that small magnitude and microearthquakes are occurring in other parts of Utah, although at lower rates of activity.

### 3.3.2 Local Seismicity

Plate 1 is an epicentral plot of all earthquakes known to have occurred within the 18 700-$km^2$ (7200 $mi^2$) study area (outlined on fig. 3.8) bounded by 40° to 41° N. latitude, 109.5° to 111.5° W. longitude, through December 1981 (Richins, 1979; NOAA, 1980; University of Utah, 1982). Only 43 of the 205 earthquakes shown, occurred prior to the installation of the dense seismograph network in 1974. These earthquakes are indicated by squares, and are generally restricted to the western portion of the map, the area directly east of, and most effectively covered by, the only two stations operating east of the Wasatch fault near the study area prior to October 1974. Also shown in plate 1 are two of the telemetered stations installed in October 1974 by the University of Utah. These stations, HTU and DAU, have provided good coverage in the back valleys of the Wasatch Mountains, but only limited coverage in the Uinta Mountains and Basin.

Additional coverage in the extreme eastern portion of the study area was provided by station UBO. This station, located near Vernal, Utah, operated for an 11-year period, but was closed in 1973, a full year before installation of the telemetered array.

Although the station coverage is limited, detection thresholds high, and location accuracies poor, it is apparent from plate 1 that the region east of the telemetered array is seismically active. Because the Uinta Mountains and Basin are, and have been, a relatively unsettled, uninhabited area, it is realistic to assume pre-October 1974 earthquake occurrence probably existed at a level comparable to post-1974, but went unnoticed throughout historic times.

A brief inspection of plate 1 reveals three areas of relatively dense earthquake occurrence within a diffuse pattern of seismicity related to the back valleys of the Wasatch Mountains and adjoining Uinta Mountains and Basin. Closer examination, including temporal data, however, indicates that the anomalous spatial density in one area is related to an earthquake swarm, and in the other two areas is the result of aftershocks of two moderate-size earthquakes.

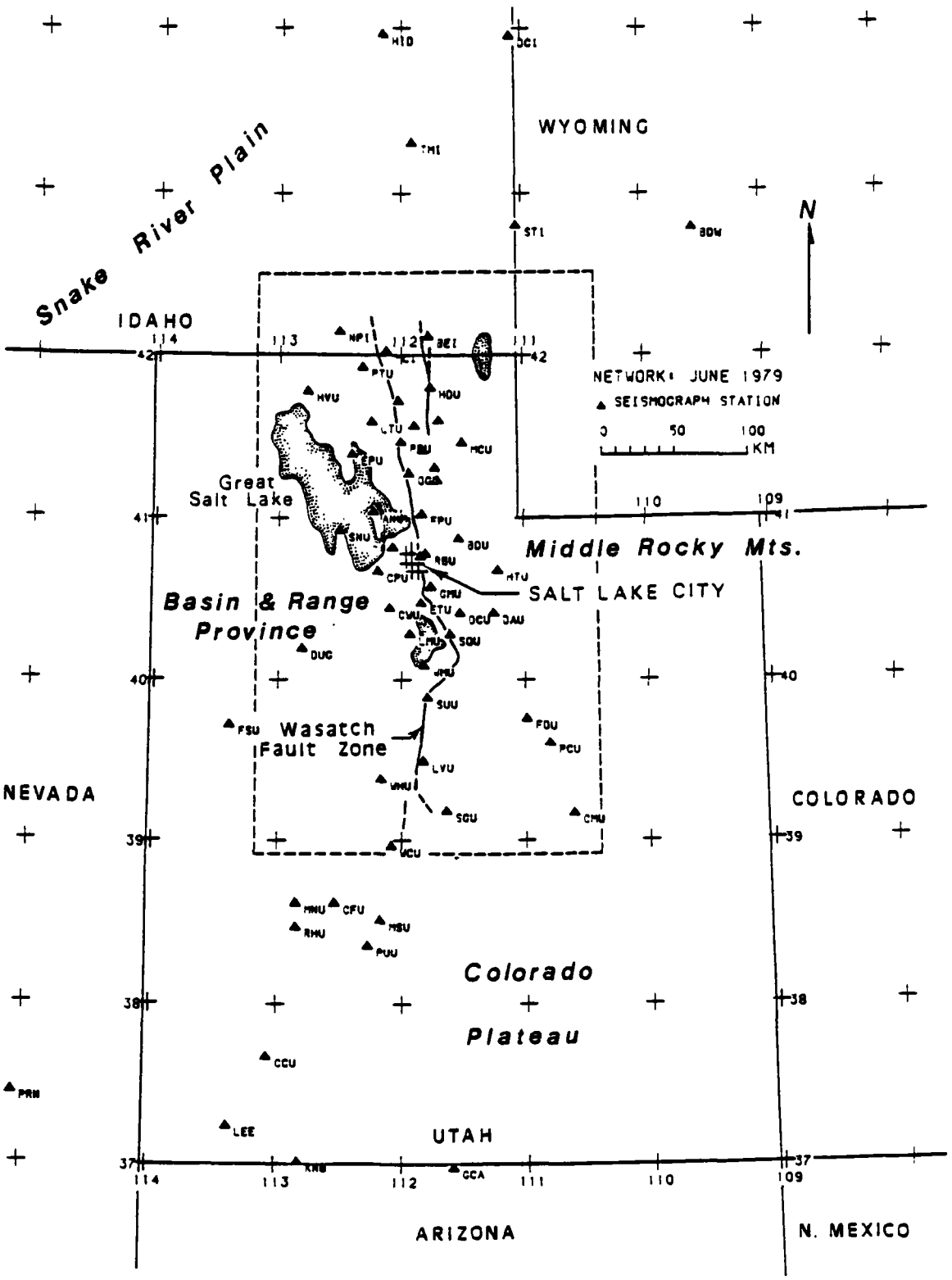



Figure 3.6. Location map of the University of Utah telemetered seismic network as of June 1979. Dashed line outlines area illustrated in figure 3.7 (Arabasz and others, 1979).

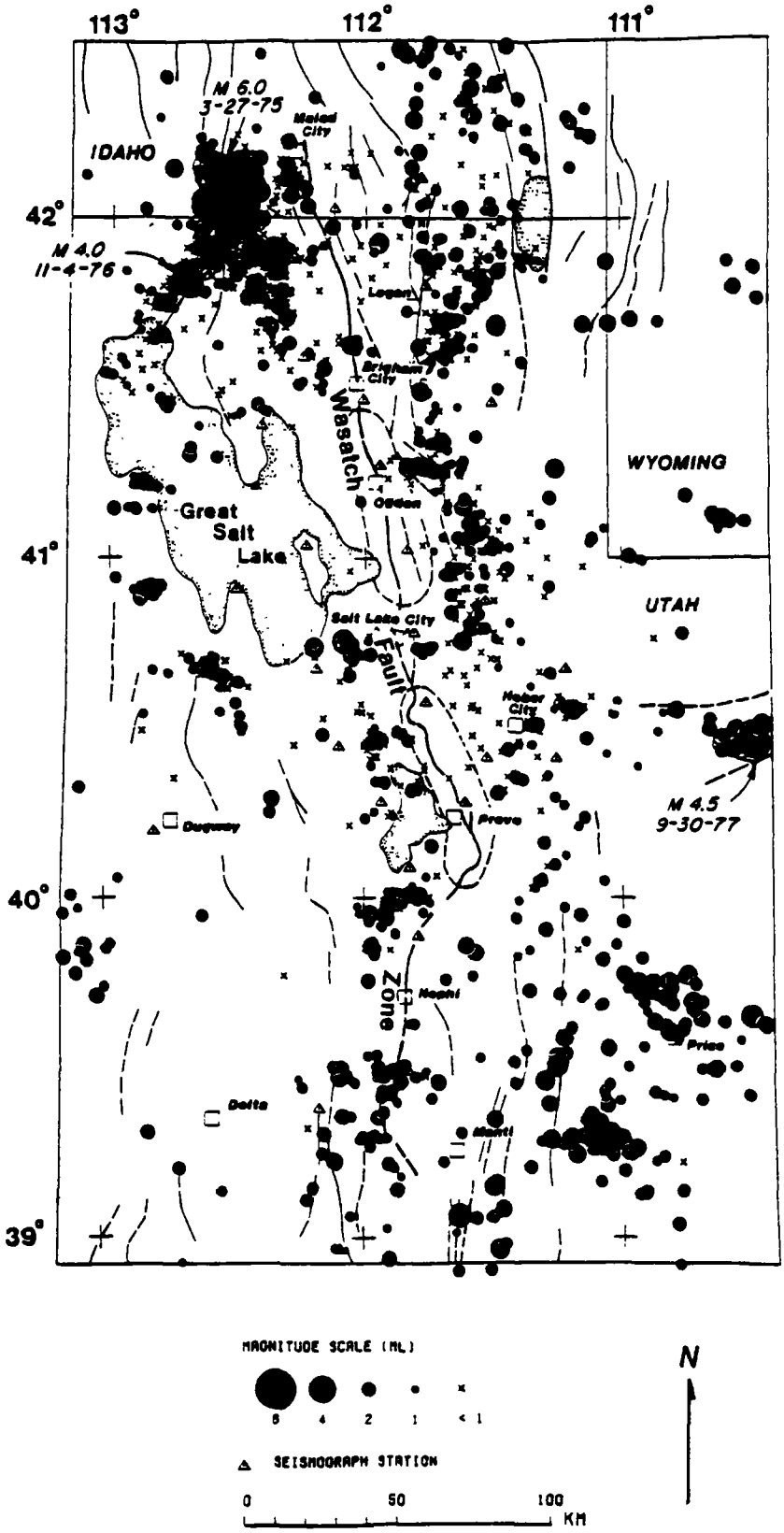



Figure 3.7. Epicenter map of the Wasatch Front earthquakes, October 1974 to June 1978. Seismic gaps along the Wasatch fault are outlined by dashed lines. Cenozoic faults shown for reference (from Arabasz and others, 1979).

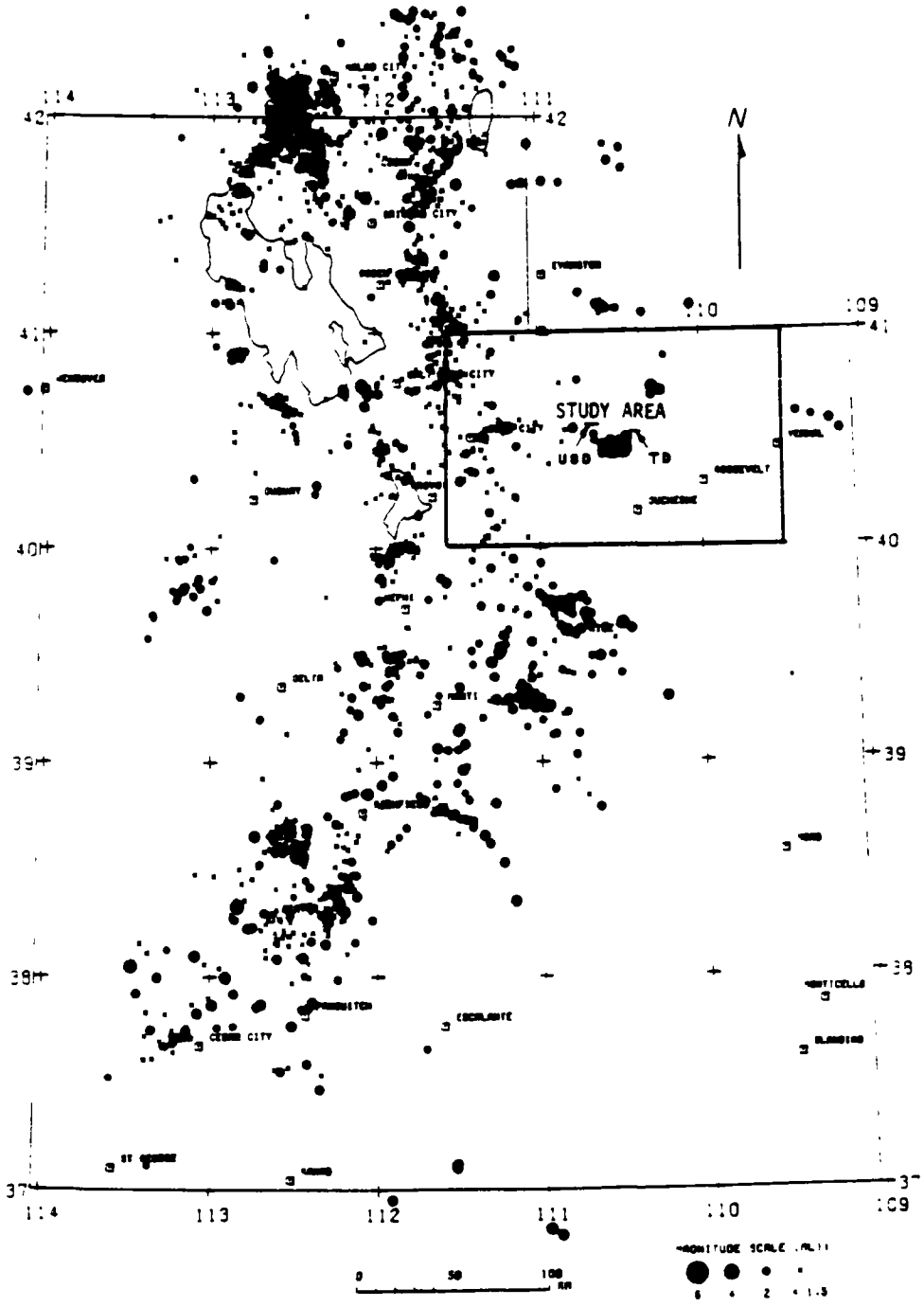



Figure 3.8. Study area location map and Utah earthquakes, October 1974 to June 1978. Taskeech and Upper Stillwater damsites are indicated by TD and USD, respectively (modified from Richins, 1979).

The epicenter of the largest earthquake (based on instrumental data) known to have occurred within the limits of plate 1 lies among the dense cluster of earthquakes near 40.5° N. latitude, 110.5° W. longitude. This magnitude 4.5 earthquake occurred on September 30, 1977, and was followed by hundreds of aftershocks (Carver and others, 1981). In 1950, another moderate-size earthquake is believed to have occurred in the same area. The magnitude estimates for this event range from 4.3 to 5.25. Due to the close proximity of the epicenters to the subject damsites, these earthquakes will be discussed in detail later in this section.

Three kilometers (2 mi) east of Heber City is one area of dense epicenter occurrence. Most of these earthquakes have occurred since of the Richter magnitude 4.3 (body-wave magnitude, $m_b$, 4.7) earthquake of October 1, 1972, and therefore, are probably aftershocks of this earthquake. The main shock produced a maximum intensity of MMI VI (Modified Mercalli Intensity) at the town of Midway west of Heber City, and was felt over an area of 6500 $km^2$ (2500 $mi^2$) (Langer and others, 1979), producing minor damage at many nearby towns. There is evidence to suggest the main shock actually consisted of two shocks, the first earthquake being followed by another one of slightly smaller magnitude approximately 90 seconds later. An aftershock study conducted by NOAA and the University of Utah recorded 28 earthquakes between October 3 and October 12, 1972. Nineteen of these aftershocks were large enough to be located by the nine-station, high-gain portable array. The epicenters of these well-located aftershocks (not shown in plate 1) cluster 5 km (3 mi) east of Heber City in a northwesterly trend. The focal depths range from 4.9 to 13.6 km (3.0 to 8.5 mi), and their depth distribution, combined with the composite fault plane solution, suggest the causative structure is a normal fault trending northwest, dipping 64° NE. Geologic mapping, however, has not revealed faulting in this area (Baker, 1959; Bromfield and others, 1970; Bromfield and Crittenden, 1971: cited in Langer and others, 1979).

Approximately 16 km (10 mi) northeast of Heber City is another area of relatively dense epicenter distribution consisting of 17 small-magnitude earthquakes. Eleven of these earthquakes occurred during a 42-hour period on October 10 and 11, 1975, followed by four earthquakes on October 26, and two earthquakes on November 2, 1975. The Richter magnitudes of all earthquakes in this sequence are less than 2.0 with the exception of one earthquake of magnitude 2.7 that occurred on October 11, 1975. Spatially, these epicenters follow a west-northwest trend along, and just west of, the western exposure of the South Flank fault, and it has been suggested this swarmlike earthquake sequence may be related to reactivation of the subsurface westerly extension of that fault (Langer and others, 1979).

The third area of high epicenter density, as mentioned earlier, is near 40.5° N. latitude, 110.5° W. longitude. This is the instrumentally determined epicenter of the earthquake that occurred January 18, 1950. Intensity data indicate only MMI IV ground shaking was reported in the epicentral area; whereas, the greatest ground shaking reportedly

occurred at Grand Junction, Colorado, 225 km (140 mi) to the southeast, where the maximum MMI was V. Apparently this discrepancy between epicenter location and region of maximum reported intensity results from a combination of local site amplification and population concentration in Grand Junction. The magnitude of this earthquake is somewhat undetermined. The maximum intensity versus magnitude relation of Gutenberg and Richter (1956), $M_L = 1 + 2/3I$, yields a magnitude estimate of 4.3. The magnitude reported by the California Institute of Technology, as determined from seismograms recorded at their observatory in Pasadena, is 5.25 (NOAA, 1980). Based on the locally observed intensity of IV in the epicentral area, the magnitude estimate of 5.25 appears high. The actual magnitude is probably less than 5.0, perhaps even less than 4.5. Because the epicenter was reported only to the nearest half degree, the implied accuracy is about 25 km (16 mi).

The rest of the earthquakes clustered near the 1950 event are associated with the September 30, 1977, Uinta Basin, Utah, earthquake. The USGS determined parameters for this event include Richter magnitude 5.1 ($m_b$ = 5.0), focal depth 5 km (3.1 mi), and epicentral location 4 km (2.5 mi) northwest of Taskeech damsite (USGS, 1977). The University of Utah estimated the Richter magnitude, focal depth, and epicentral location at 4.5, 7 km (4.4 mi), and 8 km (5.0 mi) southwest of Taskeech damsite, respectively. This discrepancy in reported magnitudes results, apparently, from the USGS using seismograms recorded as far away as Albuquerque, New Mexico ($\Delta >$ 700 km (435 mi)) to compute the magnitude, while the University of Utah used only data from their regional array. The USGS has recently recomputed the magnitude neglecting the extreme far field data, and now report it as M 4.5, in agreement with the University of Utah (D. Carver, oral communication, July 20, 1981). The epicenter of the main shock is identified by year, and shown at the University of Utah-determined location in plate 1.

A fault plane solution was computed for the main shock based on P wave first motion polarities recorded at regional and teleseismic distances (Carver and others, 1983). The solution indicates normal faulting with a small component of strike-slip movement on either a northwest trending, northeast dipping fault, or a north-trending, west dipping fault. Without additional data, it is not possible to determine which plane best represents the causative fault for this earthquake.

Figure 3.9 shows the distribution of reported intensities for this earthquake, which was similar to the earthquake of January 18, 1950, in that the maximum ground shaking experienced during this event reportedly occurred in Grand Junction, Colorado (USGS, 1977). This MMI equal to VI, however, was also reported in the immediate epicentral area, and may be due, in part, to an apparent increase in population density near the epicenter since 1950, and/or a general deterioration in the structural stability of local dwellings during the interval between events. The only evidence supporting MMI=VI near the epicenter was reported in Mountain Home, Utah, 10 km (6 mi) to the southeast, where a septic system drain was reported broken, old mortar of a log house was cracked at the corners, and some furniture shifted position (USGS, 1977). Intensity V

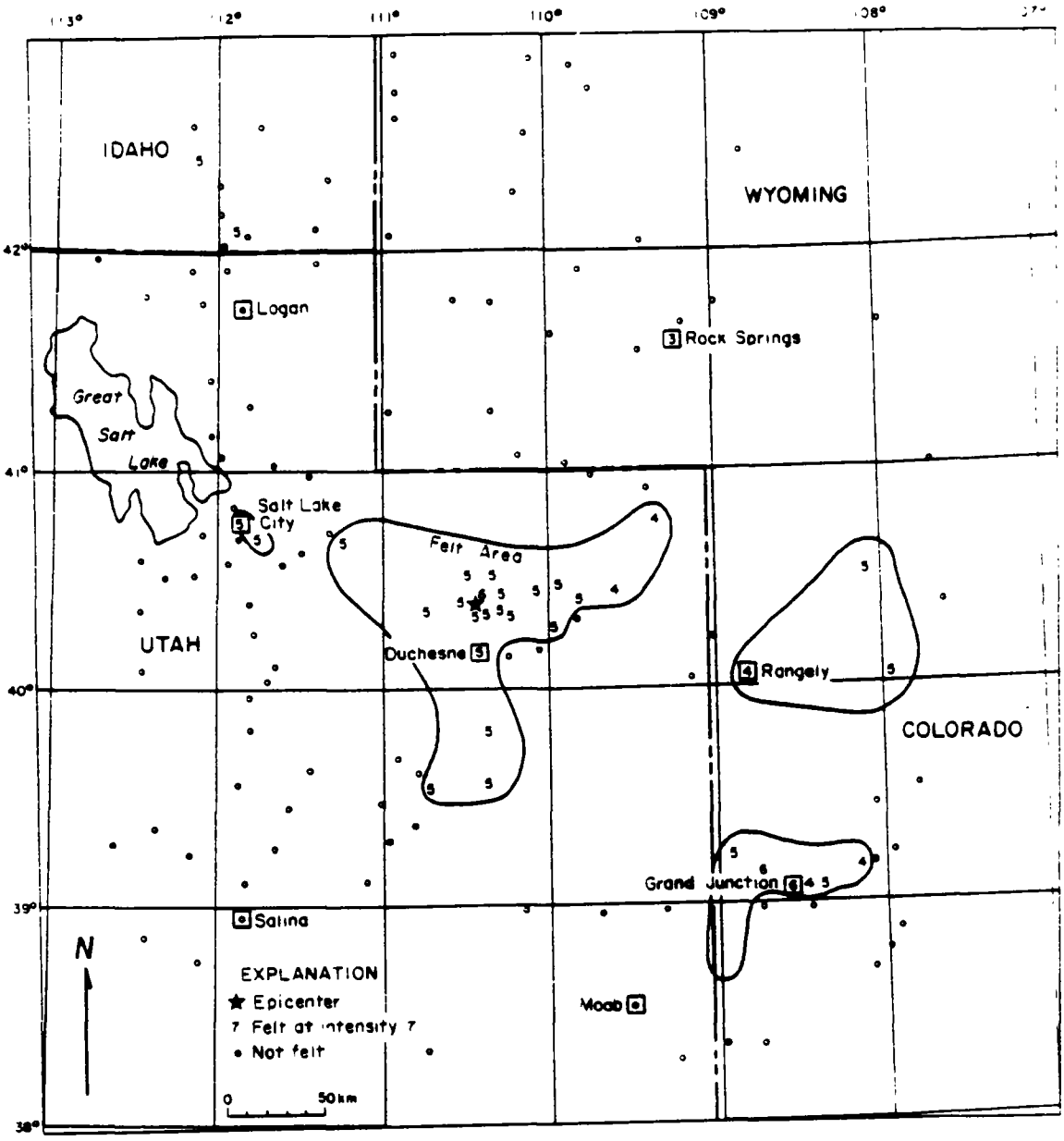



Figure 3.9. Isoseismal map of the September 30, 1977 magnitude 4.5 earthquake near Moon Lake, Utah. Arabic numerals represent reported Modified Mercalli intensities (from USGS, 1977).

ground shaking was reported throughout the epicentral area in contrast to reports of intensity IV shaking during the 1950 event, thus indicating the magnitude of this earthquake was greater than the 1950 event. These data further support the assignment of a magnitude less than 5.0 to the January 18, 1950 earthquake.

In a combined effort, the USGS and the UU (University of Utah) conducted an aftershock study from October 1 through October 15, 1977, using 12 high-gain portable seismographs (Carver and others, 1981). Hundreds of aftershocks were recorded during the 14-day study, the largest being the Richter magnitude 4.0 earthquake of October 11. Epicenters of the larger aftershocks, as listed in the University of Utah earthquake catalog (Richins, 1979), are shown in plate 1. This data set includes all epicenters clustered near the January 18, 1950, and September 30, 1977, events, as well as the nine events located west of 110.5° W. longitude, here indicated by open circles.

One gains a false impression of the spatial distribution of seismicity from considering only the epicenter plot without noting the temporal significance of these earthquakes relative to the installation of the portable array. All open circle events occurred either immediately after the main shock and before installation of the local stations, or after the aftershock study was terminated on October 15. The solution quality of these epicenter determinations, as listed in the earthquake catalog, is generally poor, and results from insufficient station coverage. Because the University of Utah station distribution is entirely to the west of the epicentral area, the solutions are biased in this direction. The subsurface velocity structure has probably been underestimated, thus resulting in a systematic mislocation of the epicenter to the west toward the points of observation (i.e., the seismograph stations).

Uniform station coverage alleviates this bias in the computed locations, as is indicated by the clustering of solid circle epicenters near the main shock. All these earthquakes occurred during the aftershock study, and are shown at the locations computed by the University of Utah from data recorded by the telemetry network, supplemented by data from the local temporary array. The listed location qualities are generally excellent for these solid circle events. The possibility exists that the open circle earthquakes are near their true locations, and thus not associated with the aftershock sequence. However, the aforementioned evidence suggests they are mislocated aftershocks. This, in turn, suggests the level of seismicity immediately west of the 1977 earthquake cluster is lower than the earthquake plot alone would indicate.

The recently published results of the aftershock study indicate that the causative structure is a north- to north-northeast-trending normal fault, dipping about 45° E. (Carver and others, 1983). These conclusions are based on composite fault plane solutions from P wave first motion patterns and on depth distribution plots of about 173 of the larger microearthquake aftershocks recorded during the study. This north to northeast trend determined from the microearthquake data is in contrast

with the northwesterly trend determined from the single event solution for the main shock. A single event fault plane solution was also computed for the largest aftershock, the magnitude 4.0 earthquake that occurred on October 11, 1977. The solution for this earthquake was very similar to the solution for the main shock, in that the focal mechanism indicates predominantly normal faulting with one nodal plane trending N. 55° W., dipping 50° NE. No explanation was offered by Carver and others (1983) as to why the computed fault plane solutions for the larger events do not agree more closely with the solutions computed for the microearthquakes. In addition, no definitive association between the inferred faulting and local geology was suggested.

A report of this earthquake in "Survey Notes," published by the Utah Geological and Mineral Survey (UGMS, 1977), indicated the September 30, 1977, earthquake occurred along the "Towanta Lineament," a zone of "fracturing and faulting, separate from the Uinta Mountains, (that) strikes N. 70° E. along the south flank of the mountains and extends out into the basin to the south. This zone apparently reflects an ancient, deep-seated rupture of the earth's crust that can be traced from near the northeast corner of Utah nearly to the Nevada State line. This fracturing and faulting is older than the Uintas and is apparently still active to some extent." The association of the September 30, 1977, earthquake with the N. 70° E. trending "Towanta Lineament" is inconsistent with the USGS/UU-determined fault orientation based on aftershock data, and with the results of microseismic investigations conducted as part of this study (sec. 4.1). Thus, this earthquake is probably not related to the "Towanta Lineament."

### 3.3.3 Earthquake Focal Depths

Of the three hypocentral parameters calculated during the earthquake location process, the focal depth is usually the least accurately determined coordinate. Following the installation of the telemetered array, the statistical error in computing epicenters for earthquakes occurring in the Wasatch Front region decreased from 5 km (3 mi) to 1 to 2 km (0.6 to 1.2 mi). The focal depth error, however, can still exceed 5 km (3 mi) depending on the size and location of the earthquake. Only when the epicenter of an earthquake is within a focal depth of a seismic station recording the event, can there be confidence in the computed depth to the hypocenter. In Utah, including east of the Wasatch fault, almost all well-constrained focal depths are less than 20 km (12 mi), and 90 percent are shallower than 10 km (6 mi) (Smith and Arabasz, 1979). Focal depths tend to follow a bimodal distribution, with clustering at 1 to 2 km (0.6 to 1.2 mi), and 7 to 8 km (4.4 to 5.0 mi). Mean focal depths for earthquakes occurring along the Wasatch Front are between 5.3 and 6.2 km (3.3 and 3.9 mi). The great majority of the earthquakes included in this data set, however, are in the magnitude range 0 to 3. Larger magnitude events can usually be expected to occur a few kilometers deeper.

### 3.3.4 Earthquake Focal Mechanisms

Focal mechanism solutions have been computed by various investigators for both composite and single earthquakes at selected locations throughout Utah (Smith and Lindh, 1978; Arabasz and others, 1979). Figure 3.10 is a schematic representation of these stress indicators, and includes the fault plane solution computed for the 1977 microearthquake aftershocks (Carver and others, 1983). Most solutions indicate the stress regime within the ISB in Utah is dominated by east-west extension, with stress release occurring along generally north-trending, high-angle normal faults. Maximum compressive stress axes (P-axes) are near vertical. The least compressive stress axes (T-axes) are horizontal, vary from west-southwest east-northeast to west-northwest east-southeast, and reflect Basin and Range style east-west extensional tectonism. This rotation of stress axes may be due to stress release on older faults or zones of weakness that were formed under a somewhat different tectonic setting.

This simple regional pattern of east-west extension is complicated northeast of Provo near Heber City where, in two areas, composite focal mechanism solutions indicate this region is undergoing local compression, similar to that observed in the interior of the Colorado Plateau (near Price). The east-west-trending Uinta Mountains intersect the north-south-trending Wasatch Mountains at this location, however, and this observed apparent reverse faulting may be the manifestation of regional east-west extension upon a locally complex structural transition.

In contrast to the predominantly normal faulting in the Great Basin and the reverse faulting in the Colorado Plateau interior, strike-slip faulting is occurring south of the Uinta Mountains in northwestern Colorado. The focal mechanism shown in figure 3.10 east of the Colorado-Utah border indicates that the least principle stress direction is nearly north-south in the Rangely, Colorado area (Zoback and Zoback, 1980). This is representative of a major change in the state of contemporary crustal stress 120 km (75 mi) east of the Taskeech damsite area.

## 3.4 Neotectonics

### 3.4.1 Crustal Structure

Two refraction profiles conducted across the Wasatch Front, both north and south of Salt Lake City, indicate that a major change in crustal structure occurs considerably east of the dominant physiographic boundary marked by the Wasatch fault. The northern line was 340 km (210 mi) long and extended into the Middle Rocky Mountains province. The data

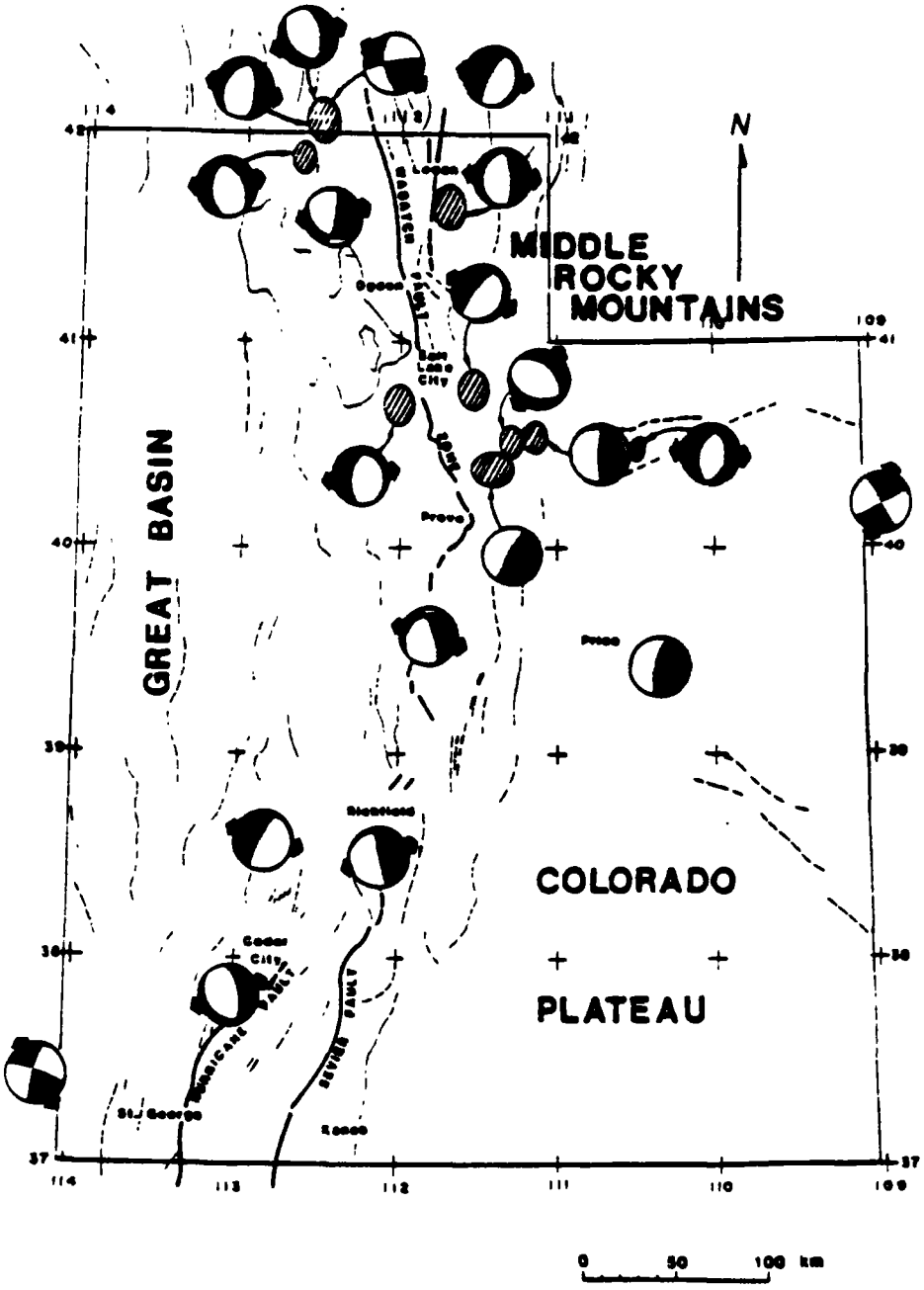



Figure 3.10. Schematic summary of fault plane solutions (lower hemisphere projections) for the Utah region. Compressional quadrants are shaded. Trends of T-axes are shown by heavy arrows. Hachured zones show sample areas for composite solutions. Cenozoic faults shown for reference (modified from Arabasz and others, 1979).

from this line indicate the crustal thickness of 28 km (17 mi) and Pn velocity of 7.6 km (4.7 mi) per second in the eastern Basin and Range increase to 40 km (25 mi) and 8.0 km (5.0 mi) per second, respectively, beginning about 40 km (25 mi) east of the Wasatch fault (Braile and others, 1974). The southern refraction line was 245 km (152 mi) long, and extended 50 km (31 mi) into the Colorado Plateau. The data from this line show that, along the entire line, the crustal structure is characterized by a 25-km (15.5-mi) thick crust and low, about 7.5 km (4.7 mi) per second, Pn velocities (Keller and others, 1975). The authors inferred the low Pn velocities to be the result of a mantle upwarp, approximately centered beneath the Wasatch Mountains, the eastern extent of which is unknown.

Both sets of refraction data also indicate the presence of a P wave LVL (low velocity layer) in the approximate depth range of 8 to 15 km (5 to 9 mi) within this transition zone. This depth range is coincident with a marked decrease in the density distribution of hypocenters of earthquakes occurring in the Wasatch Front region. Shurbert and Cebull (1971) propose that an LVL could be a zone of low rigidity capable of accommodating the large Cenozoic block faulting occurring in the Great Basin. The refraction data of Braile and others (1974) indicate the LVL in the transition zone is a region of low rigidity, as evidenced by a high Poisson ratio (0.29). The existence of this LVL west of the Wasatch fault was suggested by previous refraction surveys in the eastern Basin and Range (Mueller and Mueller, 1972; Mueller and Landisman, 1971). The existing refraction data are insufficient to indicate the eastern limit of this crustal low velocity layer.

In general, the Colorado Plateau is characterized by low heat flow, about 1.5 HFU, which is intermediate between average values for the Great Plains (1.1 HFU) and the Great Basin (2.1 HFU) (Thompson and Zoback, 1979). Recent heat flow measurements indicate that the Colorado Plateau can be subdivided into a low heat flow "thermal interior" surrounded by a periphery up to 100 km (62 mi) wide, having substantially higher heat flow. Bodell and Chapman (1982) report that heat flow values of about 2.1 HFU have been measured in north-south bands within the Colorado Plateau as much as 80 km (50 mi) east of the Wasatch fault. They interpret these data to be indicative of lateral warming and weakening of the Colorado Plateau lithosphere initiated at the Basin and Range boundary about 20 million years ago. The position of the boundary between the periphery and the "thermal interior" is consistent with the change in crustal structure inferred from the seismic refraction data.

### 3.4.2 Basin and Range Transition Zone

Published seismotectonic maps indicate that in Utah, late Quaternary surface rupture has occurred on generally north-south-trending normal faults (see, e.g., Anderson and Miller, 1979; Nakata and others, 1982). Late Quaternary normal faults bound most of the ranges in the eastern Basin and Range physiographic province, west of the Wasatch fault in central Utah. East of the Wasatch fault, in the Basin and Range

transition zone, late Quaternary normal faults also occur, although in central Utah they are significantly fewer in number than to the west.

Detailed investigations of the Wasatch fault have shown that the late Quaternary slip rate is about 1 mm/yr (0.039 in/yr) (see, e.g., Swan and others, 1980; Hanson and others, 1981; table 6). Late Quaternary faults east of the Wasatch fault have slip rates of about 0.1 mm/yr (0.0039 in/yr) or less (see Swan and others, 1983; Nelson and Martin, 1982; Sullivan and others, in preparation), suggesting that slip rates also diminish east of the Wasatch fault.

The most seismically active portion of the ISB in central and northern Utah is the area east of the Wasatch fault. Although focal mechanisms (sec. 3.3.4) suggest that earthquakes here occur predominately on north-trending normal faults, they show little spatial correlation with mapped late Quaternary surface faults. Aftershocks of two well studied events, the October 1, 1972, Heber City and September 30, 1977, Uinta Basin earthquakes, apparently occurred on faults lacking surface expression. Thus, the relationship of historical earthquakes and patterns of surface faulting in the Basin and Range transition zone remains enigmatic. Apparently east-west extensional stresses, superimposed on complex subsurface fault patterns, result in moderate magnitude earthquake occurrence on subsurface faults or "blind structures."

### 3.4.3 Colorado Plateau

The interior of the Colorado Plateau stress province is characterized by NNE-SSW least principle stress direction, perpendicular to least principle stress directions in the adjacent Basin and Range transition zone to the west (Zoback and Zoback, 1980). These conclusions are based on in situ stress measurements and earthquake focal mechanisms (also see sec. 3.3.4). This change occurs over a zone less than 50 km (30 mi) wide (Zoback and Zoback, 1980). The level of historical earthquake activity in the interior of the Colorado Plateau province is low. Faulting and folding within this province are generally considered Laramide or early Cenozoic in age; there is no published evidence of late Cenozoic tectonic deformation. However, Hansen (1983) documents late Cenozoic reactivation of faults on the north and south flanks of the Uinta Mountains, and Anderson and Miller (1979) show "suspected" Quaternary faults on the south flank of the eastern Uinta Mountains.

## 4. Seismotectonic Investigations

This section describes geologic and seismologic studies conducted for the purpose of assessing potential seismic hazards to the proposed Taskeech and Upper Stillwater Dams. Studies for each dam were conducted concurrently due to the proximity of the dams, and their similar tectonic settings. The geologic investigations were initiated in July 1979 and completed in October 1980. A 6-month microseismic monitoring program was also conducted during 1980. Results of these studies, combined with current understanding of regional earthquake occurrence and tectonics, formed the basis for an integrated evaluation of the earthquake potential in the project areas.

### 4.1 Microseismic Investigations

Microseismic monitoring of the area surrounding Taskeech and Upper Stillwater damsites commenced during the first week of May 1980 with the installation of three Sprengnether MEQ 800 smoked-paper seismographs. Three more instruments were operational by May 19, and a seventh station was installed July 11. Four additional seismographs were put into operation at the end of August, and a twelfth station was added to the net on September 25, 1980. The microseismic array, encompassing approximately 660 $km^2$ (255 $mi^2$), operated continuously until termination on November 1, 1980. For more information regarding the field operations and methods used, see appendix D.

During the 6-month study, more than 100 events originating within, or very near the boundary of the array, were detected on at least one seismograph station. Eighty-eight of these earthquakes were of sufficient magnitude to be locatable using HYPO71, a computer program developed by the USGS, and designed to compute the hypocenter of local earthquakes recorded on three or more stations (Lee and Lahr, 1975). Specific event information is cataloged in table 4.1. The estimated Richter magnitudes of most earthquakes were in the range 1 to 2, with several events perhaps as large as 2.5. Several stations operated by the University of Utah east of the Wasatch Front were useful in providing arrival times for earthquakes occurring west of the Bureau's net.

The epicenters of earthquakes recorded and located during this study can be spatially divided into four groups: Bear Wallow events, suspected South Flank fault events, southwest events, and random events.

#### 4.1.1 Bear Wallow Earthquakes

The Bear Wallow group consists of 61 microearthquakes located within an area of approximately 35 $km^2$ (13.5 $mi^2$), centered about 5 km (3 mi) west-southwest of Taskeech damsite (pl. 2). This corresponds to the epicentral area of the September 30, 1977, magnitude 4.5 earthquake.

The spatial distribution of epicenters indicates the active portion of this inferred fault, hereinafter informally referred to as the Bear Wallow fault, is between 6 and 10 km (3.7 and 6.2 mi) in length. The focal depths ranged from 3 to 9 km (1.9 to 5.6 mi).

Table 4.1. - Catalog of 1980 microearthquakes

| ID | YR | DATE | ORIG | TIME | LAT-N | LONG-W | DEPTH | MAG | NO | GAP | DMN | RMS | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 80 | 0518 | 0351 | 37.95 | 40-29.39 | 110-27.70 | 0.34 | 1.37 | 5 | 194 | 4 | .02 | C |
| 2 | 80 | 0518 | 1435 | 14.39 | 40-28.11 | 110-30.37 | 5.00 | 1.03 | 3 | 171 | 1 | .00 | C |
| 3 | 80 | 0519 | 0829 | 03.88 | 40-30.11 | 110-29.31 | 4.37 | 1.92 | 5 | 160 | 4 | .03 | C |
| 4 | 80 | 0519 | 0829 | 49.70 | 40-30.81 | 110-30.07 | 4.94 | 1.29 | 4 | 170 | 5 | .00 | C |
| 5 | 80 | 0519 | 1008 | 55.29 | 40-30.00 | 110-29.48 | 4.08 | 1.74 | 5 | 158 | 3 | .06 | C |
| 6 | 80 | 0519 | 1408 | 08.96 | 40-30.06 | 110-29.34 | 4.70 | 1.31 | 4 | 159 | 4 | .00 | C |
| 7 | 80 | 0519 | 1408 | 19.19 | 40-29.98 | 110-29.46 | 4.79 | 1.39 | 4 | 158 | 3 | .00 | C |
| 8 | 80 | 0522 | 0134 | 09.18 | 40-30.10 | 110-29.12 | 6.65 | 1.65 | 6 | 146 | 4 | .03 | B |
| 9 | 80 | 0522 | 0136 | 34.93 | 40-30.53 | 110-29.67 | 7.26 | 1.32 | 5 | 166 | 4 | .01 | C |
| 10 | 80 | 0524 | 0220 | 59.27 | 40-30.47 | 110-29.40 | 4.43 | 1.62 | 6 | 152 | 4 | .04 | B |
| 11 | 80 | 0605 | 0243 | 19.93 | 40-30.39 | 110-36.91 | 8.19 | 1.63 | 5 | 137 | 10 | .05 | C |
| 12 | 80 | 0609 | 0133 | 13.51 | 40-29.65 | 110-29.41 | 5.11 | 1.15 | 5 | 184 | 3 | .02 | C |
| 13 | 80 | 0609 | 1247 | 44.93 | 40-33.45 | 110-42.22 | 9.73 | 1.49 | 4 | 198 | 0 | .00 | C |
| 14 | 80 | 0619 | 1739 | 00.56 | 40-28.82 | 110-29.70 | 5.00 | 1.15 | 3 | 278 | 1 | .00 | C |
| 15 | 80 | 0622 | 1113 | 24.73 | 40-29.53 | 110-27.71 | 7.13 | 1.80 | 6 | 135 | 4 | .05 | B |
| 16 | 80 | 0622 | 1208 | 14.38 | 40-31.17 | 110-30.23 | 4.12 | 1.25 | 4 | 207 | 5 | .01 | C |
| 17 | 80 | 0702 | 0206 | 25.23 | 40-32.77 | 110-54.45 | 4.41 | 2.46 | 7 | 202 | 17 | .08 | C |
| 18 | 80 | 0702 | 0314 | 04.43 | 40-32.91 | 110-54.88 | 1.50 | 2.30 | 5 | 204 | 18 | .21 | D |
| 19 | 80 | 0703 | 0422 | 35.49 | 40-32.87 | 110-54.58 | 2.50 | 2.48 | 6 | 203 | 17 | .17 | D |
| 20 | 80 | 0716 | 2318 | 03.86 | 40-29.21 | 110-29.70 | 5.79 | 1.01 | 4 | 196 | 2 | .00 | C |
| 21 | 80 | 0717 | 0856 | 04.99 | 40-28.97 | 110-27.40 | 7.49 | 1.55 | 6 | 95 | 4 | .03 | B |
| 22 | 80 | 0719 | 1451 | 46.86 | 40-29.93 | 110-30.66 | 4.18 | 0.73 | 5 | 97 | 3 | .03 | C |
| 23 | 80 | 0723 | 0152 | 43.77 | 40-29.57 | 110-29.93 | 5.39 | 1.09 | 6 | 152 | 2 | .03 | B |
| 24 | 80 | 0726 | 0736 | 12.93 | 40-30.11 | 110-27.33 | 6.54 | 1.11 | 5 | 158 | 5 | .06 | C |
| 25 | 80 | 0729 | 0501 | 07.07 | 40-30.29 | 110-30.08 | 4.63 | 0.89 | 4 | 153 | 4 | .01 | C |
| 26 | 80 | 0729 | 0517 | 59.81 | 40-29.55 | 110-31.38 | 5.00 | 0.64 | 3 | 203 | 3 | .00 | C |
| 27 | 80 | 0730 | 1041 | 11.72 | 40-30.49 | 110-29.99 | 1.82 | 1.02 | 5 | 200 | 4 | .03 | C |
| 28 | 80 | 0809 | 0313 | 24.86 | 40-29.36 | 110-28.69 | 6.41 | 1.15 | 5 | 156 | 3 | .06 | C |
| 29 | 80 | 0809 | 0924 | 56.40 | 40-33.57 | 110-43.66 | 5.00 | 2.01 | 6 | 267 | 2 | .23 | D |

Table 4.1. - Catalog of 1980 microearthquakes (cont.)

| ID | YR | DATE | ORIG | TIME | LAT-N | LONG-W | DEPTH | MAG | NO | GAP | DMN | RMS | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 30 | 80 | 0812 | 0138 | 01.39 | 40-29.22 | 110-27.78 | 3.51 | 1.39 | 7 | 98 | 4 | .07 | B |
| 31 | 80 | 0818 | 1228 | 25.31 | 40-34.59 | 110-45.63 | 16.66 | 0.96 | 4 | 273 | 5 | .00 | C |
| 32 | 80 | 0820 | 1050 | 39.20 | 40-32.31 | 110-54.07 | 7.15 | 1.32 | 5 | 260 | 3 | .12 | D |
| 33 | 80 | 0820 | 1056 | 19.11 | 40-25.61 | 110-31.21 | 3.58 | 1.37 | 5 | 246 | 5 | .08 | C |
| 34 | 80 | 0825 | 0449 | 45.66 | 40-30.64 | 110-29.58 | 4.87 | 1.09 | 5 | 136 | 5 | .12 | C |
| 35 | 80 | 0825 | 0836 | 25.51 | 40-29.84 | 110-29.08 | 5.00 | 1.06 | 5 | 127 | 3 | .12 | C |
| 36 | 80 | 0902 | 0813 | 08.73 | 40-35.14 | 110-35.06 | 12.02 | 1.20 | 8 | 179 | 6 | .05 | B |
| 37 | 80 | 0902 | 1509 | 48.97 | 40-32.35 | 110-38.23 | 5.00 | 1.17 | 8 | 132 | 5 | .20 | C |
| 38 | 80 | 0906 | 0304 | 28.81 | 40-25.68 | 110-50.56 | 5.39 | 1.85 | 8 | 236 | 10 | .21 | C |
| 39 | 80 | 0906 | 2327 | 58.77 | 40-31.36 | 110-32.14 | 11.91 | 1.17 | 9 | 93 | 4 | .11 | B |
| 40 | 80 | 0906 | 2329 | 21.87 | 40-33.24 | 110-34.20 | 14.59 | 1.29 | 6 | 143 | 5 | .24 | C |
| 41 | 80 | 0907 | 1000 | 36.53 | 40-30.96 | 110-31.59 | 13.04 | 1.27 | 10 | 83 | 5 | .05 | A |
| 42 | 80 | 0907 | 1935 | 56.01 | 40-30.14 | 110-27.77 | 7.50 | 1.06 | 8 | 87 | 1 | .06 | A |
| 43 | 80 | 0908 | 1738 | 36.33 | 40-24.67 | 110-51.20 | 3.26 | 2.45 | 10 | 248 | 12 | .15 | C |
| 44 | 80 | 0909 | 0146 | 46.77 | 40-24.38 | 110-51.40 | 5.35 | 2.42 | 10 | 251 | 12 | .19 | D |
| 45 | 80 | 0909 | 0426 | 00.50 | 40-24.43 | 110-55.77 | 3.67 | 2.66 | 13 | 180 | 12 | .20 | C |
| 46 | 80 | 0910 | 0541 | 41.93 | 40-23.18 | 110-57.30 | 5.18 | 1.95 | 5 | 300 | 15 | .08 | C |
| 47 | 80 | 0910 | 2316 | 35.53 | 40-28.68 | 110-28.22 | 4.98 | 0.81 | 5 | 114 | 2 | .02 | C |
| 48 | 80 | 0912 | 1230 | 21.10 | 40-29.38 | 110-26.94 | 8.00 | 0.91 | 5 | 193 | 1 | .05 | C |
| 49 | 80 | 0914 | 0341 | 35.69 | 40-30.11 | 110-27.29 | 8.10 | 1.39 | 10 | 94 | 1 | .08 | B |
| 50 | 80 | 0915 | 0028 | 24.46 | 40-31.80 | 110-41.05 | 11.47 | 1.01 | 5 | 138 | 4 | .07 | C |
| 51 | 80 | 0916 | 1051 | 59.15 | 40-29.39 | 110-27.39 | 7.45 | 0.98 | 8 | 97 | 1 | .04 | B |
| 52 | 80 | 0916 | 1237 | 40.87 | 40-27.27 | 110-45.73 | 6.04 | 1.13 | 4 | 167 | 6 | .08 | C |
| 53 | 80 | 0916 | 1711 | 02.24 | 40-30.17 | 110-27.56 | 8.44 | 2.02 | 8 | 101 | 1 | .05 | B |
| 54 | 80 | 0918 | 2337 | 11.51 | 40-29.91 | 110-32.33 | 5.00 | 1.37 | 4 | 236 | 4 | .11 | C |
| 55 | 80 | 0919 | 1533 | 30.81 | 40-29.73 | 110-27.69 | 7.47 | 1.02 | 4 | 137 | 0 | .06 | C |
| 56 | 80 | 0921 | 0932 | 39.14 | 40-30.42 | 110-27.94 | 3.48 | 1.02 | 8 | 83 | 2 | .07 | A |
| 57 | 80 | 0928 | 1226 | 33.27 | 40-29.96 | 110-27.08 | 8.17 | 2.11 | 9 | 99 | 5 | .05 | B |
| 58 | 80 | 0928 | 2026 | 28.33 | 40-29.43 | 110-29.40 | 5.00 | 1.00 | 8 | 81 | 2 | .11 | A |

Table 4.1. - Catalog of 1980 microearthquakes (cont.)

| ID | YR | DATE | ORIG | TIME | LAT-N | LONG-W | DEPTH | MAG | NO | GAP | DMN | RMS | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 59 | 80 | 0928 | 2027 | 37.91 | 40-29.40 | 110-28.91 | 5.50 | 1.16 | 8 | 66 | 2 | .06 | A |
| 60 | 80 | 0928 | 2119 | 33.88 | 40-29.14 | 110-28.97 | 5.54 | 1.79 | 7 | 80 | 2 | .07 | A |
| 61 | 80 | 0928 | 2119 | 34.70 | 40-29.52 | 110-28.99 | 6.30 | 1.82 | 10 | 59 | 2 | .04 | A |
| 62 | 80 | 0928 | 2120 | 01.93 | 40-29.19 | 110-29.39 | 5.52 | 1.22 | 6 | 84 | 2 | .04 | A |
| 63 | 80 | 0928 | 2142 | 44.71 | 40-29.45 | 110-28.90 | 5.89 | 1.10 | 8 | 74 | 2 | .06 | A |
| 64 | 80 | 1001 | 0354 | 20.69 | 40-29.52 | 110-27.49 | 8.60 | 1.35 | 9 | 94 | 0 | .06 | B |
| 65 | 80 | 1001 | 2246 | 38.38 | 40-27.37 | 110-39.92 | 6.14 | 1.23 | 9 | 117 | 6 | .09 | B |
| 66 | 80 | 1002 | 0948 | 46.62 | 40-30.41 | 110-27.69 | 5.00 | 0.68 | 5 | 155 | 1 | .15 | C |
| 67 | 80 | 1007 | 0152 | 44.37 | 40-31.99 | 110-55.93 | 14.62 | 1.28 | 8 | 305 | 4 | .05 | D |
| 68 | 80 | 1007 | 0220 | 58.96 | 40-27.21 | 110-29.34 | 9.53 | 0.77 | 5 | 150 | 2 | .04 | C |
| 69 | 80 | 1008 | 1007 | 36.94 | 40-31.25 | 110-46.77 | 8.28 | 1.50 | 8 | 153 | 7 | .09 | B |
| 70 | 80 | 1009 | 2222 | 12.55 | 40-33.01 | 110-53.63 | 11.77 | 1.67 | 6 | 306 | 16 | .10 | D |
| 71 | 80 | 1010 | 0417 | 54.06 | 40-30.55 | 110-27.11 | 6.86 | 1.05 | 7 | 165 | 2 | .11 | C |
| 72 | 80 | 1010 | 0843 | 51.54 | 40-34.19 | 110-33.35 | 3.29 | 1.23 | 8 | 156 | 4 | .09 | B |
| 73 | 80 | 1012 | 0021 | 31.17 | 40-30.85 | 110-29.91 | 5.00 | 0.81 | 3 | 174 | 2 | .01 | C |
| 74 | 80 | 1012 | 0833 | 46.96 | 40-28.66 | 110-28.36 | 5.14 | 0.87 | 7 | 108 | 2 | .03 | B |
| 75 | 80 | 1015 | 0955 | 09.12 | 40-29.91 | 110-27.10 | 9.26 | 2.62 | 12 | 98 | 1 | .03 | B |
| 76 | 80 | 1015 | 1032 | 46.59 | 40-29.99 | 110-27.16 | 7.36 | 1.05 | 10 | 97 | 1 | .05 | B |
| 77 | 80 | 1015 | 1642 | 30.35 | 40-29.53 | 110-27.34 | 9.09 | 1.07 | 9 | 97 | 0 | .06 | B |
| 78 | 80 | 1015 | 2231 | 02.26 | 40-35.22 | 110-45.28 | 13.21 | 1.71 | 10 | 207 | 5 | .08 | C |
| 79 | 80 | 1027 | 0822 | 39.34 | 40-30.17 | 110-29.50 | 4.40 | 0.99 | 6 | 94 | 3 | .04 | B |
| 80 | 80 | 1027 | 0823 | 44.04 | 40-30.39 | 110-29.14 | 5.85 | 1.22 | 8 | 108 | 3 | .07 | B |
| 81 | 80 | 1027 | 0828 | 04.18 | 40-30.16 | 110-29.04 | 6.06 | 1.39 | 8 | 102 | 2 | .05 | B |
| 82 | 80 | 1027 | 0828 | 20.82 | 40-30.11 | 110-29.37 | 6.71 | 1.12 | 7 | 94 | 3 | .04 | B |
| 83 | 80 | 1027 | 0828 | 54.04 | 40-30.13 | 110-29.17 | 6.15 | 1.12 | 8 | 98 | 2 | .03 | B |
| 84 | 80 | 1027 | 0830 | 18.52 | 40-30.31 | 110-29.12 | 5.92 | 1.02 | 8 | 106 | 3 | .04 | B |
| 85 | 80 | 1027 | 0908 | 21.67 | 40-30.30 | 110-29.06 | 6.17 | 1.53 | 8 | 107 | 2 | .02 | B |
| 86 | 80 | 1027 | 2020 | 15.07 | 40-30.19 | 110-29.06 | 6.14 | 1.01 | 6 | 85 | 2 | .04 | A |

Table 4.1. - Catalog of 1980 Microearthquakes (cont.)

| ID | YR | DATE | ORIG | TIME | LAT-N | LONG-W | DEPTH | MAG | NO | GAP | DMN | RMS | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 87 | 80 | 1101 | 0225 | 59.77 | 40-29.28 | 110-29.73 | 6.07 | 0.92 | 4 | 116 | 2 | .04 | C |
| 88 | 80 | 1101 | 1945 | 52.10 | 40-28.25 | 110-28.86 | 4.93 | 1.09 | 4 | 183 | 2 | .01 | C |

Explanation of Headings for Table 4.1.

