Geomorphic mapping and topographic analysis of the Barker Reservoir Area, Utah

William Clement Putnam

University of Nebraska at Omaha

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GEOMORPHIC MAPPING AND TOPOGRAPHIC ANALYSIS
OF THE
BARKER RESERVOIR AREA, UTAH

A Thesis
Presented to the
Department of Geography and Geology
and the
Faculty of the Graduate College
University of Nebraska at Omaha

In Partial Fulfillment
of the Requirements for the Degree
Master of Arts

by
William C. Putnam
April, 1975
THESIS ACCEPTANCE

Accepted for the faculty of The Graduate College of the University of Nebraska at Omaha, in partial fulfillment of the requirements for the degree Master of Arts.

<table>
<thead>
<tr>
<th>Graduate Committee</th>
<th>Name</th>
<th>Department</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>John F. Shroder, Jr</td>
<td>Geography - Geology</td>
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<td>Geog. - Geol.</td>
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<td>Biology</td>
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Chairman: John F. Shroder, Jr.
Date: May 12, 1975
ACKNOWLEDGMENTS

At this time, it is appropriate for me to express my sincere appreciation to those people who contributed so greatly to the completion of this study.

To Dr. John P. Shroder Jr., my most heartfelt thanks for his help, guidance, and encouragement through all phases of this study from its inception. His high standards of personal achievement and academic excellence are an inspiration to all of us fortunate enough to be associated with him