ID - Identification number of earthquake
YR - Year
DATE - Data of earthquake occurrence, month and day
ORIG TIME - Origin time of earthquake, GMT, in hours, minutes, and seconds
LAT-N - North latitude in degrees and minutes
LONG-W - West longitude in degrees and minutes
DEPTH - Focal depth in kilometers
MAG - Duration magnitude
NO - Number of P and S arrival times used in the solution
GAP - Largest azimuthal separation in degrees between recording stations used in the solution
DMN - Epicentral distance in kilometers to the closest station
RMS - Root-mean-square error in seconds of the travel-time residuals
Q - Quality class of the hypocenter where Q is the average of S and D defined as follows:

| S | RMS | ERH | ERZ |
|---|---|---|---|
| A | <0.15 | ≤1.0 | ≤2.0 |
| B | <0.30 | ≤2.5 | ≤5.0 |
| C | <0.50 | ≤5.0 | |
| D | ≥0.50 | | |

| D | NO | GAP | DMN |
|---|---|---|---|
| A | ≥6 | <90° | ≤ DEPTH or 5 km |
| B | ≥6 | ≤135° | ≤ 2x DEPTH or 5 km |
| C | ≥6 | ≤180° | ≤ 50 km |
| D | ≤6 | | |

Several composite focal plane solutions, all indicating normal faulting, were computed for selected groups of microearthquakes based on the distribution of first motion polarities displayed on lower hemisphere, equal area projection stereo nets. The solutions shown on figures 4.1 and 4.2 are variations on the same set of 17 events, and illustrate the limits on resolution inherent in the method. The solution shown in figure 4.3 is from a different group of 16 earthquakes indicating the dependent nature of event selection on the computed solution.

Each stereographic projection defines two orthoganal planar surfaces. Assuming the earthquake source mechanism can be modeled as a simple double couple without moment, movement on either surface could have produced the observed first motion distribution. In reality, however, only one plane is the fault plane. The other plane is referred to as the nodal plane. It is not possible to distinguish between the two unless additional data, usually geologic, are available. In the absence of geologic data, and with well-located events, it is sometimes possible to eliminate one of the choices by fitting a plane to the distribution of hypocenters using the method of least squares. The Bear Wallow events are found to cluster along a north-trending plane that dips 35° to 40° east. Figure 4.4 is a projection of the hypocenters of the better-located earthquakes onto an east-west vertical plane. The data set includes only earthquakes recorded on eight or more seismographs and are identified by event number. The horizontal distance is the perpendicular distance from the epicenters to the north-south line at 110.5° W longitude. This depth section shows the data best fit, in terms of least squares, a plane dipping about 40° east. Thus, the assumed fault planes on figures 4.1, 4.2, and 4.3 are the northeast to east dipping surfaces, and the west to southwest dipping surfaces are the nodal planes. Considering all the data, the solution shown on figure 4.2, N 5° E, 34° E, is the most probable orientation of the Bear Wallow fault, although the dip may be underestimated by 5° to 10°.

Fault plane solutions and depth sections computed by the USGS for aftershocks of the September 30, 1977 earthquake define a north- to north-northeast-trending normal fault, dipping about 45° E. (Carver and others, 1981). Fault geometry defined by data collected during the present study are consistent with USGS conclusions, thus indicating the current stress field in the Bear Wallow area has not changed significantly in the 3 years following the September 30, 1977 earthquake. This suggests one of two possible conclusions regarding seismicity in the Bear Wallow region. The first is that the microearthquake activity recorded during the 1980 study consists of continuing aftershocks of the 1977 main shock, and, therefore, provide little information about the normal level of seismicity in the area. The second possibility is that the rate of seismicity in the Bear Wallow area, as defined by this study, about one earthquake occurring every 2 days, represents the actual level of seismicity, and went unnoticed during historic times due to a lack of instrumentation in the region. The fault geometry and spatial distribution of hypocenters indicate the active portion of the fault plane encompasses an area of about 79 $km^2$ (30 $mi^2$). This estimate may represent the upper limit on fault dimensions. However, considering

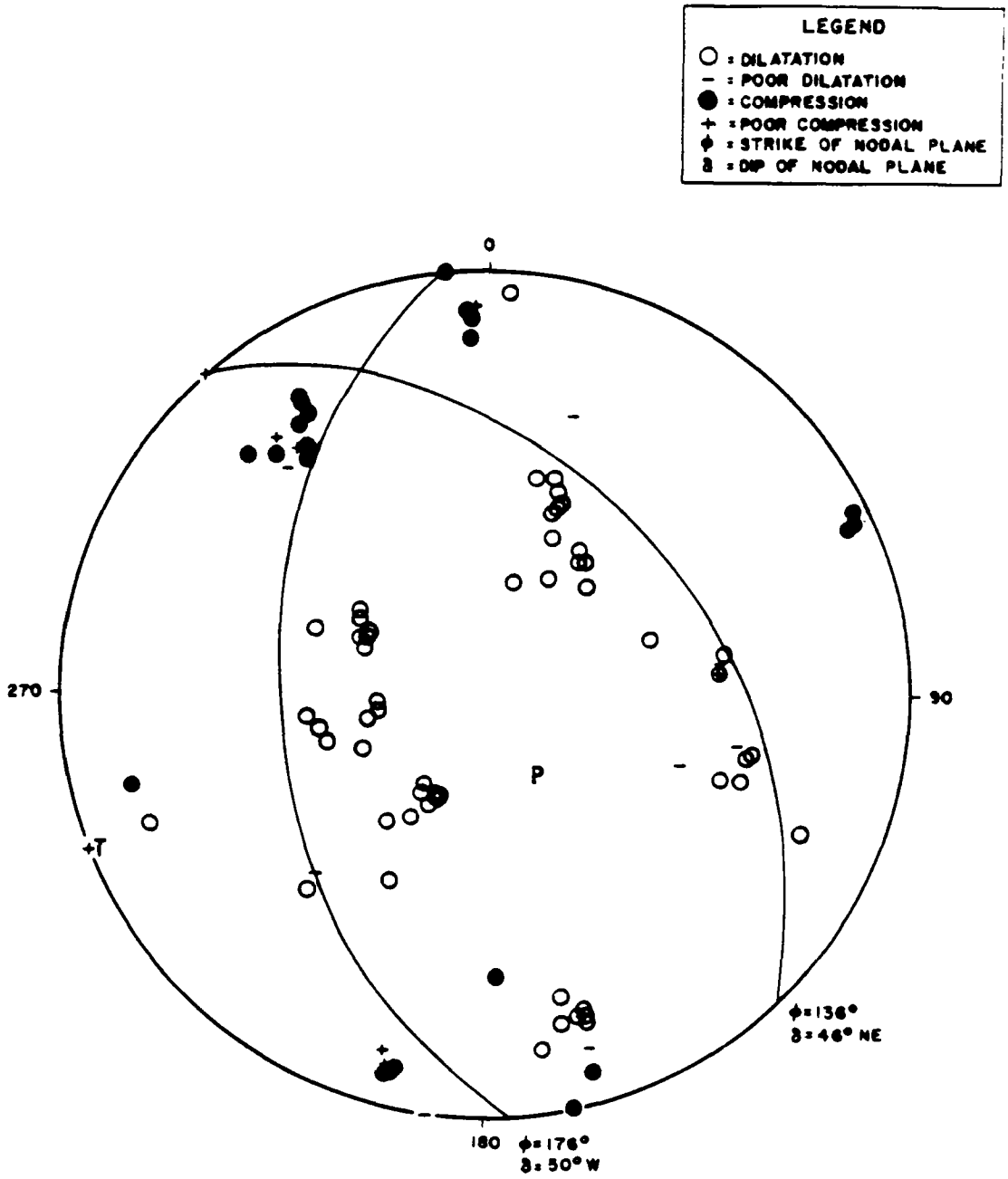



Figure 4.1. Composite focal mechanism solution No. 1 for 1980 Bear Wallow earthquakes No. 58-63, 73, 74, 79-87. First motion polarities plotted on lower hemisphere, equal area projection. P and T indicate compressional and tensional axes, respectively.

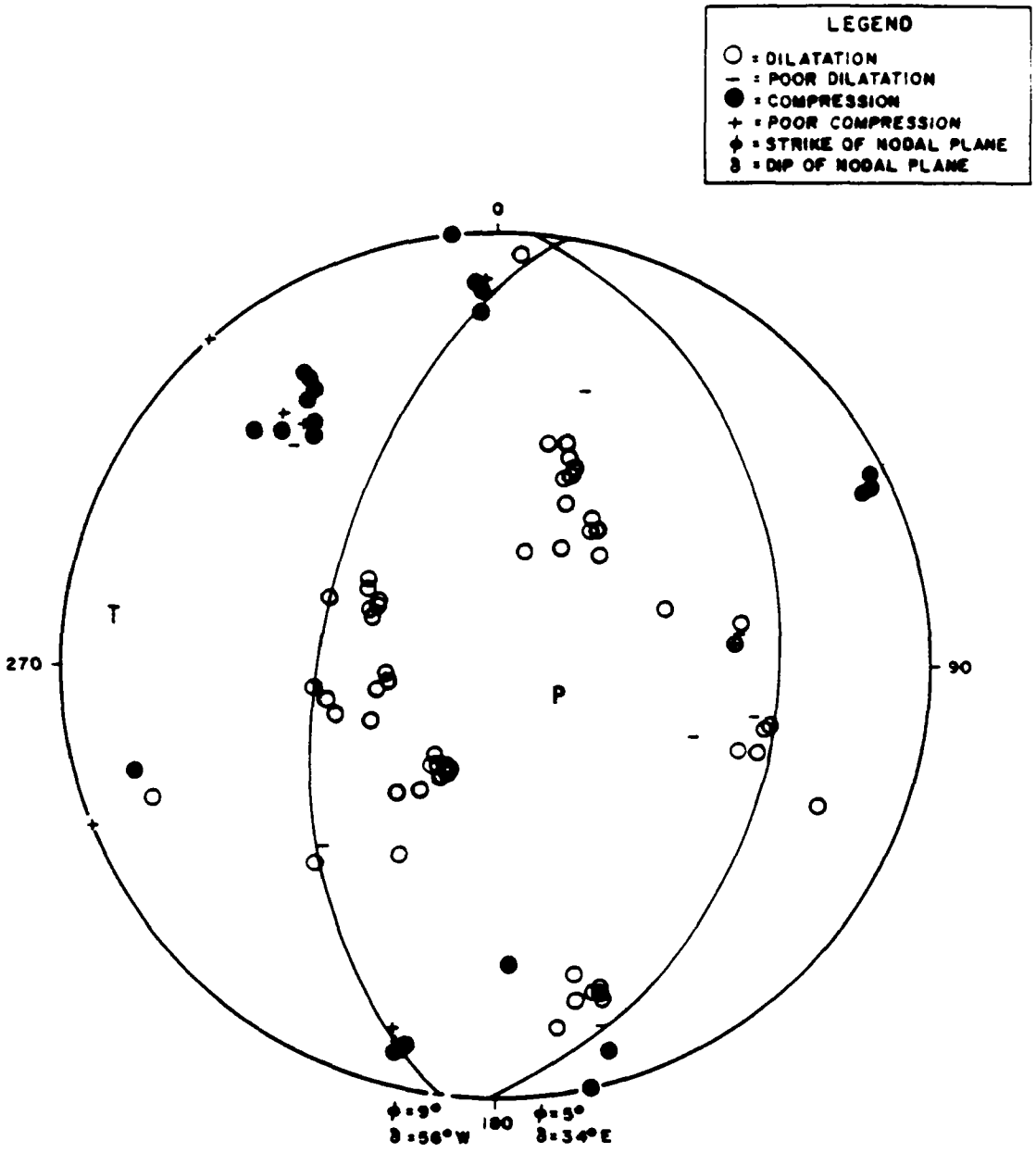



Figure 4.2. Composite focal mechanism solution No. 2 for 1980 Bear Wallow earthquakes No. 58-63, 73, 74, 79-87. First motion polarities plotted on lower hemisphere, equal area projection. P and T indicate compressional and tensional axes, respectively.

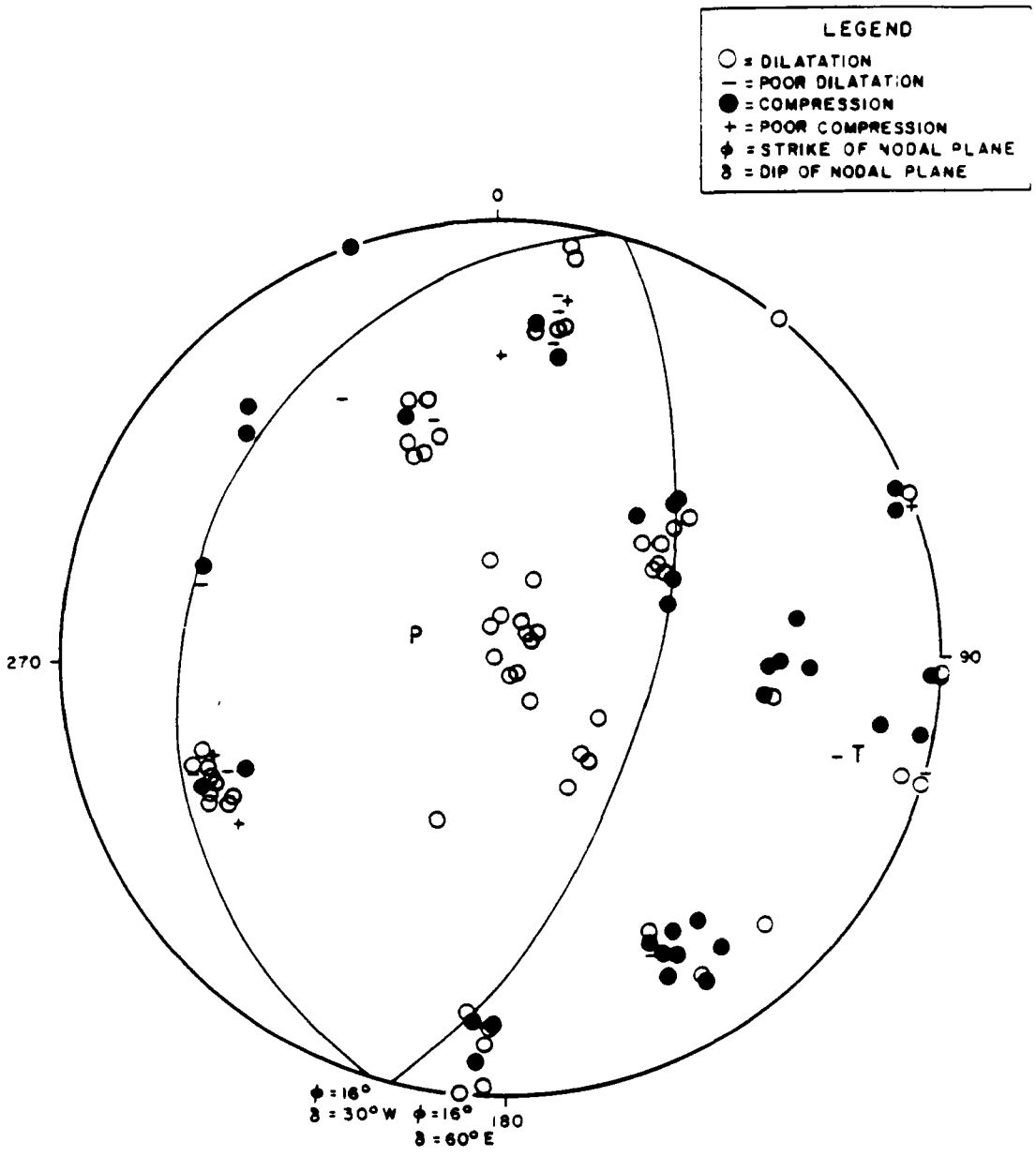



Figure 4.3. Composite focal mechanism solution for Bear Wallow earthquakes No. 15, 21, 24, 42, 48, 49, 51, 53, 55, 57, 64, 66, 71, 75, 76, and 77. First motion polarities plotted on lower hemisphere, equal area projection. P and T indicate compressional and tensional axes, respectively.

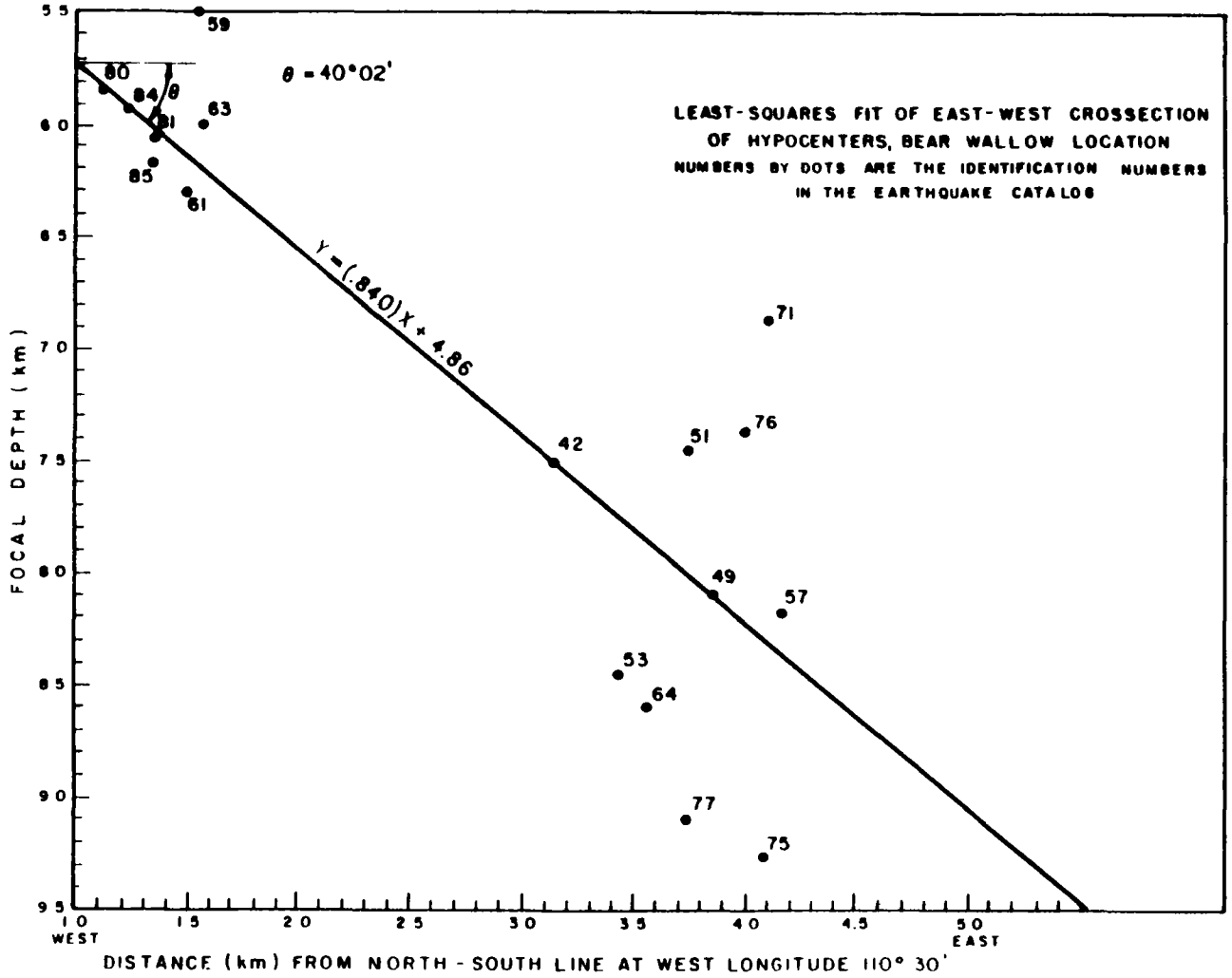



Figure 4.4. East-west hypocentral cross section (A-A') of selected Bear Wallow events.

the possibility that the earthquake occurrence is aftershock in nature, and, therefore, defines only the most recent zone of stress release, the Bear Wallow fault may be of greater extent than the data indicate.

### 4.1.2 Suspected South Flank Fault Events

The South Flank fault group includes 14 microearthquakes located within 2.5 km (1.6 mi) of the mapped trace of the South Flank fault (pl. 2). The epicenters extend along the fault from Moon Lake to about 28 km (17 mi) west of Upper Stillwater damsite. Focal depths range from 3 to 13 km (2 to 8 mi), although they are generally not very well constrained due to insufficient station coverage along this mountainous array boundary. Most of these earthquakes were located south of the surface trace of the South Flank fault at depths consistent with the assumed geometry of a south and steeply dipping normal fault. Three microearthquakes, however, were located north of the surface trace of the fault at depths greater than 9 km (5.6 mi). Provided the hypocenters are correct, the occurrence of these three earthquakes north of the fault may be indicative of an opposite sense of dip on the South Flank fault. Another possibility is that the South Flank fault events are actually due to movement on north-trending faults that are known to exist throughout this region. The velocity model used to compute the hypocenters necessarily assumes horizontal, homogeneous, and isotropic earth layers. The structure and stratigraphy along the South Flank fault, however, is quite complex and near the boundary of the array; thus, location errors of several kilometers can be expected. With the available data, it is not possible to differentiate between north-south faulting versus east-west faulting for these events that locate near the South Flank fault.

### 4.1.3 Southwest Events

The southwest group of events consists of five earthquakes that locate just outside the array in an area of known faulting 6 to 12 km (3.7 to 7.5 mi) west of Hannah, Utah. The epicenters are somewhat scattered, and depths are poorly constrained. No direct association with specific faults is possible.

### 4.1.4 Random Events

The remaining nine earthquakes located within the array are grouped as random events not spatially associated with the first three sets of data. Six of these events appear truly as random scattered events locating in the area west of the Bear Wallow events and east of the Duchesne River. Three events, however, are located 2 to 5 km (1.2 to 3.1 mi) northwest of the Bear Wallow events at a depth of about 12 km (7.5 mi). The hypocenters of two of these three events are controlled very well due to good station coverage and cannot be discounted as poorly located Bear Wallow events. The hypocenters are consistent with a south dipping South Flank fault origin, although there are other mapped faults in the area. No unequivocal fault plane solution is possible with these available data; thus, conclusive association with one particular fault is impossible.

## 4.2 Geologic Investigations

### 4.2.1 Previous Mapping

The glacial geology of the Uinta Mountains was first mapped by Atwood (1909). Forrester (1937) mapped and described the structure of the Uinta Mountains. The geology of the Taskeech and Upper Stillwater damsite areas has been mapped by Huddle and others (1951). Areas immediately to the east and west of their map have been mapped by Kinney (1951) and Huddle and McCann (1947), respectively. Quaternary deposits along the south flank of the Uinta Mountains and in the northern Uinta Basin were mapped by Osborn (1973). The Salt Lake City 1° by 2° quadrangle, Utah and Wyoming, is currently being mapped by B. Bryant (USGS, Denver, oral communication, 1980). Regional geologic maps by Andrews and Hunt (1948), Stokes and Madsen (1961), and Hintze (1980), which encompass the Taskeech and Upper Stillwater damsites, consist of compilations of previous work by various investigators.

The most definitive work concerning Quaternary faulting in the Uinta Basin and Mountains is the compilation of Anderson and Miller (1979). Their "Quaternary Fault Map of Utah" shows only limited Quaternary faulting in this region compared with the Wasatch Front and the Basin and Range province to the west. Three late Pleistocene faults are shown on their map within 50 km (31 mi) of either the Taskeech or Upper Stillwater damsites. These include the faults on Towanta Flat, a western extension of the Towanta Flat faults called the Little Valley fault, and a segment of the Strawberry fault (pl. 2). Their map does not include the Duchesne-Pleasant Valley fault system, which was reported by Osborn (1973) to have experienced late Quaternary displacement, possibly during the Holocene. However, Anderson and Miller (1979) note that their map does not necessarily delineate all the Quaternary faults in Utah, and that additional Quaternary faults undoubtedly exist.

### 4.2.2 Objectives

Review of geologic and seismologic literature, preliminary airphoto analysis, and reconnaissance mapping lead to the definition of three objectives for seismotectonic studies. These are:

1. Develop evidence for assessing late Cenozoic displacement history of the western portion of the mountain flank faults;

2. Evaluate the extent and age of reported late Quaternary faulting at Towanta Flat;

3. Determine if a causative fault is present in the area of continuing aftershocks associated with the 1977 earthquake.

In addition, limited reconnaissance studies were performed for other more distant potential seismic source zones.

### 4.2.3 Mountain Flank Faults

#### 4.2.3.1 South Flank Fault

The South Flank fault has a strike length of over 130 km (81 mi) and is within 10 and 0.5 km (6.2 and 0.3 mi) of Taskeech and Upper Stillwater damsites, respectively. While previous work suggests that major displacement on the fault occurred during the early Cenozoic, the lack of detailed mapping along the fault, evidence for Neogene and Quaternary reactivation of similar faults further east, the occurrence of moderate-magnitude earthquakes in the region, and the proximity of this major fault to the damsites, prompted the investigation of the history of faulting west of the Whiterocks River. No investigations of faulting on the south flank of the Uinta Mountains east of the Whiterocks River were conducted because of the distance from the subject damsites.

Initial investigations consisted of a review of aerial photography, and aerial overflights along the South Flank fault from the North Fork of the Provo River to the Whiterocks River (pl. 1). These investigations revealed no scarps or other evidence for late Quaternary displacement along the fault. Despite an estimated vertical, or dip slip, displacement of greater than 1 km, there is no continuous bedrock escarpment associated with the fault. Areas were selected for detailed mapping to estimate the age of most recent displacement of the fault.

Recurrently active late Cenozoic faults in the Basin and Range transition zone typically are range-front normal faults bounding uplifted mountain blocks or related, subparallel trending intrabasin faults. Typically, late Cenozoic faults juxtapose mountain blocks and alluviated basins covered by Quaternary fluvial deposits, alluvial fans, or glacial deposits along prominent linear mountain fronts. Scarps are often present in alluvial deposits at the mountain front or basinward from it. The South Flank fault does not exhibit these physiographic characteristics. There is no continuous bedrock escarpment associated with the fault; pre-Quaternary erosion surfaces are uninterrupted across the mapped trace of the fault (discussed below). No scarps or lineaments are present near the trace of the fault in Quaternary or pre-Quaternary deposits. As discussed in section 3.1.2, the basin fill deposits adjacent to the fault are Paleogene in age. Quaternary and Neogene deposits are restricted to deeply incised southflowing drainages or form thin veneers of outwash overlying Paleogene deposits.

Plate 7 presents the results of detailed mapping of three areas along the trace of the South Flank fault in the vicinity of Upper Stillwater damsite. These areas, described as East Grandaddy Mountain, Dry Ridge, and Center Park, were selected because sufficient bedrock exposure exists to constrain the trace of the fault below an erosion surface or a stratigraphic unit.

East Grandaddy Mountain

Map A, plate 7, presents the results of mapping in the vicinity of East Grandaddy Mountain along the trace of the South Flank fault. The fault is well exposed on the east side of the mountain, at the head of the South Fork of Rock Creek, as an altered zone of gouge and breccia juxtaposing north-dipping Mississippian limestones and the Precambrian Mutual Formation. Crossection A-A' is a topographic profile down the interfluve separating Hades Creek and the South Fork of Rock Creek. The remnant of an erosion surface at an elevation of about 3410 m (11 200 ft), which is preserved as the surface of the interfluve, slopes gently southward with no topographic step across the trace of the fault. Two steeply dipping, northeast-trending normal faults, exposed in the canyon side, are shown in map A. These faults have displacements of about 30 m (100 ft) and are not present on the south margin of the East Grandaddy Mountain to the northeast, suggesting they are terminated by, and subsidiary to, the South Flank fault.

Dry Ridge

At the north end of Dry Ridge along the South Flank fault zone, the fault is comprised of three major traces (map B, pl. 7). The southernmost trace is a mineralized breccia zone which yields iron minerals at the Paint Mine. Maps of Stokes and Madsen (1961), and Huddle and others (1951), suggest that the Duchesne River Formation may thicken abruptly in the vicinity of the breccia zone associated with the South Flank fault, near the Paint Mine. Detailed mapping did not reveal any evidence that the Duchesne River Formation is displaced. Rather, it appears to overlie the fault and thicken gradually to the south. Crossection B-B' is a topographic profile down the interfluve west of the head of Slate Creek. The preserved remnant of an erosion surface at an elevation of about 3230 m (10 600 ft) at the fault, has a gentle southward gradient and also is undisplaced across the traces of the South Flank fault. As depicted in section B-B', an upper portion of the Duchesne River Formation appears to overlie the erosion surface in this area.

Center Park

Mapping (map C, pl. 7) along the South Flank fault between the Lake Fork River and Yellowstone Creek confirms the interpretation of Stokes and Madsen (1961), and Huddle and others (1951), that the Duchesne River Formation overlies the South Flank fault in this area. The fault is exposed on the east side of Moon Lake and its position in Center Park is constrained by outcrops of the Mutual Formation to the north in the footwall, and outcrops of Red Pine Shale to the south in the hanging wall. In this area, the Duchesne River Formation at an elevation of 3170 m (10 400 ft) is a coarse, semiconsolidated, alluvial fan deposit which appears to represent a near-source facies.

Estimated Age of Most Recent Displacement

Hansen (1983) describes the extensive Gilbert Peak erosion surface on both the north and south flanks of the eastern Uinta Mountains. He concludes that the Oligocene-age Bishop Conglomerate overlies this surface and, therefore, concludes that the Gilbert Peak erosion surface is of Oligocene age. Hansen (1983, p. 9) also reports that the Starr Flat Member of the Duchesne River Formation rests unconformably on a truncated surface near the mountains, that is probably the Gilbert Peak erosion surface.

East of Upper Stillwater damsite, a remnant of an erosion surface cut across the South Flank fault is preserved at an elevation of 790 m (2590 ft) above the Lake Fork River. Crossection B-B' (map B) and map C (pl. 7) suggest that this erosion surface is overlain locally by deposits mapped as the Duchesne River Formation. This surface is probably of comparable age to the Gilbert Peak erosion surface. The erosion surface west of Upper Stillwater Dam is probably also about the same age.

The cross sections on plate 7 were prepared from topographic maps at a scale of 1:24,000 and, therefore, should only be considered accurate to within about 5 to 10 m. Therefore, the possibility of a total displacement of up to about 10 m since development of the Gilbert Peak erosion surface cannot be precluded. However, a history of significant recurrent surface displacements postdating the Gilbert Peak surface can be precluded along this portion of the South Flank fault.

4.2.3.2 Uinta Basin Fault

Lucas and Drexler (1975) report that little or no fault displacement is recognized in the Green River Formation of Eocene age (see fig. 3.3), which overlies the Uinta Basin fault, suggesting that major displacement occurred over 40 million years ago. However, as can be seen on plate 2 (see also sec. 4.2.4), the scarps at Towanta Flat occur near the surface projection of the Uinta Basin fault.

4.2.4 Faulting at Towanta Flat

Huddle and others (1951) first suggested that late Tertiary faulting was present on Towanta Flat, an outwash plain along the south flank of the Uinta Mountains (pls. 1 and 2). Hansen (1969a, 1969b) described the topographic scarps in outwash deposits on Towanta Flat (pl. 3) as representing late Quaternary faulting, and estimated the youngest displacement to date from 32 ka to 11 ka (thousands of years before present) based on the inferred age of the faulted Quaternary deposits. Osborn (1973) concurred with Hansen's findings, but also suggested that the faulting could be even younger. Anderson and Miller (1979) also assigned a late Quaternary age to the Towanta Flat scarps. Ritzma (1974) suggested these scarps are associated with a much larger east-west structural feature that he named the "Towanta Lineament."

Following the occurrence of the Richter magnitude 4.5 earthquake in the general area of Towanta Flat on September 30, 1977, the Utah Geological and Mineral Survey (UGMS, 1977) reported this main shock and the hundreds of aftershocks that were recorded through October 11, 1977, occurred along the "Towanta Lineament." The report also stated there are surface manifestations of relatively recent movement along the lineament, citing Towanta Flat, where displacements have occurred "perhaps as recently as 4,000 to a few hundred years" before present.

An indirect implication of this report is that earthquakes large enough to produce surface displacement are recurring on Towanta Flat at a rate comparable to that for the Wasatch fault (Swan and others, 1980), one of the most active faults (definition of Wallace, 1981) in the Intermountain west. Also, association of the Towanta Flat scarps with Ritzma's (1974) "Towanta Lineament" would imply latest Quaternary displacement on a segment of an inferred structure which Ritzma traces across most of the State of Utah.

Review of aerial photography, as well as ground reconnaissance, suggested that these features were significantly older than indicated by the Utah Geological and Mineral Survey (UGMS, 1977). Therefore, the significance of these features was further evaluated through detailed mapping, relative-age dating of displaced deposits, scarp profiling, and trenching.

Nine fault scarps are present on Towanta Flat about 6 km (4 mi) south of the mountain front (pl. 3). The primary set of scarps trends N. 50-55° E., generally subparallel to the major structures in the area (i.e., South Flank fault, Uinta Basin fault, and Uinta Basin axis), while a secondary set trends N. 70° E. (Hansen, 1969b). The scarps bound a graben that varies in width from 170 to 610 m (560 to 2000 ft). The scarps extend from immediately east of Pigeon Water Creek to near the eastern margin of a large melt-water channel, a distance of about 5 km (3 mi).

#### 4.2.4.1 Resistivity Survey

Two electrical resistivity profiles across the graben (Meiiji Resource Consultants, 1980), indicated on plate 3, were used to locate faults and estimate the amount of displacement of the contact between the Tertiary Duchesne River Formation and overlying outwash. Line 1 defines a normal fault with about 25 m (82 ft) of displacement on the southeastern edge of the graben, but the simple resistivity expression of the normal fault on the northwest side of the graben is obscured, possibly by an open cavern at depth. Three collapse pits, the largest measuring 37 by 27 by 12 m (121 by 89 by 39 ft) deep, developed along the northern fault near the western end of the graben (pl. 3) after the Farnsworth Canal, an irrigation canal running along the scarp, had been operating for about 30 years. Possibly piping of canal water along the fault plane in the underlying Duchesne River Formation created voids that caused the collapse of the canal. The collapse pits support the resistivity interpretation of an open cavern obscuring the fault.

Results from line 2 show that the graben contains a small horst block in the subsurface that has no topographic expression. The resistivity data suggest that the bedrock surface along the northwest-bounding scarp is displaced about 15 m (49 ft), but that the center of the graben may contain gravels 25 m (82 ft) thick. Near the southeast end of line 2, outcrops show about 23 m (75 ft) of bedrock relief on the southeast-bounding scarp where a small drainage has exposed the bedrock on the downthrown block.

4.2.4.2 Age of Deposits at Towanta Flat

Determination of the timing and nature of the displacements which produced the fault scarps requires an assessment of the age of the displaced deposits. Ritzma (1974), Hansen (1969a, b), and Osborn (1973, p. 159) suggested the Towanta Flat faults occurred relatively recently during the latest Quaternary. More detailed mapping of this area (pl. 3), however, indicates a greater age for the Towanta Flat deposits. No evidence of extensions of the Towanta Flat faults displacing Quaternary deposits along the Lake Fork River and Rock Creek were found, thus setting limits on the lateral extent of faulting in late Quaternary time.

Age assessments, including subdivision of deposits into relative-age groups (RAGs) (discussed extensively in appendix A), are based on:

1. Airphoto interpretation and morphostratigraphic mapping of moraines and outwash terraces in the Towanta Flat area

2. Relative dating of these landforms using surface boulder weathering data, soil profile descriptions, and soil laboratory analyses

3. Reconnaissance mapping of older alluvial surfaces mapped previously by Osborn (1973), including the use of river terrace profiles for correlation from one drainage to another

4. Amino acid and paleomagnetic analyses at one alluvial terrace site for numerical-age estimates (defined by Colman and Pierce, 1981)

5. Regional correlation of the moraine and terrace sequence along the Lake Fork River with other Quaternary chronologies in the Rocky Mountain region

None of these methods has resulted in accurate numerical-age dates for any of the deposits on Towanta Flat. However, combined use of several different RD (relative-dating) methods makes landform chronology for this part of the Lake Fork drainage more accurately dated than many Quaternary chronologies in the Rocky Mountain region.

4.2.4.3 Trenching of Scarps and Lineaments

Three trenches were excavated across suspected fault scarps on Towanta Flat to assess the age and frequency of faulting. Trench 1 (pl. 4) was located in RAG 3 deposits across the 8-m (26-ft) high scarp bounding the graben on the north near its western end. Trenches 2 and 3 (pls. 5 and 6) were placed across prominent air photograph lineaments in RAG 5-6 deposits in the melt water channel (pl. 3).

Stratigraphy and Age of Units in Trench 1

Deposits exposed in trench 1 consist of RAG 3 outwash deposits and younger colluvial deposits that were interpreted to be fault-scarp-derived grabenfill. The soil developed on the RAG 3 outwash deposits exposed in the northwestern end of trench 1 has a 22-cm (9-in) thick argillic horizon over a 57-cm (22-in) thick stage III (calcium carbonate morphology of Gile and others, 1966) K horizon (unit 1s, pl. 4) (appendix A, table A.2, profile 1). Similar soils were described from the main Towanta Flat surface (appendix A, profiles 7, 8, and 10) and are one line of evidence for the age estimates for the deposits on Towanta Flat.

In the southeastern half of trench 1, the oldest scarp-derived colluvium, unit 2, is overlain by a moderately developed clay-rich paleosol (unit 3s) that has been buried by younger colluvial deposits (units 4s and 5s) (appendix A, table A.2, profile 2). Unit 2s is interpreted to be a remnant of an argillic horizon that developed on unit 2 that was preserved in the small graben in the center of the trench (pl. 4). Where unit 2s was not downdropped into the graben, it was apparently eroded prior to deposition and subsequent development of paleosol 3s. The contact between units 2s and 3s in the small graben is inferred based on the colluvial unit 3 pod between these units (pl. 4). Colluvial unit 4s overlying the buried paleosol (unit 3s) is similar in grain size to unit 2 (appendix A, table A.2, profile 2), but has stronger argillic horizon soil structure. Because units 2s, 3s, and 4s consist of well-developed argillic horizons, the length of time it took to form them (table 4.2) is roughly estimated by correlating these horizons with argillic horizons on "Bull Lake" deposits which took up to 150 k yr to develop (appendix A).

The stratigraphic relationship of unit 5s to the fault scarp in trench 1 was obliterated by excavation of the now-abandoned Farnsworth Canal (pl. 4). The relationship was exposed, however, along the east edge of the collapse pit on the fault scarp about 200 m (660 ft) southwest of the trench (pl. 3). Unit 5s does not appear to have been disturbed by faulting since its deposition.

The soil profiles (appendix A, table A.2, profiles 2 and 3) developed on unit 5s suggest it has an age between RAG 5-6 and RAG 7-8. Both profiles in the fine-grained colluvial unit (probably partly of eolian origin) are difficult to compare to the soils developed on the adjacent coarse outwash parent material (appendix A, table A.2, profile 1). Although

Table 4.2. - Stratigraphic units, soils, and fault events with estimated ages and displacements from Towanta Flat trench 1

| Stratigraphic unit | Soil developed on unit | Fault event | Estimated age ($10^3$ years BP) Range | Best | Estimated length of soil forming interval ($10^3$ years BP) Range | Best | Minimum estimated displacements from colluvial wedge thickness 1/ (m) x 2 |
|---|---|---|---|---|---|---|---|
| 1 | | | 250-500 | 375 | | | 2/ (7.9) |
| | 1s | | | | 250-500 | 375 | |
| 2 | | A | 130-500 | 300 | | | 2.1 |
| | 2s | | | | 0-150 | 100 | |
| 3 | | B | 130-500 | 200 | | | 2.6 |
| | 3s | | | | 50-150 | 100 | |
| 4 | | C | 130-450 | 150 | | | 2.5 |
| | 4s | | | | 30-150 | 100 | |
| 5 | | | 50-150 | 3/ 75 | | | |
| | 5s | | | | 50-100 | 3/ 75 | |

1/ Assuming a significant amount of erosion of the scarp between each fault event, the thickness of the colluvial wedge produced after each fault event will approach one-half the displacement on that event.
2/ Minimum total post-unit 1 displacement from trench stratigraphy (pl. 4) (double the total exposed colluvial wedge thickness approaches this value).
3/ We interpret this unit as accumulating gradually from 150,000 years ago to present; this is an average age.

clay and carbonate accumulate more rapidly in fine-grained soils, profiles 2 and 3 (developed in the same units about 100 m (328 ft) apart) appear more strongly developed than soils on RAG 7-8 deposits in the Towanta Flat area (appendix A). This soil is also more strongly developed than soils about 15,000 years old developed on lithologically similar Lake Bonneville deposits 100 km (62 mi) to the west (Scott and others, 1982). The maximum clay content and carbonate development in the upper part of profile 3 (appendix A, table A.2) match or exceed that for profiles in RAG 5-6 deposits in the Towanta Flat area (appendix A, table A.3), suggesting the basal colluvium in this truncated profile was deposited prior to RAG 7-8 time.

This sequence of events suggests that evidence for three surface displacements is present in this trench with average displacements of 2.1 to 2.6 m (6.9 to 8.5 ft). RAG 3 deposits were not encountered below the colluvial deposits in the trench, suggesting additional events may have occurred at the site. Trench 1 also demonstrates that there are significant soil-forming intervals between surface displacements.

Sequence of Events in Trench 1

The following history of deposition and faulting is inferred from the colluvial stratigraphy and structural relationships exposed in trench 1 and the exposure in the collapse pit along the fault scarp on Towanta Flat.

1. Deposition of RAG 3 (units 1b, 1c, and 1d) outwash unconformably over the Duchesne River Formation of late Eocene and/or early Oligocene age (Andersen and Picard, 1972). This contact was not exposed in the trench.

2. Initiation of soil development on the outwash surface eventually culminating in the engulfment of a well-developed argillic horizon by a stage III K horizon (unit 1s).

3. Faulting of the outwash surface (event A, table 4.2), probably developing much of the graben structure present on Towanta Flat today. The number of surface faulting events is unknown, but colluvial wedges (units 2, 3s, and 4s) suggest three events (table 4.2). Units 1c and 1d of coarse outwash but with less clay, weaker structure, and less intense color hues than units 1s and 1b were clearly disturbed by faulting during this period, but their detailed genesis is uncertain. Clasts in unit 1d near the fault are rotated with their long axes inclined to the southeast at angles up to 80°. Cumulative net vertical displacement for all events along this part of the scarp exceeds 8 m (26 ft). Double the thickness of colluvial wedges adjacent to the fault provides a crude minimum estimate of displacement during each event (table 4.2).

4. Erosion of the fault scarp and deposition of a cobbly proximal colluvial wedge (unit 2) on the downthrown side of the fault.

5. Possible soil development on unit 2 for which little evidence remains (unit 2s). Continued soil development on the upthrown outwash surface.

6. Additional displacement (event B, table 4.2) on the main fault with an antithetic fault producing the small graben which downdropped and preserved unit 2s. Minimum displacement across the antithetic fault is 0.75 m (2.5 ft).

7. Erosion of the fault scarp (including argillic horizons on the upthrown block) with deposition of, and concurrent soil development on, unit 3 (unit 3s) over a long enough period (>50 k yr estimated) to allow considerable clay movement and obliteration of erosional-depositional soil structure in units 2s and 3s.

8. Additional displacement (event C, table 4.2) on the main fault.

9. Erosion of the fault scarp and deposition of a cobbly colluvial wedge (unit 4) over unit 3s.

10. Weak to moderate soil development on unit 4 (unit 4s). Continued soil development on the outwash surface away from the eroded scarp.

11. Continued minor erosion of the main scarp, deposition of colluvium mixed with eolian material to form a fine-grained wedge (unit 5s) on the downthrown block, and concurrent soil development with an argillic horizon and stage I to stage II calcium carbonate development. This process of deposition and soil development is continuing today.

Stratigraphy and Age of Units in Trenches 2 and 3

Trench 2 (pl. 5) was located in the melt-water channel across an air photograph lineament that is on trend with a 1- to 2-m-high (3- to 6-ft) fault scarp about 80 m (260 ft) northeast of the trench (pl. 3). The lineament is in RAG 5-6 deposits, but the scarp is developed in RAG 4-5 deposits.

Trench 3 (pl. 6) was also located in the melt-water channel across one of a series of discontinuous, N. 70° W. trending photograph lineaments which extend across much of the flat (Hansen, 1969b). The age and origin of the west-northwest trending lineaments are unknown, but they do not extend into an area of mixed alluvial fan and colluvial deposits on the western edge of Towanta Flat (pl. 3). Soil profile 12 from this area has strong colors, a high clay content, some carbonate development (stage I+) (appendix A, table A.2), and no weathered clasts. These data suggest most of this material dates from RAG 5-6 and, therefore, that many of the west-northwest-trending lineaments are developed on older surfaces.

Trenches 2 and 3, oriented at right angles to each other about 150 m (490 ft) apart (pl. 3), exposed similar stratigraphy. Soil profiles 4

(trench 2) and 9 (trench 3) (appendix A, table A.2) are difficult to interpret because the sequence of parent materials on which these soils are developed differ in age and lithology. The fine-grained material in the basal units in both trenches (units 6, 5, and 4, pl. 5; unit 4, pl. 6) gives them a gray-green color (2.5Y to 5Y color hues) in contrast to the red color (5YR hues) of the overlying unit 3 sediments. Parts of the basal units in both trenches have stage II carbonate morphology and 30 to 40 percent highly weathered clasts indicating these units are at least as old as RAG 4 (appendix A, table A.3). The quartzite cobble lithology of these units indicates outwash deposition (similar deposits are believed to underlie most of the melt-water channel), but the gray-green clay-rich matrix suggests this sediment is derived from the LaPoint Member of the Duchesne River Formation (Andersen and Picard, 1972). Outcrops along the west side of the Lake Fork River east of the melt-water channel indicate the top of the LaPoint Member is at the same elevation as the base of the melt-water channel near trenches 2 and 3. We interpret the gradual north-to-south lateral changes in lithology of the basal units in trench 2 (units 6, 5, and 4) as facies changes produced by glaciofluvial processes. No evidence of displacement or shear zones in the lower trench units were found, suggesting the airphoto lineaments intersected by trenches 2 and 3 are not related to post-RAG 4 faulting.

Above an unconformity at the top of the gray-green units are reddish (5YR hues) gravelly sands and silty sands (units 2 and 3) that are laterally discontinuous in trench 2 (pl. 5), but are thicker (80 cm; 31 in) and more continuous in trench 3 (pl. 6). This irregularity is attributed to alluvial cut and fill during the most recent episode of outwash deposition (RAG 5-6) in the melt-water channel. The moderate clay contents with argillan development in some parts of units 4 and 5, the stage I carbonate morphology in trench 3 (appendix A, table A.2, profile 9), and the low percentage of highly weathered clasts suggests these reddish units may be as old as the soils developed on RAG 5-6 moraines into which this youngest surface in the melt-water channel can be traced.

Above a second unconformity at the top of the reddish units are silty, partially laminated sediments (unit 1), which are interpreted to be sediments deposited in ponded water in low areas in the younger outwash channel. To the southeast in trench 2, unit 1 grades into unit 1A which is sandier with some cobbles suggesting higher energy fluvial deposition. Locally, unit 1 is stratified; high-angle cross-bedding (up to 40° dip, pl. 5) occurs in sandier parts. Small-scale folds are probably the result of soft-sediment deformation. Both units grade upward into colluvium-loess deposits which make up the modern A horizon. The colluvium-loess deposits are laterally continuous along the entire length of trenches 2 and 3 and lie directly on RAG 4 deposits in the southeast half of trench 2 and on RAG 5-6 deposits in the northwest half of trench 2 and in trench 3. Two depressions, each approximately 0.4 m (1.3 ft) deep and up to 0.3 m (1.0 ft) wide, were noted 8 and 11 m (26 and 36 ft) southeast of the northwest end of trench 2 (pl. 5). These depressions are krotovina (animal burrows) infilled with A and B

soil horizon material which overlies unit 1. None of these features appear to be due to shearing or faulting.

The age of unit 1 is uncertain; it overlies RAG 5-6 deposits and the modern soil is developed on it. The upper fine-grained sediments in trenches 2 and 3 contain a weak argillic horizon with argillans on ped faces (appendix A, table A.2, profiles 4 and 9), but it is difficult to compare the relative age of these soils with other soils of the area which are developed on coarse-grained parent materials. By stratigraphic position and relative soil development, this soil is much younger than RAG 5-6. The presence of an argillic horizon does suggest this soil is more than a few thousand years old and is possibly pre-Holocene in age (for example, Scott and others, 1982). Thus, at least the lowest fine-grained pond deposits probably date from RAG 7-8 or RAG 9 (appendix A).

4.2.4.4 Scarp Heights and Recurrence Intervals of Surface Displacements

Thirty-seven profiles were measured on fault scarps bounding the Towanta Flat graben during the summer of 1979 using a Jacob staff and plane table. The locations of the six groups of profiles are shown on plate 3. Three profile groups (3, 4, 6) were measured on scarps in RAG 3/4 deposits and the other three groups were measured on scarps in the melt-water channel on RAG 4 and RAG 4/5 deposits. The range of scarp height measurements and the average scarp height on each profile group are presented in table 4.3. These data, together with the interpretation of trench 1 (table 4.2), form the basis for estimates of the recurrence of surface displacements.

Analysis of topographic profiles across fault scarps developed in alluvium is the most widely used method of estimating the recency of fault movement in the Basin and Range-Rocky Mountain region (for example, Nash, 1980; Sterr, 1980; Mayer, 1982). Although the age of the Towanta Flat surfaces was estimated using other relative-age methods (appendix A), an attempt (following Wallace (1977), Bucknam and Anderson (1979), and Machette (1982)) was made to use the relation between fault scarp height and maximum fault scarp-slope angle to provide independent estimates of the ages of scarps on Towanta Flat (fig. 4.5). Whether treated as one group or divided into two or three groups of differing relative age, maximum slope angle and scarp height data do not define meaningful regression lines that can be compared with regression lines from previous fault scarp studies in Utah. Some reasons for the wide scatter in these data may include: (1) use of plane table and alidade rather than the methods of Bucknam and Anderson (1979) to measure profiles, (2) postfaulting erosion of some scarps by ephemeral streams in the graben, (3) differences in lithology compared with materials studied elsewhere in Utah, (4) the fact that these are multiple-event scarps rather than single-event scarps like those studied in some other areas, and (5) a colder and moister climate on Towanta Flat than in other studied areas. The importance of these effects cannot be evaluated at the present, and thus, figure 4.5 cannot be used to further control the age of faulting on Towanta Flat.

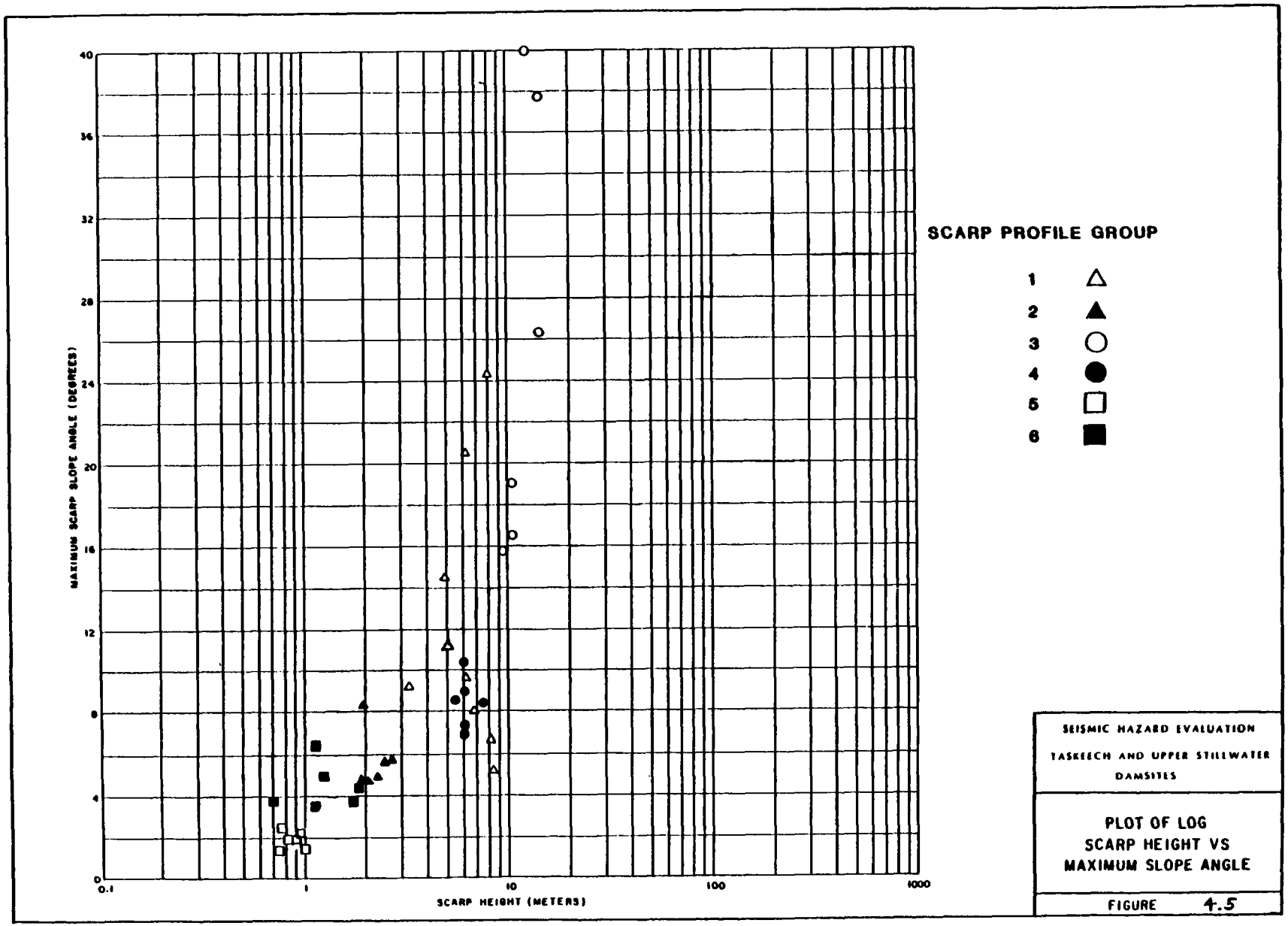
Table 4.3. - Scarp heights, estimated number of fault events, and average recurrence intervals for the Towanta Flat graben

| Map 1/ Unit | Age 2/ (Ka) | Scarp 1/ profile group | Range of scarp heights (m) | Average scarp height (m) | Apparent number 3/ of events | Slip rate 4/ from scarp height (mm/yr) | Average 4/ recurrence interval (k yr) |
|---|---|---|---|---|---|---|---|
| RAG 3 | >250-500 | | | | | | |
| NW | 375 | 3 | 7.0-11.2 | 8.6 | 3-4 | 0.04 | 58-78 |
| SE | 375 | 4 | 5.5-7.5 | 6.3 | 3 | 0.03 | 78 |
| SE | 375 | 6 | 0.3-2.6 | 2.1 | 1 | 0.01 | 235 |
| RAG 4 | 150-500 | | | | | | |
| NW | 250 | 1 | 2.9-6.7 | 4.8 | 2 | 0.04 | 55 |
| RAG 4/5 | 130-350 | | | | | | |
| SE | 200 | 2 | 1.5-2.4 | 2.1 | 1 | 0.04 | 60 |
| SE | 200 | 5 | 2.1-3.1 | 2.4 | 1 | 0.04 | 60 |
| RAG 5-6 | 130-150 | | | | | | |
| | 140 | | | 0 | 0 | 0 | |

Average displacement event recurrence interval: 30 k yr-58 k yr.
Average subsidence rate: 8.6 m in 235 k yr = 0.04 mm/yr.
Maximum subsidence rate: 23 m in 235 k yr = 0.10 mm/yr.

NOTE: Underlined numbers are our best average estimates.

1/ Relative-age units and scarp profile groups on Plate 3, NW and SE refer to scarps on northwest and southeast margins of the graben.
2/ See Appendix A for discussion.
3/ Assuming an average event displacement of 2.2 m based on trench 1 stratigraphy;
4/ Assuming no events in the last 140 k yr; because fault events postdate the map units (RAGs) slip rates are minimum values and recurrence rates are maximum values.




SEISMIC HAZARD EVALUATION
TASKEECH AND UPPER STILLWATER DAMSITES

PLOT OF LOG
SCARP HEIGHT VS
MAXIMUM SLOPE ANGLE

FIGURE 4.5

Profiles across the Towanta Flat graben on RAG 3 and RAG 4 surfaces establish that there is no net vertical displacement across the graben (estimated accuracy 1-2 m (3-6 ft)). Therefore, the assumption has been made that displacement events have contributed equally to scarp development on northwest bounding faults (scarps with down-to-the-southeast sense of displacement) and southeast bounding faults (scarps with down-to-the-northwest sense of displacement). In comparing scarp heights on surfaces of different age, mean scarp heights for each scarp profile group were used because they provide a better basis for comparison than maximum scarp heights. Trench 1 was excavated on the northwest bounding fault in RAG 3 deposits where the scarp height was about equal to the average of Profile Group 3 measurements.

Based on trench stratigraphy (sec. 4.2.4.3), average single-event displacements at the trench 1 locality are 2.1-2.6 m (6.9-8.5 ft). This average displacement estimate suggests three to four equal-sized fault events could have formed the RAG 3 surface scarp (table 4.3). Assuming the same displacement per event, average scarp heights of 6.3 and 2.1 m (20.7 and 6.9 ft) on the southeast bounding scarps (pl. 3) may represent three and one surface displacement events, respectively. Using the same assumptions along the 5-km (3-mi) length of the Towanta Flat portion of the graben, the 4.8-m (15.7-ft) average scarp height of Profile Group 1 may represent two events. Because there is no net tectonic displacement across this portion of the graben, these displacements may have been accompanied by similar-sized surface displacements along the southeast bounding faults in RAG 4/5 deposits (table 4.3). Trenches 2 and 3 establish that there have been no surface displacements since deposition of RAG 5-6 deposits.

Although the data are hardly conclusive, trench 1 stratigraphy and rough age estimates based on soil development suggest a mid- to late-Quaternary slip rate on the northern graben fault at the trench site of about 0.02 to 0.03 mm/yr (table 4.2, displacements divided by best age estimates). There is no evidence of significant displacement at this site since the deposition of unit 5. Unit 5 accumulated gradually over many tens of thousands of years (table 4.2). Soil development in unit 5 suggests it began accumulating at least 50 ka and probably 150 ka. Minimum slip rates derived from scarp heights and surface ages (assuming no slip in the last 150 k yr) are 0.03 to 0.04 mm/yr (table 4.3). Assuming all displacement events are roughly the size of those estimated at trench 1, total displacement divided by average event displacement gives an average maximum recurrence on the main graben faults of roughly 60 k yr. However, deposits interpreted to be about 150 ka (app. A) are undisplaced.

#### 4.2.4.5 Extent of Faulting

Southwest of Towanta Flat, three faults are exposed in the Duchesne River Formation (pl. 3), but erosion obscures surface traces of the faults from here to Pigeon Water Creek. These faults project toward the scarps on Towanta Flat, but none has surface expression suggesting Quaternary displacement. However, the area of mixed fluvial and collu-

vial deposits west of Pigeon Water Creek is lower than Towanta Flat, suggesting significant post-RAG 4 erosion in this area. Thus, even if the fluvial and colluvial deposits here are relatively thin (1 to 5 m; 3 to 16 ft), they may cover post-RAG 4 displacements on extensions of the Towanta Flat faults. Even so, the total mapped length of the faults would be less than 10 km (6.2 mi).

Like Hansen (1969b), no direct evidence was found that the Towanta Flat scarps extend east of the melt-water channel. However, east of the Lake Fork River (pl. 3) the gradient of an outwash surface that correlates with Towanta Flat steepens (from 11 to 17 m/km; 58 to 90 ft/mi) for about 2 km (1.2 mi) to the south. This steeper gradient and a similar gradient on Towanta Flat south of the graben (19 m/km; 100 ft/mi) may be due to tectonic warping (Osborn, 1973, p. 64; Ritzma, 1974).

4.2.4.6 Other Reported Faulting Along the "Towanta Lineament"

Based on Ritzma's work (1974), Anderson and Miller (1979) mapped a late Pleistocene fault southeast and east of Tabiona, Utah (pl. 1). Ritzma (oral communication, 1980) inferred this fault based on (1) the anomalous linear drainage of Wagstaff Hollow in an area otherwise characterized by a well-developed dendritic drainage pattern, (2) the occurrence of springs in Seep Hollow (east of Wagstaff Hollow), and (3) the fracture pattern in the Wagstaff Hollow area. This fault was suggested as a western extension of the faulting on Towanta Flat. Not only does Wagstaff Hollow drainage in sec. 36, T. 1 S., R. 7 W., and sec. 31, T. 1 S., R. 6 W. (USGS Tabiona and Blacktail Mountain, Utah, 7-1/2-minute topographic quadrangles) have the same general trend (N. 70° E.) as the faults on Towanta Flat, but it also lies along the projected strike of these faults. However, drainage in Wagstaff Hollow is incised approximately along the strike of the Duchesne River Formation (N. 75° E.). Thus, the drainage appears to have cut an asymmetrical strike valley into the Duchesne River Formation.

The fracture pattern in this area consists predominantly of vertical to near vertical (80° to 90°) joints that are consistently oriented in a north-south to N. 20° W. direction. Therefore, the Wagstaff Hollow drainage in sections 31 and 36 and the projected Towanta Flat faulting are oriented nearly perpendicular to the jointing pattern.

Finally, although Anderson and Miller (1979) show the fault trending through Hicken Hollow (sec. 3, T. 2 S., R. 7 W., on the USGS Tabiona, Utah, 7-1/2-minute topographic quadrangle), mapping along a 3.2-km (2-mi) reach of Hicken Hollow on either side of the fault failed to reveal displacement in the Duchesne River Formation, despite good exposures.

Ritzma (1974) also notes that along the trend of the "Towanta Lineament," lateral moraines on the east wall of the Whiterocks River Valley 47 km (29 mi) northeast of Towanta Flat appear to be displaced with scarps, suggesting normal faulting (down-to-the-south) that projects into a fault mapped by Covington (1964) trending N. 60° E.

However, a reconnaissance of this area indicates that the lateral moraines were involved in landsliding, and the fault mapped by Covington in the bedrock has the opposite sense of displacement (up-to-the-south) compared to the scarps in the moraines.

4.2.4.7 Conclusions

Mapping, relative-age dating, and regional correlation of deposits in the Towanta Flat area show that the fault scarps are much older than suggested by earlier studies. The colluvial stratigraphy and soil development in trench 1 suggest at least three faulting events in the last 250 to 500 k yr along this part of the graben. Three to four surface displacement events during the same period are also suggested by the scarp height data in table 4.3. No scarps were mapped in deposits interpreted to be 130 to 150 ka (RAG 5-6, appendix A) and these deposits were unfaulted in trenches 2 and 3. Four subsurface displacement events occurred between 250 to 500 ka and 130 to 150 ka indicating an average recurrence of 25 to 90 k yr. The youngest event has an estimated age >130 to 150 ka suggesting the possibility that subsidence within the graben has ceased.

Minimum subsidence rates across individual scarps on Towanta Flat were estimated at 0.02 to 0.04 mm/yr using scarp heights and surface ages (tables 4.2 and 4.3). Based on the measured displacement of the bedrock surface in the graben, maximum subsidence rates do not exceed 0.10 mm/yr (23 m in 235 k yr). These subsidence rates are an order of magnitude lower than the slip rates used by Doser and Smith (1982) who relied on earlier age estimates for the Towanta Flat deposits. It should be emphasized that there is no significant net tectonic displacement across the Towanta Flat graben (although there does appear to be gentle warping of the outwash surface). For this reason, subsidence rates on these faults cannot be used as a measure of fault zone response to regional stresses, at least in the same way as other net tectonic slip rates measured across normal faults with significant cumulative displacement.

The origin and relationship of the Towanta Flat faults to regional tectonic stresses and structures are uncertain. If the faults are a response to late Quaternary stresses, their orientation does not agree well with the orientation of faulting inferred from the microearthquakes studied by Carver and others (1983), or with the results discussed in section 4.1. The limited lateral extent of the scarps (5 km; 3 mi) and their lack of net displacement across the graben do not suggest a normal fault zone repeatedly active during the late Quaternary. Regardless of origin, although multiple displacements have occurred on the scarps, it has been at least 130 k yr (about two average recurrence intervals) since the last event. For these reasons, the Towanta Flat faults are not considered capable of significant surface displacement events.

### 4.2.5 Bear Wallow Fault

Based on the microearthquake investigations described in section 4.1, the September 30, 1977, M 4.5 earthquake occurred on a normal fault trending about N. 5° E., dipping to the east at 35° to 45°. Based on this focal mechanism and the hypocentral distribution of microearthquakes, this inferred fault was projected updip to the surface. This surface projection, shown on plate 2, is in the vicinity of Rock Creek.

The apparent strike, dip, sense of displacement, and the location of the surface trace of this inferred fault preclude the occurrence of the earthquakes on the Towanta Flat faults or the unnamed faults shown on plate 3. This conclusion suggests that the earthquakes are occurring on a previously unmapped fault. Duchesne River Formation and overlying moraines are the surficial deposits in the vicinity of the inferred surface trace. Review of aerial photographs and extensive ground reconnaissance failed to reveal any evidence of north-south trending faults in the area.

### 4.2.6 Other Potential Seismic Source Areas

#### 4.2.6.1 Strawberry and Stinking Springs Faults

Two major, and a series of minor, north- and northeast-trending faults displace the Tertiary bedrock units near Strawberry Reservoir approximately 46 km (28 mi) southwest of Upper Stillwater damsite, and 62 km (38 mi) southwest of Taskeech damsite (Stokes and Madsen, 1961; Van Arsdale, 1979). A detailed seismotectonic study of this area for Soldier Creek Dam (Nelson and Martin, 1982) concluded that the Strawberry fault (the longer of the two major faults) has experienced significant surface displacements during the Holocene (the last 10 k yr). The Stinking Springs fault, 5 km (3 mi) to the east, is structurally and physiographically similar to the Strawberry fault, but its prominent topographic scarp is less than half as long as the scarp on the Strawberry fault.

Estimates of paleoearthquake magnitudes for the Strawberry fault derived from displacement data from two exploratory trenches across a fault scarp range from M 5.9 to 7.4. The larger magnitude estimates are based on displacements which were probably the result of more than one fault event; if so, associated magnitudes would be less than 7.0. However, these displacements were measured on a subsidiary fault parallel with the main fault which may have experienced larger displacements. Fault length-magnitude relationships (Slemmons, 1977) suggest the Strawberry fault is capable of generating a magnitude 7.0 earthquake, assuming the length of the fault marked by its prominent topographic scarp ruptures in a single event. Stratigraphic units exposed in the trenches and age-dating studies indicate recurrence intervals for these largest surface faulting events on the Strawberry fault are in the range 1.5 to 10 k yr.

Although there is no direct evidence to suggest that recent displacements on the Stinking Springs fault have been less than those on the Strawberry fault, geophysical data obtained during oil exploration in the area suggest displacements at a depth of 3000 m (9800 ft) are less on the Stinking Springs fault than on the Strawberry fault (Van Arsdale, 1979). The topographic scarp of the Stinking Springs fault is also shorter than that of the Strawberry fault (11 km (7 mi) versus 28 km (17 mi)), suggesting the length of fault segments subject to repeated rupture are probably shorter. The differences in physiographic fault length and displacement at depth suggest the Stinking Springs fault is capable of generating smaller maximum magnitude earthquakes as compared to the Strawberry fault. A magnitude of 6.5, derived from fault length-magnitude relationships, corresponds with the shorter physiographic length of the Stinking Springs fault (Nelson and Martin, 1982).

#### 4.2.6.2 Little Valley Fault

The Little Valley fault, as mapped by Garvin (1969), is an east-west-trending fault about 1.7 km (1 mi) in length. This fault is located approximately 3.5 km (2.2 mi) north of the community of Tabiona, Utah, and lies about 18.5 km (11.5 mi) south and 25.5 km (15.8 mi) southwest of the Upper Stillwater and Taskeech damsites, respectively (pl. 2). Based on work by Ritzma (1974), Anderson and Miller (1979) described this fault as displacing Quaternary alluvium and classified it as late Pleistocene in age. Ritzma (oral communication, 1980) mentioned that although he believed the fault has experienced late Quaternary movement, he has found no evidence of displacement in Quaternary alluvial deposits.

Field examination of the Little Valley fault indicates this feature does not represent fault displacement, but rather block-glide landsliding on the back slope of a hogback. The fault as portrayed by Garvin (1969) displaces the Uinta Formation immediately upslope from the base of the backslope of a hogback. The Uinta Formation in this area consists of conglomerate, sandstone, siltstone, mudstone, and bentonitic shales that generally dip 25° to 35° to the south. However, in areas of deformation, the strata tend to have flatter dips and locally dip back to the north up to 20°. Generally, competent sandstone beds cap the surface of the dip slope and are underlain by bentonitic shales. Deformation near the base of the hogback suggests that sliding has occurred within the shale along segments of the hogback. This deformation is discontinuous along the hogback; a competent sandstone bed with no deformations may gradually become transitional into a bulge. Where enough sliding has taken place, the sandstone bed buckles and ruptures along a "hinge line." This rupturing has created the apparent sense of displacement (up-to-the-north) noted by Garvin (1969). Braddock and Eicher (1962) have noted this type of deformation, which they term block-glide landsliding, on the east side of the Front Range in northern Colorado along hogbacks underlain by the Dakota Group.

#### 4.2.6.3 Duchesne-Pleasant Valley Fault System

A series of discontinuous east-west-trending normal faults shown by Stokes and Madsen (1961) in the Uinta Basin south of the Duchesne River are readily discernible on Landsat images (Peterson and others, 1982) and on aerial photographs. This fault system consists of a zone of numerous parallel fractures up to 3.4 km (2.1 mi) wide, and extends about 50 km (30 mi) through a dissected badlands terrain of the Uinta Formation of Eocene age. Ray and others (1956) suggest that this fault system consists of two main faults which appear to overlap; displacement on one fault increases where the other fault begins to die out. The Uinta Formation in this portion of the basin consists of semiconsolidated shales, mudstones, siltstones, and sandstones that are quite susceptible to erosion. Topographic expression of the fault scarps is at least 12 m (40 ft) along segments of the faults; but stratigraphic displacement is unknown. There is no topographic expression of faulting in Holocene deposits in major drainages that intersect the faults.

Osmond (1964) suggested that these faults are due to differential compaction across a facies change in the underlying bedrock. Later, Osborn (1973) suggested the faulting along the Duchesne-Pleasant Valley fault system "has been quite recent, perhaps within the last one thousand years" based on the very fresh-appearing fault scarps. These faults, however, are not shown by Anderson and Miller (1979).

The major drainages flow generally to the northeast across the fault zone; however, second order drainages are structurally controlled. These minor drainages debouch from the south into grabens formed by the faults and then are directed either to the east or west along the strike of these grabens until they encounter major throughgoing drainages that intersect the grabens. Faulting has influenced the present drainage pattern, but the major drainages downcut at a greater rate than the slip rate on the faults. This indicates only that the faults are probably of Quaternary age.

The elevation of Quaternary gravels of RAG 3 (see appendix A) on terrace remnants south of the Duchesne River indicates that base level was about 50 m (150 ft) above its present position during RAG 3 deposition. Because they are lower, the fault scarps must postdate RAG 3 deposition, but no direct evidence of displaced RAG 3 gravels was found along the projected strike of the faults. Thus, the faulting is certainly younger than 500 ka and possibly younger than 150 ka (RAG 3), but older than undisplaced mid- to late-Holocene alluvial deposits. These faults are 42 km (26 mi) and 50 km (31 mi) from the Taskeech and Upper Stillwater damsites, respectively, and because they are not the controlling seismic source areas for these damsites, they were not studied further.

#### 4.2.6.4 Taskeech Ground Cracks

In late October 1977, following the earthquake events of September 30 through October 11 in the general area of Taskeech damsite, a series of ground cracks was detected near the northeast edge of the upper reservoir site (Cook, 1979). The ground cracks are located in the NE1/4 of sec. 34 and NW1/4 of sec. 35, T. 2 N., R. 5 W., at elevations ranging from about 2354 to 2366 m (7720 to 7760 ft). One to five cracks were found to extend for a cumulative length of about 400 m (1300 ft) in an arcuate pattern across a zone up to 9.1 m (30 ft) wide. This fracture pattern is convex upslope to the northeast, and both extremities appear to terminate near an irrigation canal. The crown of the cracks, approximately 274 m (900 ft) in length and trending generally to the northwest, lies about 50 m (160 ft) upslope of the canal, and the limbs approach the trend of the canal in a nearly perpendicular orientation. In addition to these ground cracks, randomly oriented subsidiary ground cracks were noted extending at least 100 m (300 ft) downslope of the canal. At the surface, the cracks are up to 0.2 m (0.5 ft) wide and are somewhat discontinuous on the ground surface. Surface inspection suggests possibly some subsidence has occurred across the 9.1-m (30-ft) wide fracture zone, although no displacement is readily discernible across individual cracks.

The cracks cross a gently southwest-sloping surface in alluvial fan deposits. These deposits, based on bedrock exposures immediately upslope, overlie the Woodside Shale and Thaynes Limestone to an unknown depth.

Subsurface investigations by Central Utah Project personnel were conducted in November 1977 to determine if the ground cracks were related to surface rupture of the September 30 through October 11, 1977, earthquake events. Two exploratory trenches were excavated in the area of the ground cracks (Travel Report of Mark McKeown dated December 28, 1977). Trench 1 was excavated across the projected strike of the northwest-trending ground cracks at a point upslope where both surficial materials and bedrock would be exposed in the trench. Trench 1 revealed no evidence of disruption or displacement of the surficial materials. However, due to their arcuate nature, it appears that trench 1 did not intersect the ground cracks where they displaced surficial material.

Trench 2 was excavated across an area of well-developed ground cracks about 60 m (200 ft) northwest of trench 1. Surface manifestations at this location suggested some displacement had occurred. This trench was excavated entirely in alluvial fan deposits and exposed four near-vertical cracks. Two of the cracks were open up to 0.1 m (0.3 ft) at the surface, but were closed at depth with only a hairline crack continuing to the bottom of the trench. The exposed alluvial fan deposits contained gravel lenses which unequivocally demonstrated that no displacement had occurred across the cracks in trench 2.

The fractures are interpreted as tension cracks that developed in an area of slope failure and do not represent surface faulting. The arcuate pattern of ground cracks probably delineates the incipient head scarp of a landslide. The exact mode of failure is unknown, but the discovery of the ground cracks shortly after the earthquake events of September 30 through October 11, 1977, suggests slope failure may have been induced by vibratory ground motions.

## 5. Maximum Credible Earthquakes

The identified seismic sources that are potentially significant to the design of the proposed Taskeech and Upper Stillwater Dams are the Bear Wallow fault, the Uinta Basin-South Flank and/or north-trending fault system (i.e., mountain flank faults) the Wasatch fault, and the Strawberry and Stinking Spring faults. The significance of these seismic sources is discussed separately below.

### 5.1 Bear Wallow Fault

The occurrence of the earthquakes of 1950 and 1977 suggest a potential local source of earthquakes in the Taskeech damsite region. The aftershock study conducted by the USGS/UU (sec. 3.3.2) and the microseismic investigation conducted during this study (sec. 4.1) defined the causative structure to be the north-trending, east-dipping Bear Wallow fault. The lack of evidence for faulting along the inferred surface projection of this fault leads to the conclusion that these earthquakes are occurring on a subsurface fault, a typical characteristic of moderate magnitude earthquakes in the ISB (sec. 3.3.1).

An MCE (maximum credible earthquake) of magnitude 6.0 is assigned to the Bear Wallow fault. This estimate is based on the lack of evidence for surface rupture associated with this fault (see sec. 5.2 for discussion on surface rupture versus magnitude in Utah), and on the fault dimensions as defined by the microseismicity using the magnitude versus fault area relationship of Wyss (1979). Assuming that the orientation of the fault plane defined on figure 4.4 is correct, the fault extends in depth from 4.7 to 9.3 km (2.9 to 5.8 mi). Using a conservative dip estimate of 40° results in a total fault width (i.e., downdip dimension) of 7.2 km (4.5 mi). A conservative estimate of the length, as defined by the epicenter distribution, is 11 km (7 mi). Thus, the fault area is approximately 79 $km^2$ (30 $mi^2$). The fault area relation of Wyss (1979):

$$M = \log_{10}A + 4.15$$

yields a maximum magnitude estimate of 6.0. The focal depth is assumed to be 7.0 km (4.3 mi), thus, placing the epicenter at 2.0 km (1.2 mi) west of Taskeech damsite.

### 5.2 Mountain Flank Faults

The concealed Uinta Basin fault is generally believed to be the major structural feature bounding the south flank of the Uinta Mountains within the study area. The South Flank fault, considered to be antithetic to the Uinta Basin fault (Campbell, 1975), developed in response to the major mountain forming upthrusting along the Uinta Basin fault during the Laramide orogeny. As the core of the Uintas was thrust vertically as well as laterally over the Paleozoic and Mesozoic sediments to the south, an isostatic imbalance and state of tension was created in the uplifted block. Adjustments to this condition apparently occurred by normal faulting along the South Flank fault. Because of their direct

structural relationship, estimation of the potential for seismic activity on one fault must include consideration of the other fault.

The Uinta Basin fault is concealed for its entire length; therefore, no outcrop evidence is available to evaluate the age of most recent faulting. The South Flank fault, however, is exposed for much of its 130-km length and in many locales is onlapped by sediments ranging in age from Oligocene (Browns Park Formation) through Holocene. No geologic evidence for displacement of these Tertiary and Quaternary sediments has been documented for the western 100-km portion of the South Flank fault, and the evidence suggests there has not been recurrent surface displacement on the fault since the Oligocene. This would suggest that the major isostatic and tensional adjustments in the uplifted block were accomplished by early Oligocene.

The existence of microseismicity in the vicinity of the South Flank fault in the study area remains to be explained. The localized relatively high rate of activity at the western limit of the mapped trace of the fault east of Kamas may indicate the South Flank fault extends west beneath undisplaced late Quaternary outwash gravels along the Provo River (Sullivan and others, in prep.). This inferred portion of the fault has a WNW strike, therefore, as a preexisting zone of weakness, could be expected to generate small magnitude events in response to obliquely directed east-west extensional stresses.

The scattered events that were located within a few kilometers both north and south of the South Flank fault west of Moon Lake during the microseismic investigation, suggest this portion of the fault may be releasing minor amounts of stress. Considering the current regional stress field, however, it is more likely that these microearthquakes are occurring on north-trending faults (similar to the Bear Wallow fault) that may or may not be expressed at the surface. This would explain why earthquakes occurred north of the surface trace of the south-dipping South Flank fault. The resolution of these data does not permit a more definitive conclusion.

The occurrence of two microearthquakes within 3 km (2 mi) of Upper Stillwater damsite during the 6 months of monitoring in 1980, the existence of the South Flank fault as a major structural zone of weakness in the vicinity of the damsite, and the existence of mapped north-trending faults in the area, indicate a local MCE should be assigned. This MCE is concluded to be M 6.0, the same as that for the Bear Wallow fault. There is no evidence of Quaternary surface displacement of any of these faults and no direct seismologic evidence for activity on any specific fault. This conclusion is predicated on the consideration that tectonic stresses are clearly being released in the area and that major zones of weakness are present, although it is not possible to specify which ones are currently active with the existing data.

This MCE of M 6.0 is consistent with the historic record of surface rupture in Utah. The only earthquake to have produced surface faulting in Utah during historic times (1847 to present) was the 1934 M 6.6 Hansel Valley event, which was accompanied by 0.5 m (1.6 ft) of surface displacement. Seven other earthquakes of magnitude greater than or equal to 6.0 but less than 6.6 have occurred in Utah without producing surface rupture. This suggests the magnitude threshold for surface displacement in Utah is in the magnitude range of 6.0 to 6.5. It is, however, apparent that earthquakes of magnitude 6.0 or less have occurred within the study area during the Quaternary without leaving surficial evidence to document such an event. Therefore, an MCE of magnitude 6.0 should be considered credible for the Upper Stillwater damsite area. The epicentral distance is judged to be 2 km (1.2 mi), the same as the epicentral distance for the MCE of M 6.0 at Taskeech damsite.

### 5.3 Wasatch Fault

Extensive studies at four sites on the Wasatch fault by Woodward-Clyde Consultants have documented the high rate of earthquake activity on this structure (Swan and others, 1980). The history of surface displacement, as revealed in trenches placed across young fault scarps, indicate earthquakes of magnitude 6.5 to 7.5 have occurred repeatedly during the Holocene. The average recurrence of earthquakes in this magnitude range has been estimated at 50 to 430 years for the entire Wasatch fault and from 500 to several thousand years for any individual segment.

Trench displacement and fault displacement-magnitude relationships (Slemmons, 1977) suggest the magnitude of the largest earthquake capable of occurring on the Wasatch fault is 7.5 (see discussion in Nelson and Martin, 1982, p. 83). Therefore, the MCE assigned to the Wasatch fault is M 7.5.

### 5.4 Strawberry and Stinking Springs Faults

Estimates of paleoearthquake magnitudes for the Strawberry fault derived from displacement data from two exploratory trenches across a fault scarp north of Strawberry Reservoir (pl. 1) are in the range of 5.9 to 7.4 (Nelson and Martin, 1982). These displacements were measured on a subsidiary fault parallel with the main fault which may have experienced larger displacements. Stratigraphic units exposed in the trenches and age-dating studies indicate recurrence intervals for the largest surface faulting events on the Strawberry fault are in the range 1.5 to 10 k yr, most probably 3 to 5 k yr. Fault length-magnitude relationships (Slemmons, 1977) suggest the Strawberry fault is capable of generating a magnitude 7.0 earthquake, assuming the length of the Strawberry fault marked by its prominent topographic scarp ruptures in a single event. The MCE for the Strawberry fault is, thus, M 7.0.

Although there exists no evidence to suggest that recent displacements on the Stinking Springs fault have been less than those on the Strawberry fault, geophysical data obtained during oil exploration in the area suggest displacements at a depth of 3000 m (10 000 ft) may be an order of magnitude less on the Stinking Springs fault than on the Strawberry fault. The topographic scarp of the Stinking Springs fault is shorter than that of the Strawberry fault [11 km (7 mi) versus 28 km (16 mi)], suggesting the length of fault segments subject to repeated rupture are shorter. A magnitude of 6.5, derived from fault length-magnitude relationships, corresponds with the physiographic length of the Stinking Springs fault (Nelson and Martin, 1982). These differences in physiographic fault length and displacement at depth suggest a somewhat smaller MCE for the Stinking Springs fault than for the Strawberry fault (Nelson and Martin, 1982). The MCE assigned to the Stinking Springs fault is, therefore, M 6.5.

## 5.5 Other Seismic Source Zones

### 5.5.1 Towanta Flat Faults

Based on the results of trenching and scarp profiling at Towanta Flat, the average recurrence interval of 2.1-2.4-m surface displacements is about 60 k yr (section 4.2.4.7). Further, it has been 130 k yr, or two or more average recurrence intervals since the last surface displacement at Towanta Flat. Therefore, future surface displacements associated with earthquakes at Towanta Flat are unlikely and are judged to pose no hazard to Taskeech or Upper Stillwater Dams. Further support for this conclusion is provided by the focal mechanisms for the Bear Wallow earthquake, in the vicinity of Towanta Flat, which suggests stress release along a plane oriented N. 5° E.; the faults at Towanta Flats, which strike N. 40° E. to N. 70° E., are apparently unfavorably oriented for contemporary surface faulting. In addition, the earthquake magnitude, surface displacement, and rupture length relations of Slemmons (1977) suggest surface displacements of 2 m (7 ft) are accompanied by surface rupture lengths of greater than 20 km (12 mi). The total length of faulting at Towanta Flat, however, can be constrained to 13 km (8 mi) or less with associated scarp lengths of only 5 km (3 mi) for the past 250 to 500 k yr.

The short fault lengths, the lack of net vertical displacement across the graben, the restricted time interval over which the displacements apparently occurred, and their unfavorable orientation in the contemporary stress field suggest that these faults may have a nonseismogenic origin.

### 5.5.2 Duchesne-Pleasant Valley Fault System

Reconnaissance geologic mapping of the Duchesne-Pleasant Valley fault system suggests that displacements along these faults postdate RAG 3 Quaternary deposits, but predate late Holocene deposits. Because this fault system is 42 and 50 km (26 and 31 mi) from Taskeech and Upper Stillwater damsites, respectively, no detailed studies were conducted to

determine the activity or inactivity of these faults as they are not considered potentially controlling seismic source areas for the subject damsites.

## 5.6 Earthquake Recurrence

The recurrence intervals of earthquakes likely to occur in the Taskeech-Upper Stillwater damsites region can be estimated from an earthquake magnitude versus frequency of occurrence relationship of the usual form:

$$\log_{10}N = a + bM$$

In this equation, N is the cumulative number of earthquakes of magnitude M or larger occurring in a specified area per year, and a and b are constants empirically determined from the available historic record. Ideally, a large data set consisting of many earthquakes of varying magnitudes occurring over a long period of time is used to derive the appropriate relationship. The historic record in the region of the damsites, however, is short and incomplete; thus, data from a larger area must be used to arrive at a statistically acceptable solution for the constants a and b.

A recurrence relation has been developed for the Wasatch Front area by Smith and Arabasz (1979) using the 129-year historic record of earthquake occurrence from 1850 through 1978. The 92 810-$km^2$ (35 850 $mi^2$) area is outlined on figure 3.6 and includes the Taskeech and Upper Stillwater damsites region. The well-known relationship of Gutenberg and Richter (1956):

$$M_L = 1 + 2/3I$$

as justified applicable in Utah by the U.S. Geological Survey (USGS, 1976), was used to convert Modified Mercalli intensities to magnitudes for noninstrumental earthquakes. The data set was corrected for incompleteness using the method of Stepp (1972). The resultant formula scaled to 1000 $km^2$ (390 $mi^2$) is:

$$\log_{10}N = 1.01 - 0.72M$$

The b value equal to 0.72 is the slope of the logarithmic curve and is at the low end of the empirical range of values. Thus, the occurrence of earthquakes during the 129-year period is characterized by a low number of small magnitude versus large magnitude events and is indicative of relatively high ambient stress within the Wasatch Front area. The a value, equal to 1.01, is a measure of the earthquake flux within the 92 810-$km^2$ (35 850 $mi^2$) Wasatch Front area. It is affected by the numerous small subareas that have not experienced earthquakes during the 129-year period, and that are included in the calculation as a consequence of the method of analysis. Therefore, the a value does not represent the expected activity on any given fault, but rather represents an average rate of activity within any 1000-$km^2$ (390 $mi^2$) area within the sampled region.

The determination of specific fault-related earthquake recurrence must include any knowledge of site-specific activity known or suspected of occurring on the fault in question. Assuming the historic record of earthquake occurrence on the Bear Wallow fault is complete since about 1900 for earthquakes of similar magnitude to the January 18, 1950, event ($M \geq 4.5$), there have been two earthquakes of magnitude 4.5 or larger in the area associated with the fault during the last 80 years. Accounting for this rate of activity results in a modified recurrence relation of the form:

$$\log_{10}N = 1.73 - 0.72M$$

as is illustrated on figure 5.1. Due to the close proximity of the damsites (23 km), this more conservative curve will be used to determine recurrence intervals for earthquakes likely to affect the design and operation of both Taskeech and Upper Stillwater Dams (see secs. 6.1.1 and 6.2.1).

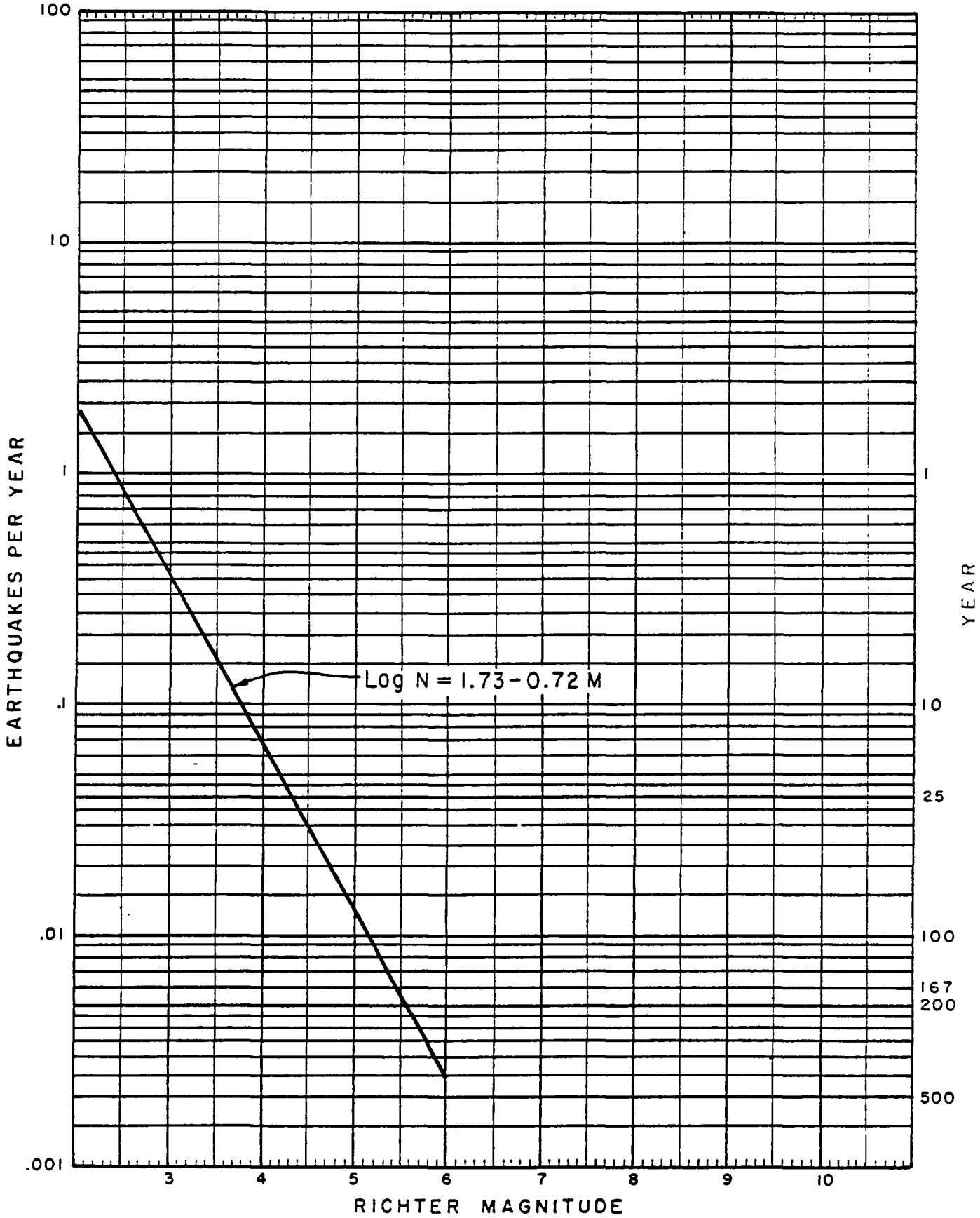



Figure 5.1. Earthquake magnitude versus frequency of occurrence for the Bear Wallow fault and surrounding area.

## 6.0 Conclusions

The following conclusions are based upon our understanding of the present tectonic regime of the Uinta Mountains and Basin, the historic seismicity of this region, and detailed geologic and seismologic investigations conducted in the vicinity of the Taskeech and Upper Stillwater damsites, Central Utah Project, Utah.

### 6.1 Site Specific Conclusions for Taskeech Dam and Reservoir

Seismically induced hazards which may be significant to the design and operation of the proposed Taskeech Dam and Reservoir include ground motions from earthquakes, slope stability, reservoir seiche, liquefaction, surface faulting, and reservoir-induced seismicity. Conclusions of these factors are presented below; however, a detailed analysis of the hazards posed by each of these effects is beyond the scope of this report.

#### 6.1.1 Design Earthquakes

Table 6.1 summarizes the pertinent data for the MCE's assigned to those seismic sources that, based on their proximity to the damsite and their inferred capability to generate moderate-to-large magnitude earthquakes, are considered significant to the design of the proposed Taskeech Dam. Also included in table 6.1 are the Richter magnitudes, epicentral distances, and focal depths of the earthquakes capable of recurring (on the average) every 25 and 100 years on the Bear Wallow fault.

Table 6.1. - Design earthquakes for Taskeech Dam

| Tectonic structure | Maximum credible earthquake | 100-year earthquake ($M_L$) | 25-year earthquake ($M_L$) | Epicentral distance (km) | Focal depth (km) |
|---|---|---|---|---|---|
| Wasatch fault | 7.5 ($M_S$) | - | - | 105 | 7 |
| Strawberry fault | 7.0 ($M_S$) | - | - | 64 | 6 |
| Stinking Springs fault | 6.5 ($M_L$) | - | - | 58 | 4.5 |
| Bear Wallow fault | 6.0 ($M_L$) | 5.2 | 4.3 | 2 | 7 |

Only the Bear Wallow fault is considered a significant seismic source for these other design earthquakes. The rationale for this determination is as follows. The magnitudes of earthquakes with average recurrence intervals of 25 and 100 years that are expected to occur on the Bear Wallow fault are estimated from the earthquake recurrence curve shown on figure 5.1. The slope of this curve, the b value, was derived from the 129-year historic record of earthquake occurrence in the ISB in central and northern Utah. Determination of the zero magnitude intercept, the a value, was based on the presumed occurrence of two magnitude 4.5 earthquakes on the Bear Wallow fault during the preceding 80 years (sec. 5.6).

For the purpose of estimating the 25- and 100-year earthquakes expected to occur on the other previously defined seismic sources, we have assumed the recurrence curve for the Bear Wallow fault is applicable throughout the study area. The 25- and 100-year earthquakes for the mountain flank faults (i.e., Uinta Basin-South Flank and/or north-trending faults) near Upper Stillwater damsite, and the Strawberry and Stinking Springs faults near Strawberry and Soldier Creek Dams will, therefore, be equivalent to the magnitude 4.3 and 5.2 earthquakes defined for the Bear Wallow fault. Because of the much greater distances from these faults to Taskeech damsite (see table 6.1), the occurrence of magnitude 4.3 and 5.2 earthquakes on those other faults has little significance compared to the Bear Wallow fault.

### 6.1.2 Slope Stability

A Richter magnitude 6.0 earthquake occurring at an epicentral distance of 2 km (1.2 mi) from the Taskeech damsite could reactivate the existing landslides and trigger additional slope instabilities in the reservoir and the area surrounding the dam. Potential slope instability and bank caving is expected to occur along the shoreline in weathered, semiconsolidated bedrock and surficial deposits, as a result of saturation and their susceptibility to wave erosion. The potential for movement in the form of rockfall in the reservoir area is low, although it does exist. The mass of rock involved, however, would be relatively minor and should not pose a hazard to the dam.

### 6.1.3 Reservoir Seiche

Seiche induced by vibratory ground motion and/or landsliding can be expected in Taskeech Reservoir. Wave generation due to ground motion, however, is believed to be of minor consequence, and reactivated landslide masses moving into the reservoir are not considered to pose a significant hazard.

### 6.1.4 Liquefaction

The liquefaction potential at the damsite is the subject of separate further studies. This potential should be evaluated considering the earthquake loadings proposed in this report.

### 6.1.5 Surface Faulting

Surface rupture has not been associated with earthquakes of magnitude 6.0 or less in the State of Utah. Therefore, we do not expect surface rupture or other significant topographic changes to be associated with the occurrence of a magnitude 6.0 or smaller earthquake in the vicinity of Taskeech damsite.

### 6.1.6 Reservoir-induced Seismicity

Reservoir-induced seismicity has been empirically related to reservoirs with the following general characteristics: (1) water depth in excess of 92 m (301.8 ft), (2) water volume in excess of $1.2 \times 10^9$ $m^3$ ($10^6$ acre-ft), and (3) active faults in the reservoir (Woodward-Clyde Consultants, 1977). The proposed Taskeech Reservoir, with a maximum water depth of about 66.5 m (218 ft) and a volume of $9.7 \times 10^7$ $m^3$ ($7.85 \times 10^4$ acre-ft), does not meet the depth or volume criteria. In the event earthquakes are induced by reservoir filling, we believe they would not exceed the magnitude 6.0 MCE proposed for the Bear Wallow fault.

## 6.2 Site Specific Conclusions for Upper Stillwater Dam and Reservoir

Seismically induced hazards which may be significant to the design and operation of the proposed Upper Stillwater Dam and Reservoir include ground motions from earthquakes, slope stability, reservoir seiche, surface faulting, and reservoir-induced seismicity. Conclusions of these factors are presented below; however, a detailed analysis of the hazards posed by each of these effects is beyond the scope of this report.

### 6.2.1 Design Earthquakes

Table 6.2 summarizes the pertinent data for the MCE's assigned to those seismic sources that are considered significant to the design of the proposed Upper Stillwater Dam based on their proximity to the damsite and their assumed capability to generate moderate to large magnitude earthquakes.

Also summarized in this table are the magnitudes, epicentral distances, and focal depths of the 25- and 100-year design earthquakes relevant to the proposed Upper Stillwater Dam.

For similar reasons to those presented for Taskeech damsite regarding the Bear Wallow fault, only the mountain flank faults (i.e., the Uinta Basin-South Flank and/or north-trending faults) are considered significant to Upper Stillwater damsite with regard to the occurrence of 25- and 100-year events. All other seismic sources are much too far away to be of significance to Upper Stillwater Dam should earthquakes of these magnitudes occur on those faults during the lifetime of the structure.

Table 6.2. - Design earthquakes for Upper Stillwater Dam

| Tectonic structure | Maximum credible earthquake | 100-year earthquake ($M_L$) | 25-year earthquake ($M_L$) | Epicentral distance (km) | Focal depth (km) |
|---|---|---|---|---|---|
| Wasatch fault | 7.5 ($M_S$) | - | - | 84 | 7 |
| Strawberry fault | 7.0 ($M_S$) | - | - | 47 | 6 |
| Stinking Springs fault | 6.5 ($M_L$) | - | - | 45 | 4.5 |
| Mountain flank faults | 6.0 ($M_L$) | 5.2 | 4.3 | 2 | 7 |

6.2.2 Slope Stability

The possibility of major deep-seated instability in the dam and reservoir area is believed to be remote. Minor instabilities should be expected in the talus deposits along the base of both valley walls at the damsite and reservoir. Materials in the reservoir area will be relatively stable with respect to wave erosion, saturation, and ice-heaving (USBR, 1978). Movement in the form of rock fall should be expected along the periphery of the reservoir. The mass of rock involved, however, will be minor and should not endanger the structural integrity of the dam.

6.2.3 Reservoir Seiche

The most likely cause of seiche phenomenon in the Upper Stillwater Reservoir is vibratory ground motion. Seiche due to ground motion is not expected to pose a significant hazard to Upper Stillwater Dam. As noted above, major landslides are not expected as a result of seismic activity and, therefore, should not induce seiche phenomenon.

6.2.4 Surface Faulting

Surface rupture has not been associated with earthquakes of magnitude 6.0 or less in the State of Utah. Therefore, we do not expect surface rupture or other significant topographic changes to be associated with a magnitude 6.0 earthquake in the vicinity of Upper Stillwater damsite.

### 6.2.5 Reservoir-induced Seismicity

Reservoir-induced seismicity has been empirically related to reservoirs with the following characteristics: (1) water depth in excess of 92 m (302 ft), (2) water volume in excess of $1.2 \times 10^9$ $m^3$ ($10^6$ acre-ft), and (3) active faults in the reservoir (Woodward-Clyde Consultants, 1977).

The proposed Upper Stillwater Reservoir, with a maximum water depth of about 82 m (270 ft) and a volume of $3.7 \times 10^7$ $m^3$ ($3.0 \times 10^4$ acre-ft), does not meet the depth or volume criteria. In the event earthquakes are induced by reservoir filling, we believe they would not exceed the magnitude 6.0 MCE proposed for the mountain flank faults.

## 7. Recommendations

1. Geologic literature and the microseismic record should be reviewed periodically as part of the SEED process for data affecting the conclusions of this report.

2. Since faulting through the Taskeech Dam foundation cannot presently be precluded, geologic mapping of the core trench should be performed to determine if faulting is present. If faults are found, the age relationships of those faults should be evaluated with respect to the findings of this report on the surface faulting hazard to Taskeech damsite.

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9. Appendices

A. Quaternary Geology of Towanta Flat Area
B. Soil Profile Descriptions
C. Stratigraphic Section Descriptions
D. Technical Information Regarding the Microseismic Survey

# APPENDIX A

# QUATERNARY GEOLOGY OF THE TOWANTA FLAT AREA

The Quaternary deposits of the western Uinta Basin and adjacent south flank of the Uinta Mountains consist of glacial, alluvial, and colluvial materials. Till and ice-contact stratified drift line the major valleys, and in some drainages older moraines extend up to 12 km (7 mi) beyond the mouths of the valleys. Extensive outwash plains extend southward from the major valleys, and glacially related alluvial deposits cover much of the bedrock surfaces north of the Duchesne River (fig. 1.1 and pl. 1). Older alluvial deposits cap scattered remnants of the highest erosion surfaces which slope southward from the Uintas. Colluvial deposition has continued throughout the Quaternary and deposits are widespread on slopes, being gradational with both glacial and alluvial sediments.

## A.1 Earlier Studies

As in much of the Rocky Mountain region, previous studies of the Quaternary geology in the Uinta Basin and Uinta Mountains have emphasized the glacial chronology. Atwood's (1909) study of glaciation in the Uinta and Wasatch Mountains was the first detailed mapping of the Quaternary deposits in this area. Atwood (1909) recognized the deposits of two episodes of glaciation and found limited evidence for a third, earlier glacial event. Moraines of each event and adjacent outwash deposits were mapped in all the major drainages of the Uinta Mountains.

In a classic study of the geomorphology of the north flank of the Uintas, Bradley (1936) discussed the development of two high-level Tertiary erosion surfaces and mapped two younger Pleistocene surfaces as well as the moraines of three glacial "stages" along tributaries of the Green River. Bradley (1936, p. 195) correlated these moraines with Blackwelder's (1915) glacial sequence in the Wind River Mountains of Wyoming.

On the south flank of the eastern Uintas, Kinney (1955) correlated the highest erosion surfaces with Bradley's (1936) oldest (Gilbert Peak) surface and mapped lower surfaces as the Lake Mountain surface of Tertiary age and the Jensen surface of latest Tertiary or earliest Quaternary age. Lower strath terraces along Ashley and Brush Creeks (pl. 1) were correlated with moraines of an "earliest glaciation," "maximum glaciation," and "latest glaciation" in the drainages of the Uinta and Whiterocks Rivers. These glacial events were tentatively correlated with Bradley's (1936) glacial "stages" (Kinney, 1955, p. 135).

Clark (1957) and Marsell (1964) provided very generalized reviews of the geomorphology of the Uinta Basin. The compilation of Stokes and Madsen (1961) shows some glacial deposits not recognized by previous workers (Osborn, 1973, p. 21).

Schoenfeld (1969) identified several pre-Bull Lake erosion surfaces and mapped glacial deposits of Bull Lake, Pinedale, and Neoglacial age in the Burnt Fork drainage on the north flank of the Uinta Mountains. Morphology, relative position in the drainage, and boulder abundance for

moraines and relative elevation for outwash terraces were the main relative-age mapping criteria used, making correlations to other areas uncertain.

The only detailed mapping of the Quaternary deposits in the Towanta Flat area is that of Osborn (1973). Osborn mapped glacial deposits of eight different relative ages in the Yellowstone and Uinta River drainages using morphostratigraphy and limited surface weathering and soils data. He then correlated these moraine and outwash terraces one for one with Richmond's (1965) standard glacial sequence in the Wind River Mountains. The remnants of former alluvial surfaces in the northern Uinta Basin were mapped in less detail, but were related to the moraine sequences at the mouths of the Lake Fork and Uinta River valleys with reconstructed terrace profiles. Osborn (1973) concluded his work with an extended discussion of these alluvial surfaces and the Quaternary history of the basin.

Other recent thesis work in the area by Grogger (1974) is for the most part concerned with Holocene and Neoglacial deposits in the upper parts of drainages on the north flank of the Uintas and provides only generalized descriptions of the moraines deposited during earlier periods of major glaciation. Grogger (1974) offers no detailed relative-age data or mapping to substantiate his application of a more detailed subdivision of Bradley's (1936) glacial chronology to the moraines in his study area (Grogger, 1974, p. 43) or his correlation of this sequence to others in the Western United States (Grogger, 1974, p. 202).

## A.2 Quaternary Deposits of Towanta Flat Area

We mapped Quaternary glacial, alluvial, and colluvial deposits of nine relative ages in the Towanta Flat area, (pl. 3) using the genetic symbol mapping system of Soil Survey Committee (1978) and Keaton (1980). Modifiers to the main genetic symbol indicate the surface form of the deposit (lower case letters) and its relative age (numbers). We have used the flight of alluvial terraces along the Lake Fork River (Atwood, 1909, pp. 49 and 52) as a reference point for determining relative age. At least seven distinct terraces are present near the river (levels 3 through 9 on pl. 3 and fig. A.1), and the older high-level surfaces in the area can be divided in two groups (RAGs (relative-age groups) 1 and 2). However, the difference in elevation of the river terraces does not imply a significant time difference between any two or three terraces. Relative weathering data (discussed below) indicate the major time breaks in the sequence. We have grouped terrace levels 5 and 6 and 7 and 8 into single relative-age groups (RAG 5-6 and RAG 7-8) on the basis of the major relative weathering breaks indicated by soils and surface weathering data (discussed below). Where the age of a particular map unit is uncertain, or where materials of several ages are included in the same unit, a range of relative ages is indicated (see explanation of pl. 3).

We have relied on Osborn's (1973) morphostratigraphic mapping over most of his area of study, but we disagree with his correlation of moraines

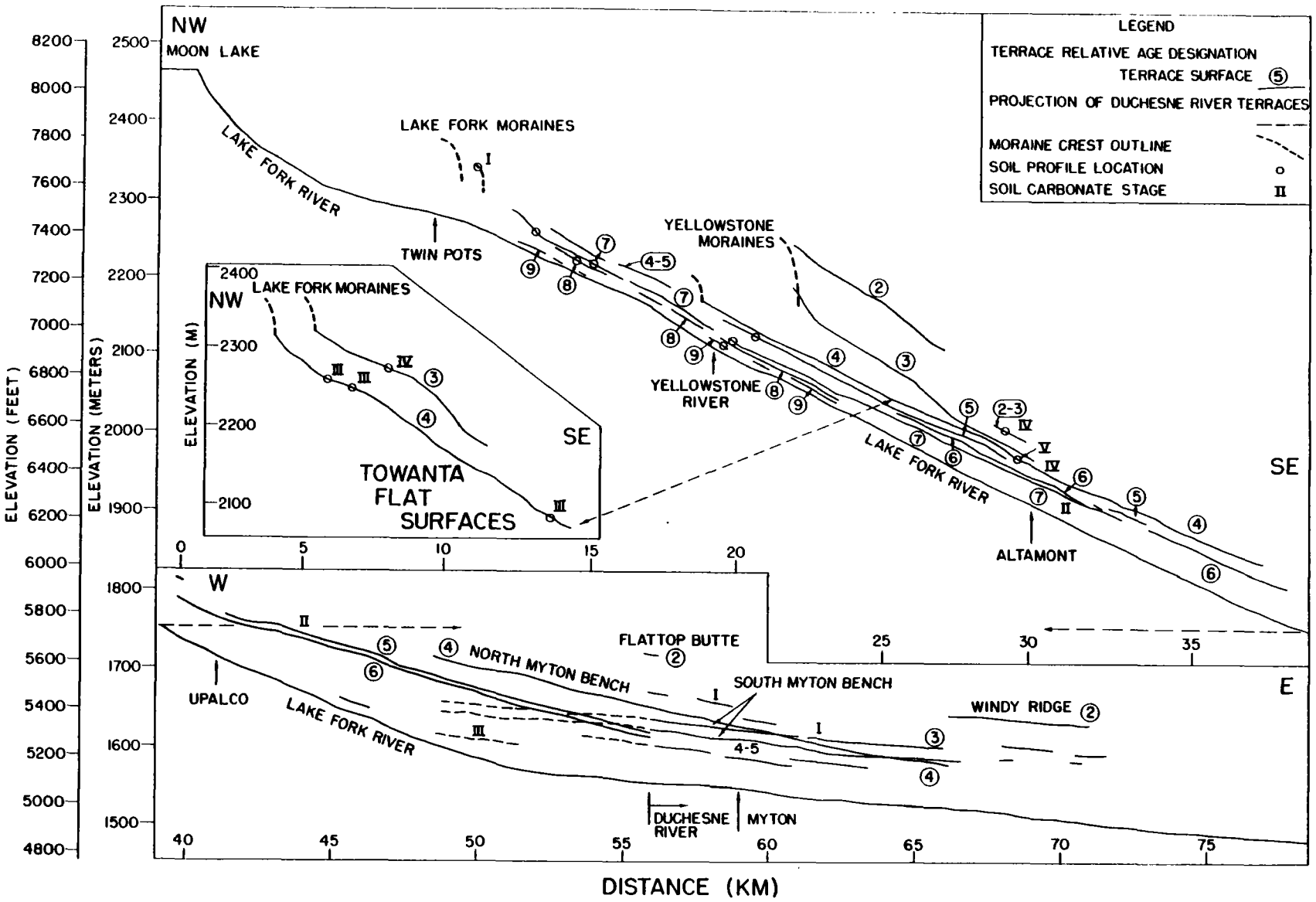



Figure A.1. Terrace surface profiles along the Lake Fork River showing the projection of correlative surfaces on Towanta Flat and along part of the Duchesne River, moraine crest outlines, soil profile description locations, and soil carbonate morphology stage (Gile and others, 1966) in exposures. Terrace surfaces have been numbered from highest to lowest, 2 through 9, to provide informal relative-age categories for deposits in the area.

and terraces along the Lake Fork River north of Towanta Flat (pl. 3) with the glacial sequence in the Yellowstone River valley (1973, p. 78). For this reason, and because the local names he proposed for glacial events have not been published or used elsewhere, we prefer to assign numbers to our Quaternary deposits of differing relative age (for example, Birkeland and others, 1979) (pl. 3, figs. A.1 and A.2).

Below, we discuss the moraines and terraces of RAG 3 and younger deposits in the vicinity of Towanta Flat. Landforms and deposits of RAGs 1 and 2 are discussed in a later section (A.3) on the relationship of the Towanta Flat deposits to Quaternary alluvial sediments elsewhere in the Uinta Basin.

### A.2.1 Moraines

Although no moraines in the Towanta Flat area are apparently displaced by faults, emphasis was placed on relative-age dating the moraines as well as the terraces because most other RD (relative-dating) studies in the Rocky Mountain region have been done on moraines. Moraine data are the basis for correlating the Towanta Flat sequence with other chronologies in the region.

Four areas of moraines which differ in their relative degree of dissection, number of closed depressions, surface slopes, and crest widths (table A.1) are found along the south side of the Lake Fork River, north of Towanta Flat. The most eroded moraines grade into the outwash making up Towanta Flat and the younger moraines are nested within the older (pl. 3). However, the boundaries between each group of moraines are not everywhere distinct. For example, RAG 5-6 moraines gradually grade northward from moderate-sized terminal moraines into ice-stagnation moraines with a different orientation and morphology. In some cases, younger moraines can be distinguished from older because low outwash terraces which grade into the younger moraines extend downstream through channels eroded through the older moraines. Where terraces are not present, however, surface weathering and soils data show where the boundaries between different ages of moraines should be drawn.

#### A.2.1.1 Surface weathering and morphology

Morphologic and surface weathering criteria have been very useful in many areas of the North American Cordillera in mapping glacial deposits of different relative age (e.g., Nelson, 1954; Burke and Birkeland, 1979). Our use of moraine surface relative weathering techniques focused on the moraines mapped as Yellow Ledges and Hell's Canyon by Osborn (1973, p. 78) north of Towanta Flat. Although he did not find most of these techniques useful in his mapping, Osborn (1973, p. 34) as well as Atwood (1909, p. 53) felt that the percentage of moraine surface boulders retaining some polish was of some use in distinguishing one moraine from another (for example, Hell's Canyon from Yellow Ledges moraines in some areas). However, the percentage of polished boulders did not consistently decrease on older moraines. Osborn also admitted

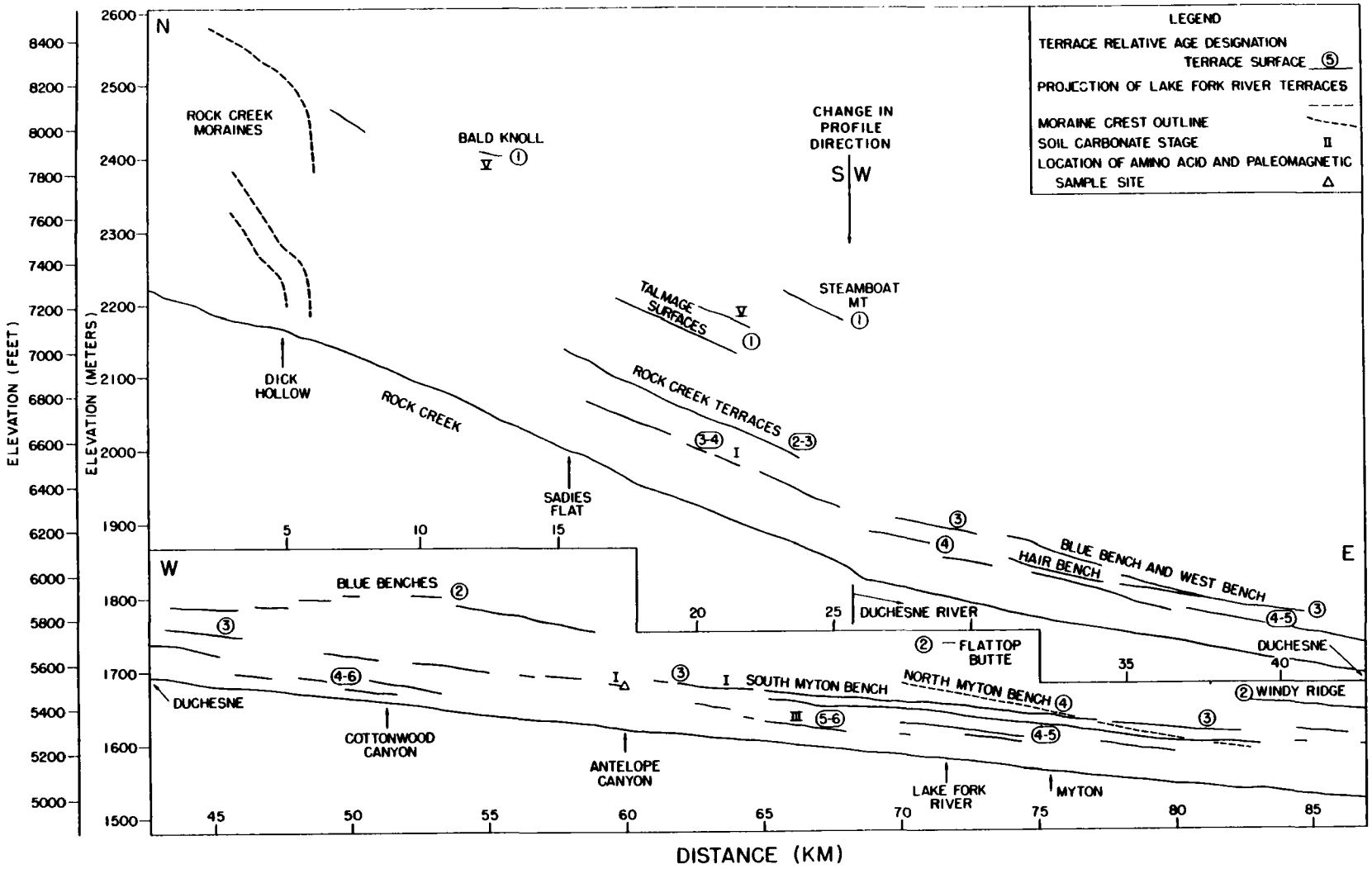



Figure A.2. Terrace surface profiles along Rock Creek and Duchesne River showing the projection of correlative surfaces along the Lake Fork River, moraine crest outlines, soil carbonate stage (Gile and others, 1966) in exposures, and the location of the Antelope Canyon gravel pit where paleomagnetic and amino acid samples were collected. Terrace surfaces have been numbered using the relative-age groups defined using the terraces along the Lake Fork River (fig. A.1).

Table A./. - Surface weathering and morphological data for Yellowstone, Lake Fork, and Rock Creek Moraines 1/

| Moraines | Site (fig.) | Vegetation 3/ | Moraine morphology | | | Surface boulders 2/ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Crest width (m) | Maximum slope angles | | % split | % polished | Frequency | Maximum clast size (cm) | Pits | | | Rinds | | |
| | | | | Distal | Proximal | | | | | % with | Depth (mm) Max. | Depth (mm) Average | % with | Thickness (mm) Max. | Thickness (mm) Average |
| **Yellowstone River** | | | | | | | | | | | | | | | |
| Age group 9 | 39 | LP,G | 8 | 15.3°±1.5 | 23.7°±2.0 | 60 | 12 | 174 | 60 | 64 | 10 | 3.4±2.6 | 12 | 1 | <0.5 |
| **Lake Fork River** | | | | | | | | | | | | | | | |
| Age group 7-8 | 20 | SB,G | 3 | 21.0°±0 | 20.3°±1.5 | 8 | 48 | 176 | 160 | 40 | 35 | 6.7±8.9 | 8 | 25 | 4.4±2.8 |
| | 19 | SB,G,M | 12 | 25.3°±1.5 | 13.7°±2.5 | 16 | 36 | 172 | 100 | 28 | 30 | 11.3±8.3 | 16 | 55 | 1.6±1.0 |
| | 24 | LP,G,M | 13 | 27.7°±2.5 | 27.0°±2.6 | 40 | 20 | 148 | 260 | 60 | 25 | 6.6±5.0 | 28 | 7 | 3.3±0.9 |
| Age group 5-6 | 17 | SB,G,M | 12 | 14.3°±2.1 | 18.7°±1.5 | 60 | 8 | 118 | 60 | 40 | 14 | 6.6±3.3 | 28 | 25 | 2.3±1.3 |
| | 25 | LP,G,M | 7 | 18.3°±3.2 | 25.3°±0.6 | 64 | 8 | 152 | 110 | 64 | 25 | 9.0±6.9 | 32 | 35 | 3.0±0.9 |
| | 26 | LP,G,M | 17 | 15.7°±0.6 | 13.7°±0.6 | 48 | 4 | 86 | - | 32 | 15 | 6.6±3.5 | 32 | 25 | 2.2±1.1 |
| | 16 | SB,G,M | 5 | 19.3°±4.5 | 21.6°±3.2 | 44 | 4 | 150 | 110 | 28 | 10 | 4.1±2.0 | 28 | 8 | 2.3±1.1 |
| | 27 | SB,G,M | 9 | 11.0°±0.8 | 17.0°±3.2 | 48 | 12 | 262 | 100 | 48 | 28 | 7.8±6.1 | 32 | 45 | 2.5±1.3 |
| | 14 | SB,G | 21 | 7.5° | - | 44 | 4 | 184 | 150 | 44 | 22 | 8.8±4.7 | 24 | 32 | 2.5±1.4 |
| Age group 4 | 11 | SB,G | 36 | 5.5° | 2.5° | 24 | 8 | 136 | 120 | 48 | 31 | 8.7±6.5 | 28 | 15 | 2.5±1.4 |
| | 13 | SB,G | 26 | 14.8°±3.1 | 12.7°±0.6 | 28 | 4 | 138 | 140 | 24 | 37 | 10.3±9.7 | 12 | 4 | 1.8±0.9 |
| Age group 3 | 15 | SB,G | 51 | 8.3°±0.6 | 9.0°±1.0 | 64 | 0 | 98 | 150 | 84 | 20 | 7.1±5.0 | 32 | 30 | 2.4±1.1 |
| **Rock Creek** | | | | | | | | | | | | | | | |
| Age group 4 | 30 | SB,G | 21 | 9.0°±1.0 | 23.0°±1.0 | 32 | 4 | 186 | 210 | 84 | 38 | 8.3±7.2 | 32 | 35 | 2.2±1.3 |
| | 31 | SB,G | 23 | 11.7°±1.5 | 11.3°±1.5 | 24 | 24 | 192 | 110 | 52 | 28 | 6.9±6.0 | 32 | 30 | 2.7±1.8 |
| Age group 3 | 29 | SB,G | 78 | 10.3°±0.6 | 6.3°±0.6 | 36 | 0 | 20 | 150 | 76 | 15 | 7.1±1.3 | 56 | 25 | 2.5±0.9 |
| | 28 | SB,G | 26 | 5.3°±0.6 | 12.0°±1.0 | 60 | 0 | 104 | 140 | 86 | 31 | 9.2±5.5 | 64 | 45 | 2.1±0.8 |

1/ Methods of Burke and Birkeland (1979) except that boulders include clasts > 25-cm diameter.
2/ ± values are one standard deviation.
3/ LP = lodgepole pine, G = grasses, SB = sagebrush, M = mountain mahogany and manzanita.

there was considerable variation in these values from one site to another and presented little quantitative data.

Comparison of reconnaissance data using most of the weathering parameter methods used by Osborn (1973), Shroba (1977), and Burke and Birkeland (1979) suggested 12 parameters were most useful in distinguishing moraines of different age (table A.1). These parameters were measured at 12 sites in the Lake Fork moraines (pl. 3). Measurements were made at one site on the terminal Jackson Park moraines of Osborn (1973, his pl. 1) (site 39, pl. 1) in the Yellowstone drainage in order to compare values on these youngest moraines with those from the Lake Fork moraines. We also sampled four sites on the moraines along Rock Creek west of Towanta Flat (sites 28 through 31; pl. 1) to help in correlating them with the Lake Fork moraines.

Parameter values (table A.1) were quite variable from site to site even within moraines of the same mapped relative-age group. For some parameters, such as moraine widths, slope angles, and percent polished stones, the values measured on the oldest moraines were clearly different from those on younger moraines nearer the Lake Fork River. However, other parameters did not show clear age dependency and the problems of where to draw the boundary between moraines of RAG 5-6 and RAG 7-8 (Yellow Ledges and Hell's Canyon moraines of Osborn, 1973), and the relative age relationship of the Rock Creek moraines to the Lake Fork moraines could not be resolved from inspection of the raw surface weathering data.

Other glacial geologists have noted similar problems with using RD techniques in the Uintas (R. R. Shroba and P. E. Carrara, USGS, Denver, oral communication, 1979) due to the predominance of quartzites of the Uinta Mountain Group in the drift. The quartzites, entirely lacking in easily weatherable minerals, weather much more slowly and more unevenly than the granitic rocks most often used in surface weathering studies. Diffuse rinds of irregular thickness form in some of the older, coarser-grained quartzites. Some of the white to yellow quartzites of the Uinta Mountain Group grussify more rapidly than the dark purple quartzites, but do not develop rinds. Large pits and projections that have developed on very old boulders appear to be the result of grain size and bedding changes within the quartzite. Near Towanta Flat on the south flank of the Uintas, up to 10 percent of other more weatherable lithologies (limestone, shale, sandstone, and chert derived from the exposed Paleozoic and Mesozoic sections) can be found in the drift, but not enough of these rocks are found at the surface of the moraines to use in weathering studies.

Because the weathering data from some of our sites suggested some age dependency, discriminant analysis (a multivariate statistical technique) was used to determine whether these surface weathering data could be used along with morphostratigraphy to map the Lake Fork moraines into consistent groups of significantly different age. The analysis also showed how statistically distinct the resulting relative-age groups are.

A direct discriminant analysis was done using the methods of Nie and others (1975) on the data from all geologically reasonable combinations of weathering sites. In all seven analyses, the standardized canonical discriminant function coefficients for each measured weathering parameter indicated that moraine crest width, average maximum proximal moraine slope angle and, to a lesser extent, the percentage of split stones were the most useful parameters for distinguishing groups of sites of different relative age.

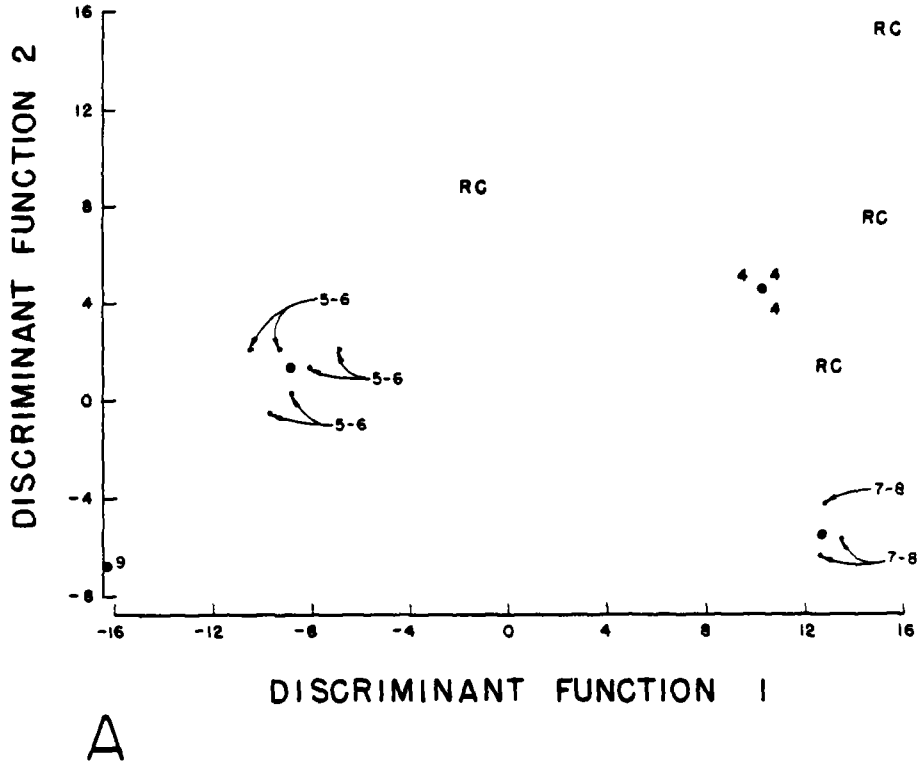
The results of the seven analyses show that our mapping of the Lake Fork moraines using moraine morphology into relative age groups (pl. 3) gives a wider separation of groups than any other combination of weathering sites on moraines. This is shown by a plot of first and second discriminant function scores for each site (fig. A.3-A). Sites in groups defined on the basis of Osborn's (1973, p. 78) mapping of the Hell's Canyon-Yellow Ledges boundary farther south than in plate 3 are not as distinct (fig. A.3-B, table A.1). Thus, multivariate analysis of surface weathering data supports our mapping of the boundary between RAG 5-6 and RAG 7-8 moraines, although the absence of true random sampling and the limited number of weathering stations prevent a rigorous statistical interpretation of the discriminant analysis results.

Most of the discriminant analyses also suggested that the four weathering stations on the Rock Creek moraines, mapped by Atwood (1909, p. 55) with deposits of his earliest glaciation, had surface weathering characteristics more similar to those of the oldest Lake Fork moraines (RAGs 3 and 4) than to those of younger moraines (fig. A.3). This result was anticipated for the high, broad outermost moraines in Rock Creek (sites 28 and 29, table A.1), but was a surprise for the much more bouldery moraines near the floor of Rock Creek Valley (sites 30 and 31, table A.1) which appear morphologically younger.

### A.2.1.2 Soil Development

Most geologists working in the Uintas have felt that the degree of soil development was of little use in relative dating glacial deposits (Kinney, 1955, p. 131; Schoenfeld, 1969, p. 29; R. R. Shroba, and P. E. Carrara, USGS, Denver, oral communication, 1979). In most areas of the Uintas, the lack of weatherable minerals in the quartzite-dominated drift prevents development of brightly colored, clayey, or carbonate-rich soil horizons which can be used to assess the relative age of soils developed on moraines. On the south flank of the Uintas, in addition to the Paleozoic and Mesozoic sedimentary rocks exposed near the mouths of the valleys, the Tertiary Duchesne River Formation laps up on the flanks of the mountains reaching elevations of nearly 3350 m (11 000 ft) (Anderson and Picard, 1972). Calcareous shales (Stokes and Madsen, 1961) are present in the Mesozoic section, and much of the Duchesne River Formation consists of brightly colored (2.5 YR and 5 YR Munsell color hues) mudstones. Thus, near the mouths of the valleys on the south flank, sufficient iron, clay, and carbonate are present in the drift for well-developed soil profiles to form over timespans comparable

Figure A.3. - Plot of the first and second discriminant function scores (methods of Nie and others, 1975) for surface weathering sites on the Lake Fork and Rock Creek moraines (A) as mapped by us (pl. 3) and (B) as mapped by Osborn (1973). Numerals indicate sites in each relative-age group (table 5.1), RC shows unclassified sites on the Rock Creek moraines, and large dots show group centroids. The standardized canonical discriminant function coefficients calculated in the analysis show moraine width, maximum proximal slope angle, and the percentage of split stones are the main contributors to the first discriminant function; all moraine morphology parameters and the percentage of pitted stones contribute significantly to the second discriminate function. The second function ranks groups in the proper age order while the first function provides a greater separation of the groups. Our mapping of the moraines using morphology and surface weathering data (A) gives a wider separation of moraine groups than any other combination of weathering sites. The unclassified sites on the Rock Creek moraines appear most similar in weathering characteristics to the RAG 4 sites.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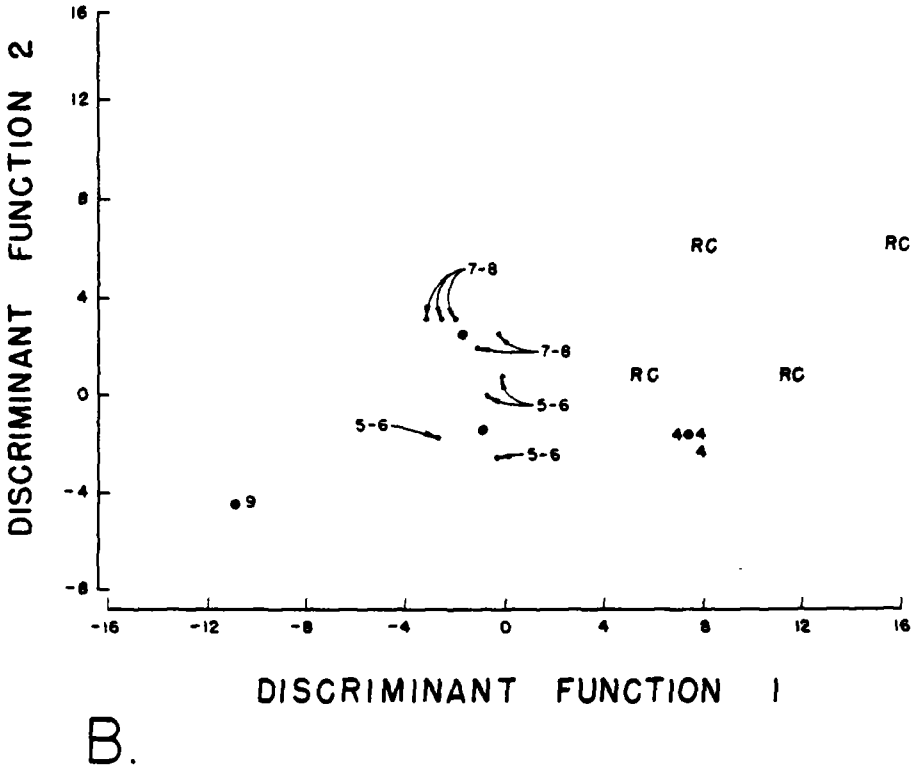
DISCRIMINANT FUNCTION 1

A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DISCRIMINANT FUNCTION 1

B.

to those needed for soil development on moraines in granitic terrains in the Rockies (Osborn, 1973, p. 23). Furthermore, the main valley glaciers on the south flank (Lake Fork, Yellowstone, Uinta, pl. 1) extended beyond the edge of the mountains onto outwash plains, where the climate was sufficiently arid for significant carbonate accumulation in the soil.

Although Osborn (1973) claimed to have been the first to successfully use soil profile descriptions in relative dating glacial deposits in the Uintas, he failed to demonstrate a significant relative-age difference using soil development between more than three of the eight deposits of different ages he mapped. He described only 12 soil profiles and most were on slopes so steep (10 to 30°) that comparisons for relative dating are suspect. More importantly, some of the more signficant profiles (Nos. 1, 2, 6, Osborn, 1973, pp. 250-255) were incorrectly described and interpreted (discussed below).

A number of studies (for example, Birkeland, 1974, and references therein) have shown the broad age dependency of some soil profile characteristics. As in most other RD studies using soil development, properties of the B and Cox soil horizons and indexes derived from them are most useful in distinguishing different aged soils in the Towanta Flat area (tables A.2 and A.3).

The soils on the crests of moraines north of Towanta Flat range from Alfisols on the most distal moraine to Entisols on the terminal moraines of RAG 7-8 (appendix B). Profile 15 on the oldest moraines (RAG 3) does not differ significantly in development from profiles 11 and 13 on moraines mapped in RAG 4 using relative moraine position and crosscutting relationships. Profiles 13 and 15 are Typic Eutroboralfs (classification system of Soil Survey Staff, 1975), while profile 11 is a Typic Argiboroll because the A horizon meets the requirements for a Mollisol. All have Bt horizons with high color indexes, moderate to high clay contents, and strong argillan development (table A.3). The stage of carbonate morphology (Gile and others, 1966) is higher in profile 15, possibly suggesting a greater age, but absolute amounts of carbonate are similar to those in profile 13. Its location on top of a high, steep-sided moraine and the lower clay content and color index of profile 13 suggest it has been subject to more erosion than the other profiles. A wedge of silty clay (II B23tb horizon; appendix B) in the profile suggests cryogenic disturbance following deposition of this moraine.

Profile 4 of Osborn (1973, p. 253) (site 36, pl. 3) was described from a moraine in the Yellowstone drainage correlated with the older Lake Fork moraines, but it resembles our profiles from these moraines only in its color intensity. Its location on a 30° slope makes comparisons with our profiles in more stable landscape positions difficult. Profiles from the Uinta River area described by Osborn on moraines he felt were of similar age are either incomplete (profiles 1 and 3, pp. 250 and 252) (sites 40 and 44, pl. 1) or incorrectly described (B horizons in profiles 1 and 2, site 41, are probably relatively unaltered till derived from clay-rich beds of the Duchesne River Formation).

Table A.2. - Summary of horizon properties for soils developed on outwash and till in the Towanta Flat area

| Profile | Horizon 1/ | Average depth (cm) | Munsell color (dry) | pH 2/ | Percent by weight 3/ | | | Estimated percent by volume | | | Ratio of 3/ | Percent organic 4/ | Percent | Bulk density 6/ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Sand (2.0-0.5 mm) | Silt (50-2 μm) | Clay (<2 μm) | Gravel (0.2-8 cm) | Cobbles (8-25 cm) | Boulders (>25 cm) | <1 μm/<2 μm | matter | $CO_3$ 5/ | ($g/cm^3$) |
| 1 | A1 | 0-6 | 5YR 4/4 | 5.6 | 68 | 21 | 12 | 0 | 0 | 0 | 0.88 | 4.7 | 0.1 (0) | 1.70 |
| | B1 | 6-16 | 5YR 5/5 | 6.5 | 69 | 17 | 14 | 20 | 30 | 0 | 0.91 | 1.8 | 0.1 (tr) | 1.85 |
| | IIB21tb | 16-38 | 5YR 5/8 | 6.9 | 75 | 5 | 19 | 20 | 40 | 0 | 0.94 | 1.2 | 0.2 (1) | 1.85 |
| | IIB22b | 38-48 | 7.5YR 6/4 | 7.9 | 82 | 5 | 13 | 20 | 40 | 0 | 0.90 | 0.9 | 31 (31) | 1.50 |
| | IIK1b | 48-105 | 7.5YR 8/2 | 7.9 | 76 | 5 | 19 | 20 | 30 | 5 | 0.97 | 1.0 | 62 (68) | 1.30 |
| | IIIC1cab | 105-190 | 2.5YR 4/7 | 8.2 | 77 | 7 | 16 | 10 | 40 | 30 | 0.69 | 0.2 | 7 (7) | 1.80 |
| | IIIC2cab | 190-298+ | 5YR 5/8 | 8.2 | 82 | 9 | 9 | 10 | 40 | 30 | 0.57 | 0.1 | 7 (2) | 1.90 |
| 2 | AB | 0-18 | 7.5YR 6/6 | 6.3 | 55 | 26 | 19 | 2 | 0 | 0 | | 1.1 | 0.0 | |
| | B21t | 18-52 | 5YR 5/6 | 6.9 | 46 | 27 | 27 | 2 | 0 | 0 | | 0.4 | 0.0 | |
| | B22t | 52-128 | 5YR 5/6 | 7.9 | 56 | 25 | 20 | 2 | 0 | 0 | | 0.1 | 0.8 | |
| | IIB23tb | 128-174 | 5YR 6/6 | 7.9 | 55 | 24 | 22 | 30 | 30 | 10 | | 0.2 | 0.7 | |
| | IIIB24tb | 174-203 | 2.5YR 5/6 | 7.7 | 49 | 20 | 31 | 25 | 25 | 20 | | 0.2 | 0.6 | |
| | IIIB3tb | 203-228+ | 5YR 5/6 | 7.7 | 57 | 22 | 21 | 25 | 25 | 20 | | 0.1 | 0.6 | |
| 3 | B21 | 0-36 | 5YR 5/6 | | 55 | 26 | 19 | 2 | 0 | 0 | | | 0.0 | |
| | B22 | 36-46 | 7.5YR 8/3 | | - | - | - | 2 | 0 | 0 | | | 44.0 | |
| | B23ca | 46-130 | 5YR 5/6 | | 59 | 24 | 17 | 2 | 0 | 0 | | | 7.0 | |
| | B24t | 130-224 | 5YR 5/6 | | 56 | 25 | 18 | 2 | 0 | 0 | | | 0.1 | |
| | IIB25b | 224-249 | 5YR 6/5 | | 63 | 23 | 14 | 30 | 30 | 20 | | | 0.0 | |
| | IIIB26tb | 249-291 | 5YR 5/8 | | 58 | 17 | 24 | 10 | - | - | | | 0.1 | |
| | IVB27tb | 291-345+ | 5YR 5/8 | | 64 | 16 | 20 | 30 | 20 | 10 | | | 0.1 | |
| 4 | A | 0-19 | 7.5YR 5/3 | 6.7 | 47 | 34 | 19 | 0 | 0 | 0 | 0.82 | 4.0 | 0.2 (tr) | |
| | IIB21b | 19-41 | 7.5YR 5/3 | 7.5 | 38 | 29 | 33 | 0 | 0 | 0 | 0.94 | 0.6 | 0.2 (tr) | |
| | IIB22b | 41-65 | 10YR 7/4 | 7.8 | 40 | 34 | 26 | 0 | 0 | 0 | 0.85 | 0.5 | 0.2 (1) | |
| | IIB3b | 65-83 | 2.5YR 8/3 | 8.2 | 40 | 37 | 24 | 0 | 0 | 0 | 0.92 | 0.5 | 4.0 (6) | |
| | IICb | 83-121 | 2.5Y 8/3 | 8.3 | 70 | 19 | 11 | 2 | 5 | 0 | 0.89 | 0.1 | 1.0 (3) | |
| | IIIB3b | 121-144 | 5YR 7/3 | 8.2 | 89 | 6 | 5 | 10-30 | 2-15 | 0 | 0.89 | 0.1 | 0.2 (1) | |
| | IVCb | 144-246+ | 5Y 8/2 | 8.3 | 41 | 28 | 30 | 5-10 | 1-15 | <1 | 0.96 | 0.1 | 0.2 (3) | |
| 5 | AB | 0-33 | 5YR 5/4 | | 68 | 12 | 20 | 30 | 25 | 5 | | | 2 | 1.88 |
| | B2t | 33-121 | 2.5YR 5/6 | | 58 | 6 | 37 | 30 | 25 | 5 | | | 1 | |
| | K2 | 121-181 | 10YR 8/3 | | - | - | - | 20 | 30 | 5 | | | 71.0 | |
| | IIC1cab | 181-251 | 5YR 8/3 | | 80 | 9 | 11 | 50 | 30 | 10 | | | 8.0 | |
| | IIC2b | 251-450 | 5Y 8/3 | | 74 | 3 | 23 | 50 | 30 | 10 | | | 1.0 | |
| | IIIC3b | 450-530 | 7.5YR 7/8 | | 90 | 3 | 7 | 40 | 35 | 2 | | | 0.0 | |
| | IIIC4b | 530-730+ | 5YR 5/6 | | 85 | 4 | 11 | 40 | 35 | 2 | | | 0.1 | 1.70 |
| 6 | A1 | 0-17 | 7.5YR 4/3 | 7.2 | 66 | 22 | 12 | 40 | 40 | 1 | 0.86 | 2.1 | (0) | |
| | A2 | 17-44 | 5YR 5/3 | 7.2 | 68 | 20 | 12 | 45 | 10 | 1 | 0.89 | 1.6 | (0) | |
| | AC | 44-70 | 5YR 5/5 | 7.1 | 90 | 8 | 2 | 50 | 40 | 1 | 0.70 | 0.5 | (0) | |
| | C | 70-130+ | 5YR 5/5 | 6.2 | 95 | 3 | 2 | 50 | 40 | 1 | 0.86 | 0.2 | (0) | |
| 7 | A1 | 0-17 | 7.5YR 5/4 | | 66 | 23 | 11 | 25 | 20 | 5 | | | 0.0 | |
| | B21t | 17-31 | 5YR 4/8 | | 52 | 20 | 28 | 25 | 20 | 5 | | | 0.5 | |
| | B22t | 31-66 | 5YR 4/8 | | 62 | 12 | 27 | 25 | 20 | 5 | | | 0.5 | |
| | K2 | 66-117 | 8/0 | | - | - | - | 15 | 40 | 10 | | | 51.0 | 1.84 |
| | Cca | 117-166+ | 7.5YR 7/5 | | 82 | 8 | 10 | 15 | 40 | 10 | | | 7.0 | |
| 8 | A | 0-16 | 7.5YR 6/4 | 6.7 | 68 | 21 | 11 | 25 | 30 | 5 | 0.86 | 1.9 | 0 (tr) | |
| | B21t | 16-31 | 5YR 4/6 | 7.0 | 56 | 18 | 26 | 25 | 30 | 5 | 0.96 | 1.3 | 0.5 (tr) | |
| | B22t | 31-58 | 2.5YR 5/6 | 7.2 | 60 | 10 | 30 | 25 | 30 | 5 | 0.98 | 0.7 | 0.5 (tr) | |
| | K2 | 58-95 | 8/0 | 8.0 | 74 | 10 | 16 | 25 | 20 | 5 | 0.95 | 0.9 | 63.0 (70) | 1.64 |

Table A.2. - Summary of horizon properties for soils developed on outwash and till in the Towanta Flat area - Continued

| Profile | Horizon 1/ | Average depth (cm) | Munsell color (dry) | pH 2/ | Percent by weight 3/ | | | Estimated percent by volume | | | Ratio of 3/ | Percent organic 4/ | Percent | Bulk density 6/ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Sand (2.0-0.5 mm) | Silt (50-2 μm) | Clay (<2 μm) | Gravel (0.2-8 cm) | Cobbles (8-25 cm) | Boulders (>25 cm) | <1 μm/<2 μm | matter | $CO_3$ 5/ | ($g/cm^3$) |
| 9 | A | 0-18 | 7.5YR 6/3 | 7.0 | 53 | 26 | 20 | 0 | 0 | 0 | | 0.1 | 0.0 | |
| | IIB2b | 18-34 | 5YR 6/4 | 7.1 | 53 | 23 | 24 | 0 | 0 | 0 | | 0.6 | 0.0 | |
| | IIB3b | 34-54 | 7.5YR 6/4 | 7.9 | 62 | 19 | 19 | 1 | 1 | 0 | | 0.7 | 2.0 | |
| | IIC1b | 54-66 | 7.5YR 7/4 | 8.4 | 66 | 19 | 15 | 25 | 35 | 0 | | 0.4 | 4.4 | |
| | IIIC2oxb | 66-98 | 7.5YR 7/4 | 8.3 | 74 | 13 | 13 | 15 | 25 | 1 | | 0.3 | 2.6 | |
| | IVC3b | 98-130 | 5YR 7/4 | 8.4 | 84 | 8 | 8 | 20 | 30 | 1 | | 0.1 | 1.2 | |
| | VC4b | 130-172+ | 2.5Y 7/3 | 8.3 | 65 | 11 | 24 | 5 | 5 | 0 | | 0.1 | 1.5 | |
| 10 | A1 | 0-15 | 5YR 4/4 | | 63 | 23 | 14 | 30 | 30 | 10 | | | 2.0 | |
| | B1 | 15-32 | 5YR 5/5 | | 62 | 19 | 19 | 30 | 30 | 10 | | | 0.4 | |
| | B21t | 32-65 | 5YR 5/7 | | 58 | 12 | 30 | 20 | 40 | 10 | | | 2.0 | |
| | B22t | 65-119 | 2.5YR 4/6 | | 54 | 8 | 38 | 20 | 40 | 10 | | | 2.0 | |
| | K | 119-155+ | 5YR 5/7 | | - | - | - | 20 | 40 | 10 | | | 42.0 | |
| 11 | A1 | 0-23 | 5YR 5/4 | | 72 | 18 | 9 | 15-20 | 5 | 0 | | | 0.0 | |
| | B1 | 23-64 | 7.5YR 5/4 | | 68 | 19 | 14 | 15-20 | 5 | 0 | | | 0.0 | |
| | IIB21cab | 64-85 | 5YR 6/6 | | 62 | 18 | 20 | 15 | 20 | 5 | | | 8.0 | |
| | IIB22tb | 85-148 | 5YR 6/6 | | 62 | 20 | 18 | 15 | 20 | 5 | | | 5.0 | |
| | IIB23tb | 148-173 | 5YR 6/6 | | 72 | 13 | 15 | 15 | 10 | 5 | | | 1.0 | |
| | IIIB24b | 173-184+ | 2.5YR 5/6 | | 69 | 17 | 14 | 15 | 10 | 5 | | | 3.0 | |
| 12 | A | 0-13 | 7.5YR 6/3 | | 66 | 23 | 11 | 10 | <1 | 0 | | | 0.1 | |
| | AB | 13-28 | 5YR 5/4 | | 64 | 18 | 18 | 10 | <1 | 0 | | | 0.0 | |
| | B21t | 28-55 | 5YR 5/6 | | 64 | 15 | 21 | 10 | 2 | 0 | | | 0.1 | |
| | IIB22tb | 55-87 | 2.5YR 5/7 | | 54 | 5 | 41 | 50-60 | 10-20 | <1 | | | 0.6 | |
| | IIIB23tb | 87-108 | 5YR 6/7 | | 76 | 3 | 21 | 5 | 0 | 0 | | | 0.2 | |
| | IVB3b | 108-140 | 5YR 6/6 | | 81 | 3 | 16 | 40 | 5-20 | <1 | | | 0.0 | |
| | VCb | 140-161+ | 5YR 6/7 | | 58 | 17 | 26 | 0 | 0 | 0 | | | 2.0 | |
| 13 | A | 0-20 | 7.5YR 6/4 | | 66 | 25 | 9 | 20 | 10 | 5 | | | 0.0 | |
| | B1 | 20-42 | 5YR 7/5 | | 68 | 20 | 13 | 20 | 10 | 5 | | | 0.0 | |
| | B21ca | 42-66 | 5YR 8/3 | | 67 | 20 | 14 | 20 | 10 | 5 | | | 6.0 | 1.60 |
| | B22t | 66-106 | 5YR 7/4 | | 70 | 16 | 13 | 20 | 10 | 5 | | | 3.0 | |
| | IIB23tb | 106-132 | 5YR 5/6 (moist) | | - | - | - | 0 | 0 | 0 | | | 25.0 | |
| | IB24t | 132-162+ | 5YR 8/4 | | 67 | 20 | 13 | 20 | 10 | 5 | | | 10.0 | |
| 14 | A | 0-17 | 5YR 5/3 | 6.8 | 66 | 20 | 14 | 20 | 15 | 5 | 0.82 | 1.6 | 0.0 (tr) | |
| | B1 | 17-44 | 5YR 5/4 | 6.6 | 56 | 24 | 20 | 20 | 15 | 5 | 0.89 | 0.5 | 0.0 (tr) | |
| | B21t | 44-67 | 5YR 5/8 | 6.8 | 60 | 20 | 20 | 20 | 15 | 5 | 0.94 | 0.5 | 0.2 (tr) | |
| | B31 | 67-122 | 5YR 7/4 | 6.7 | 73 | 16 | 11 | 20 | 15 | 5 | 0.87 | 0.2 | 0.0 (tr) | |
| | B32 | 122-143 | 5YR 7/5 | 6.8 | 86 | 7 | 7 | 20 | 15 | 5 | 0.94 | 0.2 | 0.0 (tr) | |
| | IIB33 | 143-163+ | 2.5YR 5/5 | 8.1 | 66 | 19 | 16 | 20 | 15 | 5 | 0.85 | 0.3 | 3.0 (5) | |
| 15 | A | 0-9 | 5YR 5/3 | 6.9 | 71 | 17 | 11 | 20 | 25 | 10 | 0.84 | 1.8 | 0.0 (tr) | 1.62 |
| | B1 | 9-23 | 5YR 5/4 | 7.0 | 67 | 16 | 18 | 20 | 25 | 10 | 0.90 | 1.1 | 0.1 (tr) | |
| | B2 | 23-46 | 5YR 4/6 | 7.5 | 71 | 14 | 15 | 20 | 25 | 10 | 0.90 | 0.7 | 0.0 (2) | |
| | Bca | 46-80 | 7.5YR 8/3 | 8.1 | 77 | 14 | 9 | 20 | 25 | 10 | 0.86 | 0.6 | 12.0 (24) | |
| | Cca | 80-171+ | 5YR 6/4 | 8.5 | 73 | 17 | 10 | 15 | 0 | 0 | 0.82 | 0.1 | 3.5 (4) | |
| 16 | A | 0-18 | 5YR 6/2 | | 60 | 31 | 8 | 15 | 10 | 1 | | | 0.0 | 1.70 |
| | B1 | 18-34 | 2.5YR 7/3 | | 72 | 19 | 9 | 15 | 10 | 1 | | | 0.0 | |
| | B21t | 34-68 | 2.5YR 5/6 | | 64 | 16 | 20 | 15 | 10 | 1 | | | 0.0 | 1.90 |
| | B22t | 68-119 | 2.5YR 6/6 | | 68 | 12 | 20 | 15 | 10 | 1 | | | 0.0 | 2.0 |
| | B23t | 119-157 | 2.5YR 6/5 | | 71 | 13 | 15 | 15 | 10 | 1 | | | 0.0 | 1.90 |
| | C | 157-172+ | 5YR 7/4 | | 74 | 14 | 12 | 15 | 10 | 1 | | | 0.0 | 1.90 |

Table A.2. - Summary of horizon properties for soils developed on outwash and till in the Towanta Flat area - Continued

| Profile | Horizon 1/ | Average depth (cm) | Munsell color (dry) | pH 2/ | Percent by weight 3/ Sand (2.0-0.5 mm) | Silt (50-2 μm) | Clay (<2 μm) | Estimated percent by volume Gravel (0.2-8 cm) | Cobbles (8-25 cm) | Boulders (>25 cm) | Ratio of 3/ <1 μm/<2 μm | Percent organic 4/ matter | Percent $CO_3$ 5/ | Bulk density 6/ ($g/cm^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 17 | A11 | 0-21 | 7.5YR 5/2 | | 67 | 26 | 7 | 20 | 15 | 8 | | | 0.0 | |
| | A12 | 21-52 | 7.5YR 7/3 | | 76 | 17 | 7 | 20 | 15 | 8 | | | 0.0 | |
| | B2t | 52-107 | 5YR 6/8 | | 74 | 10 | 16 | 15 | 15 | 8 | | | 0.1 | |
| | C1ca | 107-127 | 5YR 8/3 | | - | - | - | 15 | 15 | 8 | | | 46.0 | |
| | C2 | 127-161 | 5YR 7/4 | | 77 | 17 | 5 | 15 | 15 | 8 | | | 0.5 | |
| | C3 | 161-184+ | 5YR 6/4 | | 91 | 5 | 4 | 15 | 15 | 8 | | | 0.0 | |
| 18 | A11 | 0-11 | 7.5YR 6/4 | | | | | 0 | 0 | 0 | | | | |
| | A12 | 11-26 | 7.5YR 6/4 | | | | | 0 | 0 | 0 | | | | |
| | B1 | 26-59 | 7.5YR 5/4 | | | | | 0 | 0 | 0 | | | | |
| | B2 | 59-87 | 5YR 6/6 | | | | | 0 | 0 | 0 | | | | |
| | B3 | 87-114 | 7.5YR 7/6 | | | | | 0 | 0 | 0 | | | | |
| | IICox | 114-129 | 2.5Y 8/3 (moist) | | | | | 0 | 0 | 0 | | | | |
| | IIIC | 129-175+ | 5YR 7/3 (moist) | | | | | 0 | 0 | 0 | | | | |
| 19 | A11 | 0-27 | 7.5YR 6/3 | 6.1 | 70 | 20 | 10 | 30 | 15 | 2 | | 2.5 | 0.0 | |
| | A12 | 27-50 | 7.5YR 7/3 | 6.3 | 76 | 18 | 6 | 25 | 15 | 2 | | 0.7 | 0.0 | |
| | C1 | 50-70 | 5YR 8/3 | 6.5 | 77 | 18 | 5 | 20 | 15 | 2 | | 0.2 | 0.0 | |
| | C2 | 70-98 | 5YR 8/4 | 6.6 | 74 | 19 | 7 | 20 | 15 | 2 | | 0.3 | 0.0 | |
| | C3 | 98-140 | 5YR 8/3 | 8.4 | 78 | 18 | 4 | 20 | 15 | 2 | | 0.2 | 1.3 | |
| | C4 | 140-162+ | 5YR 8/4 | 8.5 | 77 | 19 | 4 | 20 | 15 | 2 | | 0.1 | 3.0 | |
| 20 | A11 | 0-18 | 7.5YR 5/3 | | 62 | 32 | 6 | 20 | 15 | 0 | | | 0.0 | |
| | A12 | 18-32 | 5YR 7/4 | | 71 | 23 | 6 | 20 | 15 | 1 | | | 0.0 | |
| | C1ca | 32-54 | 5YR 7/4 | | - | - | - | 20 | 15 | 1 | | | 20.0 | |
| | C2 | 54-154+ | 5YR 8/4 | | 63 | 30 | 7 | 20 | 15 | 1 | | | 8.0 | |
| 21 | A1 | 0-24 | 7.5 YR 5/4 | | 74 | 17 | 8 | 50 | 10 | 1 | | | 0.1 | |
| | B2 | 24-58 | 5YR 6/4 | | 72 | 19 | 9 | 50 | 15 | 5 | | | 0.0 | |
| | C1ox | 58-124 | 5YR 5/5 | | 88 | 6 | 6 | 40 | 30 | 5 | | | 0.2 | |
| 22 | A11 | 0-6 | 7.5YR 6/4 | 6.5 | 69 | 20 | 11 | 25 | 1 | 0 | 0.81 | 1.7 | 0.0 (tr) | |
| | B1 | 6-19 | 5YR 5/4 | 6.6 | 62 | 18 | 20 | 50 | 10 | 0 | 0.86 | 1.7 | 0.0 (tr) | |
| | B21t | 19-32 | 5YR 5/7 | 6.6 | 56 | 14 | 30 | 60 | 10 | 0 | 0.98 | 1.1 | 0.2 (tr) | |
| | B22t | 32-58 | 2.5YR 4/6 | 6.6 | 63 | 5 | 32 | 60 | 10 | 2 | 0.98 | 0.7 | 0.4 (tr) | |
| | B3 | 58-125 | 2.5YR 5/7 | 6.6 | 83 | 3 | 13 | 60 | 10 | 10 | 0.97 | 0.2 | 0.1 (tr) | |
| | C | 125-169+ | 2.5YR 5/7 | 6.8 | 86 | 3 | 11 | 60 | 10 | 10 | 0.97 | 0.2 | 0.1 (tr) | |
| 23 | A1 | 0-16 | 7.5YR 5/4 | | 70 | 19 | 11 | 20 | 10 | 2 | | | 1.0 | |
| | B2 | 16-35 | 7.5YR 6/4 | | 59 | 7 | 24 | 20 | 10 | 2 | | | 5.0 | |
| | B3ca | 35-58 | 7.5YR 7/3 | | - | - | - | 20 | 10 | 2 | | | 12.0 | |
| | IIC1cab | 58-83 | 8/0 | | - | - | - | 25 | 25 | 10 | | | 22.0 | |
| | IIC2cab | 83-158+ | 2.5Y 8/2 | | - | - | - | 30 | 40 | 10 | | | 14.0 | |

1/ Nomenclature follows Soil Survey Staff (1975), Birkeland (1974), and Gile and Grossman (1979).
2/ Soil reaction measured with a Hack pH meter using a 1:2.5 soil/water ratio.
3/ Particle size distribution of <2 mm fraction using sieve-pipette methods (e.g., Carver, 1971) and Sedigraph for silt-clay fractions of profiles 1, 4, 8, 14, 15, 22, and 24 with prior removal of carbonates and organic matter using methods of Jackson (1956).
4/ Organic matter determined by loss on ignition (2 hours at 450 °C), corrected for structural water loss by subtracting loss on ignition of organic free silt + clay fraction.
5/ Percent carbonate by method 4 of Allison and Moodie (1965, p. 1387), values in parentheses by method of Dreimanis (1962), tr = trace.
6/ Clod method of Blake (1965, p. 381).

Table A.3. - Indexes of soil development for profiles on moraines, outwash, and colluvial deposits in the Towanta Flat area and Lake Fork River and Yellowstone River valleys

| Profile No. | Site No. | Max. dry color index 1/ of B/C horizon | Clay (< 2 m) Total Max. % | Clay (< 2 m) Total ($g/cm^2$) 2/ | Clay (< 2 m) $g/cm^3$ 2/ | Maximum argillan development index 3/ | Calcium carbonate Total Max. % | Calcium carbonate Stage 4/ | Calcium carbonate Total ($g/cm^2$) 5/ | Calcium carbonate $g/cm^3$ 5/ | Max. percentage highly weathered clasts 6/ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Relative age group 3 (Mud Springs Draw glaciation 7/)** | | | | | | | | | | | |
| Moraines | | | | | | | | | | | |
| 15 | 15 | 60 | 18 | 4 | 0.02 | 136 | 24 | IV | 12 | 0.07 | 30 |
| Outwash | | | | | | | | | | | |
| 1 | 1 | 80 | 19 | 18 | 0.06 | 64 | 68 | III | 75 | 0.25 | 50 |
| 7 | 7 | 80 | 28 | 19 | 0.11 | 168 | 51 | IV | 51 | 0.31 | 70 |
| **Relative age group 4 (Willow Spring glaciation 7/)** | | | | | | | | | | | |
| Moraines | | | | | | | | | | | |
| 11 | 11 | 60 | 20 | 20 | 0.11 | 100 | 5 | II+ | 10 | 0.05 | 20 |
| 13 | 13 | 50 | 14 | 7 | 0.04 | 44 | 25 | III- | 21 | 0.13 | 10 |
| 4 8/ | 36 | 80 | 10 | - | - | - | - | I * | - | - | |
| Outwash | | | | | | | | | | | |
| 5 9/ | 5 | 72 | 37 | 54 | 0.21 | 296 | 71 | V- | 87 | 0.34 | 30 |
| 8 | 8 | 72 | 30 | 34 | 0.18 | 312 | 70 | III+ | 38 | 0.20 | 70 |
| 10 | 10 | 72 | 38 | 49 | 0.32 | 420 | 42 | III- | 38 | 0.25 | 60 |
| 23 | 23 | 32 | 24 | 49 | 0.31 | 52 | 22 | III | 34 | 0.21 | 30 |
| **Relative age group 5-6 (Yellow Ledges glaciation 7/)** | | | | | | | | | | | |
| Moraines | | | | | | | | | | | |
| 14 | 14 | 80 | 20 | 30 | 0.18 | 164 | 5 | I | 1 | 0.007 | <1 |
| 16 | 16 | 7237.9 | 20 | 38 | 0.24 | 248 | 0 | 0 | 0 | 0 | <1 |
| 17 | 17 | 80 | 16 | 14 | 0.07 | 28 | 46 | II+ | 16 | 0.08 | 2 |
| 5 8/ | 32 | 24 | 7 | - | - | - | - | I- * | - | - | - |
| 6 8/ | 42 | 32 | 7 | - | - | - | - | I+ * | - | - | - |
| Outwash | | | | | | | | | | | |
| 4 | 4 | 24 | 10/ 33 | 10/ 80 | 10/ 0.33 | 10/ 144 | 6 | I- | 3 | 0.01 | 2 |
| 9 | 9 | 40 | 8 | 39 | 0.23 | 48 | 4 | I+ | 5 | 0.03 | 10 |
| 22 | 22 | 72 | 32 | 25 | 0.15 | 260 | 0.4 | 0 | 0.2 | 0.001 | 0 |
| Colluvium | | | | | | | | | | | |
| 2 | 2 | 60 | 27 | 58 | 0.25 | 92 | 0.8 | I | 2 | 0.009 | <2 |
| 3 | 3 | 80 | 24 | 62 | 0.18 | 72 | 44 | II+ | 17 | 0.05 | <2 |
| 12 | 12 | 84 | 21 | 44 | 0.28 | 200 | 2 | I+ | 0.8 | 0.005 | 0 |
| **Relative age group 7-8 (Hells Canyon glaciation 7/)** | | | | | | | | | | | |
| Moraines | | | | | | | | | | | |
| 19 | 19 | 40 | 7 | 3 | 0.02 | 0 | 3 | I- | 2 | 0.01 | <1 |
| 20 | 20 | 40 | 7 | 5 | 0.03 | 20 | 20 | II | 23 | 0.15 | 0 |
| 7 8/ | 33 | 18 | 4 | - | - | - | - | - | - | - | - |
| Outwash | | | | | | | | | | | |
| 18 | 18 | 60 | - | - | - | 0 | - | 0 | - | - | - |
| 21 | 21 | 60 | 9 | 5 | 0.03 | 8 | 0.2 | 0 | 0.1 | 0.001 | 0 |
| **Relative age group 9 (Crystal Creek and Jackson Park glaciations 7/)** | | | | | | | | | | | |
| Moraines | | | | | | | | | | | |
| 9 8/ | 37 | 24 | 5 | - | - | - | - | 0 | - | - | - |
| 10 8/ | 34 | 18 | 3 | - | - | - | - | 0 | - | - | - |
| 11 8/ | 35 | 24 | 6 | - | - | - | - | 0 | - | - | - |
| Outwash | | | | | | | | | | | |
| 6 | 6 | 50 | 2 | - | - | 0 | 0 | 0 | 0 | 0 | 0 |

1/ Index of Buntley and Westin (1965) except that a numerical notation of hue (2.5 YR = 12, 5 YR = 10, 7.5 YR = 8, 10 YR = 6, 2.5 Y = 4) is multiplied by chroma (e.g., Meierding, 1977, p. 189).
2/ Method of Machette (1978) substituting percent clay for percent carbonate; bulk density estimated from measurement of selected samples (table A.2), 10 percent initial clay assumed for RAG 3 and 4 deposits, 5 percent for younger deposits.
3/ Index derived from assigning following numerical values to field profile argillan descriptors (appendix B ) of Soil Survey Staff (1975) and summing: very few = 1, few = 2, common = 3, many = 4, continuous = 5; thin = 2, moderately thick = 4, thick = 6; clay bridges = 2, clay lining pores = 4, clay coating clasts = 6, clay coating peds = 8.
4/ Terminology of Gile and others (1966) and Bachman and Machette (1977).
5/ Method of Machette (1978); bulk density estimated from measurement of selected samples (table A.2).
6/ Clasts which can be broken by hand.
7/ Correlative informal glacial-stratigraphic terminology of Osborn (1973, p. 39).
8/ Data from soil profile descriptions of Osborn (1973, appendix).
9/ Only upper 251 cm of profile used in calculations.
10/ Clay content of lowest unit in profile of RAG 4 age.

Immediately proximal to moraines of RAGs 3 and 4 is a narrow, steep-sided continuous ridge of much less massive terminal moraines of RAG 5-6 (pl. 3). Osborn (1973, p. 104) noted that these moraines appear draped over the proximal edge of the older moraines, although his mapping and age assessments in this area (1973, p. 78) differ from ours.

Soil profiles developed at three sites on moraines of RAG 5-6 do not indicate these moraines are significantly younger than the moraines onto which they lap. As with the profiles on the older moraines, the profiles on the terminal moraine (14 and 16, appendix B, table A.2, pl. 3) are Typic Eutroboralfs, and profile 17 on a recessional moraine has a mollic A horizon making it a Typic Argiboroll. Argillic horizons with strong colors are well developed in all three profiles, although they are thicker with higher clay contents and stronger argillan development on the terminal moraine. In fact, argillan development and absolute amounts of clay and carbonate suggest these soils are at least as old as those developed on the older moraines (table A.3). Carbonate morphology is less developed on the RAG 5-6 moraines, however, and far fewer clasts are highly weathered (those that disintegrate with gentle hammer blow). The morphologic contrasts between the RAG 5-6 moraines and those of RAG's 4 and 5 indicate the RAG 5-6 moraines are significantly younger. Because of this, and the striking contrasts in soil development between the outwash terraces associated with these moraines, we attribute the lack of a difference in soil development on the moraines to gradual erosion of the older moraines.

Profile 17 is important because it demonstrates that the ice-stagnation and recessional moraines north of the RAG 5-6 terminal moraine ridge are of the same relative age as the terminal moraine and should not be grouped with the high moraines of RAG 7-8 enclosing the Twin Pots (pl. 3) as suggested by Osborn. Both the argillic horizon and carbonate stage II+ morphology of profile 17 demonstrate it is much older than profiles 19 and 20 on the RAG 7-8 moraines. These latter profiles lack B horizons entirely. Both would be Ustorthents except that the A horizon of profile 20 meets the requirements for a mollic epipedon making it a Haploboroll. Thus, soil development data strongly support our mapping of the boundary between RAG 5-6 and RAG 7-8 moraines (pl. 3).

### A.2.1.3 Theoretical Glacier Profiles

Studies in other mountainous regions have effectively used reconstruction of former glaciers using theoretical ice profiles to set limits on the extent of past glacial events and for correlation of glacial deposits from one drainage to another (Nelson and others, 1979, Pierce, 1979). Because all moraines north of Towanta Flat occur at about the same elevation and position, reconstruction of the glaciers which deposited these moraines using these methods (for example, Mathews, 1967) offers no new information about ice extent. However, comparison of ELA's (estimated glacier equilibrium line altitudes) (method of Porter, 1975) for the RAG 7-8 Lake Fork glacier with ELA's estimated for the glaciers which deposited the moraines in Rock Creek might provide an estimate of the extent of RAG 7-8 glaciers in the Rock Creek Valley

(assuming the same ELA for adjacent drainages). This would then help us determine the relative age relationship between the Rock Creek and Lake Fork moraines, which would aid in estimating the relative age of the unfaulted outwash terraces downstream from the Rock Creek moraines.

An attempt was made to determine the parameters necessary for calculation of these former glaciers, but not enough continuous lateral moraine segments are preserved in upper Rock Creek or the Lake Fork River Valleys to obtain reliable values for basal glacier shear stresses along the valley. In Rock Creek, calculations at three points in the upper valley indicated shear stresses of 0.65, 0.74, and 2.5 Pa (bars), while in the Lake Fork River Valley values were 0.32, 0.52, 0.60, and 1.11. This wide range of values far exceeds the requirements for meaningful comparison of calculated ELA's from one drainage to another.

### A.2.2 Outwash Terraces

Outwash plains and terraces which slope southward from the Lake Fork moraines can be divided into seven different levels (3 through 9) based on their relationships with the moraines and/or elevation above the Lake Fork River (fig. A.1). Older alluvial surfaces in the Towanta Flat area are discussed in the next section (A.3). In contrast to Osborn (1973, p. 35), we feel the degree of soil development in profiles on the outwash surfaces allows them to be easily grouped into three categories of different relative age. Most of these outwash surfaces grade into the Lake Fork moraines, and the major relative weathering breaks on the terraces indicated by soil development are the same as those suggested by the surface weathering and soils data collected from the moraines.

The large, high-level outwash plain of Towanta Flat grades into the subdued moraines of RAGs 3 and 4. Channels on the surface of Towanta Flat show it was partially covered by braided streams during both periods of moraine deposition, making the surface a mixture of both RAG 3 and RAG 4 outwash. In addition, the western edge of Towanta Flat was partially dissected by melt water streams issuing from RAG 5-6 moraines at the northwest corner of the flat where they overrode the older moraines at the edge of the mountains (pl. 3).

Our soil profiles (Nos. 1 and 7) are from the higher areas of the main Towanta Flat surface, and, therefore, are representative of soil development on outwash of RAG 3. Profiles 1 and 7 (table A.2, appendix B), like the soils on the moraines, are Typic Eutroboralfs with thin A horizons and thick argillic B horizons. These and other soils in the area were mapped chiefly as Brown Soils by Wilson and others (1940) except for alluvial soils on the youngest terraces. Clay contents reach 28 percent with 18 g of clay/$cm^2$ in these soils, but an even greater age is indicated by the carbonate accumulation in K and Cca horizons. K horizons exceed stage III morphology in both profiles, and carbonate percentages are 68 and 51. More than half the clasts in the K horizons are highly weathered, and color indexes for Bt horizons are as high as for any soils described.

A large (2-km, 1.2-mi) wide melt-water channel extends north-south across Towanta Flat, which is floored over most of its surface with outwash of RAG 4. This surface can be correlated on the basis of elevation and gradient with a wide (1.5-km, 0.9-mi) outwash terrace which grades into the Yellowstone River moraines (Mud Spring draw moraines of Osborn, 1973, his pl. 2) on the east side of the Lake Fork River (fig. A.1 and pl. 3). The channel is 25 m lower and, therefore, somewhat younger than the main Towanta Flat surface (RAG 3), but is at least as old as the RAG 4 moraines which extend into its head (pl. 3, Osborn, 1973, p. 79).

Soils on the main surface of the melt-water channel are similar to those on the higher Towanta Flat surface (RAG 3). All are Typic Eutroboralfs with argillic B horizons over carbonate horizons with stage III morphology. Profiles 8 and 10 (table A.3, appendix B) have maximum clay percentages of 30 and 38, total clay values of 34 and 49 g/cm$^2$, and the highest argillan indexes of any profiles described. K horizons are much like those on the higher surface, and other carbonate data are similar. Color indexes, however, are lower (table A.3). Profile 23 from the southernmost end of the melt-water channel (pl. 3, appendix B) has similar clay and carbonate data, but no K horizon, weaker argillan development, and a lower color index. However, the color of profile 23 is not directly comparable with the colors of other profiles because it is developed on outwash gravels locally incorporating the clay-rich, greenish-gray (2.5Y and 5Y hues) La Point member of the Duchesne River Formation (Andersen and Picard, 1972). The percentage of highly weathered clasts in these profiles is quite variable (all > 30 percent) with maximum values in the K horizons similar to those on the RAG 3 surface.

Profile 5 (pl. 3, appendix B) is on the RAG 4 terrace on the Lake Fork River south of Towanta Flat which is correlated with the melt-water channel (fig. A.1). It is very similar to the other RAG 4 profiles on outwash, except that the thick (60 cm) K horizon displays initial stage V morphology (table A.3). Possibly, this is an exhumed remnant of an older surface but is more likely representative of the maximum carbonate development on surfaces of RAG 4. Profile 5 is 12 km (7.5 mi) south of most of the Towanta Flat profiles, and a probable slightly lower annual precipitation (Moon Lake = 47 cm, Neola = 32 cm, Myton = 17 cm) may account for some of the greater carbonate accumulation in this profile. However, this degree of carbonate accumulation still suggests that the other profiles on Towanta Flat are not representative of the maximum degree of carbonate development for their age. A final interesting aspect of profile 5 is the change in color of the outwash parent material of the profile (table A.2), depending on which member of the Duchesne River Formation the Lake Fork River was eroding during transportation of the outwash load. These different colored parent materials are important in interpreting the stratigraphy exposed in our exploratory trenches (sec. 5.1.4).

Soils on the moraines of RAGs 3 and 4 are generally less well developed than soils on the outwash surfaces of the same relative age (table A.3). The unweathered till of the moraines contains more silt and clay than

the original unaltered outwash in the Towanta Flat area. Because soil development proceeds more rapidly in finer grained parent materials, the soils on the moraines would be expected to have stronger development. The outwash soils may be more strongly developed because they are less subject to erosion. They are also slightly lower in elevation (probably lower precipitation) and may, therefore, retain more carbonate in the solum than the morainal soils.

Within the main melt-water channel are much smaller channels which head in the moraines of RAG 5-6. Two of our exploratory trenches across suspected faults (trenches 2 and 3, pls. 5 and 6) exposed the outwash flooring in these younger channels, but complete soil profiles developed on this outwash are not present in either trench due to erosion and subsequent deposition of pond deposits, colluvium, and loess (see sec. 5.1.4). A complete profile (No. 22, appendix B) is available, however, from a correlative terrace along the Lake Fork River which grades into the Yellowstone moraines of RAG 5-6 (Yellow Ledges moraines of Osborn, 1973).

Profile 22 from terrace level 6 (RAG 5-6) east of Towanta Flat (pl. 3, fig. A.1) is developed on coarse outwash of this age. The well-developed, brightly colored, argillic horizon in this profile is very similar to those in the soils on the moraines of RAG 5-6, making it a Typic Eutroboralf as well. Carbonate accumulation is minimal, however, and no highly weathered clasts are present.

Soils on the outwash terraces of RAG 7-8, which grade into moraines on the Lake Fork and Yellowstone Rivers, are similar to those on the corresponding moraines in having much less clay and carbonate and lower color indexes than soils on the older terraces and moraines. Profile 18 in the outwash channel draining the Lake Fork moraines (pl. 3) is developed entirely in sand; only a cambic B horizon is present (appendix B) making it an inceptisol (Typic Ustochrept). Profile 21 on the next higher terrace along the Lake Fork River (pl. 3, fig. A.1) is also an inceptisol (Udic Ustochrept) with a cambic B horizon and almost no accumulation of carbonate. As with the soils on the corresponding moraines, neither profile has any highly weathered clasts, and soil structure is very weak to nonexistent (massive).

As were the soils described by Osborn (1973) on moraines in the upper reaches of the Yellowstone River, our single profile (No. 24) on outwash of RAG 9 on the lowest terrace of the Lake Fork River (fig. A.1) is an Entisol (Typic Ustorthent) with little evidence of pedogenesis. Only 2 percent clay and no argillans or carbonate are present. The color index is higher than those for some of the morainal soils, but the lack of even a weak cambic horizon indicates this color is inherited from the parent material (derived from Duchesne River Formation).

### A.2.3 Relative-age Summary

In summary, soil development and surface boulder weathering data indicate two major breaks in the degree of relative weathering in the Lake

Fork moraine-terrace sequence. This demonstrates this sequence is composed of materials of at least three significantly different ages.

Our data do not clearly distinguish moraines and outwash surfaces of RAGs 3 and 4 from each other. Either these moraines and surfaces do not differ significantly in age, or the rate of soil development as indicated by the properties we are measuring is too low to show significant differences on materials of this age. Our basis for separating these landforms into two relative-age groups is their relative position and the more eroded appearance of the RAG 3 moraines.

The degree of carbonate development in terms of morphology, total profile carbonate, and $g/cm^3$, and the percentage of highly weathered clasts does distinguish RAGs 3 and 4 deposits from the younger moraines and outwash sediments of RAG 5-6. The clay content and morphology of profiles in RAG 5-6 are not significantly different from those in soils on older deposits, but are quite different from those in the soils on the RAG 7-8 moraines and terraces which lack argillic horizons. Similarly, maximum profile colors are not much different on RAG 5-6 deposits than on older surfaces, but are more intense than those on RAG 7-8 deposits. Carbonate morphology is less useful in distinguishing RAG 7-8 deposits from older materials, although most profiles in RAG 7-8 contain less carbonate than those in older age groups.

Finally, although the profiles in RAG 9 are Entisols with little evidence of pedogenesis, we have too few data to be sure they can always be distinguished from deposits of RAG 7-8 on the basis of relative weathering data. The relative position of RAG 9 features is the main criteria for their recognition.

## A.3 Alluvial Surfaces in the Western Uinta Basin

### A.3.1 Terrace Correlation and Relative Ages

The relative weathering data discussed above indicated the major age breaks in the sequence of deposition of moraines and terraces in the Towanta Flat area. However, estimates of the numerical age of these deposits, and, hence, of the faulting events offsetting them, require both local and regional correlation. Correlation of the outwash terraces along the Lake Fork River downstream into the central Uinta Basin (figs. A.1 and A.2) provides a basis for better age assessment through, (1) relating the Towanta sequence to the older Quaternary alluvial surfaces in the basin which sets an upper limit on the age of Towanta Flat, and (2) the use of an age estimate derived from amino acid and paleomagnetic analysis of materials from an alluvial terrace in the central basin.

Osborn (1973) correlated the suite of outwash terraces along the Lake Fork River east of Towanta Flat with terrace surfaces farther downstream and with terraces along the Duchesne and Uinta Rivers. Our terrace profiles (figs. A.1 and A.2) are similar to Osborn's (1973, pls. 5, 7, and 9) relying primarily on relative elevation above the present river

or lower, more continuous terraces, and terrace gradient for correlation. However, Osborn connected all his terrace elevations with smooth lines which makes it difficult to determine where his profiles are based on field data and where they are inferred. To emphasize the problems of terrace correlation downstream, we have plotted only the elevation of surfaces along the Lake Fork and Duchesne Rivers shown on 1:24 000 USGS topographic quadrangles. Continuous lines indicate a relatively continous terrace surface on one or both sides of the river. We have also extended our profiles up the Duchesne River and into Rock Creek in order to assess the age of the Rock Creek terraces (fig. A.2).

Relative-age assignments for the older alluvial surfaces in the Uinta Basin are based primarily on relative elevation above the modern rivers. The morphologic stage of carbonate development in soils on the surfaces in the basin gives only a broad indication of relative age (fig. A.4) (Osborn, 1973, p. 35.) Most exposures in these surfaces are in the eroded edges of terraces. An additional problem is that the amount of carbonate in soils in the central basin is not directly comparable with the amount in soils at the edge of the mountains due to differences in precipitation history between the two areas. However, profiles with the maximum amount of carbonate for a given RAG show a linear trend which indicates the maximum amount of carbonate development for each RAG (fig. A.4). In addition, Osborn (1973, p. 36) noted that the degree of preservation of stream-cut scarps and braided channels on outwash terraces helped group them into relative-age categories.

High-level isolated remnants of former alluvial surfaces are placed in RAG 1. They include erosion surfaces (defined by Kinney, 1955, p. 127) cut on the Uinta and Duchesne River Formations with only a thin (< 1 m) (< 3.3 ft) quartzite gravel lag remaining (for example, Tower Ridge, site 46, pl. 1), as well as areas with a thicker (> 3 m) (> 10 ft) alluvial cover of coarse quartzite gravel. These surfaces are more than 400 m (1300 ft) lower than the highest erosion surfaces in the area on Tabby Mountain, Dry Mountain, and Bear Wallow (pl. 1) which may be correlative with some of the high-level erosion surfaces mapped by Bradley (1936) and Kinney (1955) of pre-Quaternary age (Marsell, 1964; Osborn, 1973, p. 183). On Bald Knoll, (pl. 1), and the Talmage surfaces directly south of Towanta Flat (site 47, fig. A.2, pl. 1), carbonate K horizons are more strongly developed than on the lower surfaces in the area with 85 and 54 percent carbonate by weight, respectively.

Surfaces well below the RAG 1 surfaces, but older (higher) than the main Towanta Flat surface (RAG 3), are mapped in RAG 2. In the central basin, strath terraces with only a few meters of alluvial gravels are most common, but nearer the mountains the older surfaces (such as John Starr Flat, pl. 1) are probably underlain by much thicker alluvium (exposures are rare).

At least some parts of Osborn's (1973, his pl. 1) Burnt Spring Mill and 77 Flat outwashes fall into RAG 2 and Osborn's (pls. 7, 8, and 9) and our (figs. A.1 and A.2) terrace correlations suggest many of the higher surfaces in the central basin are of approximately the same relative age.

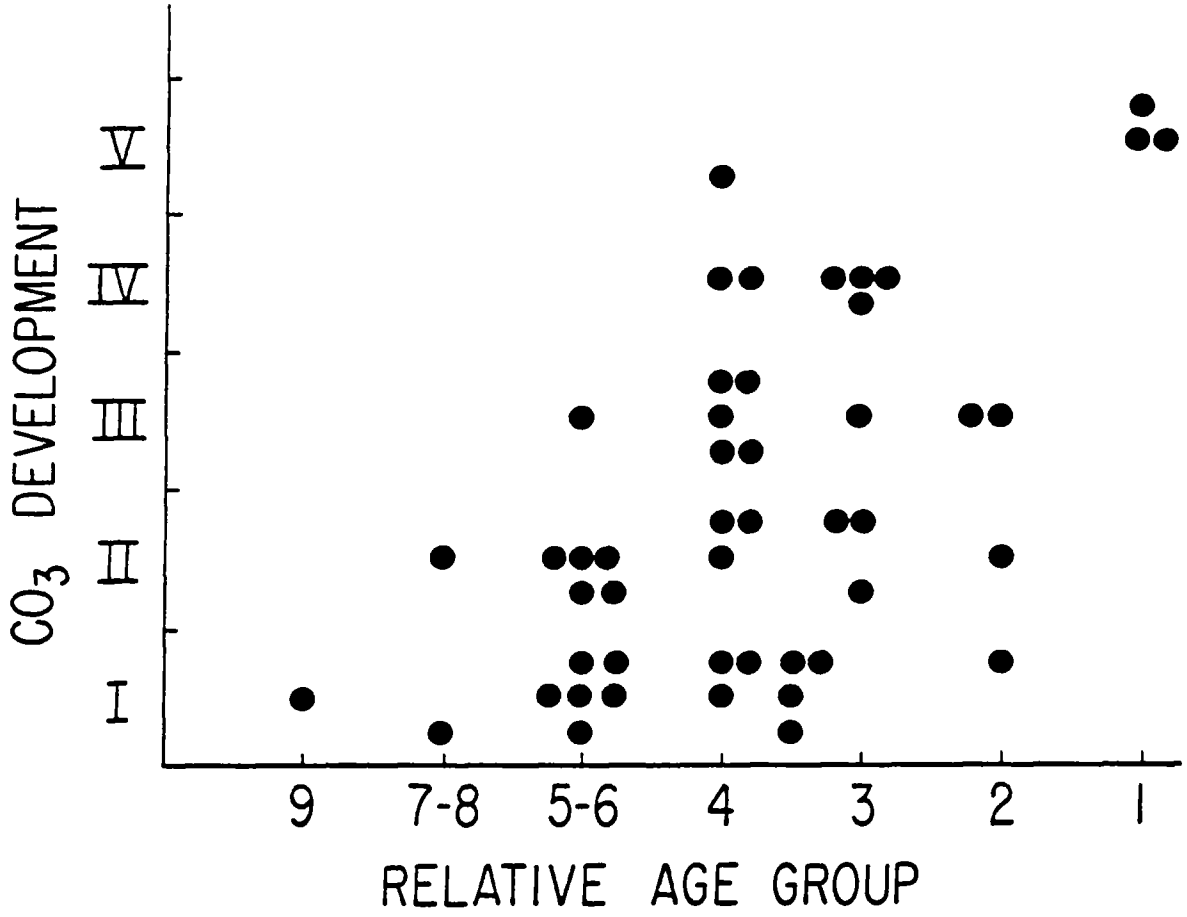



Figure A.4. Soil calcium carbonate development (morphologic stages of Gile and Grossman (1966) and Bachman and Machette (1977)) on alluvial surfaces and moraines of increasing relative age in the western Uinta Basin. Most soil exposures show less than the maximum carbonate development for surfaces of a particular relative-age group due to differences in elevation (vegetation and precipitation), original amounts of primary carbonate, and erosion of original surfaces.

Parts of the Jensen surface of Kinney (1955, p. 128) may correlate with RAG 2 surfaces, but Osborn (1973, p. 187) states Kinney's mapping of these and younger erosion surfaces does not agree with his more detailed mapping of the same area.

Exposures in RAG 2 deposits are rare and generally eroded, but a probable remnant of RAG 2 on the RAG 3 terrace north of Altamont (designated 2-3 on fig. A.1 shows stage IV soil carbonate development (K horizon with 52 percent carbonate). Because one of the lower terraces has a greater degree of carbonate development, this exposure does not represent the maximum carbonate development for this surface (fig. A.4). This remnant is isolated from the RAG 2 surface (Osborn, 1973, p. 71), but is 25 m (80 ft) higher than the RAG 3 surface on which it sits. If this remnant is the same age as the RAG 2 surface to the north, considerable uplift has taken place between the remnant and this surface. A lesser degree of warping is indicated by the lower RAG 3 surface in this area, as well as the RAG 3 surface on Towanta Flat (fig. A.1). An alternate interpretation is that the remnant is intermediate in age between RAG 2 and RAG 3, and that uplift and erosion have offset its former surface by an amount similar to that for the RAG 3 surface.

The outwash plains making up the RAG 3 surface are more extensive than those of RAG 2, but are still separated by a gap of 20 to 25 km (12 to 15 mi) from probable correlative erosion surfaces along the Duchesne River. Our correlations of these surfaces are based on their elevation and relative position above younger, more continuous terraces along the Lake Fork River.

The outwash terraces of RAG 4 are the key surfaces in our study of the Quaternary history of the area. They are more continuous along the Lake Fork and Duchesne Rivers than are upper or lower terraces, and so serve as the basis for our correlation of our site with numerical-age estimates (fig. A.1) and the Rock Creek terraces with the Towanta Flat surfaces. One site (No. 5, pl. 1) on the RAG 4 surface has a greater degree of carbonate development (stage V, 71 percent carbonate) than all but the oldest (RAG 1) surfaces in the area indicating this is the maximum development for surfaces of this age.

The terrace of RAG 4 extends from the moraines of RAG 4 on the Yellowstone River (Willow Springs moraines of Osborn, 1973, p. 68) (fig. A.1), continuously along the Lake Fork River to just north of Upalco. About 12 km (8 mi) downstream, it is again preserved as the 17 km (11 mi) long North Myton Bench north of the Lake Fork and Duchesne Rivers. When North Myton Bench and the correlative terraces upstream were deposited, the Lake Fork River flowed north of its present position joining the Uinta River before reaching the Duchesne River as it does now (Osborn, 1973, pp. 77, 189). For this reason, the gradient of North Myton Bench is steeper than the gradient of probable correlative terraces and erosion surfaces south of the Duchesne River. Because North Myton and South Myton Benches are 7 km (4.4 mi) apart, their gradients are different, and, because neither extend far enough downstream to be certain that their surfaces merge, we have taken the more conservative

approach (as did Osborn, 1973, p. 199) and correlated North Myton Bench with less continuous remnants of the terraces (RAGs 4 and/or 5) immediately below the two levels of South Myton Bench (fig. A.1). By relative position, this makes South Myton Bench, including our site with a numerical-age estimate (Antelope Canyon gravel pit, fig. A.2, appendix C) of RAG 3 age - the same age as the main Towanta Flat surface.

Outwash terraces of levels 5, 6, and 7 (fig. A.1) are fairly continuous from a few kilometers below the Lake Fork moraines to Altamont. Because we recognize no fault scarps in these deposits, we attribute minor irregularities in the profiles of these terraces to depositional and erosional processes. Terrace levels 5 and 6 are also quite continuous from Upalco to the confluence with the Duchesne River providing a guide in the correlation of the RAG 4 surface over the 12-km (8-mi) interval where it is not preserved. No doubt these terraces are the age equivalents of some of the discontinuous erosion surfaces, many partially covered with colluvial debris, along the Duchesne River (fig. A.2) but exact correlations are uncertain. The stage III carbonate development in a gravel pit exposure in a terrace 6 km (4 mi) west of Antelope Canyon (site 50, pl. 1, fig. A.2), only 26 m (85 ft) above the Duchesne River, indicates it is correlative with at least level 6 (RAG 5-6) along the Lake Fork River.

Outwash terrace remnants of levels 8 and 9 are much less continuous than upper terraces. They are easily distinguished only in the area between the Lake Fork and Yellowstone moraines. Downstream, they are not easily differentiated from modern flood plain deposits.

### A.3.2 Rock Creek Terraces

Using the age assignments given the erosion surfaces along the Duchesne River through correlation with the Lake Fork terraces, we can estimate the relative age of terraces along Rock Creek by tracing the Duchesne River surfaces upstream into Rock Creek (fig. A.2). Although the terraces are not continuous and there are many projection problems with surfaces at varying distances from the river, South Myton Bench appears correlative with the lower levels of the Blue Benches north of Duchesne (Osborn, 1973, his pl. 9). The relative age of lower surfaces is less certain, but, on the basis of position, they are probably in RAG 4 or RAG 5-6.

Profile projection problems and the sharp change in flood plain gradient at the confluence of Rock Creek with the Duchesne River prevent positive correlation of the Duchesne River surfaces with the Rock Creek terraces (fig. A.2). The most conservative approach is to match the higher Rock Creek terraces with the Blue Benches (RAG 3) and the lower terrace with Hair Bench (RAG 4). However, even the lower Rock Creek terrace is 80 m (262 ft) above the creek, and a projection of its surface upstream to the Rock Creek moraines rises well above the base of the lower moraines. On the basis of surface weathering data, the lower moraines are thought to be older than RAG 5-6. If these moraines are of RAG 4 age, and the lower Rock Creek terrace rises above them, then it may be of RAG 3 age.

The higher terrace could be in either RAG 3 or RAG 2. Thus, although there is considerable uncertainty in their relative age, both of the unfaulted Rock Creek terraces are at least as old as the melt-water channel on Towanta Flat (RAG 4).

## A.4 Regional Correlation and Numerical-Age Estimates for Quaternary Deposits in the Towanta Flat Area

The soils and surface weathering data discussed previously provide a basis for the regional correlation of the younger Towanta Flat deposits. Because these correlations suggest many of the younger Towanta Flat deposits are considerably older than previously thought, the age of the older moraines and terraces in this area is uncertain. Fortunately, amino acid and paleomagnetic data from one site along the Duchesne River (fig. A.1 and site 51, pl. 1) allow us to make numerical-age estimates for South Myton Bench which we correlate with the main Towanta Flat surface (RAG 3). These age estimates help us evaluate our regional correlations and age estimates for younger and older deposits.

### A.4.1 RAG 1

Surfaces and deposits of RAG 1 are probably of early Quaternary age. They are considerably lower 400 m (1300 ft) than the oldest erosion surfaces in the area such as Dry Mountain (pl. 1), which may correlate with some of the high level erosion surfaces of Bradley (1936) and Kinney (1955) of late Tertiary age. Except for the Talmage surfaces (fig. A.2, pl. 1), remnants of RAG 1 surfaces are considerably higher than younger surfaces and in some exposures have the most extensive carbonate development of any deposits mapped (stage V).

### A.4.2 RAG 2

Based on their relative elevation, deposits and surfaces of RAG 2 are younger than those of RAG 1, but older than RAG 3 surfaces. Soil development on RAG 2 deposits is similar to that on younger RAG 3 and RAG 4 deposits. No ash beds which might provide numerical-age estimates have been found in these deposits. No doubt these materials have a considerable age span, perhaps from early to late Quaternary. Their elevation, only 40 to 100 m (130 to 330 ft) above more continuous RAG 3 deposits of similar lithology, however, suggests most are probably not a great deal older than RAG 3 deposits.

### A.4.3 RAG 3

RAG 3 surfaces are lower and, therefore, younger than RAG 2 surfaces. Carbonate morphology and soil development in RAG 3 deposits do not exceed that of RAG 4 deposits, and, therefore, do not aid in age estimation. Laboratory analyses of RAG 3 deposits exposed in a gravel pit at the mouth of Antelope Canyon (fig. A.5 and site 51, pl. 1), provides numerical-age estimates for deposits of this RAG.

The stratigraphic section at the Antelope Canyon pit consists of coarse quartzite gravels overlain by massive, pink, sandy silts and silty sand

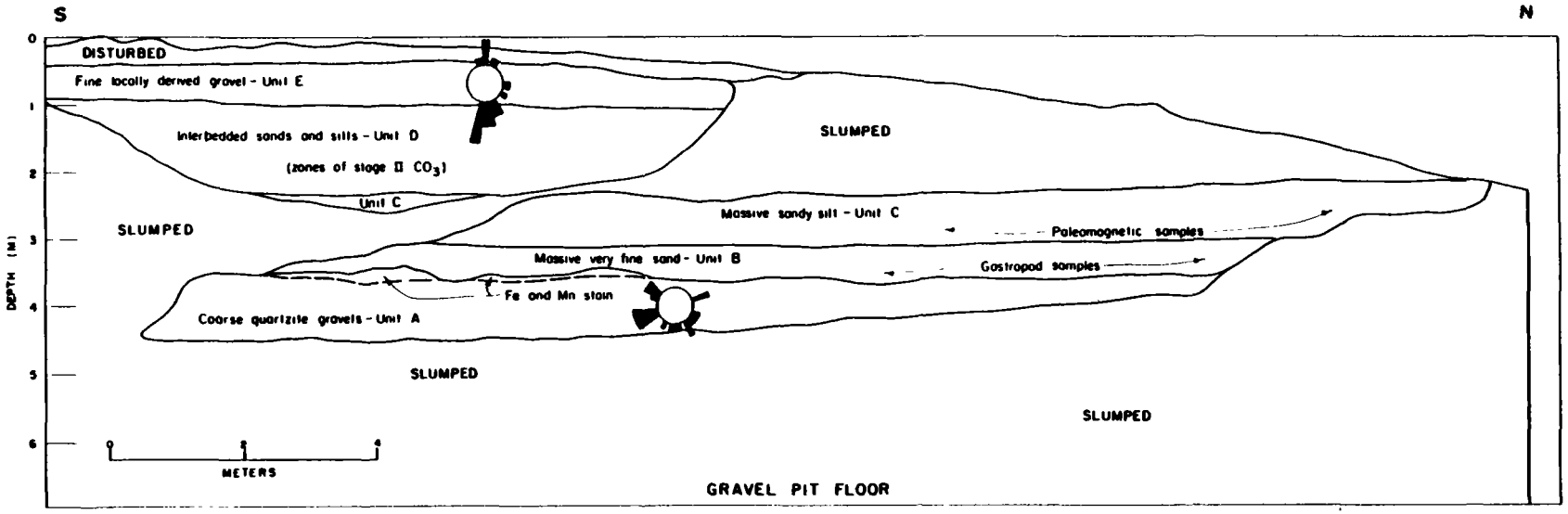



Figure A.5 - Sketch of the stratigraphy exposed in a gravel pit in RAG 3 terrace gravels at the mouth of Antelope Canyon (fig. A.2). The location of samples collected for paleomagnetic analysis of fine-grained sediment (table A.4) and amino acid analysis of gastropods (table A.5) is shown. The rose diagrams show the orientation of 50 elongate (long axis $\geq$ 2 x short axis) pebbles in units A and E. Flow directions suggested by the pebble orientations suggest unit A is a mainstream deposit and unit E was deposited by sidestreams.

overlain by gray stratified sand overlain by fine locally derived gravel (fig. A.5, appendix C). The quartzite gravels are imbricated east-west while clasts in the uppermost fine gravels have a roughly perpendicular orientation (fig. A.5). We interpret this sequence as outwash gravels derived from the Uinta Mountains deposited during a glaciation of RAG 3 age buried by later side slope colluvial-alluvial deposits. Eight species of land snails from the colluvium-alluvium (appendix C, identified by E. Evanoff, University of Colorado, Boulder) indicate a terrestrial environment suggesting our interpretation is correct. One species may suggest the climate was cold during deposition of this unit (Evanoff, written communication, 1980). Following deposition of the side slope material, fluvial sediments of moderate energy covered the site followed by higher energy deposition of sidestream gravels locally derived from the Uinta Formation. Very similar stratigraphic sections from the White River Valley in western Colorado have been given a similar interpretation (Evanoff, oral communication, 1981).

One hundred and fifty meters (500 ft) south of the main gravel pit exposure, quartzite gravels occur up to an elevation of 8 m (26 ft) above their upper contact in the main exposure. Because there are no offsets of this magnitude in the bedrock units (Uinta Formation) underneath the quartzite gravels, this difference in elevation is not due to faulting. The lower gravel was apparently deposited in a channel which is now the terrace cut into South Myton Bench which can be traced along much of the north edge of the bench (fig. A.2).

A.4.3.1 Paleomagnetic Analyses

Measurement of the remanent magnetization in sediments is widely used for the correlation and dating of continuous sequences of Cenozoic sediments or sedimentary units whose approximate age can be estimated independently (Watkins, 1972). Based on our terrace correlations (sec. A.3.1), South Myton Bench and the Antelope Canyon pit sediments are of late to mid-Quaternary age. Although much younger geomagnetic field reversals and excursions have been reported within the Brunhes normal polarity chron, none have been confirmed as worldwide geomagnetic events (Verosub and Banerjee, 1977). Thus, consistently reversed paleopole directions in the Antelope Canyon pit sediments would indicate an age greater than 0.73 Ma (million years) (Matuyama reversed chron), while normal polarity would most likely indicate an age of less than 0.73 Ma (Mankinen and Dalrymple, 1979).

Ten separately oriented blocks (4 by 6 by 10 cm) of sandy, silty colluvium-alluvium were cut from two stratigraphic horizons within unit C at the Antelope Canyon gravel pit (fig. A.5). Cubes, 2 cm on a side, were cut from these blocks; rare zones of iron-staining and carbonate accumulation within the blocks were avoided. The direction and intensity of remanent magnetization in 14 cubes were measured with a Schonstedt spinner magnetometer operating in a six-spin mode. One cube from each of the 10 blocks was demagnetized in a Schonstedt alternating field demagnetizer in eight steps to 600 oe, and duplicate cubes from four blocks were thermally demagnetized at 200 °C and 400 °C (table A.4).

Table AA - M (mean intensity), D (declination), and I (inclination) for paleomagnetic samples from Antelope Canyon Pit measured for NRM (natural remnant magnetization) and for samples demagnetized in an alternating field at 50, 150, 200, 300, 400, 500, and 600 oersteds and at temperatures of 200 and 400 °C 1/

| Sample No. | NRM | | | 50 Oe | | | 100 Oe | | | 150 Oe | | | 200 Oe | | | 300 Oe | | | 400 Oe | | | 500 Oe | | | 600 Oe | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | D (degrees) | I | M ($10^{-6}$ emu/cm$^3$) | D (degrees) | I | M ($10^{-6}$ emu/cm$^3$) | D (degrees) | I | M ($10^{-6}$ emu/cm$^3$) | D (degrees) | I | M ($10^{-6}$ emu/cm$^3$) | D (degrees) | I | M ($10^{-6}$ emu/cm$^3$) | D (degrees) | I | M ($10^{-6}$ emu/cm$^3$) | D (degrees) | I | M ($10^{-6}$ emu/cm$^3$) | D (degrees) | I | M ($10^{-6}$ emu/cm$^3$) | D (degrees) | I | M ($10^{-6}$ emu/cm$^3$) |
| 105A | 345 | 72 | 6.7 | | | | | | | | | | 343 | 75 | 2.7 | 357 | 83 | 1.7 | 316 | 82 | 1.5 | 44 | 88 | 0.8 | 319 | 55 | 0.8 |
| 106A | 126 | -58 | 4.2 | 117 | -67 | 3.4 | 83 | -56 | 1.3 | 103 | -67 | 2.0 | 97 | -69 | 1.6 | 113 | -69 | 1.3 | 78 | -64 | 0.8 | 92 | -78 | 0.8 | 307 | -62 | 0.5 |
| 107 | 353 | 52 | 6.3 | 356 | 49 | 4.6 | 354 | 47 | 3.7 | 357 | 45 | 2.9 | 359 | 45 | 2.3 | 355 | 31 | 1.8 | 344 | 28 | 1.6 | 353 | 28 | 1.1 | 330 | 25 | 1.3 |
| 108 | 335 | 62 | 9.6 | 352 | 61 | 7.2 | 359 | 60 | 5.3 | 1 | 59 | 4.3 | 348 | 63 | 3.2 | 4 | 60 | 1.9 | 353 | 52 | 1.5 | 332 | 63 | 1.1 | 351 | 72 | 9.0 |
| 109A | 292 | 67 | 8.6 | 295 | 70 | 6.6 | 295 | 68 | 5.3 | 289 | 65 | 4.2 | 295 | 64 | 3.7 | 295 | 63 | 2.6 | 311 | 52 | 1.7 | 302 | 53 | 1.3 | 333 | 59 | 1.3 |
| 110A | 12 | 65 | 7.4 | 13 | 63 | 5.9 | 0 | 62 | 4.6 | 356 | 60 | 3.7 | 348 | 60 | 3.1 | 357 | 60 | 2.3 | 356 | 56 | 1.5 | 310 | 58 | 1.0 | 323 | 66 | 8.6 |
| 111 | 358 | 58 | 10.0 | 6 | 57 | 7.8 | 1 | 57 | 5.7 | 0 | 57 | 4.7 | 358 | 54 | 4.0 | 351 | 55 | 2.3 | 339 | 55 | 1.8 | 322 | 61 | 1.1 | 317 | 54 | 1.1 |
| 153 | 40 | 54 | 6.1 | 296 | 66 | 4.4 | 43 | 53 | 3.9 | 46 | 52 | 3.1 | 53 | 53 | 2.6 | 36 | 57 | 1.8 | 60 | 51 | 1.4 | 82 | 68 | 0.9 | 86 | 53 | 1.1 |
| 154 | 0 | 65 | 7.8 | 356 | 56 | 4.3 | 1 | 57 | 3.3 | 353 | 60 | 2.7 | 351 | 63 | 1.9 | 344 | 72 | 1.4 | 332 | 77 | 0.7 | 25 | 67 | 0.6 | 342 | 53 | 0.6 |
| 155 | 256 | 62 | 5.1 | 265 | 60 | 3.9 | 262 | 60 | 2.9 | 254 | 62 | 2.4 | 235 | 55 | 2.1 | 240 | 51 | 1.5 | 258 | 50 | 0.7 | 41 | 40 | 1.2 | 234 | 46 | 0.9 |
| | | | | 200 °C | | | 400 °C | | | | | | | | | | | | | | | | | | | | |
| 105B | 5 | 71 | 3.6 | 344 | 59 | 1.6 | 357 | 59 | 0.8 | | | | | | | | | | | | | | | | | | |
| 106B | 115 | -41 | 3.3 | 81 | -50 | 1.7 | 96 | -48 | 0.6 | | | | | | | | | | | | | | | | | | |
| 109B | 317 | 81 | 4.8 | 306 | 55 | 2.1 | 328 | 59 | 0.8 | | | | | | | | | | | | | | | | | | |
| 110B | 34 | 56 | 5.3 | 359 | 49 | 2.6 | 4 | 46 | 1.6 | | | | | | | | | | | | | | | | | | |

1/ Laboratory facilities provided by R. Reynolds, USGS - Denver.

The remanent magnetization in most of these samples is strong (mean NRM intensity = 6.3 x $10^{-6}$ emu/$cm^3$) and fairly stable (mean declination and inclination change to 200 oe = 13° and 4°) until the higher demagnetization steps are reached. All but one of the samples clearly retain a normal remanent magnetization. Sample 106 is reversed but behaves similarly to the other samples during both AF and thermal demagnetization. On the basis of the consistency of the paleopole directions in the other samples (table A.4), we attribute this single reversed sample to an orientation error during sample preparation. Thus, we consider these sediments to have been deposited in the Brunhes field making them less than 0.73 Ma old.

A.4.3.2 Amino Acid Age Estimates

Amino acid ratios derived from the analysis of the organic matrix within carbonate fossils have proven very useful in the relative dating and correlation of a variety of Quaternary stratigraphic units worldwide (Schroeder and Bada, 1975; Wehmiller, 1982). Many earlier studies attempted to calculate numerical age dates using amino acid racemization data, but because of the large uncertainties in racemization kinetics and the difficulty in estimating the exact temperature history of fossils, the reliability of many of these dates is questionable (Williams and Smith, 1977; Miller and Hare, 1980). However, if independently dated calibration samples are available from the same region as samples of unknown age, the approximate age of the unknown samples can be estimated by using amino acid ratios to interpolate from the calibration samples (for example, Bada and Protsch, 1973).

Unit B at the Antelope Canyon gravel pit (appendix C) contains land gastropods dispersed throughout the unit. Only recently have attempts been made to use amino acid ratios measured on terrestrial gastropods in relative dating of Quaternary deposits (for example, Miller and others, 1979; 1982). We are fortunate in our study in having access to unpublished amino acid analyses of cf. Catinella (table A.5) from immediately below the Lava Creek ash near Baggs, Wyoming, (sample collected by R. F. Madole, USGS, Denver, Colorado) only 250 km (150 mi) east of Antelope Canyon at a 240-m (790-ft) higher elevation. D-alloisoleucine/L-isoleucine ratios in the total hydrolyzate amino acid fraction (the primary ratio used in relative dating) in gastropods from Baggs are similar to those in Catinella and Zonitoides from Antelope Canyon (table A.5). Present-day temperatures near Antelope Canyon (Myton, fig. A.2) are somewhat warmer (7.7 °C mean annual temperature) than those near Baggs (5.4 °C), but, if the following assumptions are correct, we can estimate the age of the snails from the Antelope Canyon pit, and, hence, the age of South Myton Bench and correlative surfaces on Towanta Flat.

1. The general form of isoleucine racemization (epimerization) in Catinella and Zonitoides is similar to that in other studied gastropods (Miller and others, 1982) and can be approximated by the equations in Williams and Smith (1977). Because our ratios from the Antelope Canyon pit are similar to those from the calibrated sample

Table A.5. - D-alloisoleucine/L-isoleucine ratios in free and total (free + peptide-bound) amino acid fractions and calculated ages for fossil gastropods from Antelope Canyon Pit, Uinta River Valley, and Baggs, Wyoming

| INSTAAR Lab No. | Species | Sample weight (mg) | Allo/iso ratio [1] | | Value used | Assumed Arrhenius parameters | | Mean annual temperature (°C)[2] | Estimated mean diagenetic temperature (°C)[3] | Calculated age (yr BP x $10^3$)[4] | Average range using ± 1 °C (yr BP x $10^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Free | Total | | A | B | | | | |
| **Calibration Sample** | | | | | | | | | | | |
| Baggs, Wyoming (sec. 6, T. 12 N., R. 91 W.) - immediately below Pearlette-O ash [8] | | | | | | | | | | | |
| AAL-341A | cf. Catinella | 5.1 | | 0.48 | 0.48 | 17.04 | 6210 [5] | 5.4 | -4.9 | | Fission track |
| AAL-341B | cf. Catinella | 47.7 | | 0.47 | 0.48 | 17.15 | 6287 [6] | 5.4 | -2.8 | | date of |
| AAL-341C | cf. Catinella | 2.2 | | 0.26 | 0.48 | 17.29 | 6417 [7] | 5.4 | 1.1 | | 600 |
| **Duchesne County, Utah Samples** | | | | | | | | | | | |
| Antelope Canyon Gravel Pit, Duchesne County, Utah (SE1/4, sec. 9, T. 4 S., R. 3 W.) | | | | | | | | | | | |
| DAN-79A | Zonitoides arboreus | 4.0 | 0.38 | 0.45 | 0.45 | 17.04 | 6210 [5] | 7.7 | -2.6 | 356 | 434-294 |
| DAN-79B | Zonitoides arboreus | 6.0 | 0.39 | 0.46 | 0.45 | 17.15 | 6287 [6] | 7.7 | -0.5 | 355 | 431-292 |
| DAN-79C | Zonitoides arboreus | 8.0 | 0.40 | 0.44 | 0.45 | 17.29 | 6417 [7] | 7.7 | 3.4 | 359 | 435-296 |
| DAN-82A | cf. Catinella | 2.8 | 0.42 | 0.46 | 0.49 | 17.04 | 6210 [5] | 7.7 | -2.6 | 391 | 476-323 |
| DAN-82B | cf. Catinella | 3.7 | 0.66 | 0.52 | 0.49 | 17.29 | 6417 [7] | 7.7 | 3.4 | 394 | 478-325 |
| Uinta River Valley, Duchesne County, Utah (NE1/4, SW1/4, sec. 10, T. 2 N., R. 2 W.) | | | | | | | | | | | |
| DAN-78A | Zonitoides arboreus | 15.6 | <0.03 | ND [9] | | Indistinguishable from modern samples | | | | | |
| DAN-78B | Zonitoides arboreus | 30.0 | <0.02 | 0.02 | | Indistinguishable from modern samples | | | | | 10 maximum |
| DAN-78C | Zonitoides arboreus | 9.0 | <0.06 | ND | | almost indistinguishable from modern samples | | | | | |

1/ Allo/iso ratio measured using methods of Miller and Hare (1980).
2/ Mean annual air temperature at nearest station from Ruffner (1978).
3/ Mean effective diagenetic temperature (Wehmiller and others, 1977) estimated from the difference between the mean annual air temperature and the effective diagenetic temperature calculated using fission track date on Pearlette-O ash (Naeser and others, 1973) for calibration sample assuming listed Arrhenius parameters.
4/ Age calculated using equation 18 in Williams and Smith (1976) with K' = 0.77.
5/ Values of constants in Arrhenius equation (No. 9 in Williams and Smith, 1976) determined for Lymnea by W. D. McCoy (unpublished data) using 14C dated samples and heating experiments.
6/ Values of constants in Arrhenius equation determined for Mya truncata by Miller (1980).
7/ Values of constants in Arrhenius equation determined for Mercenaria by Mitterer (1977).
8/ Sample collected by R. F. Madole, USGS - Denver.
9/ None detectable.

of the same species at Baggs, even if the rate or raceminization in Catinella is markedly different from that in other species, our age estimates will be little affected.

2. The difference in the effective diagenetic temperatures of the fossil snails from the Antelope Canyon pit and Baggs is the same as the difference between the present mean annual air temperatures at these sites. Samples at both sites were collected below a 2-m (7-ft) depth, and, therefore, should be little affected by diurnal and seasonal temperature changes (Miller and Hare, 1980; Miller and others, 1982). Because of the uncertainty in this assumption, we have calculated age estimates from each sample using a $\pm$1°C range of temperatures (table A.5).

3. The effective diagenetic temperature at each site for the last 375 k yr (thousand years) is closely approximated by the effective diagenetic temperature for the last 600 ka years (Miller and Hare, 1980). Reliable temperature estimates for the continental interior during these periods are not available, but, if the direction, duration, and relative magnitude of temperature change in this region were similar to those indicated by oxygen isotope data from the marine record for the same periods, then this assumption is reasonable.

Combining our age estimates from table A.5, we estimate the age of the snails from the Antelope Canyon pit at 375 $\pm$ 120 ka. Although we are indicating a great deal of uncertainty as to the age of this site, we note that the assumptions used in our age calculations are more conservative than those used in many earlier amino acid geochronologic studies (for example, Wehmiller and Belknap, 1978). The snails at Antelope Canyon pit overlie the quartzite gravels correlative with outwash terraces upstream (RAG 3). Thus, our age estimate for the snails provides only a minimum age estimate for South Myton Bench and the correlative Towanta Flat surface.

### A.4.4 RAG 4

Soils developed on moraines and terraces of RAG 4 have strong Bt horizon colors, high clay contents, and extensive argillan development, and significantly more carbonate than soils on younger landforms (table A.3). In addition, outwash of both RAG 3 and RAG 4 grades into broad, eroded moraines with gentle slopes and few undrained depressions. Deposits with similar characteristics in many parts of the Rocky Mountain region have been mapped as of "pre-Bull Lake" age (Richmond, 1965; Madole, 1976) (Quaternary stratigraphic usage in this report follows the guidelines of Ostenaa and others, 1985, appendix C.) By relative position, RAG 4 deposits are younger than those of RAG 3, but soil development does not suggest a great age difference between these two RAGs. Both groups may correspond in age with "pre-Bull Lake" deposits elsewhere in the region (Osborn, 1973, p. 134).

The differences in the rate of carbonate accumulation and history of Quaternary climate change between the Uinta Basin and central New Mexico

are unknown. However, using the average rate of carbonate accumulation calculated by Machette (1978) for a sequence of paleosols near Albuquerque, New Mexico, our carbonate data (table A.3) for outwash soils of RAG 4 indicate ages of 286 ka to 485 ka. These age estimates are in the same range as our amino acid age estimates. Unless long-term average soil carbonate accumulation rates are much higher in the Uinta Basin than in central New Mexico, the carbonate-rich soils suggest a "pre-Bull Lake" age for RAG 4 deposits.

The marine oxygen-isotope record (Shackelton and Opdyke, 1973) indicates several periods of extensive worldwide glaciation younger than 600 ka but older than dated "Bull Lake" deposits (discussed below). Uranium series dates on speleothems suggest two cold intervals during the younger part of this period in the northern Rocky Mountains (Harmon and others, 1977). Deposits in RAG 4 may well date from one of these cold periods, but without better local dating control, more specific age assignments cannot be made. Thus, RAG 4 deposits are probably $\leq$ 500 ka, but older than dated "Bull Lake" deposits.

A.4.5 RAG 5-6

The degree of carbonate accumulation in soils on RAG 5-6 moraines and terraces separates them from soils on RAG 4 deposits (sec. A.2.3). A significant difference in the amount of downcutting by the Lake Fork River also suggests a major time interval between these two RAGs (Osborn, 1973, p. 135).

Bt horizon development in RAG 5-6 soils clearly indicates they are significantly older than the soils developed on the moraines and terraces of RAG 7-8. Surface weathering data also support a major break between the RAG 5-6 and RAG 7-8 moraines. Because the characteristics of the break in soil development and surface weathering data between, and the relative position of the RAG 5-6 and 7-8 moraines and corresponding outwash terraces is similar to the break between "Bull Lake" and "Pinedale" moraines mapped in other parts of the Rocky Mountains, we correlate our RAG 5-6 deposits with "Bull Lake" deposits elsewhere in the region. Hansen (1969a; 1969b) also mapped the moraines on the north edge of Towanta Flat (RAG 5-6) as of Bull Lake age.

The best numerical-age dates on "Bull Lake" moraines in the Rocky Mountain region come from Yellowstone National Park. The relative morphology and degree of soil development on moraines mapped as Bull Lake near West Yellowstone support a correlation to Bull Lake moraines at the type area in the Wind River Mountains (Pierce and others, 1976) and to some, but not necessarily all, Bull Lake moraines in other areas, (Pierce, 1979; Colman and Pierce, 1981, p. 36).

At West Yellowstone, a rhyolite flow that was emplaced in the interval between the deposition of the Bull Lake and Pinedale terminal moraines is K-Ar dated at 114.5 $\pm$7.3 ka, the weighted average for five K-Ar ages on sanidine and glass (Pierce and others, 1976; Madole and Shroba, 1979). Using a calibration curve for obsidian hydration dating based on

the above K-Ar dates and an additional date of 179 ±3 ka from an older flow, hydration rinds on obsidian clasts from the Bull Lake moraines indicate an average age of 140 ka with a range of about 130 to 155 ka.

The Louviers Alluvium in the Front Range piedmont of Colorado (Scott, 1963) has generally been correlated with the ""Bull Lake" glaciation on the basis of relative soil development. A recent uranium series trend analysis on soil carbonate from a Louviers alluvial terrace gave an age of 140 ±23 ka (Rosholt, 1980). Other uranium series dates on bone in the Louviers Alluvium gave an average age of 102 ka, but this may well be a minimum age (Szabo, 1980).

The extensive study of weathering rinds on glacially derived clasts by Colman and Pierce (1981) indicates that although a 140 ka glacial event is widely represented, other major glacial advances occurred in some areas about 35 to 50 ka and 60 to 70 ka. Thus, "Bull Lake" deposits in some areas may postdate the last interglacial (marine oxygen isotope substage 5e, about 125 ka) rather than predate it.

Closer to our study area at Little Cottonwood Canyon in the central Wasatch Mountains, the organic fraction of a soil developed on an older till with strong Bt horizon development has been $^{14}C$ dated at 26,080 + 1,200/ -1,100 years B.P. (GX-4737) (Madsen and Currey, 1979). This date is clearly a minimum age for the till which has been suggested to correlate with oxygen-isotope stage 6, from the marine record (Shackelton and Opdyke, 1973), spanning the period 130 to 190 ka. Scott and others (1982) suggested that Lake Bonneville sediments just west of the Wasatch Mountains deposited during the next-to-the-last major lake cycle also date from isotope stage 6. Amino acid ratios from freshwater snails in these lake sediments indicate they are > 50 ka, but, if they date from stage 6, the climate during the last 150 ka in this area has been considerably colder for a longer period than previously thought (McCoy, 1981). Because major climate changes are thought to be approximately globally synchronous, it seems reasonable to correlate our RAG 5-6 deposits, the products of the next-to-the-last major glaciation for which there is evidence in the area, with the older till in Cottonwood Canyon, with Scott and others (1982) deposits of the next-to-the-last cycle of Lake Bonneville, and with "Bull Lake" deposits in Yellowstone National Park. RAG 5-6 deposits could correlate with the 60- to 70-ka event identified by Colman and Pierce (1981). However, the contrast in RD data between RAG 5-6 and RAG 7-8 suggests to us that a correlation with isotope stage 6 is more likely. Based on these correlations, RAG 5-6 deposits date from approximately 130 to 150 ka.

A.4.6 RAG 7-8

The morphology of the narrow-crested, steep-sided moraines in the Lake Fork drainage, their position immediately proximal to moraines correlated with "Bull Lake" glacial deposits, and their surface weathering and soil development characteristics strongly support a correlation with "Pinedale" moraines elsewhere in the Rockies (Osborn, 1973, p. 135).

A number of $^{14}C$ dates provides numerical age control for "Pinedale " deposits in the Rocky Mountain region (Porter and others, 1983), although none are available from the Uinta Mountains. Several $^{14}C$ analyses from Yellowstone Park on wood in lake silts overlain by Pinedale deposits and underlain by Bull Lake till indicate an infinite $^{14}C$ age for this unit (> 45 ka) (Pierce and others, 1976). Nelson and others (1979) also obtained $^{14}C$ dates which they interpreted as minimum ages ($\geq$ 30 ka) on organic silt from beneath "Pinedale" till in the Fraser River Valley on the west slope of the Front Range. On the east side of the Front Range, the oldest of the 12 radiocarbon dates for sediments from glacial Lake Devlin suggests the last major Pinedale advance, which was at least as extensive as earlier advances, was approaching its maximum about 22,400 $\pm$ 2,300 years B.P., (DC-870) (Madole, 1980). Obsidian hydration rinds on clasts in early Pinedale terminal moraines and outwash in Yellowstone indicate an age of about 30 ka for the maximum "Pinedale" advance. Radiocarbon dates from the above areas overlying deposits of the maximum "Pinedale" advance are in the range of 14 to 12 ka (for example, Madole, 1976; Nelson and others, 1979) indicating ice recession had begun in many areas by at least 14 ka. Of interest here are dates of 14,900 $\pm$ 250 years B.P. (W-4209) and 14,130 $\pm$ 150 years B.P.(W-4289) on plant fragments from lakebeds in a cirque showing that the San Juan Mountains of southwestern Colorado were extensively deglaciated prior to 14 ka (Carrara and Mode, 1979).

At Little Cottonwood Canyon, the $^{14}C$ date on the soil on the older till provides a maximum age for the younger overlying till and correlative moraines immediately upvalley (Madsen and Curry, 1979). The younger till marks the farthest extent of the last major glaciation in the area, and is, thus, correlative with our RAG 7-8 moraines and adjacent outwash terraces. Overlying the surface till in Little Cottonwood Canyon is a wedge of lacustrine sediment correlated with the lower member of the Bonneville Formation deposited during the last major lake cycle. Radiocarbon dates on wood indicate that Lake Bonneville was approaching its last major high stand by 21 to 20 ka (Scott and others, 1982). Based on interpretation of a bog date in the upper reaches of Little Cottonwood Canyon, deglaciation of the canyon began 14 to 13 ka (Madsen and Curry, 1979).

Osborn (1973, p. 117) suggested that small wedge-shaped bodies of marl on the proximal side of the moraines of Crystal Creek (RAG 7-8) age along the Uinta River date from the deglaciation of these moraines. However, our amino acid analyses of snails from these marls indicate they are < 10,000 years old, probably of mid-Holocene age (table A.5). The marls probably formed in depressions created by landsliding in this area long after deglaciation.

Thus, assuming RAG 7-8 deposits are chronocorrelative with "Pinedale" deposits in the Rockies and the younger till in Little Cottonwood Canyon, this period of glacier advances began prior to 30 to 40 ka, reached its maximum extent 20 to 30 ka, and had receded from its outermost terminal moraines by at least 13 to 14 ka.

A.4.7 RAG 9

Radiocarbon dates in the Front and Park Ranges indicate the latest "Pinedale" advances are older than 10 ka and possibly 11 ka (Madole and Shroba, 1979; Madole, 1980). Younger dates in the range of 7 to 8 ka from several areas give only minimum ages for ice recession. The record from Little Cottonwood Canyon is similar - deglaciation of much of the upper reaches of the canyon probably took place before 10 ka and deglaciation was complete by at least 7 to 8 ka (Madsen and Curry, 1979). Most latest "Pinedale" deposits are older than 11.5 ka (Porter and others, 1983).

The Jackson Park moraines of Osborn (1973) occur in a relative position in the Yellowstone and Uinta River Valleys similar to that for "late Pinedale" moraines in other parts of the Rockies. Based on its position below RAG 7-8 terraces, but above the modern flood plain and on its minimal soil development, our RAG 9 terrace is probably correlative with the Jackson Park moraines, and thus, probably dates from this period (11 to 14 ka).

Modern flood plain and correlative deposits (RAG 10, pl. 3) are, thus, interpreted as of Holocene ($\leq$ 10 ka) age. Most probably date from the last few thousand years.

# APPENDIX B

# SOIL PROFILE DESCRIPTIONS

SOIL PROFILE DESCRIPTION 1

Classification: Typic Eutroboralf

Location: Towanta Flat Trench No. 1, Station 0+27; Mountain Home Quad.; NW1/4, NW1/4, sec. 10, T. 1. S., R. 5 W.

Physiographic position: Upthrown surface of faulted glaciofluvial gravels 18 m (58 ft) back from edge of 5.2-m (17-ft) scarp; (7300-ft) 2226 m elevation.

Topography: Smooth surface sloping 2° SE.

Drainage: Well drained.

Vegetation: Sagebrush and short grasses; scattered juniper.

Parent material: Thin colluvium over glaciofluvial gravels.

Age: Pre-Bull Lake?

Sampled by: A. R. Nelson, December 4, 1979.

Remarks: Clast volume percentages visually estimated.

A1 0-6 cm. Dull reddish brown (5YR 4/4) dry, dark reddish brown (5YR 3/4) moist; sandy loam; very weak medium to coarse subangular blocky; soft (dry), slightly sticky and nonplastic (wet); no effervescence; 2% highly weathered clasts; clear wavy boundary.

B1 6-16 cm. Dull reddish brown (5YR 5/5) dry, (5YR 4/5) moist; very gravelly loam; weak coarse angular blocky; soft (dry), slightly sticky and slightly plastic (wet); many colloidal stains on mineral grains; no effervescence; 20% pebbles and 30% cobbles by volume; 2% highly weathered clasts; clear wavy boundary.

IIB21t 16-38 cm. Bright reddish brown (5YR 5/8) dry, reddish brown (5YR 4/8) moist; very gravelly sandy clay loam; moderate to strong coarse angular blocky; hard (dry), sticky and plastic (wet); many thin argillan bridges, few moderately thick argillans on clasts; no effervescence; 20% pebbles and 40% cobbles by volume; 5% highly weathered clasts; abrupt wavy boundary.

IIB22 38-48 cm. Dull orange (7.5YR 6/4) dry, bright brown (7.5YR 5/6) moist; very gravelly sandy clay loam; very weak medium angular blocky; soft (dry), slightly sticky and slight plastic (wet); common thin argillan bridges; matrix violently effervescent, evenly distributed carbonate about 10% by volume

(estimated), carbonate stage I to II; 20% pebbles and 40% cobbles by volume; 5% highly weathered clasts; clear broken boundary.

IIK1b 48-105 cm. White (7.5YR 8/0) to light gray (7.5YR 8/2) with small areas of matrix bright brown (2.5YR 5/6) dry, dull orange (7.5YR 7/4 to 7.5YR 8/3) moist; very gravelly loam; moderate coarse platy breaking to strong medium angular blocky; hard to very hard (dry), slightly sticky and nonplastic (wet); entire matrix violently effervescent; dense carbonate rinds on clasts average 1.54 $\pm$ 0.81 mm thick, carbonate about 50% by volume (estimated), carbonate stage III; 20% pebbles, 30% cobbles, and 5% boulders by volume; 40 to 50% highly weathered clasts; clear wavy boundary.

IIIC1cab 105-190 cm. Reddish brown (2.5YR 4/7) to white (8/0) dry, bright reddish brown (5YR 5/8) to light gray (5YR 8/2) moist; very gravelly loam; massive to moderate medium angular blocky; soft to hard (dry), sticky and slightly plastic (wet); common thin argillan bridges in interclast areas; matrix slightly effervescent, violently effervescent near clasts; 20% carbonate by volume (estimated) mostly coating clasts, carbonate stage II; 10% pebbles, 40% cobbles, and 30% boulders by volume; 2% highly weathered clasts; diffuse irregular boundary.

IIIC2cab 190-298 cm. Bright reddish brown (5YR 5/8) to white (8/0) dry, reddish brown (5YR 4/8) to light gray (5YR 8/2) moist; very gravelly loam; massive to moderate medium angular blocky; soft to hard (dry), sticky and slightly plastic (wet); common thin argillan bridges in interclast areas; matrix slightly effervescent, near clasts; 15% carbonate by volume (estimated) mostly coating clasts and gradually decreasing with depth, carbonate stage I to II; 10% pebbles, 40% cobbles, and 30% boulders by volume; 2% highly weathered clasts.

## SOIL PROFILE DESCRIPTION 2

Classification: Typic Eutroboralf

Location: Towanta Flat Trench No. 1, Station 1+58; Mountain Home Quad.; NW1/4, NW1/4, sec. 10, T. 1 S., R. 5 W.

Physiographic position: Downthrown surface of faulted glaciofluvial gravels with overlying colluvial apron 21 m (70 ft) back from edge of 5.2-m (17-ft) scarp; 2221-m (7284-ft) elevation

Topography: Smooth surface sloping 4° SE.

Drainage: Well drained.

Vegetation: Sagebrush and short grasses.

Parent material: Thick colluvium over glaciofluvial gravels.

Age: Pre-Bull Lake? overlain by Bull Lake to Holocene colluvium.

Sampled by: A. R. Nelson, December 4, 1979.

Remarks: Clast volume percentages visually estimated.

AB 0-18 cm. Orange (7.5YR 6/6) to bright reddish brown (5YR 5/6) dry, reddish brown (5YR 4/6) to dull reddish brown (5YR 4/4) moist; sandy loam to loam; weak medium to coarse angular blocky to very weak medium platy; soft to slightly hard (dry), sticky to slightly sticky and slightly plastic to nonplastic (wet); common thin argillan bridges; slightly stratified with irregular mixture of sandy loam and loam material due to ground disturbance; no effervescence; 2% pebbles by volume; abrupt wavy boundary.

B21t 18-52 cm. Bright reddish brown (5YR 5/6) dry, (5YR 4/6) moist; sandy clay loam; strong medium prismatic; hard (dry), sticky and plastic (wet); continuous moderately thick argillan bridges, many thin argillans lining pores, few thin argillans on ped faces; no effervescence; 2% pebbles by volume; gradual irregular boundary.

B22t 52-128 cm. Orange (7.5YR 6/6) to bright reddish brown (5YR 5/6) dry, light yellow orange (7.5YR 8/4) vertical carbonate joint fillings, bright brown (7.5YR 5/6) to reddish brown (5YR 4/6) moist; loam; strong coarse prismatic; hard to very hard (dry), slightly sticky and slightly plastic (wet); continuous moderately thick argillan bridges, continuous moderately thick argillans lining pores, very few thin argillans on ped faces; matrix slightly effervescent, carbonate joint-fillings strongly to violently effervescent; 1% carbonate by volume

(estimated), carbonate stage I; 2% pebbles by volume; clear wavy boundary.

IIB23tb 128-174 cm. Dull orange (5YR 7/4) to orange (5YR 6/6) dry, argillans on clasts bright reddish brown (5YR 5/8), (5YR 5/6) to reddish brown (5YR 4/6) moist; very gravelly coarse sandy clay loam; moderate to strong medium angular blocky; slightly hard to hard (dry), slightly sticky and slightly plastic (wet); few thin argillan bridges, very few moderately thick argillans on clasts; matrix very slightly effervescent, common carbonate coatings on clasts violently effervescent, 2% carbonate by volume (estimated), carbonate stage I; 30% pebbles, 30% cobbles, and 10% boulders; less than 2% highly weathered clasts; clear wavy boundary.

IIIB24tb 174-203 cm. Bright brown (2.5YR 5/6) to bright reddish brown (5YR 5/8) dry, reddish brown (2.5YR 4/6) to (5YR 4/8) moist; very gravelly coarse sandy clay loam; strong medium angular blocky; very hard (dry), very sticky and plastic (wet); continuous thick argil- lans bridging grains and lining pores, few moderately thick argillans on ped faces; matrix slightly effervescent, common carbonate clast coatings violently effervescent; 2% carbonate by volume (estimated), carbonate stage I; 25% pebbles, 25% cobbles, and 20% boulders by volume; less than 2% highly weathered clasts.

IIIB3tb 203-228 cm. Dull orange (5YR 7/4) to bright reddish brown (5YR 5/6) dry, argillans lining pores bright reddish brown (5YR 5/8), (5YR 5/6) to reddish brown (5YR 4/6) moist; very gravelly loam; moderate fine to medium angular blocky; slightly hard (soft), slightly sticky and slightly plastic (wet); many thin argillans bridging grains and lining pores, very few thick argillans on clasts; matrix very slightly effervescent, very few carbonate coatings on clasts slightly effervescent; initial carbonate stage I; 25% pebbles, 25% cobbles, and 20% boulders; less than 2% highly weathered clasts.

## SOIL PROFILE DESCRIPTION 3

Classification: Typic Eutroboralf

Location: E edge of collapse pit 200 m SW of Towanta Flat Trench No. 1; Mountain Home Quad; NW1/4, NW1/4, sec. 10, T. 1 S., R. 5 W.

Physiographic position: Downthrown surface of faulted glaciofluvial gravels with overlying colluvial apron 10 m (30 ft) back from edge of scarp; 2217 m (7270 ft) elevation.

Topography: Smooth erosional surface sloping 9° SE.

Drainage: Well drained.

Vegetation: Sagebrush and short grasses.

Parent material: Thick colluvium over glaciofluvial gravels.

Age: Pre-Bull Lake? overlain by Bull Lake to Holocene colluvium.

Sampled by: A. R. Nelson, December 4, 1979.

Remarks: Clast and carbonate volume percentages visually estimated.

B21 0-36 cm. Bright brown (7.5YR 5/6) to bright reddish brown (5YR 5/6) dry, brown (7.5YR 4/6) to reddish brown (5YR 4/6) moist; sandy loam+; weak to moderate coarse prismatic; soft to slightly hard (dry), sticky and plastic (wet); few thin argillan bridges; upper 5 cm of horizon disturbed; none to very slightly effervescent; 2% pebbles by volume; abrupt wavy boundary.

B22 36-46 cm. Light gray (7.5YR 8/1) to light yellow orange (7.5YR 8/3) dry, light brownish gray (7.5YR 7/1) to dull orange (7.5YR 7/3) moist; sandy loam+; moderate very coarse platy; slightly hard (dry), sticky and slightly plastic (wet); many thin argillan bridges, few thin argillans lining pores; matrix violently effervescent; thick carbonate (20% by volume) lining all pores and joints, carbonate stage II+; 2% pebbles by volume; clear wavy boundary.

B23ca 46-130 cm. Bright reddish brown (5YR 5/6) dry, reddish brown (5YR 4/6) moist; sandy loam+; moderate to strong coarse angular blocky; hard (dry), slightly sticky and slightly plastic (wet); many thin argillan bridges, few thin argillans lining pores; matrix violently effervescent; carbonate (10% by volume) lining discontinuous vertical to random imped dentritic tubular very fine pores, carbonate stage II; 2% pebbles by volume; gradual irregular boundary.

B24t 130-224 cm. Bright reddish brown (5YR 5/6) dry, reddish brown (5YR 4/6) moist; sandy loam+; strong coarse prismatic; hard (dry), sticky and slightly plastic (wet); many thin argillan bridges, common thin argillans lining pores, few thin argillans on ped faces; matrix strongly effervescent; thick carbonate (5% by volume) lining pores and joints, carbonate stage I; 2% pebbles by volume; clear wavy boundary.

IIB25b 224-249 cm. Dull orange (5YR 6/5) dry, bright reddish brown (5YR 5/6) moist; gravelly sandy loam; moderate fine to medium angular blocky; slightly hard (dry), slightly sticky and slightly plastic (wet); many thin argillan bridges, few thin argillans lining pores; matrix strongly effervescent, carbonate coatings on clasts (8% by volume) violently effervescent; carbonate stage I; 30% pebbles, 30% cobbles, and 5% boulders by volume; clear wavy boundary.

IIIB26tb 249-291 cm. Bright reddish brown (5YR 5/8) dry, reddish brown 5YR 4/8) moist; sandy clay loam; moderate to strong medium prismatic; hard (dry), sticky and plastic (wet); continuous moderately thick argillan bridges, many thin argillans lining pores, common thin argillans (5YR 5/8) on ped faces, few thick argillans on clasts; matrix slightly effervescent, carbonate lining joints (3% by volume) violently effervescent; carbonate stage I; 10% pebbles by volume; clear irregular boundary.

IVB27tb 291-345+ cm. Bright reddish brown (5YR 5/8) dry, reddish brown (5 YR 4/8) moist; gravelly sandy clay loam-; moderate to strong medium angular blocky; hard (dry), slightly sticky and slightly plastic (wet); many thin argillan bridges, few thin argillans lining pores, few thin argillans coating clasts; matrix very slightly effervescent, strongly effervescent on few (1% by volume) carbonate clast coatings; carbonate stage I; 30% pebbles, 20% cobbles, and 10% boulders by volume; <2% grusified clasts.

## SOIL PROFILE DESCRIPTION 4

Classification: Typic Eutroboralf

Location: Towanta Flat Trench No. 2, Station 0+25 to 0+30; Mountain Home Quad.; SW1/4, SE1/4, sec. 35, T. 1N., R. 5 W.

Physiographic position: Lowest alluvial surface within graben on glaciofluvial plain; elevation 2224 m (7298 ft.).

Topography: Smooth surface, 0° slope.

Drainage: Well drained.

Vegetation: Sagebrush and short grasses.

Parent material: Fine-grained colluvium - eolian material over lake sediments over glaciofluvial sands and gravel over gravelly-clayey alluvium derived from Duchesne River Fm.

Age: Pre-Bull Lake? to Holocene.

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 11, 1980.

A 0-19 cm. Dull brown (7.5YR 5/3) dry, brown (7.5YR 4/3) moist; sandy clay; moderate very coarse platy to moderate very coarse angular blocky; slightly hard (dry), slightly sticky and very slightly plastic (wet); no effervesence; less than 1% clasts; clear wavy boundary.

IIB21 19-41 cm. Dull brown (7.5YR 5/3) dry, brown (7.5YR 4/3) moist; sandy clay; moderate to strong weak to moderate angular blocky; hard (dry), sticky and slightly plastic (wet); many thin argillan bridges, common thin argillans lining pores, common moderately thick argillans on ped faces; no effervescence; less than 1% clasts; clear wavy boundary.

IIB22 41-65 cm. Dull yellow orange (10YR 7/4) dry, dull orange (10YR 6/4) moist; sandy clay; strong coarse angular blocky breaking to strong fine angular blocky; very hard (dry), sticky and slightly plastic (wet); continuous thin argillan bridges, many thin argillans lining pores, common moderately thick argillans on ped faces; no effervesence; less than 1% clasts; clear wavy boundary.

IIB3 65-83 cm. Light gray (2.5Y 8/2) to pale yellow (2.5Y 8/3) dry, light yellow (2.5Y 7/3) moist; clay; moderate to strong medium angular blocky; very hard (dry), very slightly sticky and slightly plastic (wet); continuous thin argillan bridges, very few thin argillans lining pores; very slightly to

slightly effervescent; carbonate stage I-, common thin carbonate bridges, common thin carbonate films lining pores; less than 1% clasts; clear wavy boundary.

IIC 83-121 cm. Pale yellow (2.5Y 8/3) dry, light yellow (2.5Y 7/3) moist; yellow orange (10YR 8/5) dry, bright yellowish orange (10YR 7/5) moist; few, fine, prominent mottles; loamy sand-; weak fine to medium angular blocky; hard (dry), nonsticky and nonplastic (wet); continuous thin clay bridges; strongly effervescent; carbonate stage I, common moderately thick carbonate films lining pores, common moderately thick carbonate films on ped faces, very thin carbonate joint fillings; less than 2% pebbles, 5% cobbles by volume; abrupt wavy boundary.

IIIB3 121-144 cm. Dull orange (5YR 7/3) dry, dull orange (5YR 6/4) moist; gravelly sand; massive to very weak moderate angular blocky; loose to soft (dry), nonsticky and nonplastic (wet); few thin argillans on clasts, very few thin argillan bridges; none to slightly effervescent; carbonate stage I-; 10% to 30% pebbles, 2% to 15% cobbles by volume; 2% highly weathered clasts; abrupt wavy boundary.

IVC 144-246+ cm. Light gray (5Y 8/2) with rare inclusions olive yellow (7.5Y 6/3) to olive gray (10Y 6/2) dry (probably weathered fragments Duchesne River Formation), light yellow (5Y 7/3) with rare inclusions grayish olive (7.5Y 5/3) to olive gray (10Y 5/2) moist; sandy clay; moderate coarse angular blocky; hard (dry), sticky and very slightly plastic; continuous thick clay bridges; very slightly to strongly effervescent, violently effervescent on carbonate joint fillings; carbonate stage I+ to II-, many thick carbonate pore fillings, many thick carbonate films on ped faces, 1-4 mm carbonate joint fillings; 5% to 10% pebbles, 1% to 15% cobbles, less than 1% boulders by volume; 30% highly weathered clasts.

## SOIL PROFILE DESCRIPTION 5

Classification: Typic Eutroboralf

Location: Altamount Quad.; NE1/4, SE1/4, sec. 27, T. 1 S., R. 4 W.

Physiographic position: Edge of dissected glaciofluvial terrace; 1970 m (6460 ft) elevation.

Topography: Smooth surface, 0° slope.

Drainage: Well drained.

Vegetation: Disturbed surface, grasses and scattered juniper.

Parent material: Glaciofluvial gravel.

Age: Pre-Bull Lake.

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 8, 1980.

AB 0-33 cm. Dull reddish brown (5YR 5/4) dry, reddish brown (5YR 4/6) moist; gravelly cobbly sandy loam; weak very coarse platy to weak moderate to strong angular blocky; soft (dry), very slightly sticky and nonplastic (wet); common thin argillan bridges, few thin argillans on clasts; strongly effervescent; many 1-4 mm carbonate nodules, carbonate stage I+; 30%, pebbles, 25% cobbles, and 5% boulders by volume; no highly weathered clasts; clear broken boundary.

B2t 33-121 cm. Bright brown (2.5YR 5/6) dry, bright brown (2.5YR 5/6) moist; gravelly cobbly sandy clay loam; moderate fine angular blocky; hard (dry), slightly sticky and slightly plastic (wet); continuous moderately thick argillan bridges, many moderately thick argillans lining pores, many moderately thick to thick argillans on clasts and ped faces; strongly effervescent; 1 mm carbonate seams, carbonate stage I+; 30% pebbles, 25% cobbles, and 5% boulders by volume; no highly weathered clasts; very abrupt irregular boundary.

K2b 121-181 cm. Light gray (8/0) to light yellow orange (10YR 8/3) dry, light gray (8/0) to light yellow orange (10YR 8/3) moist; very strong very coarse platy; extremely hard (dry); violently effervescent; 1 to 10 mm rinds on clasts, carbonate stage V-; 20% pebbles, 30% cobbles, and 5% boulders by volume; 30% highly weathered clasts; clear wavy boundary.

IIC1cab 181-251 cm. Pale orange (5YR 8/3) dry, dull orange (5YR 7/3) moist; gravelly cobbly sand+; weak medium to coarse angular blocky; loose (dry), nonsticky and nonplastic (wet); violently

effervescent; common moderately thick carbonates lining pores, continuous thin carbonate bridges, common thick carbonates on clasts, carbonate stage II+; 50% pebbles, 30% cobbles, and 10% boulders by volume; 5% highly weathered clasts; gradual irregular boundary.

IIC2b 251-450 cm. Pale yellow (5Y 8/3) dry, light yellow (5Y 7/3) moist; gravelly cobbly loamy sand-; very weak fine to medium angular blocky; soft (dry); very slightly sticky and nonplastic (wet); common thin argillan bridges; strongly effervescent; many thin carbonate bridges, common thin carbonates lining pores, many thick carbonates on clasts, carbonate stage I; 50% pebbles, 30% cobbles, and 10% boulders by volume; no highly weathered clasts; very abrupt broken boundary.

IIIC3b 450-530 cm. Orange (7.5YR 7/6) to yellow orange (7.5YR 7/8) dry, orange (7.5YR 6/6) to bright brown (7.5YR 5/6) moist; gravelly cobbly sand; massive to very weak very coarse angular blocky; loose (dry), nonsticky and nonplastic (wet); few thin argillan bridges, few moderately thick argillans on clasts; matrix not effervescent but slightly effervescent near thin carbonate coatings on clasts; carbonate stage I-; 40%, pebbles, 35% cobbles, and 2% boulders by volume; no highly weathered clasts; abrupt broken boundary.

IIIC4b 530-730+. Orange (5YR 6/6) dry, bright reddish brown (5YR 5/6) moist; gravelly cobbly sand; massive to very weak very coarse angular blocky; loose (dry), nonsticky and nonplastic (wet); common thin argillan bridges, common moderately thick argillans on clasts; not effervescent to slightly effervescent near thin carbonate coatings on clasts; carbonate stage I-; 40% pebbles, 35% cobbles, and 2% boulders by volume; no highly weathered clasts; diffuse broken boundary.

## SOIL PROFILE DESCRIPTION 6

Classification: Typic Ustorthent

Location: Altonah Quad.; NE1/4, SW1/4, sec. 32, T. 1 N., R. 4 W.

Physiographic position: Edge of fluvial terrace; 2098 m (6880 ft) elevation.

Topography: Smooth surface, 0° slope.

Drainage: Well drained.

Vegetation: Sagebrush and grass.

Parent material: Fluvial gravel.

Age: Holocene?

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, July 28, 1980.

A1 0-17 cm. Brown (7.5YR 4/3) dry, brownish black (7.5YR 3/2) moist; gravelly cobbly sandy loam-; weak coarse platy; soft (dry), nonsticky and nonplastic (wet); no effervescence; 40% pebbles, 40% cobbles, and 1% boulders by volume; no highly weathered clasts; clear wavy boundary.

A2 17-44 cm. Dull reddish brown (5YR 5/3) dry, dark reddish brown (5YR 3/2.5) moist; gravelly loamy sand; very weak medium angular blocky; soft (dry), nonsticky and nonplastic (wet); no effervescence; 45% pebbles, 10% cobbles, and 1% boulders by volume; no highly weathered clasts; clear wavy boundary.

AC 44-70 cm. Bright reddish brown (5YR 5/5) dry, dull reddish brown (5YR 4/4) moist; gravelly cobbly sand; single grain; loose (dry), nonsticky and nonplastic (wet); no effervescence; 50% pebbles, 40% cobbles, and 1% boulders by volume; no highly weathered clasts; clear wavy boundary.

C 70-130 cm. Bright reddish brown (5YR 5/5) dry, reddish brown (5YR 4/6) moist; gravelly cobbly sand; single grain; loose (dry), nonsticky and nonplastic (wet); no effervescence; 50% pebbles, 40% cobbles, and 1% boulders by volume; no highly weathered clasts.

## SOIL PROFILE DESCRIPTION 7

Classification: Typic Eutroboralf

Location: Mountain Home Quad.; NW1/4, SW1/4, sec. 35, T. 1 N., R. 5 W.

Physiographic position: Glaciofluvial plain; 2271 m (7445 ft) elevation.

Topography: Smooth surface, 0° slope.

Drainage: Well drained.

Vegetation: Sagebrush and grasses.

Parent material: Glaciofluvial gravels.

Age: Pre-Bull Lake.

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 6, 1980.

A1 0-17 cm. Dull brown (7.5YR 5/3.5) dry, dark reddish brown (5YR 3/3.5) moist; gravelly sandy loam; weak very coarse platy; soft (dry), very slightly sticky and nonplastic (wet); no effervescence; 25% pebbles, 20% cobbles, 5% boulders by volume 5% highly weathered clasts; abrupt wavy boundary.

B21t 17-31 cm. Reddish brown (5YR 4/8) dry, reddish brown (5YR 4/6) moist; dark reddish brown (5YR 3/6) dry, reddish brown (5YR 4/6) moist stain on ped surfaces; gravelly sandy clay loam; moderate very coarse platy to moderate medium angular blocky; hard (dry), sticky and plastic (wet), many thin to moderately thick argillan bridges, common thin argillans lining pores, few moderately thick argillans lining pores and ped faces, few moderately thick argillans on clasts; no effervescence; very rare carbonate spots on bottom of clasts; 25% pebbles, 20% cobbles, 5% boulders by volume; <5% highly weathered clasts; clear wavy boundary.

B22t 31-66 cm. Reddish brown (5YR 4/8) dry, reddish brown (5YR 4/8) moist; rare zones of orange (5YR 6/8) dry, bright reddish brown (5YR 5/8) moist; gravelly sandy clay loam; moderate to strong fine to medium angular blocky; very hard (dry), sticky and slightly plastic (wet); continuous thin to moderately thick argillan bridges, many thin argillans lining pores, few moderately thick argillans lining pores, many moderately thick argillans on clasts, few moderately thick argillans on ped faces; no effervescence; 25% pebbles, 20% cobbles, 5% boulders by volume; <5% highly weathered clasts; very abrupt irregular boundary.

K2b 66-117 cm. White (8/0) dry, light yellow orange (10YR 8/3) moist; some zones of light yellow orange (7.5YR 8/3) dry in lower half; cobbly sandy loam; strong very coarse platy to moderate medium angular blocky; very hard to extremely hard (dry), nonsticky and nonplastic (wet); violently effervescent; carbonate forms 1-8 mm rinds on clasts, carbonate greater than 90% of matrix, discontinuous laminar zone in upper 10 cm has platy structure and minor mamillary structure, carbonate stage III+ to IV; 15% pebbles, 40% cobbles, 10% boulders by volume; 70% highly weathered clasts; gradual irregular boundary.

Ccab 117-166+ cm. Orange (7.5YR 7/5) dry, orange (7.5YR 6/7) moist; some areas orange (5YR 6/7) moist; cobbly loamy sand+; massive; loose (dry), nonsticky and nonplastic (wet); few thin argillan bridges, very few thin argillans lining pores; matrix slightly effervescent, strongly to violently effervescent near clasts; matrix 20% carbonate by volume (estimated), common thin carbonate lining pores, thick carbonate on clasts, carbonate stage II; 15% pebbles, 40% cobbles, 10% boulders by volume; 20% highly weathered clasts.

## SOIL PROFILE DESCRIPTION 8

Classification: Typic Eutroboralf

Location: Mountain Home Quad.; NW1/4, NE1/4, sec. 35, T. 1 N., R. 5 W.

Physiographic position: Wide (1.5 km) channel in glaciofluvial plain; 2252 m (7385 ft) elevation.

Topography: Smooth surface, 0° slope.

Drainage: Well drained.

Vegetation: Sagebrush and short grasses.

Parent material: Glaciofluvial gravels.

Age: Pre-Bull Lake.

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 6, 1980.

A 0-16 cm. Dull orange (7.5YR 6/4) dry, brown (7.5YR 4/4) moist; cobbly gravelly sandy loam; weak very coarse platy; soft (dry), very slightly sticky and nonplastic (wet); no effervescence; 25% pebbles, 30% cobbles, 5% boulders by volume; <2% highly weathered clasts; clear wavy boundary.

B21t 16-31 cm. Reddish brown (5YR 4/6) dry, reddish brown (5YR 4/6) moist; cobbly gravelly sandy clay; weak to moderate fine to medium angular blocky; slightly hard (dry), sticky and slightly plastic (wet); continuous thin argillan bridges, common moderately thick argillan bridges, many moderately thick argillans lining pores, many moderately thick argillans on clasts and ped faces; no effervescence; 25% pebbles, 30% cobbles, 5% boulders by volume; <2% highly weathered clasts; clear wavy boundary.

B22t 31-58 cm. Bright brown (2.5YR 5/6) dry, reddish brown (5YR 4/9) moist; cobbly gravelly sandy clay; moderate to strong medium to coarse angular blocky; very hard (dry), sticky and plastic (wet) continuous moderately thick argillan bridges, continuous moderately thick argillans lining pores, many thick argillans on clasts and ped faces; argillan coatings on clasts dark reddish brown (5YR 3/4) dry, dull reddish brown (5YR 4/3) wet; no effervescence; 25% pebbles, 30% cobbles, 5% boulders by volume, 5% highly weathered clasts; very abrupt wavy boundary.

K2 58-95 cm. White (8/0) dry, light yellow orange (10YR 8/3) moist; gravelly sandy loam; very weak fine angular blocky;

soft (dry), nonsticky and nonplastic (wet); violently effervescent; carbonate stage III+, greater than 90% carbonate in matrix, very thick (1-6 mm) powdery rinds; 25% pebbles, 20% cobbles, 5% boulders by volume; 70% highly weathered clasts; clear irregular boundary.

Cca 95-192+cm. White (8/0 to 8/3) dry, bright reddish brown (5YR 5/8) moist; cobbly gravelly sandy clay-; weak medium to coarse angular blocky; slightly hard (dry), slightly sticky and slightly plastic (wet); many thin argillan bridges, few thin argillans lining pores; matrix slightly effervescent, carbonate violently effervescent; 30% to 40% of matrix carbonate, carbonate stage II, carbonate pale orange (5YR 8/4) moist, many thick carbonate films on clasts, ped faces, and lining pores; 25% pebbles, 30% cobbles, 5% boulders by volume; 30% highly weathered clasts.

## SOIL PROFILE DESCRIPTION 9

Classification: Typic Eutroboralf

Location: Towanta Flat Trench No. 3, Station 0+35; Mountain Home Quad.; SW1/4; SE1/4, sec. 35, T. 1 N., R. 5 W.

Physiographic position: Lowest alluvial surface adjacent to southern scarp of graben on glaciofluvial plain: elevation 2230 m (7310 ft).

Topography: Smooth surface, sloping 1° N.

Drainage: Well drained.

Vegetation: Sagebrush and short grasses.

Parent material: Fine-grained colluvium - eolian material over glaciofluvial sands and gravel over gravelly-clayey alluvium derived from Duchesne River Fm.

Age: Pre-Bull Lake? to Holocene.

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, July 27, 1980.

A 0-18 cm. Dull brown (7.5YR 6/3) dry, brown (7.5YR 4/3) moist; loam; moderate to strong medium angular blocky; hard to slightly hard (dry), slightly sticky and slightly plastic (wet); no effervescence; clear wavy boundary.

IIB2b 18-34 cm. Dull orange (5YR 6/4) dry, dull reddish brown (5YR 5/4) moist; clay loam-; moderate to strong medium angular blocky; hard (dry), sticky and slightly plastic (wet); continuous colloidal stains on mineral grains, common thin argillans lining pores, common thin argillans on ped faces; no effervescence; clear wavy boundary.

IIB3b 34-54 cm. Dull yellow orange (10YR 6/4) to dull orange (7.5YR 6/4) dry, dull brown (7.5YR 5/4) moist; sandy loam; weak medium angular blocky to platy; hard (dry), very slightly sticky and nonplastic (wet); many thin colloidal stains on mineral grains, few thin argillans lining pores, few thin argillans on ped faces; slightly effervescent, clasts strongly effervescent; 1% pebbles and 1% cobbles by volume; clear irregular boundary.

IIC1b 54-66 cm. Dull orange (7.5YR 7/4) dry; dull brown (7.5YR 5/4) moist; cobbly gravelly sandy loam; massive; hard (dry), very slightly sticky and nonplastic (wet); few thin argillans on

clasts; violently effervescent; carbonate stage I- to I; 25% pebbles and 35% cobbles by volume; 10% highly weathered clasts; abrupt wavy boundary.

IIIC2oxb 66-98 cm. Dull orange (7.5YR 7/4) to light yellow orange (7.5YR 8/4) dry, orange (7.5YR 6/6) moist; common medium prominent mottles, orange (7.5YR 6/8) dry, orange (7.5YR 6/8) moist; weakly stratified cobbly loamy sand; weak medium to coarse angular blocky; slightly hard to hard (dry), nonsticky and nonplastic (wet); few colloidal stains on mineral grains, many thin argillans on ped faces; strongly effervescent, violently effervescent on clasts; carbonate stage I+; 15% pebbles, 25% cobbles, and 1% boulders by volume; 10% highly weathered clasts; clear irregular boundary.

IVC3b 98-130 cm. Dull orange (5YR 7/4) dry, dull orange (7.5YR 6/4) moist; weakly stratified gravelly cobbly sand; massive to weak medium angular blocky; loose to soft (dry), nonsticky and nonplastic (wet); very few colloidal stains on mineral grains; many thin argillans on ped faces, few moderately thick argillans on ped faces; none to slightly effervescent, violently effervescent on clasts; carbonate stage I+, many thin carbonate films on ped faces, few thin carbonate films lining pores; 20% pebbles, 30% cobbles, and 1% boulders by volume; 10% highly weathered clasts; abrupt irregular boundary.

VC4b 130-172 cm. Light yellow (2.5Y 7/3) to pale yellow (2.5Y 8/3) dry, light yellow (2.5Y 7/3) to light yellow (2.5Y 7/4) moist; many medium prominent mottles, yellow orange (10YR 7/8) dry, orange (10YR 6/6 and 10YR 6/8) moist; clay loam; moderate to strong very coarse angular blocky; very hard (dry), sticky and slightly plastic (wet); continuous thick argillan bridges; slightly to strongly effervescent, violently effervescent on clasts; carbonate stage II-, many moderately thick, carbonate films lining pores, continuous, thick, carbonate films on ped faces; 5% pebbles and 5% cobbles; 40% highly weathered clasts.

## SOIL PROFILE DESCRIPTION 10

Classification: Typic Eutroboralf

Location: Mountain Home Quad.; NE1/4, SW1/4, sec, 26; T. 1 N., R. 5 W.

Physiographic position: Glaciofluvial channel adjacent to subdued moraine; 2266 m (7430 ft) elevation.

Topography: Smooth slightly channeled surface, 0° slope.

Drainage: Well drained.

Vegetation: Sagebrush and grass.

Parent material: Glaciofluvial gravels.

Age: Pre-Bull Lake.

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 6, 1980.

A1 0-15 cm. Dull reddish brown (5YR 4/3.5) dry,. dark reddish brown (5YR 3/3.5) moist; gravelly cobbly sandy loam; weak to moderate, very coarse platy; soft (dry), very slightly sticky and nonplastic (wet); common thin argillan bridges; strongly to violently effervescent; carbonates in 1-4 mm nodules, carbonate stage I-; 30% pebbles, 30% cobbles, 10% boulders by volume; 2-5% highly weathered clasts; clear wavy boundary.

B1 15-32 cm. Bright reddish brown (5YR 5/5) dry, reddish brown (5YR 4/5) moist; gravelly cobbly sandy clay loam; weak medium angular blocky; slightly hard (dry), slightly sticky and slightly plastic (wet); many thin argillan bridges, common thin argillans lining pores, many thin argillans on clasts; strongly to violently effervescent; carbonates in 1-4 mm nodules and thick coatings on bottom of clasts, carbonate stage I-; 30% pebbles, 30% cobbles, 10% boulders by volume, 5% highly weathered clasts; clear wavy boundary.

B21t 32-65 cm. Bright reddish brown (5YR 5/7) dry, reddish brown (5YR 4/7) moist; cobbly gravelly sandy clay-; moderate fine to medium angular blocky; hard (dry), sticky and plastic (wet); continuous moderately thick argillan bridges, common moderately argillans lining pores, continuous thin argillans lining pores, many moderately thick argillans on clasts and pore faces; strongly effervescent, violently effervescent on carbonate seams; discontinuous thin carbonate coatings on clasts, carbonate stage I; 20% pebbles, 40% cobbles, 10% boulders by volume; 20% highly weathered clasts; clear irregular boundary.

B22t 65-119 cm. Reddish brown (2.5YR 4/6) dry, reddish brown (2.5YR 4/6) moist; cobbly gravelly sandy clay; moderate to strong medium angular blocky breaking to moderate to strong fine angular blocky; very hard (dry), sticky and plastic (wet); continuous thick argillan bridges, continuous thick argillans lining pores, continuous thick argillans on ped faces; patchy interclast areas in lower 20 cm of horizon have continuous thin argillan bridges, common thin argillans lining pores, many moderately thick argillans on clasts; strongly effervescent, violently effervescent on seams; carbonate as veins and thin coatings on clasts, carbonate seams light gray (8/0) dry, light yellow orange (7.5 8/4) moist, in lower 20 cm carbonates on ped faces, carbonate stage II; 20% pebbles, 40% cobbles, 10% boulders by volume; 20% highly weathered clasts; abrupt broken boundary.

K 119-155+ cm. Bright reddish brown (5YR 5/7) dry, reddish brown (5YR 4/7) moist; cobbly gravelly sandy loam; platy; soft (dry), very friable (moist), very slightly sticky and nonplastic (wet); many thin argillan bridges, few moderately thick argillan bridges; violently effervescent; carbonates compose 70% of matrix, thick carbonates on ped faces and inside pores, carbonates light gray (8/0) dry, light yellow orange (7.5 YR 8/4) moist, carbonate stage III-; 20% pebbles, 40% cobbles, 10% boulders by volume; 60% highly weathered clasts.

## SOIL PROFILE DESCRIPTION 11

Classification: Typic Argiboroll

Location: Mountain Home Quad.; NE1/4, NW1/4, sec. 26, T. 1 N., R. 5 W.

Physiographic position: Low, broad moraine crest; 2305 m (7558 ft) elevation.

Topography: Smooth surface, sloping 1° S.

Drainage: Well drained.

Vegetation: Sagebrush and some grass.

Parent material: Eolian? - colluvial mantle over till.

Age: Pre-Bull Lake.

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 6, 1980.

A1 0-23 cm. Dull reddish brown (5YR 5/3.5) dry, dark reddish brown (5YR 3/3.5) moist; gravelly sandy loam; weak very coarse platy breaking to very weak medium angular blocky; soft (dry), very slightly sticky and nonplastic (wet); weakly effervescent; carbonates in few 1-4 mm nodules, carbonate stage I-; 15-20% pebbles, 5% cobbles by volume; no highly weathered clasts; clear smooth boundary.

B1 23-64 cm. Dull brown (7.5YR 5/4) dry, brown (7.5YR 4/4) moist; sandy loam+; very weak medium to coarse angular blocky; soft (dry), slightly sticky and nonplastic (wet); many thin argillan bridges, very few thin argillans lining pores, very few thin argillans on clasts; matrix strongly effervescent; carbonates as 1 cm nodules and thin coatings on bottom of clasts, carbonate stage I; 15-20% pebbles, 5% cobbles by volume; <1% highly weathered clasts; abrupt irregular boundary.

IIB21cab 64-85 cm. Orange (5YR 6/6) dry, bright reddish brown (5YR 5/8) moist; cobbly sandy clay loam; very weak medium angular blocky to weak to moderate coarse platy; slightly hard to hard (dry), sticky and slightly plastic (wet), continuous thin argillan bridges, common thin, argillans lining pores, common thin argillans on clasts; violently effervescent; matrix 20-50% carbonate, carbonate in 1-3 mm rinds around clasts, carbonates light gray (8/0) dry, pale orange (5YR 8/4) moist, carbonate stage II+; 15% pebbles, 20% cobbles, 5% boulders by volume, 20% highly weathered clasts; clear irregular boundary.

IIB22tb 85-148 cm. Orange (5YR 6/6) dry, bright reddish brown (5YR

5/8) moist; cobbly sandy loam+; very weak coarse angular blocky to massive; slightly hard (dry), slightly sticky and nonplastic (wet); continuous thin argillan bridges, common thin argillans lining pores, common thin argillans on clasts; matrix none to weakly effervescent, carbonate thin seams and coatings on clasts violently effervescent; carbonates light gray (8/0) dry, pale orange (5YR 8/4) moist, carbonate stage II-; 15% pebbles, 20% cobbles, 5% boulders by volume; 10% highly weathered clasts; gradual wavy boundary.

IIB23tb 148-173 cm. Orange (5YR 6/6) dry, reddish brown (5YR 4/8) to bright reddish brown (5YR 5/8) moist; sandy loam; massive; slightly hard (dry), very slightly sticky and nonplastic; many thin argillan bridges, few thin argillans lining pores; matrix not effervescent, carbonates on clasts violently effervescent; carbonates in discontinuous coatings on clasts, carbonate stage I; 15% pebbles, 10% cobbles, 5% boulders by volume; 10% highly weathered clasts; abrupt wavy boundary.

IIIB24b 173-184+ cm. Bright brown (2.5YR 5/6) moist; sandy clay loam-; weak to moderate coarse platy; slightly hard (dry), sticky and nonplastic (wet); continuous moderately thick argillan bridges, common thin argillans lining pores, few thin argillans on clasts; matrix not effervescent, carbonates in 1-5 mm seams, violently effervescent; carbonate stage II-; 15% pebbles, 10% cobbles, 5% boulders by volume; 10% highly weathered clasts.

## SOIL PROFILE DESCRIPTION 12

Classification: Typic Eutroboralf

Location: Mountain Home Quad.; SE1/4, SE1/4; sec. 29, T. 1 N., R. 5 W.

Physiographic position: Distal edge of colluvial-alluvial fan; 2290 m (7510 ft) elevation.

Topography: Smooth slightly channeled surface, 0-1° slope.

Drainage: Well-drained.

Vegetation: Sagebrush and grass.

Parent material: Gravelly colluvium and alluvium.

Age: Bull Lake?

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 7, 1980.

A 0-13 cm. Dull brown (7.5YR 6/3) dry, dark brown (7.5YR 3/3) moist; loamy sand; weak coarse platy; soft (dry), nonsticky and nonplastic (wet); no effervescence; 10% pebbles, less than 1% cobbles by volume; no highly weathered clasts; abrupt wavy boundary.

AB 13-28 cm. Dull reddish brown (5YR 5/4) dry, dull reddish brown (5YR 4/4) moist; sandy loam-; very weak medium angular blocky; slightly hard (dry), slightly sticky and very slightly plastic (wet); many thin argillan bridges, few thin argillans lining pores, few thin argillans on clasts and ped faces; no effervescence; 10% pebbles, less than 1% cobbles by volume; no highly weathered clasts; clear wavy boundary.

B21 28-55 cm. Bright reddish brown (5YR 5/6) dry, reddish brown (5YR 4/6) moist; sandy loam; very weak medium to coarse angular blocky; slightly hard (dry), slightly sticky and slightly plastic (wet); continuous thin to moderately thick argillan bridges, many thin argillans lining pores, many moderately thick argillans on clasts and ped faces, continuous thin argillans on clasts and ped faces; no effervescence; very thin carbonate coatings on bottom of clasts, carbonate stage I-; 10% pebbles, 2% cobbles by volume; no highly weathered clasts; gradual irregular boundary.

IIB22tb 55-87 cm. Bright brown (2.5YR 5/6 to 2.5YR 5/7) dry, bright brown (2.5YR 5/6) moist, dull reddish brown clast coatings (2.5YR 4/3) dry and moist; gravelly sandy clay; moderate to strong fine angular blocky; very hard (dry), sticky and

plastic (wet); continuous thick argillan bridges, many moderately thick argillans lining pores, continuous thick argillans on clasts, many thick argillans on ped faces; no effervescence; thin carbonate coatings on 2/3 of clasts, carbonate stage I; 50 to 60% pebbles, 10 to 20% cobbles, less than 1% boulders by volume; no highly weathered clasts; abrupt wavy boundary.

IIIB23tb 87-108 cm. Orange (5YR 6/7) dry, bright reddish brown (5YR 5/8) moist; sandy loam; massive; hard (dry), very slightly sticky and nonplastic (wet); many moderately thick argillan bridges, continuous thin argillan bridges, many thin argillans lining pores, common moderately thick argillans on clasts and ped faces, few moderately thick argillans lining pores; no effervescence; carbonate stage I; 5% pebbles; no highly weathered clasts; clear broken boundary.

IVB3b 108-140 cm. Orange (5YR 6/6) dry, bright reddish brown (5YR 5/8) moist; gravelly sand; massive to very weak fine angular blocky; slightly hard (dry), nonsticky and nonplastic (wet); continuous colloidal stains on mineral grains, few thin argillan bridges, few thin argillans on clasts; no effervescence; rare carbonate impregnated matrix, carbonte stage I+; 40% pebbles, 5 to 20% cobbles, less than 1% boulders by volume; no highly weathered clasts; abrupt wavy boundary.

VCb 140-161+ cm. Orange (5YR 6/7) dry, bright reddish brown (5YR 5/7) moist; sandy clay loam-; massive; very hard (dry), sticky and slightly plastic (wet); many thin argillan bridges, very few thin argillans lining pores; matrix not effervescent, violently effervescent on few, thin carbonate seams; carbonate stage I+; no coarse fraction.

## SOIL PROFILE DESCRIPTION 13

Classification: Typic Eutroboralf

Location: Mountain Home Quad.; NW1/4; SW1/4, sec. 23, T. 1 N., R. 5 W.

Physiographic position: Crest of broad, high moraine; 2365 m (7755 ft) elevation.

Topography: Smooth surface, sloping 1° E.

Drainage: Well drained.

Vegetation: Sagebrush and short grasses.

Parent material: Till with ice-wedge cast?

Age: Pre-Bull Lake.

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 5, 1980.

A 0-20 cm. Dull orange (7.5YR 6/4) dry, brown (7.5YR 4/4) to dull reddish brown (5YR 4/4) moist; gravelly sandy loam; weak fine to medium subangular blocky; soft (dry), nonsticky and nonplastic (wet); not effervescent; carbonate stage II-; 20% pebbles, 10% cobbles, 5% boulders by volume; <1% highly weathered clasts; clear wavy boundary.

B1 20-42 cm. Orange (7.5YR 7/5 to 5YR 7/5) dry, bright reddish brown (5YR 5/6) moist; gravelly sandy loam; massive; slightly hard (dry), slightly sticky and nonplastic (wet); many colloidal stains on mineral grains, common thin argillan bridges; not effervescent; carbonate stage I-; 20% pebbles, 10% cobbles, 5% boulders by volume; <1% highly weathered clasts; clear wavy boundary.

B21ca 42-66 cm. Pale orange (5YR 8/3) dry, orange (5YR 6/6 to 5YR 6/8) moist; gravelly sandy loam; very weak medium angular blocky to weak coarse platy; hard (dry), sticky and slightly plastic (wet); continuous colloidal stains on mineral grains, continuous thin argillan bridges, common thin argillans lining pores; violently effervescent; carbonates in 1-2 mm rinds, carbonates are light grey (8/0) dry, pale orange (5 YR 8/3) moist, carbonate stage II+ to III-; 20% pebbles, 10% cobbles, 5% boulders by volume; 10% highly weathered clasts; clear irregular boundary.

B22t 66-106 cm. Dull orange (5YR 7/4) dry, bright reddish brown (5YR 5/6) moist; gravelly sandy loam; massive; hard (dry), slightly sticky and nonplastic (wet); continuous colloidal

stains on mineral grains, continuous thin argillan bridges, common thin argillans lining pores; violently effervescent; many 1-3 mm seams of carbonate, carbonate stage I+; 20% pebbles, 10% cobbles, 5% boulders by volume; 5% highly weathered clasts; abrupt broken boundary.

IIB23tb 106-132 cm. Dull orange (5YR 6/4), bright reddish brown (5YR 5/6), pale orange (5YR 8/3), and dull orange (7.5YR 7/3) all moist; silty clay; massive; friable (moist), sticky and plastic (wet); strongly effervescent, violently effervescent in carbonate bands; carbonate stage II; abrupt broken boundary.

IB24t 132-162+ cm. Pale orange (5YR 8/4) dry, reddish brown (5YR 4/8) moist; gravelly sandy loam; massive; slightly hard (dry), very slightly sticky and nonplastic (wet); many thin argillan bridges, very few thin argillans lining pores; strongly effervescent; common carbonate seams and thin clast coatings, carbonate stage I; 20% pebbles, 10% cobbles, 5% boulders by volume; 5% highly weathered clasts.

## SOIL PROFILE DESCRIPTION 14

Classification: Typic Eutroboralf

Location: Mountain Home Quad.; SE1/4, NW1/4, sec. 23, T. 1 N., R. 5 W.

Physiographic position: Crest of low, narrow moraine; 2339 m (7670 ft) elevation.

Topography: Surface with scattered boulders, 0° slope.

Drainage: Well drained.

Vegetation: Sagebrush and grasses.

Parent material: Till - ablation over basal or flow till?

Age: Bull Lake.

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 5, 1980.

A 0-17 cm. Dull reddish brown (5YR 5/3) dry, dark reddish brown (5YR 3/3) moist; gravelly sandy loam; very weak fine to medium subangular blocky; soft (dry), very slightly sticky and nonplastic (wet); no effervescence; 20% pebbles, 15% cobbles, 5% boulders by volume; <1% highly weathered clasts; clear wavy boundary.

B1 17-44 cm. Dull reddish brown (5YR 5/4) dry, dull reddish brown (5YR 4/4) moist; gravelly sandy clay; very weak medium angular blocky; slightly hard to hard (dry), sticky and slightly plastic (wet); many thin argillan bridges, few thin argillans lining pores, few thin argillans on clasts; no effervescence; 20% pebbles, 15% cobbles, 5% boulders by volume; <1% highly weathered clasts; clear wavy boundary.

B21t 44-67 cm. Bright reddish brown (5YR 5/6 to 5/8) dry, reddish brown (5YR 4/8) moist; gravelly clay; weak coarse angular blocky; hard to very hard (dry), sticky and plastic (wet); continuous thin to moderately thick argillan bridges, many thin argillans lining pores, common thin to moderately thick argillans on ped faces and clasts; no effervescence; 20% pebbles, 15% cobbles, 5% boulders by volume; <1% highly weathered clasts; clear irregular boundary.

B31 67-122 cm. Dull orange (5YR 7/4) dry, reddish brown (5YR 4/7) moist; gravelly sandy loam; massive to very weak medium angular blocky; slightly hard (dry), very slightly sticky and nonplastic (wet); many thin argillan bridges, few thin argillans lining pores, few thin argillans on ped faces and

clasts; no effervescence; 20% pebbles, 15% cobbles, 5% boulders by volume, <1% highly weathered clasts; clear wavy boundary.

B32 122-143 cm. Dull orange (5YR 7/5) dry, orange (5YR 6/5) to bright reddish brown (5YR 5/5) moist; gravelly sand+; massive to very weak fine to medium angular blocky; soft (dry), nonsticky and nonplastic (wet); common thin argillan bridges, very few thin argillans lining pores, very few thin argillans on ped faces and clasts; no effervesence; 20% pebbles; 15% cobbles; 5% boulders by volume; <1% highly weathered clasts; abrupt smooth boundary.

IIB33 143-163+ cm. Bright brown (2.5YR 5/5) moist; gravelly sandy loam; massive to weak to moderate very coarse platy; hard (dry), very slightly sticky and nonplastic (wet); many thin to moderately thick argillan bridges, common thin to moderately thick argillans lining pores, few thin argillans on ped faces and clasts; matrix none to slightly effervescent, carbonate seams violently effervescent; carbonate stage I, carbonate seams up to 2 cm thick, light yellow orange (7.5YR 8/3) moist, on tops of horizon and thin (1-2 mm) carbonate films on bottom of clasts; 20% pebbles, 15% cobbles, 5% boulders by volume; <1% highly weathered clasts.

## SOIL PROFILE DESCRIPTION 15

Classification: Typic Eutroboralf

Location: Mountain Home Quad.; NW1/4, NW1/4, sec. 22, T. 1 N., R. 5 W.

Physiographic position: Crest of low, broad moraine, 2388 m (7830 ft) elevation.

Topography: Smooth surface sloping 1° SE.

Drainage: Well drained.

Vegetation: Sagebrush and grasses.

Parent material: Till.

Age: Pre-Bull Lake.

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 7, 1980.

A 0-9 cm. Dull reddish brown (5YR 5/3) dry, dark reddish brown, (5YR 3/3) moist; cobbly pebbly loamy sand+; weak medium to coarse subangular blocky; soft (dry), nonsticky and nonplastic (wet); no effervescence; 20% pebbles, 25% cobbles, 10% boulders; no highly weathered clasts; abrupt wavy boundary.

B1 9-23 cm. Dull reddish brown (5YR 5/4) dry, reddish brown (5YR 4/5) moist; cobbly pebbly sandy loam; weak to moderate coarse platy breaking to weak to moderate fine angular blocky; slightly hard (dry), slightly sticky and nonplastic (wet); continuous colloidal stains on mineral grains, common thin argillan bridges, common thin argillans on clasts and ped faces, very few argillan lining pores; no effervescence; 20% pebbles, 25% cobbles, 10% boulders; 10% highly weathered clasts; clear wavy boundary.

B2 23-46 cm. Reddish brown (5YR 4/6) to bright reddish brown (5YR 5/6) dry, reddish brown (5YR 5/6 to 5YR 4/6) moist; cobbly pebbly sandy clay; weak medium to coarse angular blocky; hard (dry), sticky and slightly plastic (wet); continuous thin argillan bridges, common thin argillan lining pores, common moderately thick argillans on ped faces and clasts, continuous thin argillans on ped faces and clasts; no effervescence, rare 1-2 mm carbonate nodules; 20% pebbles, 25% cobbles, 10% boulders by volume; 10% highly weathered clasts, very abrupt broken boundary.

Bca 46-80 cm. Light yellow orange (7.5YR 8/3) dry; (7.5YR 8/4) moist; very weak medium angular blocky; gravelly sandy loam;

hard (dry), very slightly sticky and nonplastic (wet); continuous colloidal stains on mineral grains, continuous thin argillans lining pores; violently effervescent; most of matrix impregnated by carbonate (white, 8/0 dry), carbonate stage III+, rare zones of carbonate stage IV in upper 10 cm of horizon; 20% pebbles, 25% cobbles, and 10% boulders by volume; 30% highly weathered clasts; gradual broken boundary.

Cca 80-171+ cm. Dull orange (5YR 6/4) dry, bright reddish brown (5YR 5/7) moist; loamy sand; massive; slightly hard (dry), very slightly sticky and nonplastic (wet); continuous colloidal stains on mineral grains, continuous thin argillans lining pores; slight to strong effervescence; many 5-10 mm horizontal carbonate seams, carbonate stage I+ to II; 15% pebbles by volume.

## SOIL PROFILE DESCRIPTION 16

Classification: Typic Eutroboralf

Location: Mountain Home Quad.; SE1/4, NW1/4, sec. 16, T. 1 N., R. 5 W.

Physiographic position: Sharp crest of low, narrow moraine; 2431 m (7970 ft) elevation.

Topography: Slightly undulating surface sloping steeply on either side of site; 1° slope to N at pit.

Drainage: Well drained.

Vegetation: Sagebrush, grasses, manzanita, and leafy ground plants.

Parent material: Till.

Age: Bull Lake.

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 5, 1980.

A 0-18 cm. Grayish brown (5YR 6/2 to 7.5YR 6/2) dry, dark brown (7.5YR 3/3) moist; sandy loam+; very weak fine subangular blocky; soft (dry), very slightly sticky and slightly plastic (wet); no effervescence; 15% pebbles, 10% cobbles, 1% boulders by volume; clear wavy boundary.

B1 18-34 cm. Dull orange (5YR 7/3) to pale reddish orange (2.5YR 7/3) dry, dull reddish brown (5YR 5/4) to dull reddish brown (2.5YR 5/4) moist; sandy loam; massive; soft to slightly hard (dry), very slightly sticky and nonplastic (wet); very few thin argillans lining pores, common thin argillan bridges; no effervescence; 15% pebbles, 10% cobbles, 1% boulders by volume; clear wavy boundary.

B21t 34-68 cm. Bright brown (2.5YR 5/6) dry, reddish brown (2.5YR 4/6) moist; sandy clay loam-; weak to moderate medium angular blocky; very hard (dry), sticky and plastic (wet); continuous colloidal stains on grains, continuous moderately thick argillan bridges, continuous moderately thick argillans lining pores, many moderately thick argillans on ped faces and clasts; no effervescence; 15% pebbles, 10% cobbles, 1% boulders; gradual wavy boundary.

B22t 68-119 cm. Orange (2.5YR 6/6) dry, bright brown (2.5YR 5/6) moist; sandy clay loam-; very weak medium angular blocky; hard (dry), slightly sticky and slightly plastic (wet); continuous colloidal stains on mineral grains, few thin argillans lining pores, many thin argillan bridges; common thin argillans on

clasts; 15% pebbles, 10% cobbles, 1% boulders by volume; gradual wavy boundary.

B23t 119-157 cm. Orange (2.5YR 6/5) dry, bright brown (2.5YR 5/5) moist; sandy loam; massive; slightly hard (dry), slightly sticky and nonplastic (wet); continuous colloidal stains on mineral grains, common thin argillan bridges, very few thin argillans on clasts; 15% pebbles, 10% cobbles, 1% boulders by volume; abrupt wavy boundary.

C 157-172+ cm. Dull orange (5YR 7/4) dry, bright reddish brown (5YR 5/6 to 5YR 5/8) sand; massive; soft to slightly hard (dry), very slightly sticky and nonplastic; common colloidal stains on mineral grains; 15% pebbles, 10% cobbles, 1% boulder by volume.

## SOIL PROFILE DESCRIPTION 17

Classification: Typic Argiboroll

Location: Mountain Home Quad.; NE1/4, NE1/4, sec. 15, T. 1 N., R. 5 W.

Physiographic position: Sharp crest of round morainal hill; 2368 m (7763 ft) elevation.

Topography: Slightly undulating surface sloping steeply on all sides; 1° slope to E at pit.

Drainage: Well drained.

Vegetation: Sagebrush, grasses, manzanita, and leafty ground plants.

Parent material: Till - ablation and flowtill?

Age: Bull Lake.

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 5, 1980.

Ail 0-21 cm. Grayish brown (7.5YR 5/2) dry, brownish black (7.5YR 3/2); gravelly sandy loam-; very weak medium subangular blocky (near clasts); soft (dry), nonsticky and nonplastic (wet); no effervescence; 20% pebbles, 15% cobbles, 8% boulders by volume; <1% highly weathered clasts; gradual wavy boundary.

A12 21-52 cm. Dull orange (7.5YR 7/3) dry, brown (7.5YR 4/3) to dull reddish brown (5YR 4/3) moist; gravelly loamy sand+; massive; soft (dry), nonsticky and nonplastic; common colloidal stains on mineral grains; no effervescence; 20% pebbles, 15% cobbles, 8% boulders by volume; <1% highly weathered clasts; gradual wavy boundary.

B2t 52-107 cm. Orange (5YR 6/8) dry, bright reddish brown (5YR 5/8) moist; sandy loam; very weak very coarse angular blocky; hard (dry), slightly sticky and nonplastic; continuous colloidal stains on mineral grains, common thin argillan bridges, few thin argillans lining pores; clay not evenly distributed, concentrated in 2-8 mm seams; no effervescence; 15% pebbles, 15% cobbles, 8% boulders by volume; <1% highly weathered clasts; abrupt smooth boundary.

C1ca 107-127 cm. White (8/0) to pale orange (5YR 8/3) dry, light gray (5YR 8/2) to dull orange (5YR 7/3) moist; sandy clay loam; weak coarse platy; friable (moist), sticky and plastic (wet); violently effervescent; carbonate stage II+, common carbonate bridges; discontinuous, random, inped, simple pores; 15% pebbles, 15% cobbles, 8% boulders by volume, 0% to 2% highly weathered clasts; clear wavy boundary.

C2 127-161 cm. Pale orange (5YR 8/3) to dull orange (5YR 7/4) dry, dull orange (5YR 6/4) moist; few 1-4 mm orange (5YR 6/8) seams, moist; loamy sand; massive; soft to slightly hard (dry), nonsticky and nonplastic (wet); continuous colloidal stains on mineral grains, common argillan bridges in seams; no effervescence, upper 5 cm slightly effervescent; carbonate stage I-; 15% pebbles, 15% cobbles, 8% boulders by volume; <1% highly weathered clasts; abrupt smooth boundary.

C3 161-184+ cm. Dull orange (5YR 6/4) with zones of orange (5YR 6/6 to 6/8) dry, dull orange (5YR 7/4) with zones of orange (5YR 6/6 to 6/8) moist; sand; massive; loose (dry), nonsticky and nonplastic (wet); no effervescence; 15% pebbles, 15% cobbles, 8% boulders by volume; <1% highly weathered clasts.

## SOIL PROFILE DESCRIPTION 18

Classification: Typic Ustochrept

Location: Mountain Home Quad.; NW1/4, NW1/4, sec. 13, T. 1 N., R. 5 W.

Physiographic position: Center of flat glaciofluvial channel (300 m wide); 2257 m (7400 ft) elevation.

Topography: Smooth surface sloping 1° SE.

Drainage: Well drained.

Vegetation: Grass and scattered sagebrush.

Parent material: Glaciofluvial sands and silts.

Age: Pinedale.

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 4, 1980.

A11 0-11 cm. Dull orange (7.5YR 6/4) dry, dark brown (7.5YR 3/4); loamy sand-; strong coarse platy; soft (dry), nonsticky and nonplastic (wet); no effervescence; abrupt wavy boundary.

A12 11-26 cm. Dull orange (7.5YR 6/4) dry, dark brown (7.5YR 3/4); loamy sand; massive; soft (dry), nonsticky and nonplastic (wet); no effervescence, clear smooth boundary.

B1 26-59 cm. Dull brown (7.5YR 5/4) dry, brown (7.5YR 4/4) moist; loamy sand+; massive; soft (dry), nonsticky and nonplastic (wet); common colloidal stains on mineral grains; no effervescence; clear smooth boundary.

B2 59-87 cm. Dull orange (5YR 6/4) to orange (5YR 6/6) dry, brown (7.5YR 4/4) to brown (7.5YR 4/6) moist; many, large, faint mottles, orange (5YR 6/6) dry; loamy sand+; massive; soft (dry), very slightly sticky and nonplastic (wet); many colloidal stains on mineral grains; no effervescence; gradual irregular boundary.

B3 87-114 cm. Orange (7.5YR 7/6) dry, bright brown (7.5YR 5/6) moist; many large faint mottles, orange (7.5YR 6/8) dry; loamy sand+; massive; soft (dry), very slightly sticky and nonplastic (wet); many colloidal stains on mineral grains; no effervescence; very abrupt smooth boundary.

IICox 114-129 cm. Light gray (2.5Y 8/2) to pale yellow (2.5Y 8/3) moist; many fine prominent mottles, orange (7.5YR 6/8) moist; silty clay to loam; weak to moderate fine to medium angular

blocky in clay zones, massive otherwise; slightly sticky to sticky and slightly plastic to plastic (wet); few thin argillas lining pores within clay zones; very slightly effervescent in clay zones; well stratified, 1-2 cm. beds; very abrupt smooth boundary.

IIIC 129-175+ cm. Dull orange (5YR 7/3) to dull brown (7.5YR 6/3) moist; sand; massive; nonsticky and nonplastic (wet); no effervescence; well stratified, 1-10 cm beds.

## SOIL PROFILE DESCRIPTION 19

Classification: Typic Ustorthent

Location: Mountain Home Quad.; NW1/4, NE1/4, sec. 11, T. 1 N., R. 5 W.

Physiographic position: Crest of round morainal hill; 2335 m (7655 ft) elevation.

Topography: Slightly undulating bouldery surface sloping steeply on all sides; 0° to 1° slope to SE at pit.

Drainage: Well drained.

Vegetation: Sagebrush, short grasses, and manzanita.

Parent material: Till.

Age: Pindale.

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 4, 1980.

A11 0-27 cm. Dull brown (7.5YR 6/3) dry, brown (7.5YR 4/3) moist; gravelly sandy loam; weak coarse subangular blocky; soft (dry), very slightly sticky and nonplastic (wet); no effervescence; 30% pebbles, 15% cobbles, and 2% boulders by volume; <1% highly weathered clasts; clear wavy boundary.

A12 27-50 cm. Dull orange (7.5YR 7/3) dry, dull brown (7.5YR 5/4) moist; gravelly loamy sand-; massive; soft to hard (dry), nonsticky and nonplastic (wet), no effervescence; 25% pebbles, 15% cobbles, and 2% boulders by volume; <1% highly weathered clasts; gradual wavy boundary.

C1 50-70 cm. Light yellow orange (7.5YR 8/3) to pale orange (5YR 8/3) dry, dull orange (7.5YR 7/4 to 5YR 7/4) moist; gravelly loamy sand-; massive; soft to loose (dry), nonsticky and nonplastic (wet); no effervescence; 20% pebbles, 15% cobbles, and 2% boulders by volume; <1% highly weathered clasts; gradual irregular boundary.

C2 70-98 cm. Dull orange (5YR 8/4) dry, orange (5YR 6/6), moist; gravelly loamy sand-; massive; loose (dry), nonsticky and nonplastic (wet); no effervescence; 20% pebbles, 15% cobbles, and 2% boulders by volume; <1% highly weathered clasts; gradual irregular boundary.

C3 98-110 cm. Pale orange (5YR 8/3) dry, dull orange (5YR 6/4) moist; gravelly sand+; massive; loose (dry), nonsticky and nonplastic (wet); no effervescence; very few thin carbonate

coatings on clasts, carbonate stage I-; 20% pebbles, 15% cobbles, and 2% boulders by volume; <1% highly weathered clasts; gradual irregular boundary.

C4 140-162+ cm. Pale orange (5YR 8/4) dry, orange (5YR 7/6) moist; gravelly sand+; massive; loose (dry), nonsticky and nonplastic (wet); matrix violently effervescence; thin discontinuous carbonate coatings on clasts, carbonate stage I-; 20% pebbles; 15% cobbles and 2% boulders by volume; <1% highly weathered clasts.

## SOIL PROFILE DESCRIPTION 20

Classification: Typic Haploboroll

Location: Lake Fork Mtn. Quad.; SW1/4, SW1/4, sec. 2, T. 1 N., R. 5 W.

Physiographic position: Crest of narrow recessional moraine; 2338 m (7655 ft) elevation.

Topography: Slightly undulating bouldery surface sloping steeply to E and W; 1° slope to S at pit.

Drainage: Well drained.

Vegetation: Scattered sagebrush and grass.

Parent material: Till.

Age: Pinedale.

Remarks: Percentages are visually estimated..

Sampled by: A. R. Nelson, June 4, 1980.

A11 0-18 cm. Dull brown (7.5YR 5/3) dry, dark brown (7.5YR 3/3) moist; gravelly sandy loam; weak medium to coarse subangular blocky (between clasts); soft to loose (dry), nonsticky and nonplastic (wet), no effervescence; 20% pebbles, 15% cobbles by volume; clear wavy boundary.

A12 18-32 cm. Dull orange (5YR 7/4) dry, bright reddish brown (5YR 5/5) moist; gravelly sandy loam; massive; soft to loose (dry); nonsticky and nonplastic (wet); colloidal stains on mineral grains; strongly effervescent in matrix, carbonate stage I-; 20% pebbles, 15% cobbles, 1% boulders by volume; abrupt irregular boundary.

C1ca 32-54 cm. Dull orange (5YR 7/4) dry, dull orange (5YR 6/4 to 7.5YR 6/4) moist; gravelly sandy loam; massive to weak fine to medium angular blocky; soft (dry), very slightly sticky and nonplastic (wet); very few thin argillans lining pores, very few thin argillans on clasts; carbonates pale orange (5YR 8/3 to 5YR 8/4) dry, dull orange (5YR 7/4) moist, carbonates slightly hard (dry), carbonate rinds 1-3 mm thick underclasts, carbonate stage II; 20% pebbles, 15% cobbles, 1% boulders by volume; clear wavy boundary.

C2 54-154+ cm. Pale orange (5YR 8/4) dry, orange (5YR 6/5) moist; gravelly sandy loam; massive; soft to loose (dry), very slightly sticky and nonplastic (wet); few colloidal stains on mineral grains; violently effervescent; carbonate in discontinuous coatings, carbonate stage 0 to I-; 20% pebbles, 15% cobbles, 1% boulders by volume.

## SOIL PROFILE DESCRIPTION 21

Classification: Typic Ustochrept

Location: Altonah Quad.; SW1/4, NE1/4, sec. 32, T. 1 N., R. 4 W.

Physiographic position: Center of slightly channeled fluvial terrace; 2123 m (6960 ft) elevation.

Topography: Smooth surface, 0° slope.

Drainage: Well drained.

Vegetation: Sagebrush, grasses, and scattered cedar.

Parent material: Glaciofluvial gravel.

Age: Pinedale.

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 4, 1980.

A1 0-24 cm. Dull brown (7.5YR 5/4) dry, dark brown (7.5YR 3/4) moist; gravelly loamy sand, single grain to very weak fine to medium subangular blocky; loose to soft (dry); nonsticky and nonplastic (wet); no effervescence; 50% pebbles, 10% cobbles, and 1% boulders by volume; no highly weathered clasts; clear irregular boundary.

B2 24-58 cm. Orange (7.5YR 6/6) to dull orange (5YR 6/4) dry, brown (7.5YR 4/6) to reddish brown (5YR 4/5) moist; gravelly loamy sand+; very weak fine to medium angular blocky; soft (dry), nonsticky and nonplastic (wet); many colloidal stains on mineral grains, few thin argillan bridges; no effervescence; 50% pebbles, 15% cobbles, 5% boulders by volume; no highly weathered clasts; clear wavy boundary.

C1ox 58-124 cm. Bright brown (7.5YR 5/5) to bright reddish brown (5YR 5/5) dry, brown (7.5YR 4/5) to reddish brown (5YR 4/6) moist; gravelly cobbly sand+; single grain; loose (dry), nonsticky and nonplastic (wet); many colloidal stains on mineral grains; no effervescence; very thin discontinuous carbonate coatings on the bottom of clasts, carbonate stage I-; 40% pebbles, 30% cobbles, 5% boulders by volume; no highly weathered clasts; gradual wavy boundary.

C2 124-156+ cm. Bright reddish brown (5 YR 5/6) dry, reddish brown (5 YR 4/6) wet; gravelly cobbly sand+; single grain; loose (dry); nonsticky and nonplastic (wet); common colloidal stains on mineral grains; no effervescence; very thin discontinuous carbonate coatings on the bottom of clasts, carbonate

stage I-; 40% pebbles, 30% cobbles, 5% boulders by volume; no highly weathered clasts.

## SOIL PROFILE DESCRIPTION 22

Classification: Typic Eutroboralf

Location: Altonah Quad.; NW1/4, SW1/4, sec. 33, T. 1 N., R. 5 W.

Physiographic position: Center of wide (1 km) glaciofluvial terrace; 2128 m (6978 ft) elevation.

Topography: Smooth surface, 0° slope.

Drainage: Well drained.

Vegetation: Sagebrush, grasses, and scattered cedar.

Parent material: Glaciofluvial gravel.

Age: Bull Lake.

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 4, 1980.

A11 0-6 cm. Dull orange (7.5YR 6/4) dry, brown (7.5YR 4/4) moist; gravelly loamy sand; weak medium to coarse subangular blocky to weak very coarse platy; soft (dry), nonsticky and nonplastic (wet); no effervescence; 25% pebbles, 1% cobbles by volume; no highly weathered clasts; abrupt irregular boundary.

B1 6-19 cm. Dull reddish brown (5YR 5/4) dry, dark reddish brown (5YR 3/4) moist; gravelly sandy loam+; massive; loose to soft (dry), slightly sticky and very slightly plastic (wet); no effervescence; 50% pebbles, 10% cobbles by volume; no highly weathered clasts; abrupt irregular boundary.

B21t 19-32 cm. Bright reddish brown (5YR 5/6 to 5YR 5/7) dry, reddish brown (5YR 4/6) moist; gravelly sandy clay-; weak medium angular blocky; hard (dry), sticky and plastic (wet); continuous thin argillan bridges, many thin argillans inside pores, many moderately thick argillans on ped faces and clasts, argillans are dull reddish brown (5YR 4/4) dry; no effervescence; 60% pebbles, 10% cobbles by volume; no highly weathered clast; clear irregular boundary.

B22t 32-58 cm. Bright brown (2.5YR 5/6) to reddish brown (2.5YR 4/6) dry, reddish brown (2.5YR 4/6) moist; gravelly sandy clay; weak to moderate medium to coarse angular blocky; hard (dry), sticky and plastic (wet); continuous moderately thick argillans inside pores, continuous moderately thick argillans on ped faces and clasts, argillans are reddish brown (5YR 4/8) dry; no effervescence; 60% pebbles, 10% cobbles, and 2% boulders by volume; no highly weathered clasts; gradual wavy boundary.

B3 58-125 cm. Bright brown (2.5YR 5/7) dry, reddish brown (2.5YR 4/7 to 5YR 4/7) moist; gravelly loamy sand; very weak medium coarse angular blocky; soft (dry), very slightly sticky and nonplastic (wet); continous colloidal stains on mineral grains, few thin argillan bridges, common thin argillans on ped faces and clasts; no effervescence; 60% pebbles, 10% cobbles, and 10% boulders by volume; no highly weathered clasts; gradual wavy boundary.

C 125-169+ cm. Bright brown (2.5YR 5/7) dry, bright brown (2.5YR 5/6) moist; gravelly sandy+; single grain; loose to soft (dry), nonsticky and nonplastic (wet); continuous colloidal stains on mineral grains; no effervescence; 60% pebbles, 10% cobbles, and 10% boulders by volume; no highly weathered clasts.

## SOIL PROFILE DESCRIPTION 23

Classification: Typic Eutroboralf

Location: Altonah Quad.; NW1/4, NE1/4, sec. 23, T. 1 S., R. 4 W.

Physiographic position: Edge of dissected strath glaciofluvial terrace; 2091 m (6856 ft) elevation.

Topography: Smooth surface, 0° slope.

Drainage: Well drained.

Vegetation: Sagebrush, grasses, scattered juniper and pine.

Parent material: Glaciofluvial gravels.

Age: Pre-Bull Lake?

Remarks: Percentages are visually estimated.

Sampled by: A. R. Nelson, June 10, 1980.

A1 0-16 cm. Dull brown (7.5YR 5/4) dry, dark brown (7.5YR 3/4) moist; gravelly sandy loam; very weak fine to medium subangular blocky; soft (dry), nonsticky and nonplastic (wet); strongly effervescent; 2 mm to 6 mm carbonate nodules, carbonate stage I+; 20% pebbles, 10% cobbles, and 2% boulders by volume; no highly weathered clasts; clear wavy boundary.

B2 16-35 cm. Dull orange (7.5YR 6/4) dry, brown (7.5YR 4/4) moist; gravelly sandy loam; massive to very weak fine angular blocky; loose to soft (dry), very slightly sticky and nonplastic (wet); common thin argillan bridges, few thin to moderately thick argillans lining pores; violently effervescent; 1 to 2 cm carbonate nodules, light yellow orange (7.5YR 8/4) dry, orange (7.5YR 7/6) moist, carbonate stage II; 20% pebbles, 10% cobbles, and 2% boulders by volume; no highly weathered clasts; abrupt broken boundary.

B3ca 35-58 cm. Dull orange (7.5YR 7/3) dry, dull brown (7.5YR 5/4) moist; gravelly sandy loam-; very weak medium angular blocky; slightly hard (dry), nonsticky and nonplastic (wet); very few thin argillan bridges; violently effervescent; many thin carbonate bridges, common thin carbonate lining pores, light yellow orange (7.5YR 8/3) dry, light yellow orange (7.5YR 8/4) moist, carbonate stage II; 20% pebbles, 10% cobbles, and 2% boulders by volume; no highly weathered clasts; abrupt broken boundary.

IIC1cab 58-83 cm. White (8/0) dry, white (8/0) to light yellow orange (7.5YR 8/3) moist; strong medium to coarse platy; extremely

hard (dry); violently effervescent; 1 to 8 mm carbonate rinds, carbonate stage II+ to III; 25% pebbles, 25% cobbles, and 10% boulders by volume; 30% highly weathered clasts; gradual broken boundary.

IIC2cab 83-158+ cm. Light gray (2.5Y 8/2) to olive yellow (5Y 6/3) dry, light yellow (2.5Y 7/3) to light yellow (5Y 7/3) moist; cobbly gravelly sandy clay loam; weak to moderate medium to coarse angular blocky; hard (dry), sticky and very slightly plastic (wet); few moderately thick clay bridges; violently effervescent; carbonate continuous and thick, white (8/0), carbonate stage II+; 30% pebbles, 40% cobbles, 10% boulders by volume; 5% highly weathered clasts.

# APPENDIX C

# STRATIGRAPHIC SECTION DESCRIPTIONS

Stratigraphic Section Description 1

Gravel Pit at Mouth of Antelope Canyon, Duchesne Co., Utah

Location: SW1/4, NE1/4, SE1/4, sec. 9, T. 4 S., R. 3 W.; 10 mi E. of Duchesne, Utah.

Described by: A. R. Nelson, June 8, 1980. All colors are dry, percentage values visually estimated, angularity scale of Powers (1953).

| Depth (m) | Unit | Description |
|---|---|---|
| 0-1.2 | E | Sandy gravel; light gray (2.5Y 8/2) (dry); 70% pebbles (>90% <3 cm long) and 2% cobbles (max 12 cm long); almost entirely flat and elongate clasts of sandstone, limestone, mudstone, and chert locally derived from Uinta Fm.; angularity (Powers, 1953) 1 = 2, 2 = 4, 3 = 27, 4 = 16, 5 = 1, 6 = 0; weakly stratified with lenticular to interlayered, discontinuous, even, uniform (3-10 cm thick), nonparallel beds; matrix of sandy silt loam with weak angular blocky structure, matrix infiltration shown by thicker coatings on top of clasts and moderately thick cutans between sand grains and lining pores; weak to moderate reaction with HCl; clear wavy boundary; upper contact of unit disturbed by bulldozer. |
| 1.2-2.3 | D | Fine to coarse sands (10% of unit) and very fine sands (40%) interbedded with sandy silts (50%); light gray (2.5Y 8/2) to pale yellow (2.5Y 8/3) (dry) with streaks of iron staining on joints, root casts, and coarser beds, bright yellowish brown (10YR 7/6) to brown (7.5YR 3/8); well stratified with interlayered, even, uniform, parallel beds 1 to 15 cm thick; planar cross-stratification in some fine sand beds, curved, tangential forsets (5 to 8 cm wide, 2-4 cm thick) in coarse sand lenses (5 to 10 cm thick); some clay-silt drapes; silt beds have moderate fine angular blocky structure and discontinuous concentrations of stage II carbonate (1-2 cm thick) near upper bed contacts; moderate to strong HCl reaction; abrupt smooth boundary. |
| 2.3-3.0 | C | Massive fine sandy silt to clayey silt; light yellow orange (7.5YR 8/3) to dull orange (7.5YR 6/4) with common vertical mottles, orange (7.5YR 6/8); moderate very coarse prismatic structure; |

| | | |
|---|---|---|
| | | 1 to 10 cm thick clayey silt bed near top of unit and 2 to 3 cm clayey silt beds near bottom of unit have stage I- carbonate development, moderately thick carbonate lining some pores; moderate HCl reaction; abrupt smooth boundary. Samples of clayey units for paleomagnetic analysis. |
| Depth (m) | Unit | Description |
| 3.0-3.5 | B | Massive very fine to silty fine sand; light yellow orange (7.5YR 8/3) to dull orange (7.5YR 7/5) with rare vertical streaks, orange (7.5YR 6/8); weak very coarse prismatic structure; weak HCl reaction; abrupt wavy to irregular boundary (probable unconformity). Dispersed gastropods throughout unit including Zonitoides arboreus, Euconulus fulvus, Discus cronkhitei, Vallonia cyclophorella, V. pulchella, Pupilla blandi, Gastrocopta holzingeri (E. Evanoff, written comm., 1980). |
| 3.5-4.5 | A | Coarse gravel; pale orange (5YR 8/3) to light yellow orange (7.5YR 8/3) with some Fe and Mn staining in upper 20 cm, yellow orange (7.5YR 7/8); 50% pebbles, 30% cobbles, and 2% boulders (max 40 cm) unevenly distributed in lenses; weak stratification with even, uniform, discontinuous, parallel beds 50-100 cm thick; angularity 1 = 0, 2 = 0, 3 = 1, 4 = 7, 5 = 30, 6 = 12; lithology mostly Uinta Mt. Group quartzite with some limestone; matrix medium to coarse sand with discontinuous moderately thick silt coatings on top of clasts; HCl reaction weak to none; very few thin carbonate coating bottom of clasts in upper 20 cm; slump from 4.5 m to floor of pit at 6.9 m. |

# APPENDIX D

# TECHNICAL INFORMATION REGARDING THE MICROSEISMIC SURVEY

## MICROSEISMIC INVESTIGATION

In an attempt to provide additional data pertaining to earthquake hazards near USBR damsites along the south flank of the Uintas, a microseismic survey was conducted. This survey involved about 6 months of monitoring for microearthquakes along the south flank of the Uinta Mountains in the vicinity of Taskeech and Upper Stillwater damsites during the months of May through October 1980. The specific details of this microearthquake investigation will be discussed below beginning with a section on data acquisition which will describe the type of instrumentation used and the procedures followed in the field. This will be followed by a description of the data reduction techniques. Results of this study can be found in section 4.1.

### Data Acquisition

The instrumentation used during this study included up to 12 short-period, high-gain, portable seismograph systems. Each field unit consisted of a W. F. Sprengnether Instrument Company model MEQ 800 amplifier/recorder, a Mark Products L-4C seismometer, and an external $\pm$12-volt gel-cell battery pack.

The MEQ 800 amplifier/recorder is a self-contained, weatherproof instrument, weighing about 14.5 kg, that uses a metal stylus to write records on drum-mounted smoked paper. The drum rotation and stylus translation speeds are variable and allow for up to 16 days of continuous recording before requiring a change of paper. Record timing marks at intervals of seconds, minutes, and hours are provided by an internal crystal clock with a manufacturer's quoted average stability of about $\pm 5 \times 10^{-8}$/day (0.004320 second/day). A portable crystal clock (Sprengnether model TS-400) was used to periodically reset the internal clocks.

Optional signal conditioning is provided by an attenuator, high- and low-cut filters, and a maximum pen deflection limiter. Maximum amplification occurs at a dial setting of 120 dB. Gains can be reduced in 6-dB increments down to a setting of 60 dB. Available high-cut filter settings are 5, 10, 30, and 70 (out) Hz. Low-cut filters can be set to 0.3 (out), 5, 10, and 30 Hz. The manufacturer's quoted typical voltage sensitivities for various filter combinations at maximum gain are shown on figure D.1. The voltage response characteristics for the amplifier/recorder are shown on figure D.2. The stylus can be limited to maximum deflections of 5, 10, or 25 mm.

The seismometers used to detect ground motions were Mark Products model L-4C 1-Hz vertical component geophones. The L-4C is a velocity responsive transducer with a flat frequency response from about 2.5 to 50 Hz. These very sensitive instruments are ideal for detecting short-period, low-amplitude seismic waves typically generated by microearthquakes. They can easily be saturated by noise, however, and therefore require extremely quiet sites for optimum performance. The maximum sensitivity characteristics for the combined MEQ 800/L-4C seismograph system is shown in figure D.3.

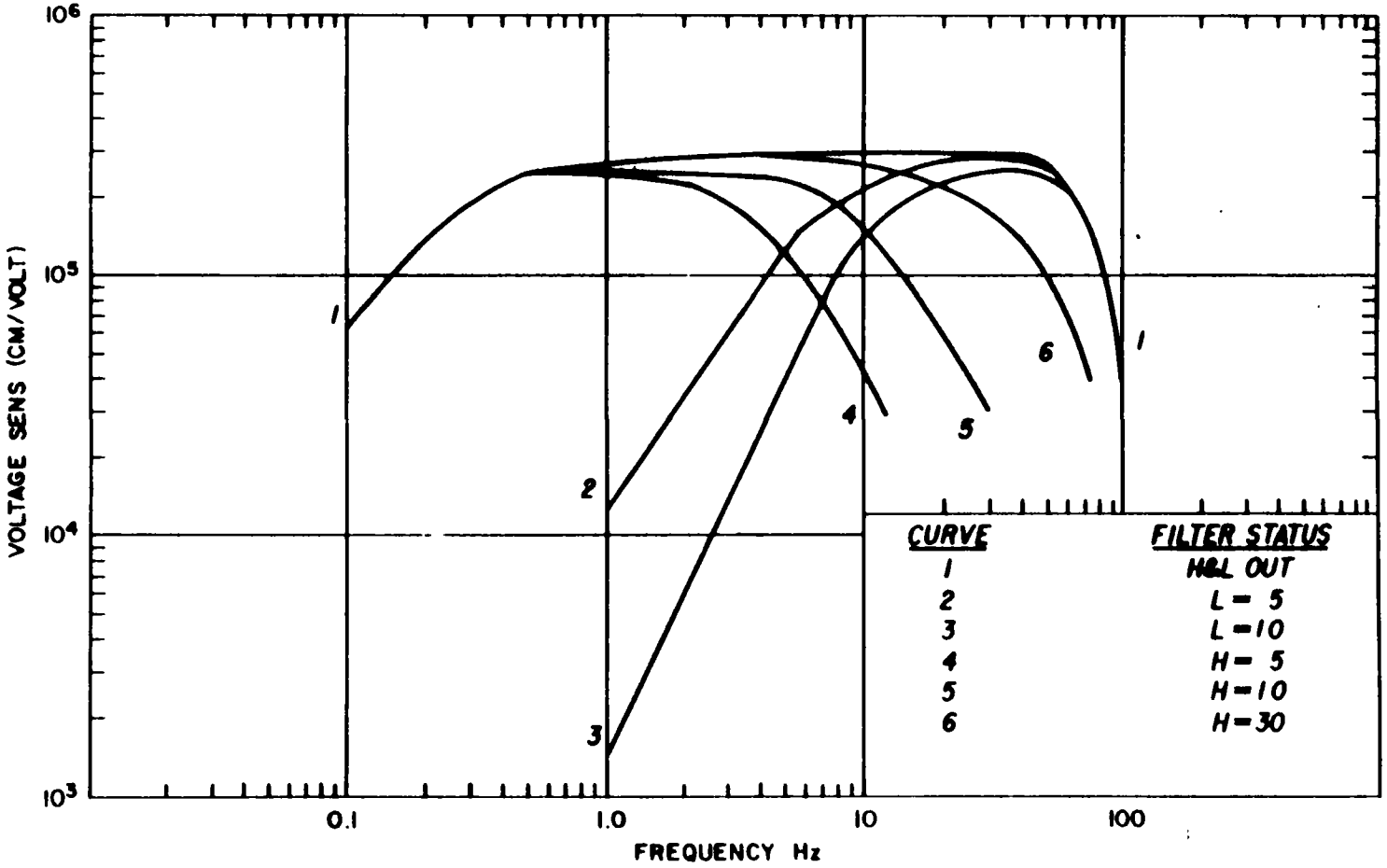



Figure D.1. Typical voltage sensitivity at maximum gain for the MEQ 800 amplifier/recorder.

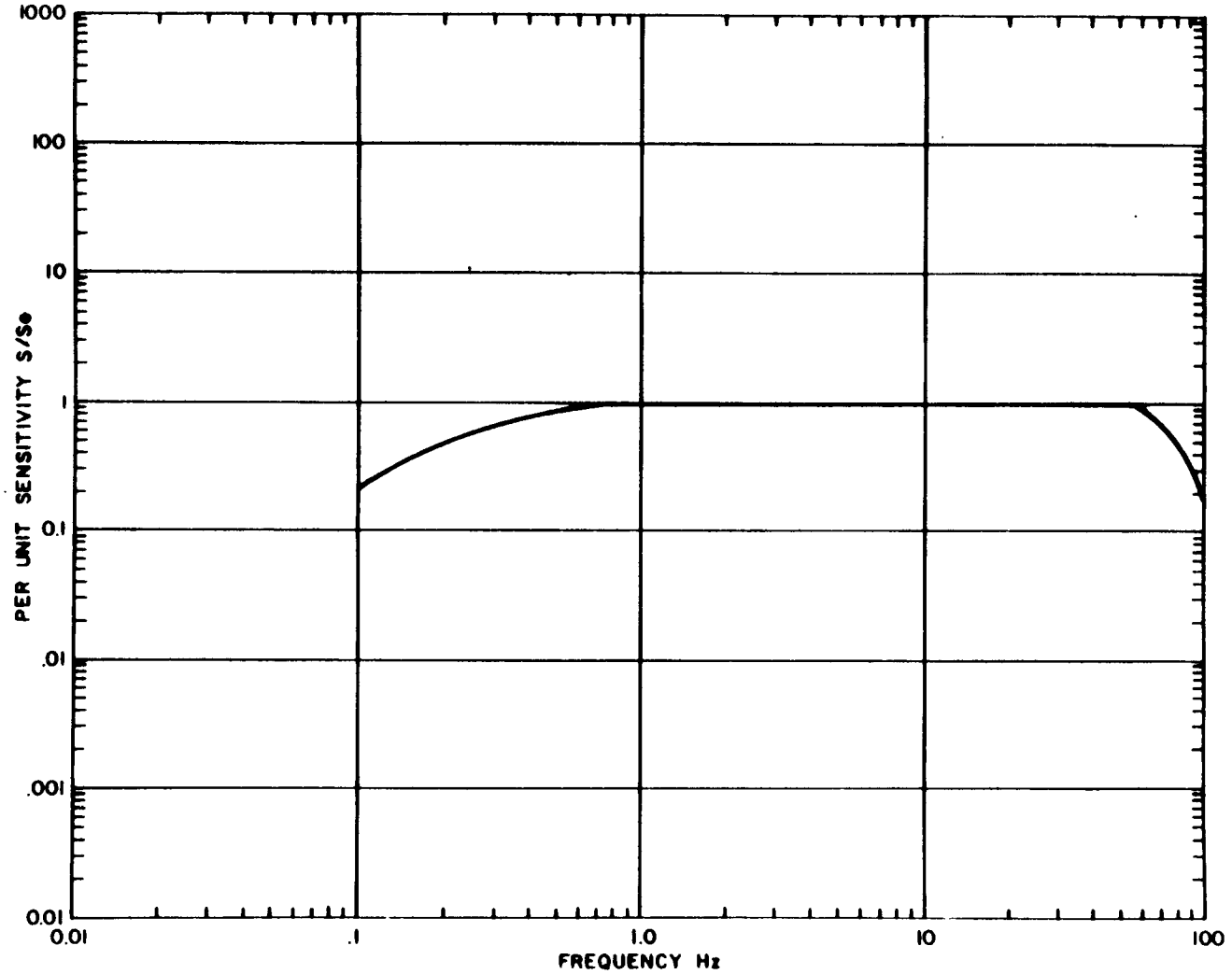



Figure D.2. Voltage response characteristics for the MEQ 800 amplifier/recorder (normalized to unity, both filters "OUT").

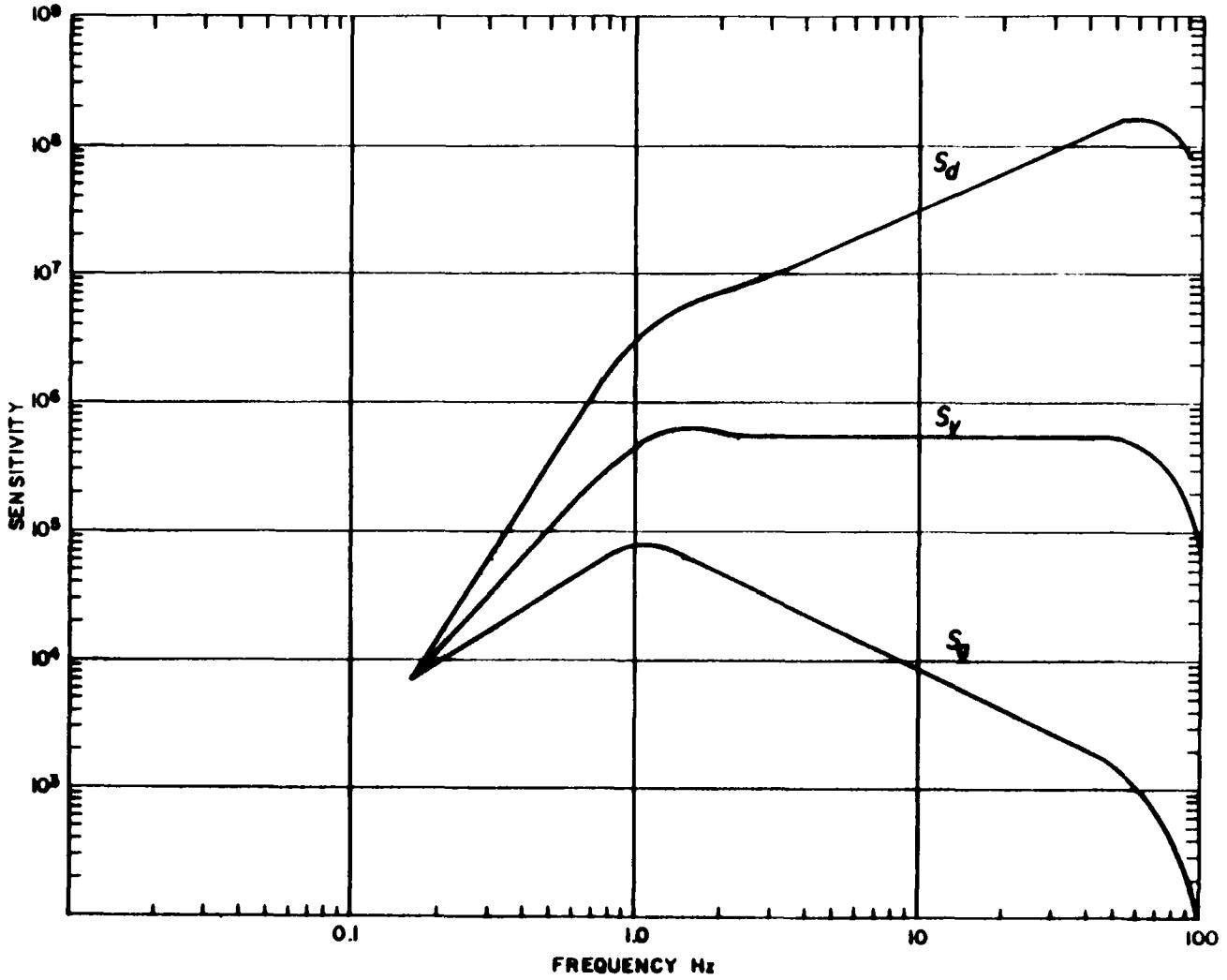



Figure D.3. Maximum sensitivity for the MEQ 800/L-4C seismograph system. Displacement - Sd cm/cm, Velocity - Sv cm/cm/sec, Acceleration - Sa cm/cm/sec$^2$.

The microseismic monitoring commenced the first week of May 1980 with the installation of three seismographs. Three more seismographs were operational by May 19, and a seventh station, initially intended to be operational in May, experienced mechanical problems and was finally installed on July 11, after being repaired by the manufacturer. Four additional instruments on loan from the USGS were operational by the end of August, and the 12th seismograph, also USGS-owned, was installed on September 25, 1980. The microseismic array, encompassing about 660 $km^2$, operated until November 1, 1980.

The possible station distributions and configurations were limited by several factors including large study area, mountainous and inaccessible terrain, and the presumed availability of only seven seismographs with which to sample the seismicity. After several weeks of station readjustments, a network configuration was arrived at that was believed to be capable of providing sufficient coverage along the South Flank fault as well as the adjacent area to the south. The array consisted of stations BKN, LFK, PGN, CWH, RCK, and YLG, as shown in plate 2.

When the seventh seismograph was repaired and returned, it was installed at station MLK. The drum rotation speed was set to record at 120 mm per minute, thereby requiring daily record changes. Most of the locally recorded seismicity was originating in the epicentral area of the September 30, 1977, earthquake, hereinafter referred to as the Bear Wallow area. Some activity, however, was originating outside the network to the west. The array was readjusted in August when the seismograph at station LFK was moved to station RCN and the seismograph at station MLK was moved to station HCN. This new station distribution significantly increased the time required to change records each day; therefore, the recording speed was reduced to 60 mm per minute and records changed every 2 days.

The consensus at this time was that this station array would suffice for the remainder of the study. The availability of first four, and later five, seismographs from the USGS, however, provided a unique opportunity to increase the station coverage in the Bear Wallow area. This resulted in the occupation of stations TFL, BAR, BWL, CSP, PTR, WLD, and KNF. A total of 19 stations was occupied during the entire study.

The actual site selection was greatly dependent on the availability of competent outcrops, road accessibility, wind noise, and cultural effects, including vehicular travel, fence lines, irrigation canals, animal grazing patterns, and possible hunter and camper intervention. Most seismometers were cemented to bedrock outcrops to assure adequate coupling, and in all cases the seismometers and cables were buried to reduce wind-generated noise. In the Bear Wallow area, the lack of bedrock outcrops due to the predomenance of till, outwash, and alluvium required coupling with these surficial deposits and resulted in lower gains. This did not present a problem, however, due to the close proximity of those stations to the epicenters of those earthquakes they were intended to detect. The pertinent station parameters are listed in table D.1. Figure D.4 illustrates the daily operational status of the occupied seismograph stations.

Table D.1. - Seismograph station parameters

| STN | N. Lat | W. Long | Elev (m) | Date Open | Date Closed | Days Run | No. P Picks | Gain** (dB) | Outcrop |
|---|---|---|---|---|---|---|---|---|---|
| IND | 40°30.22' | 110°21.94' | 2353 | 5/6/80 | 5/24/80 | 18 | 10 | 90 | Sandstone* |
| PWS | 40°28.38' | 110°30.55' | 2432 | 5/7/80 | 5/28/80 | 21 | 10 | 90 | Sandstone* |
| BKN | 40°23.98' | 110°28.66' | 2243 | 5/7/80 | 11/1/80 | 178 | 64 | 90 | Sandstone |
| RCK | 40°33.47' | 110°42.35' | 2444 | 5/16/80 | 11/1/80 | 169 | 45 | 102 | Shale* |
| LFK | 40°24.78' | 110°21.60' | 2097 | 5/18/80 | 8/16/80 | 90 | 12 | 84 | Sandstone* |
| YLG | 40°31.63' | 110°21.87' | 2572 | 5/19/80 | 11/1/80 | 166 | 43 | 90 | Boulder* |
| PGN | 40°28.23' | 110°30.07' | 2457 | 5/27/80 | 11/1/80 | 158 | 69 | 96 | Sandstone* |
| CWH | 40°25.28' | 110°42.79' | 2199 | 5/29/80 | 10/30/80 | 154 | 55 | 96 | Sandstone* |
| MLK | 40°34.67' | 110°33.05' | 2908 | 7/11/80 | 8/16/80 | 36 | 11 | 96 | Sandstone* |
| HCN | 40°37.10' | 110°26.80' | 3197 | 8/17/80 | 10/30/80 | 74 | 44 | 10 | Quartzite* |
| RCN | 40°30.63' | 110°53.97' | 2810 | 8/18/80 | 10/31/80 | 74 | 14 | 96 | Limestone* |
| PTR | 40°31.26' | 110°35.29' | 2329 | 8/30/80 | 9/26/80 | 27 | 12 | 84 | Sandstone* |
| TFL | 40°26.55' | 110°25.92' | 2272 | 8/30/80 | 11/1/80 | 63 | 33 | 90 | Drift |
| BWL | 40°29.63' | 110°27.59' | 2486 | 8/31/80 | 11/1/80 | 62 | 46 | 90 | Drift |
| WLD | 40°34.49' | 110°30.80' | 2517 | 8/31/80 | 11/1/80 | 62 | 46 | 96 | Quartzite* |
| CSP | 40°30.00' | 110°32.33' | 2597 | 9/25/80 | 11/1/80 | 37 | 26 | 96 | Sandstone* |
| TPT | 40°31.58' | 110°26.43' | 2329 | 9/28/80 | 10/3/80 | 5 | 6 | 90 | Drift |
| BAR | 40°31.22' | 110°28.45' | 2639 | 10/9/80 | 11/1/80 | 23 | 8 | 90 | Boulder* |
| KNF | 40°25.40' | 110°31.77' | 2201 | 10/31/80 | 11/1/80 | 1 | 1 | 84 | Alluvium |

* Indicates seismometer cemented to outcrop.
** Refers to MEQ 800 amplifier dial setting.

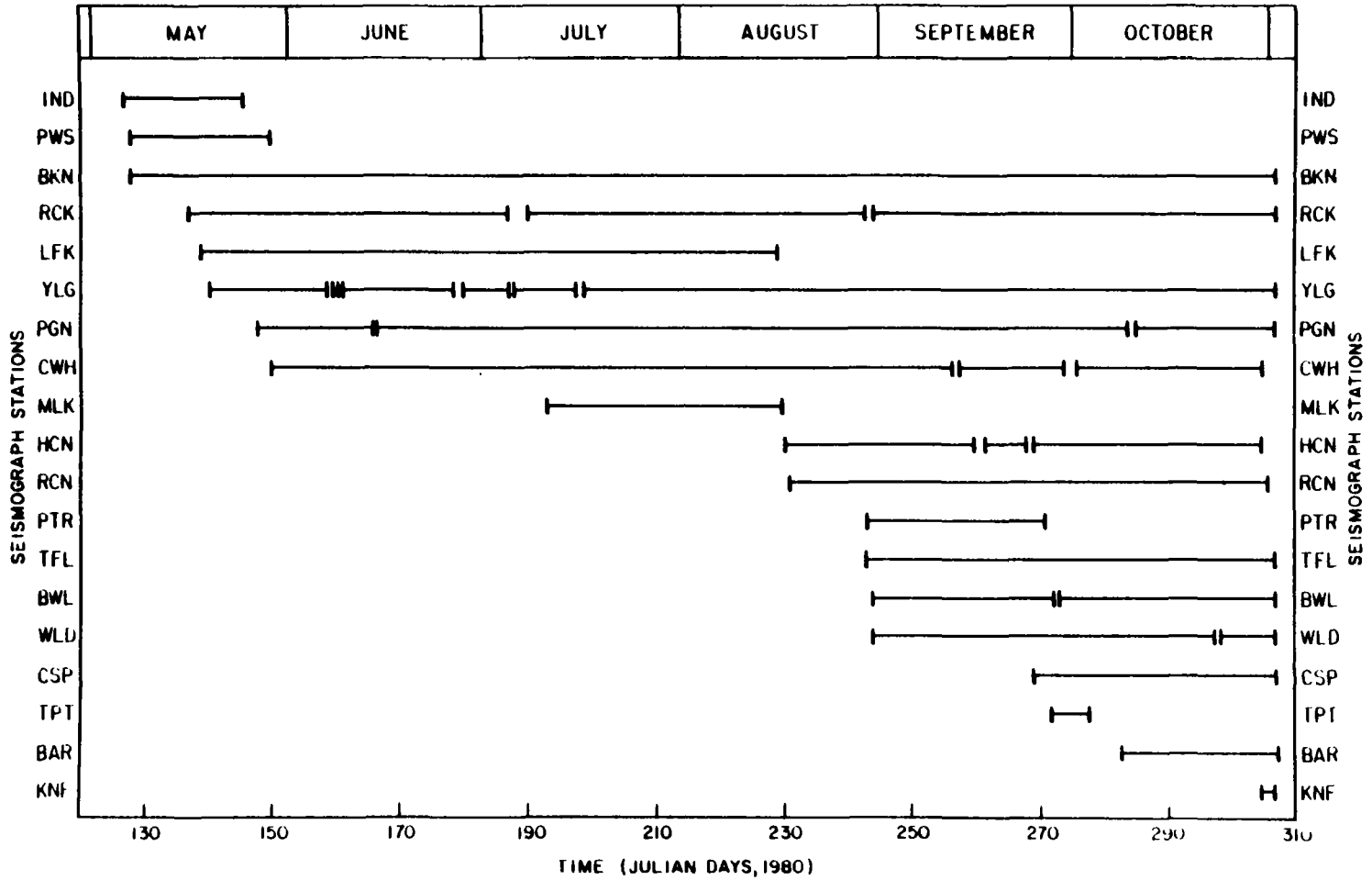



Figure D.4. Daily operational status of seismograph stations occupied in 1980. Horizontal bar indicates period of operation.

The achievable amplifier gain settings on the MEQ 800's ranged from 84 dB for the stations situated in alluvium and drift to 108 dB for station RCK which was fortuitously located 300 m within the Upper Stillwater Tunnel, as it was not under construction during the study. Maximum pen deflection was set to 25 mm with low- and high-cut filters set to 5 and 10 Hz, respectively. These instrument settings correspond to ground displacement magnifications of $2.32 \times 10^5$ to $3.72 \times 10^6$ at 10 Hz.

The MEQ 800 internal crystal clocks were synchronized with a portable "master" crystal clock (Sprengnether model TS-400) at the beginning and end of each 24- or 48-hour record. The portable master clock was synchronized with WWV (time standard broadcast by National Bureau of Standards) in the morning before going to the stations and again at the completion of the route, typically 8 to 10 hours later. Two master clocks were used during this study. The first clock drifted from 10 to 30 milliseconds during the course of the day. This drift was linearly interpolated to determine the corrections to be made to the MEQ 800 clock drifts as determined at each station. The master clock used during the second half of the study was more stable and usually drifted less than 2 milliseconds in a 10-hour period; thus, no additional correction was necessary.

## Data Reduction

The hypocenters of events recorded at three or more stations were determined by computer program HYP071 (Lee and Lahr, 1975). The program uses Geiger's method (Geiger, 1912) to compute latitude, longitude, and focal depth by minimizing the residuals between observed and calculated arrival times in terms of least squares. The arrival times from a trial hypocenter are computed for a horizontal multilayer velocity model by a technique developed by Eaton (1969).

The compressional wave velocity model used for processing data recorded during this study is that used by the USGS during the 1977 aftershock study, and is shown on figure D.5. The P wave velocity of the upper 3.8 km of strata was derived from sonic logs from a Gulf Oil exploration well in T. 1 N., R. 4 W., near the Yellowstone River (pl. 2). The velocities for the remainder of the model were derived from Rayleigh wave dispersion studies conducted in the Uinta Basin (Keller and others, 1976). P wave station delays were computed based on a velocity of 4.22 km per second, and the difference between station elevation and a datum of 2300 m above sea level. The S wave velocities used in the solution were computed from the P wave velocities assuming a Poisson ratio of 0.25.

| VELOCITY (km./sec.) | DEPTH TO TOP OF LAYER (km.) | THICKNESS (km.) |
|---|---|---|
| 4.22 | 0.0 | 3.8 |
| 4.5 | 3.8 | 1.2 |
| 5.3 | 5.0 | 3.0 |
| 6.1 | 8.0 | 4.0 |
| 6.4 | 12.0 | 5.0 |
| 6.7 | 17.0 | 5.0 |
| 6.9 | 22.0 | 18.0 |
| 7.8 | 40.0 | SEMI-INFINITE |

Figure D.5. P-wave velocity model.

The average seismograph clock was found to drift 20 to 50 milliseconds per day. This deviation from WWV was linearly interpolated over the entire record to arrive at the appropriate net drifts for each recorded event. Earthquake arrival times were manually determined using a precision micrometer that had inherent picking errors of less than 20 milliseconds. The overall accuracy of P wave arrival times was $\pm$0.05 second for 24-hour records where the recording speed was 120 mm per minute, and $\pm$0.1 second for 48-hour records where the recording speed was 60 mm per minute. S arrival times, when available, are probably in error by as much as 0.5 second due to single-component recording, and, therefore, poorly defined S waves.

The magnitudes of located microearthquakes, as computed by HYP071, are based on the duration of the coda. With a sufficient data set a good estimate of the Richter magnitudes can be obtained from an empirical relation of the form:

$$Md = a_1 + a_2 \log t + a_3 d + a_4 h$$

In this equation, Md is the duration magnitude, t is the signal duration in seconds, d is the epicentral distance in kilometers, and h is the focal depth in kilometers (Lee and Stewart, 1981). $a_1$, $a_2$, $a_3$, and $a_4$ are empirical constants determined by comparing signal duration with Richter magnitudes for a set of earthquakes, accounting for focal depth and epicentral distance. With respect to the MEQ 800 seismograms, the signal duration was defined as the time in seconds from the onset of the P wave arrival to the point where the signal begins to get lost in the noise. This point is approximately where the signal to noise ratio declines to less than 1.5. During the study, there were too few earthquakes to solve for special constants for the Uinta Front. Therefore, the constants derived for central California by Lee, Bennet, and Meagher (1972) were used to arrive at estimates of Richter magnitudes. The appropriate equation is:

$$Md = -0.87 + 2.0 \log t + 0.0035 d$$

It should be emphasized, however, that there are several problems with using this method to calculate equivalent Richter magnitudes for these microearthquakes in Utah.

First, though the application of duration magnitude is becoming widely used throughout the world, there exists no universally accepted definition of total signal duration. The constants derived for central California result from arbitrarily assuming that the signal ends when the peak-to-peak amplitude falls below 1 cm as viewed on a Geotech develocorder viewer. Though this definition allows for internal consistancy and reproducibility among individual develocorder users, it does not lend itself very well to MEQ 800 records where 1 cm spans 10 or more traces. Because of this small scale recording, the duration of the coda was chosen to be the point where the signal and noise are indistinguishable. Obviously, this is greatly dependent on the background noise level at the time of the event. Thus, relative to a quiet day, some

microearthquakes may be underestimated if the background noise level is high. The severity of the situation is lessened, however, by considering that the signal duration enters into the calculation only as a log function and that the computed magnitude is an average of many stations.

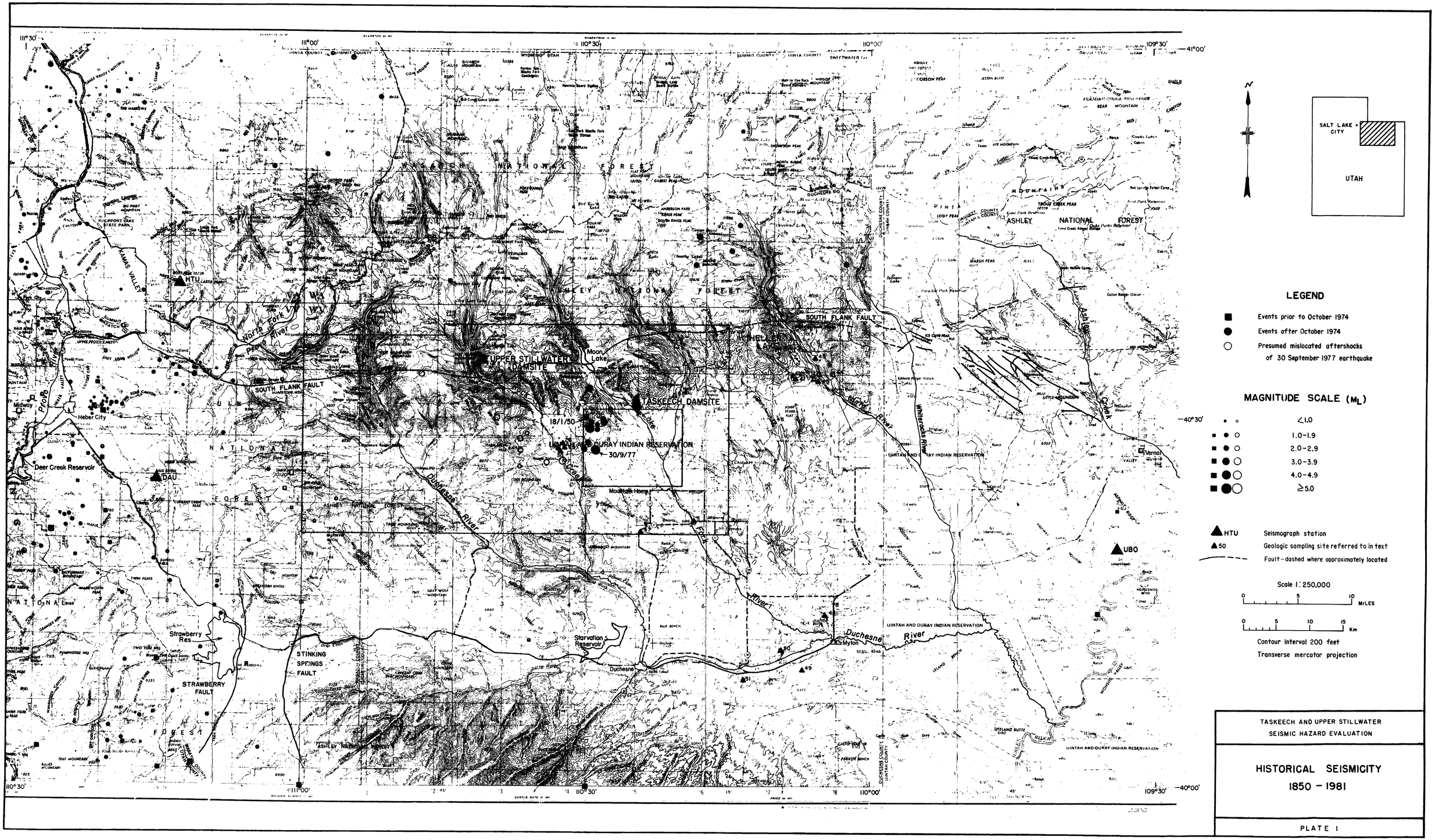
A second problem with applying the California equation to Utah earthquakes results from a probable difference in the seismic wave attenuation characteristics of the two regions. Attenuation within the contiguous United States has been shown to be greater and quite variable west of the Great Plains (Nuttli, 1973). Isoseismic data indicate attenuation is greater in coastal California than in the Mountain States (Evernden, 1975). In the frequency range 1 to 10 Hz, and for distances up to 150 km, attenuation appears to be greater in Utah than in California (King and Hays, 1977). Griscom (1980), however, has shown that the Richter magnitude scale, as originally defined (Richter, 1958), is generally applicable to Utah (within $\pm$0.3 magnitude units). Thus, since the coefficients developed for central California were empirically derived from earthquakes whose magnitudes were computed based on Richter's definition, they may provide reasonable approximations in Utah.

One additional problem relates to the range of magnitudes for which the empirical relationship for California is applicable. The original data set of Lee, Bennet, and Meagher (1972) included earthquakes in the magnitude range 1.75 to 4.75. Recent studies have shown that it is not justifiable to extrapolate coda length magnitude relations down below about magnitude 1.5 without special calibration (Bakun and Lindh, 1977; Suteau and Whitcomb, 1979). The aftershocks of the September 30, 1977, earthquake illustrate the need for special calibration in the study area. The nine previously mentioned mislocated aftershocks indicated by open circles in plate 1 have magnitudes ranging from 1.7 to 3.0 $M_L$, as defined by the University of Utah telemetered seismic network. The telemetered seismic network operating at the time of the 1977 earthquakes has remained essentially unchanged in proximity to the study area through 1980. None of the earthquakes recorded during the 1980 microseismic monitoring program, however, are listed in the University of Utah earthquake catalog (University of Utah, 1982). This is in direct conflict with the fact that 17 of the 1980 microearthquakes have magnitudes, as defined by the duration magnitude method, in the range 1.7 to 2.6.

This need for calibration is further substantiated by data recorded during the USGS/UU 1977 aftershock study. A magnitude 2.0 earthquake, apparently mislocated because only data from the telemetry network were used in the solution (Richins, 1979), is indicated on plate 1 as the open circle located furthest to the southwest. This earthquake was recorded by an MEQ 800 seismograph used in the aftershock study at their station TOW on October 15, 1977. The duration of this event on the MEQ 800 seismogram is about 80 seconds. Based on the California duration coefficients, an 80-second duration should correspond to about magnitude 3. Thus, it appears that attenuation is less in Utah than in

California and that the values computed for the 1980 microearthquakes may be overestimated by as much as an order of magnitude.

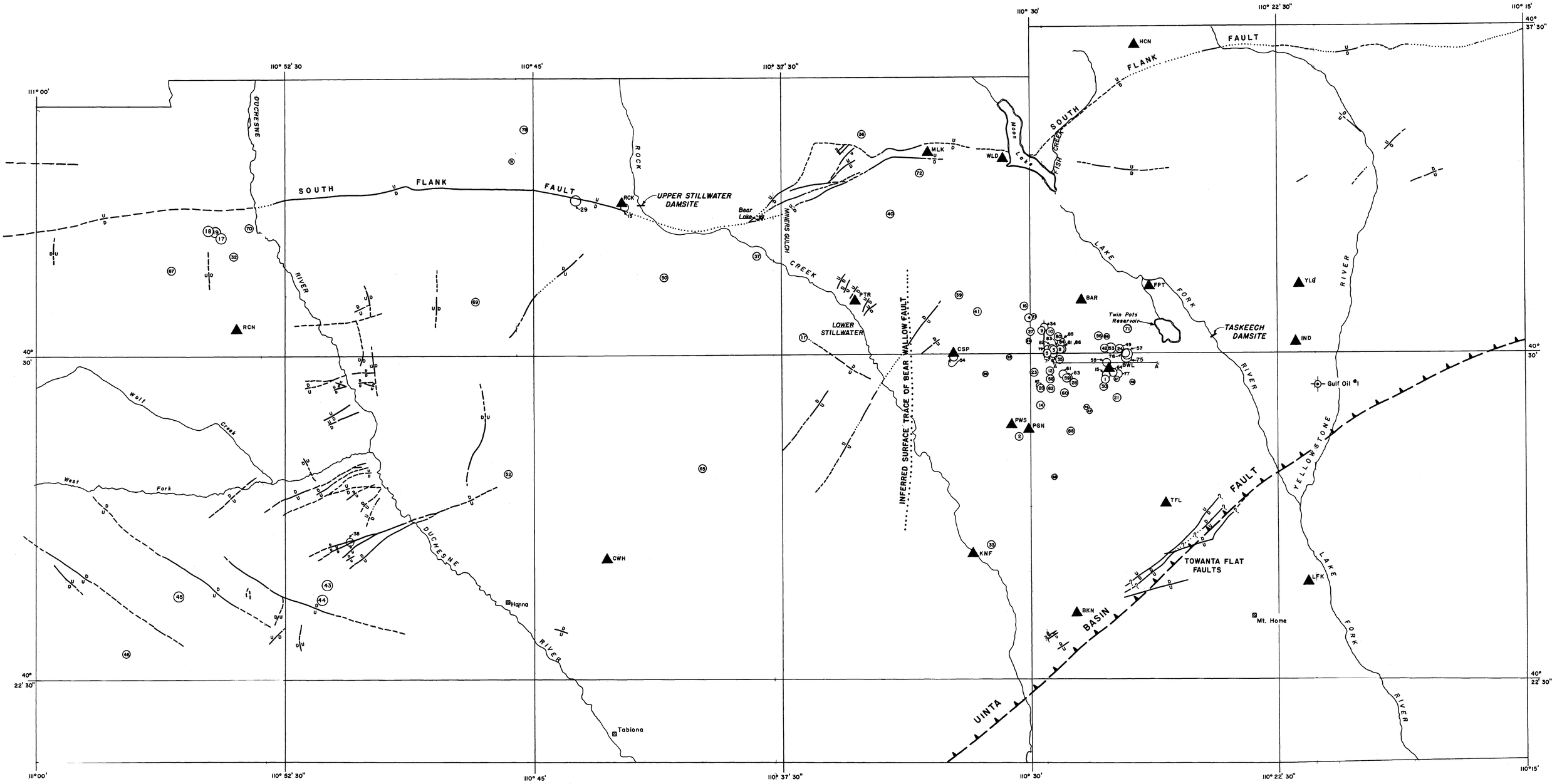
Since it was not possible to calibrate the data recorded during this microearthquake investigation and because of the other mentioned problems of applicability, the values computed using this method are clearly only crude estimates of Richter magnitudes. They are only important in representing the relative size of an event versus the other located microearthquakes recorded during this study.




TASKEECH AND UPPER STILLWATER
SEISMIC HAZARD EVALUATION

HISTORICAL SEISMICITY
1850 - 1981

PLATE I




SCALE

1 .5 0 1 2 3 km

1 .8 .6 .4 .2 .0 1 2 MILES

MAGNITUDE SCALE

○ <1 ○ 1-2 ◯ >2

LEGEND

⑮ EARTHQUAKE WITH EVENT NUMBER

▲ SEISMOGRAPH STATION

NORMAL FAULT (DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED)

APPROXIMATE SUBSURFACE TRACE OF UINTA BASIN FAULT. (BARB ON UPTHROWN SIDE)

TASKEECH AND UPPER STILLWATER SEISMIC HAZARD EVALUATION

# 1980 MICROEARTHQUAKE EPICENTERS AND SEISMOGRAPH STATION LOCATIONS

PLATE 2

## EXPLANATION

### QUATERNARY GEOLOGY OF TOWANTA FLAT AREA

#### DESCRIPTION OF MAP UNITS

Ff 4-6

**GENETIC SYMBOL**

F - FLUVIAL
G - GLACIAL
FG- GLACIOFLUVIAL
C - COLLUVIAL
L - LANDSLIDE
R - BEDROCK
(/ SIGNIFIES AREA OF DEPOSITS OF MIXED GENESIS; — SIGNIFIES UNCERTAINTY OF GENESIS)

**MORPHOLOGIC QUALIFIER**

f - FAN
m- SUBDUED MORAINE
h- HUMMOCKY MORAINE
fp-FLOODPLAIN

**RELATIVE AGE GROUP**

1 THROUGH 10, OLDEST TO YOUNGEST
(/ SIGNIFIES AREA OF DEPOSITS OF SEVERAL RELATIVE AGES;
— SIGNIFIES UNCERTAINTY OF AGE)

#### SYMBOLS

- GEOLOGIC CONTACT
- GRADATIONAL GEOLOGIC CONTACT
- FAULT, DOTTED WHERE CONCEALED
- FAULT SCARP, ③ SCARP PROFILE GROUP, 2.4 m-AVERAGE SCARP HEIGHT BAR AND BELL ON DOWNTHROWN SIDE
- AIRPHOTO LINEATION
- SURFACE WEATHERING SITE
- SITE NUMBER
- SOIL PROFILE DESCRIPTION SITE
- TRENCH SITE
- TRENCH NUMBER
- RESISTIVITY LINE

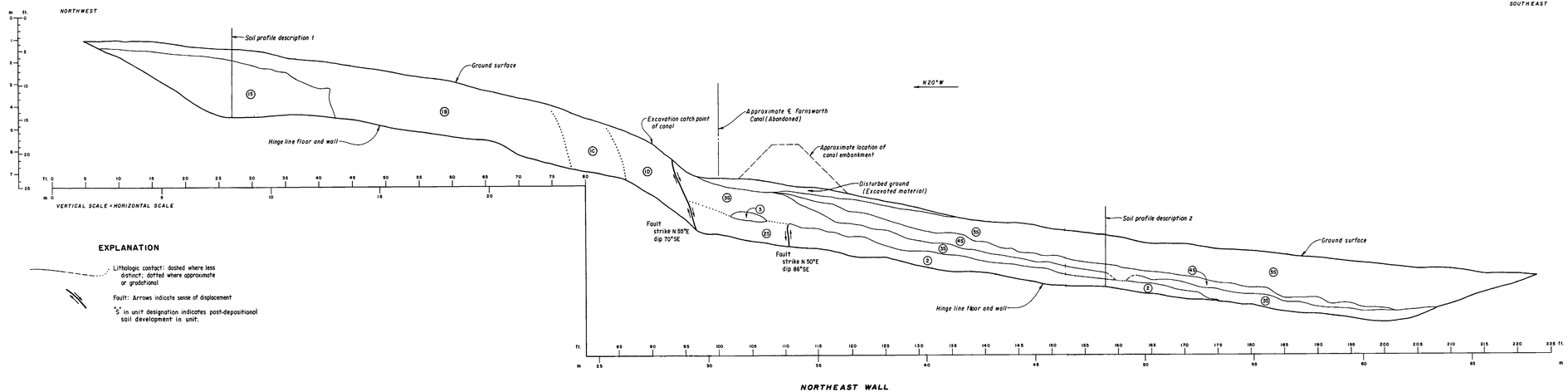
0 1000 2000 1 MILE
SCALE OF FEET
0 1 Km

BASE: MOUNTAIN HOME, LAKE FORK MT., BURNT SPRING MILL, AND ALTAMONT, UT. USGS 1:24,000 QUADRANGLES. NORTHEAST CORNER OF MAP BASED ON OSBORN (1973, PLATE 1)

SEISMIC HAZARD EVALUATION
TASKEECH AND UPPER STILLWATER DAMSITES

QUATERNARY GEOLOGY
OF TOWANTA FLAT AREA

PLATE 3




## EXPLANATION

Lithologic contact: dashed where less distinct; dotted where approximate or gradational

Fault: Arrows indicate sense of displacement

"s" in unit designation indicates post-depositional soil development in unit.

## NOTES

See Plate 3 for trench location.
See Appendix B for soil profile descriptions.

## UNIT DESCRIPTIONS

### OUTWASH

1. Sandy Gravel With Cobbles and Boulders (Outwash): Red to yellowish red (2.5 YR 4/7 to 5 YR 5/8) dry; estimate (by volume) 25-30% subrounded gravel, 25 to 125 mm, 10-15% subrounded cobbles 125 to 300 mm, and 5-10% subrounded boulders, remainder minus 75 mm; minus 76 mm fraction (by weight) 60-65% fine to coarse, subrounded gravel, 25-30% coarse to predominantly fine, subangular to subrounded sand, and 5-10% nonplastic fines (SP-SM); maximum size-450 mm; nonstratified; poorly sorted; calcium carbonate coatings on clasts; carbonate stage 1 to 11; 45% highly weathered clasts; slight HCl reaction.

1S. Silty Sand With Cobbles and Boulders (Outwash): White to pinkish white (7.5 YR 8/0 to 8/2) dry, with small areas of matrix red (2.5 YR 5/6) dry; estimate (by volume) 20% subrounded cobbles 75 to 125 mm, 10% subrounded cobbles 125 to 300 mm, and 5% subrounded boulders, remainder minus 75 mm; minus 75 mm fraction (by weight) 50% coarse to predominantly fine, subangular to subrounded sand, 35-40% fine to coarse, subrounded gravel, and 10-15% nonplastic fines (SP-SM); maximum size-350 mm; nonstratified; poorly sorted; dense calcium carbonate rinds on clasts average 1.5 mm thick; carbonate stage 111; 40-50% highly weathered clasts; violent HCl reaction.

1B. Gravelly Sand With Cobbles and Boulders (Outwash): Yellowish red to light brown (5 YR 5/8 to 7.5 YR 6/4) dry; estimate (by volume) 15-20% subrounded cobbles 75 to 125 mm, 10% subrounded cobbles 125 to 300 mm, and 5% subrounded boulders, remainder minus 75 mm; minus 75 mm fraction (by weight) 60-65% fine to coarse, subrounded gravel, 30-40% fine to coarse, subangular to subrounded sand, and 10% nonplastic fines (SP-SM); maximum size-600 mm; nonstratified; poorly sorted; none to strong HCl reaction.

1C. Sandy Gravel With Cobbles and Boulders (Outwash): Light brown (7.5 YR 6/4) dry; estimate (by volume) 20% subrounded cobbles 75 to 125 mm, 10% subrounded cobbles 125 to 300 mm, and 5% subrounded boulders, remainder minus 75 mm; minus 75 mm fraction (by weight) 50% fine to coarse, subrounded gravel, 40-45% fine to coarse, subangular to subrounded sand, and 5-10% nonplastic fines (SP-SM); maximum size-750 mm; nonstratified; poorly sorted; none to slight HCl reaction.

1D. Sandy Gravel With Cobbles and Boulders (Outwash): Yellowish red to reddish yellow (5 YR 5/8 to 6/8) dry; estimate (by volume) 15-20% subrounded cobbles 75 to 125 mm, 5-10% subrounded cobbles 125 to 300 mm, and 5% subrounded boulders, remainder minus 76 mm; minus 75 mm fraction (by weight) 50% fine to coarse, subrounded gravel, 40-45% fine to coarse, subangular to subrounded sand, and 5-10% nonplastic fines (SP-SM); maximum size-400 mm; nonstratified; poorly sorted; none to slight HCl reaction.

### COLLUVIUM

2. Silty Gravel With Cobbles (Colluvium): Yellowish red to pink (5 YR 5/6 to 7/4) dry; estimate (by volume) 20% subrounded cobbles 75 to 125 mm, 10% subrounded cobbles 125 to 300 mm, and a trace of boulders, remainder minus 75 mm; minus 75 mm fraction (by weight) 70-75% fine to coarse, subrounded gravel, 20% coarse to predominantly fine, subangular to subrounded sand, and 5-10% nonplastic fines (GP-GM); maximum size-350 mm; nonstratified; poorly sorted; a few clasts have thin calcium carbonate coatings; initial carbonate stage 1; very slight HCl reaction.

2S. Clayey Gravel With Cobbles (Colluvium): Red (2.5 YR 4/6 to 5/8) dry; estimate (by volume) 15% subrounded cobbles 75 to 125 mm, 5% subrounded cobbles 125 to 300 mm, and a trace of boulders, remainder minus 75 mm; minus 75 mm fraction (by weight) 60-65% fine to coarse, subrounded gravel, 25-30% coarse to predominantly fine, subangular to subrounded sand, and 10% low to medium plasticity fines (GP-GC); maximum size-350 mm; nonstratified; poorly sorted; very slight to slight HCl reaction.

3. Silty Gravel With Cobbles (Colluvium): Light brown (7.5 YR 6/4) dry; estimate (by volume) 20% subrounded cobbles 75 to 125 mm, 10% subrounded cobbles 125 to 300 mm, remainder minus 75 mm; minus 75 mm fraction (by weight) 60-65% fine to coarse, subrounded gravel, 30% coarse to predominantly fine, subangular to subrounded sand, and 5-10% nonplastic fines (GP-GM); maximum size-300 mm; nonstratified; poorly sorted; very slight HCl reaction.

3S. Clayey Gravel With Cobbles (Colluvium): Red (2.5 YR 5/6 to 5/8) dry; estimate (by volume) 15-20% subrounded cobbles 75 to 125 mm, 5-10% subrounded cobbles 125 to 300 mm, and a trace of boulders, remainder minus 75 mm; minus 75 mm fraction (by weight) 70-75% fine to coarse, subrounded gravel, 15-20% coarse to predominantly fine, subangular to subrounded sand, and 10-15% low to medium plasticity fines (GP-GC); maximum size-350 mm; nonstratified; poorly sorted; occasional clasts have thin calcium carbonate coatings; carbonate stage 1; slight HCl reaction.

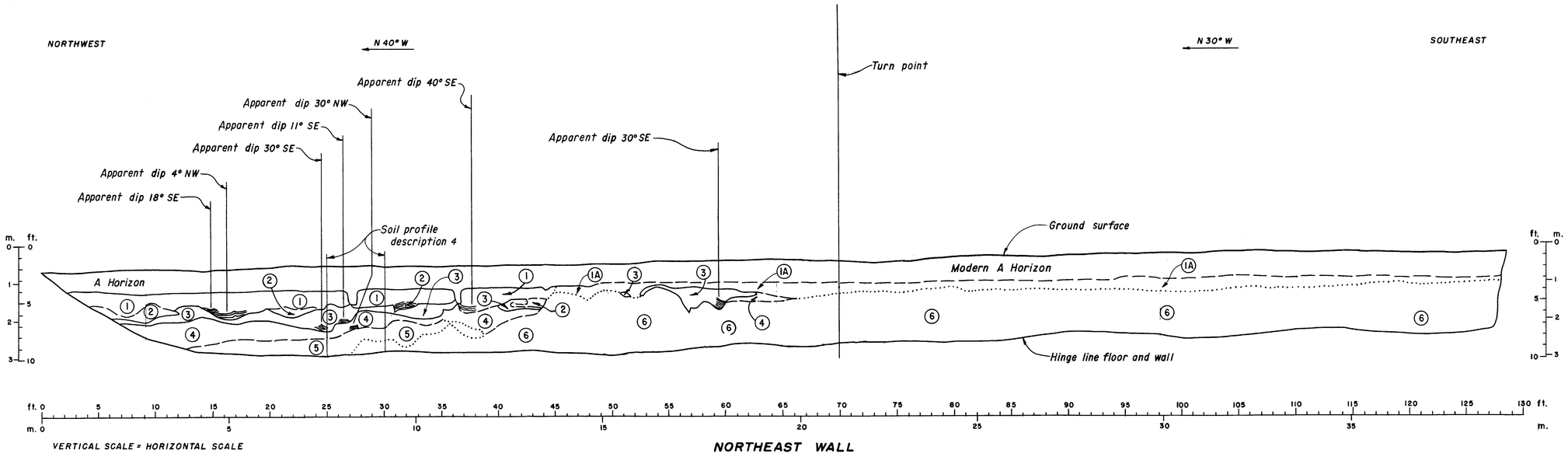
4S. Silty Gravel With Cobbles (Colluvium): Reddish yellow to pink (5 YR 6/6 to 7/4) dry; estimate (by volume) 15-20% subrounded cobbles 75 to 125 mm, 10% subrounded cobbles 125 to 300 mm, and a trace of boulders, remainder minus 75 mm; minus 75 mm fraction (by weight) 85% fine to coarse, subrounded gravel, 10% coarse to predominantly fine, subangular to subrounded sand, and 5% nonplastic fines (GP-GM); maximum size-350 mm; nonstratified; poorly sorted; occasional clasts have thin calcium carbonate coatings; car bonate stage 1; very slight HCl reaction.

5S. Sandy silt (Colluvium): Yellowish red to light brown (5 YR 5/8 to 7.5 YR 6/4) dry; estimate (by weight) 55% none to low-plasticity fines, 45% coarse to predominantly fine sand, and a trace of fine gravel (SM-ML); maximum size-25 mm; nonstratified; numerous vertical, irregular, randomly oriented joints with calcium carbonate coatings mostly in lower portion of unit; carbonate stage 1; in lower portion of unit; none to slight HCl reaction.

SEISMIC HAZARD EVALUATION
TASKEECH AND UPPER STILLWATER DAMS

# LOG OF TOWANTA FLAT TRENCH 1

PLATE 4




VERTICAL SCALE = HORIZONTAL SCALE

**NORTHEAST WALL**

## EXPLANATION

Lithologic contact: dashed where less distinct; dotted where approximate or gradational

## NOTES

See Plate 3 for trench location.
See Appendix B for soil profile description.

## UNIT DESCRIPTIONS

1. Silty Sand (Lacustrine/colluvium-loess): Light yellow to bright yellowish orange (2.5 Y 7/3 to 10 YR 7/5) moist; estimate (by weight) 65% coarse to predominantly fine, subangular to subrounded sand, 30% nonplastic fines, 5% coarse to predominantly fine, subrounded gravel, and a trace of cobbles (SM); maximum size-80 mm; nonstratified except laminated stratification locally; moderately sorted; carbonate stage I- to I; very slight to strong HCl reaction.

1A. Silty Sand With Cobbles (Colluvium-loess): Gray to grayish brown (5 Y 6/1 to 2.5 Y 5/2) moist; estimate (by volume) 10% subrounded cobbles 75 to 125 mm, 5% subrounded cobbles 125 to 300 mm, and a trace of boulders, remainder minus 75 mm; minus 75 mm fraction (by weight) 55-60% coarse to predominantly fine, subangular to subrounded sand, 20-25% nonplastic fines, and 20% fine to coarse, subrounded gravel (SM); maximum size-350 mm; nonstratified; poorly sorted; carbonate stage I; slight to strong HCl reaction.

2. Silty Sand With Cobbles (Outwash): Yellowish red (5 YR 5/6) moist; estimate (by volume) 20% subrounded cobbles 75 to 125 mm, remainder minus 75 mm; minus 75 mm fraction (by weight) 70% coarse to predominantly fine, subangular to subrounded sand, 20% nonplastic fines, and 10% fine to coarse, subrounded gravel (SM); maximum size-125 mm; nonstratified except crude laminated stratification locally; poorly sorted; carbonate stage I; strong HCl reaction.

3. Gravelly Sand With Cobbles (Outwash): Light reddish brown (5 YR 6/4) moist; estimate (by volume) 10% subrounded cobbles 75 to 125 mm, and a trace of cobbles 125 to 200 mm, remainder minus 75 mm; minus 75 mm fraction (by weight) 60% fine to coarse, subangular to subrounded sand, 30% fine to coarse, subrounded gravel, and 5-10% nonplastic fines (SP-SM); maximum size-200 mm; nonstratified except crude laminated stratification locally; poorly sorted; <5% highly weathered clasts; carbonate stage I-; none to slight HCl reaction.

4. Clayey Sand (Outwash): Pale yellow (5 Y 7/3) moist; estimate (by volume) 5% subrounded cobbles 75 to 100 mm, remainder minus 75 mm; minus 75 mm fraction (by weight) 55% coarse to predominantly fine, subangular to subrounded sand, 30-35% low plasticity fines, and 10-15% fine to coarse, subrounded gravel (SC); maximum size-100 mm; nonstratified except crude laminated stratification locally; poorly sorted; 30% highly weathered clasts; carbonate stage I+ to II-; very slight to strong HCl reaction.

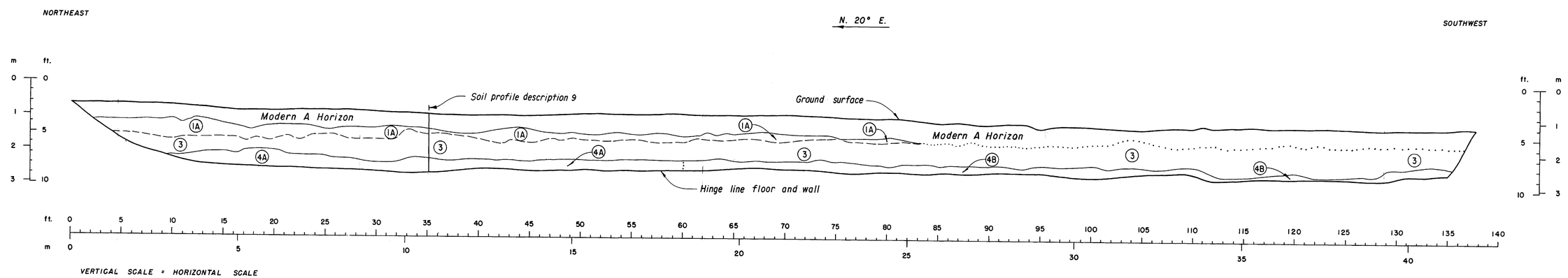
5. Sandy Clay (Outwash): Olive gray (10 Y 5/2) moist; estimate (by volume) 5% subrounded cobbles 75 to 100 mm, remainder minus 75 mm; minus 75 mm fraction (by weight) 45-50% low plasticity fines, 40-45% coarse to predominantly fine, subangular to subrounded sand, and 10% fine to coarse, subrounded gravel (SC-CL); maximum size-100 mm; nonstratified; 30% highly weathered clasts; carbonate stage I+ to II-; very slight to strong HCl reaction.

6. Sandy Gravel With Cobbles and Boulders (Outwash): Pale olive (5 Y 6/3) moist; estimate (by volume) 20-25% subrounded cobbles 75 to 125 mm, 10-15% subrounded cobbles 125 to 300 mm, and 5% subrounded boulders, remainder minus 75 mm; minus 75 mm fraction (by weight) 50% fine to coarse, subrounded gravel, 40-45% fine to coarse, subangular to subrounded sand, and 5-10% nonplasticity to low plasticity fines (GP-GC); maximum size-600 mm; nonstratified; poorly sorted; 30% highly weathered clasts; numerous clasts have calcium carbonate coatings; carbonate stage II-; strong HCl reaction.

SEISMIC HAZARD EVALUATION
TASKEECH AND UPPER STILLWATER DAMS

# LOG OF TOWANTA FLAT TRENCH 2

PLATE 5




## SOUTHEAST WALL

### EXPLANATION

Lithologic contact: dashed where less distinct; dotted where approximate or gradational

### NOTES

See Plate 3 for trench location.
See Appendix B for soil profile description.

### UNIT DESCRIPTIONS

1A. Silty Sand (Lacustrine/colluvium-loess): Brown (7.5 YR 5/4) moist; estimate (by weight) 70-75% coarse to predominantly fine, subangular to subrounded sand, 20-25% nonplastic fines, 5% coarse to predominantly fine, subrounded gravel, and a trace of cobbles (SM); maximum size-80 mm; nonstratified; moderately sorted; none to moderate HCl reaction.

3. Gravelly Sand With Cobbles (Outwash): Brown to reddish yellow (7.5 YR 5/4 to 6/6) moist; estimate (by volume) 20% subrounded cobbles 75 to 125 mm, 5% subrounded cobbles 125 to 300 mm, and a trace of boulders, remainder minus 75 mm; minus 75 mm fraction (by weight) 60-65% coarse to predominantly fine, subangular to subrounded sand, 20-25% fine to coarse, subrounded gravel, and 15% nonplastic fines (SM); maximum size-350 m; nonstratified; poorly sorted; 10% highly weathered clasts; carbonate stage I- to I+; none to strong HCl reaction.

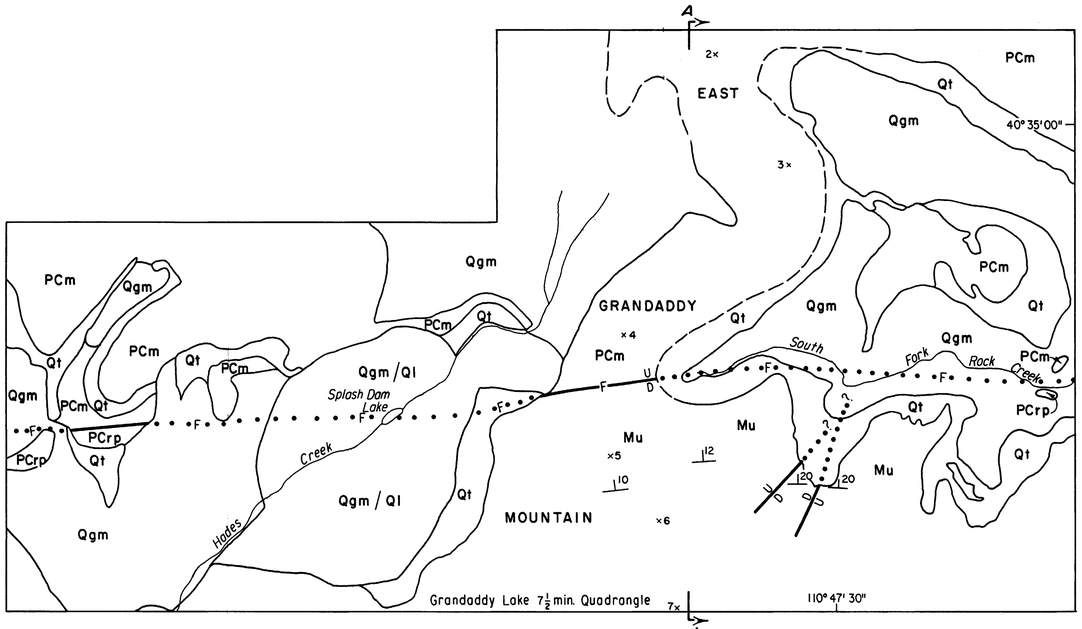
4A. Clayey Sand (Outwash): Light yellow to pale yellow (2.5 Y 7/3 to 7/4) moist; estate (by volume) 5% subrounded cobbles 75 to 125 mm, remainder minus 75 mm; minus 75 mm fraction (by weight) 45-50% coarse to predominantly fine, subangular to subrounded sand, 35-40% low plasticity fines, and 10-15% fine to coarse, subrounded gravel (SC); maximum size-125 mm; nonstratified; poorly sorted; 40% highly weathered clasts; carbonate stage II; slight to strong HCl reaction.

4B. Clayey Sand (Outwash): Pale yellow (5 Y 7/3) moist; estimate (by volume) 5% subrounded cobbles 75 to 125 mm, remainder minus 75 mm; minus 75 mm fraction (by weight) 55-60% coarse to predominantly fine, subangular to subrounded sand, 25-30% low plasticity fines, and 10-15% fine to coarse, subrounded gravel (SC); maximum size-125 mm; nonstratified; poorly sorted; 40% highly weathered clasts; carbonate stage II; slight to strong HCl reaction.

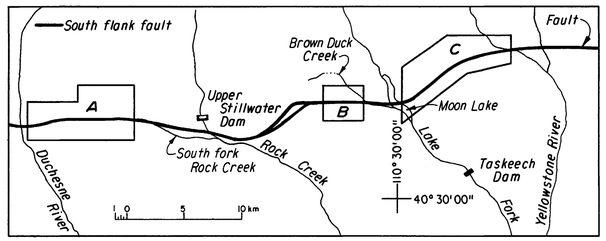
SEISMIC HAZARD EVALUATION
TASKEECH AND UPPER STILLWATER DAMS

# LOG OF TOWANTA FLAT TRENCH 3

PLATE 6




MAP A

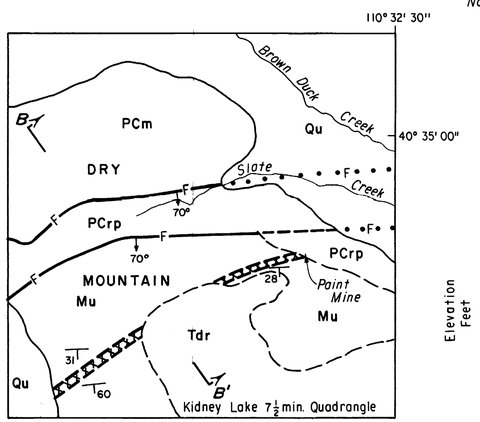



LOCATION MAP

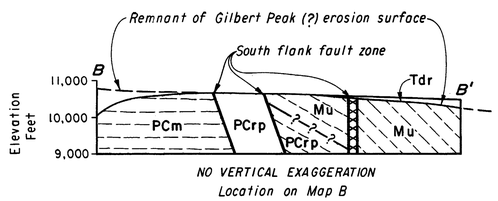



NO VERTICAL EXAGGERATION
Location on Map A

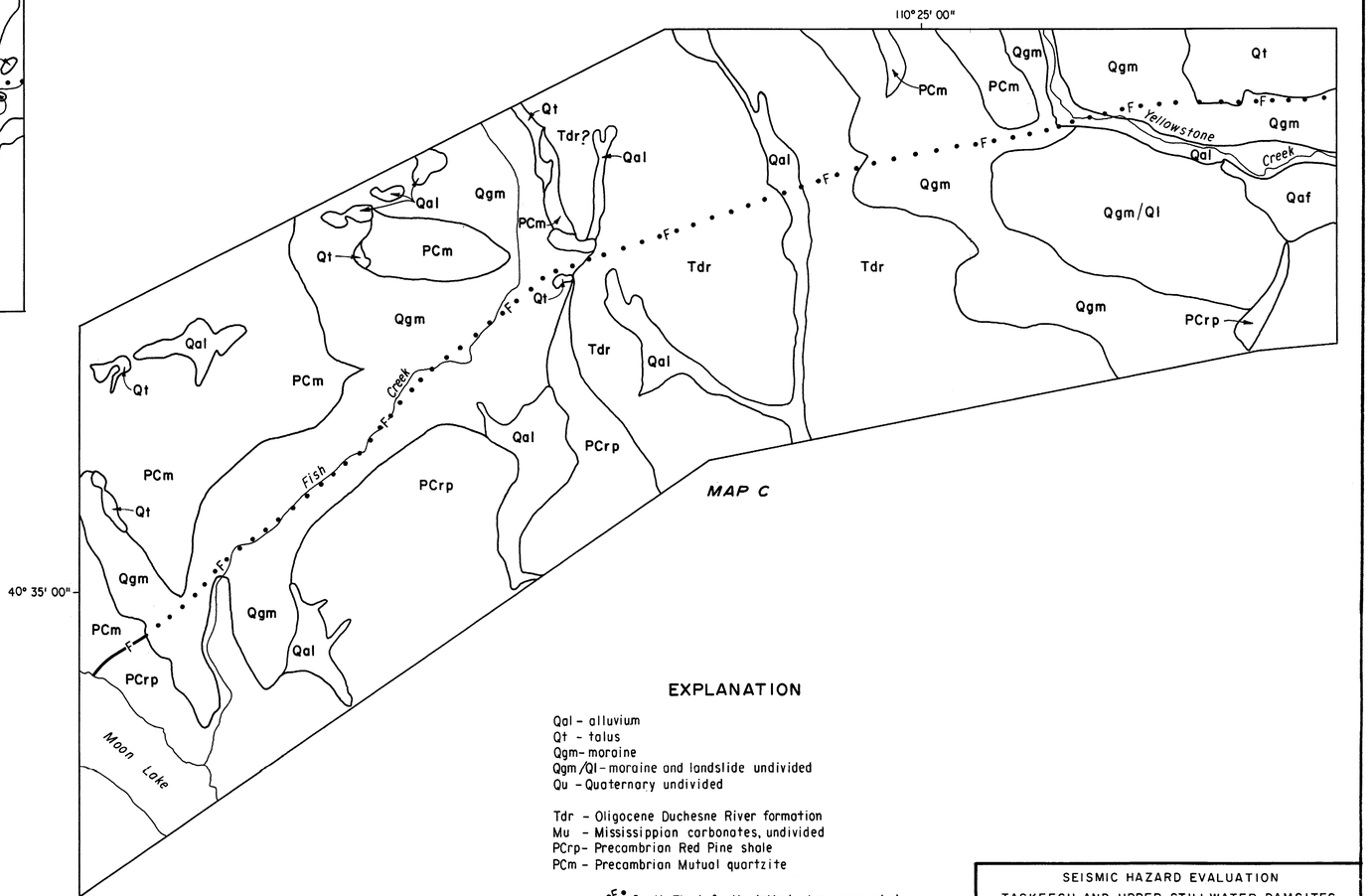
Note: Spot elevations #2-7(x) projected onto line of section.




MAP B




NO VERTICAL EXAGGERATION
Location on Map B




MAP C

## EXPLANATION

Qal – alluvium
Qt – talus
Qgm – moraine
Qgm/Ql – moraine and landslide undivided
Qu – Quaternary undivided

Tdr – Oligocene Duchesne River formation
Mu – Mississippian carbonates, undivided
PCrp – Precambrian Red Pine shale
PCm – Precambrian Mutual quartzite

F U D — South Flank fault, dotted where concealed, U=up, D=down, arrow indicates dip direction.
Breccia zone associated with South Flank fault.
Other faults, dotted where concealed.
28° Strike and dip of bedding.
Geologic contact, dashed where approximately located.

0 1 2
SCALE OF KILOMETERS

SEISMIC HAZARD EVALUATION
TASKEECH AND UPPER STILLWATER DAMSITES

# GEOLOGIC MAPS OF PORTIONS OF THE SOUTH FLANK FAULT

PLATE 7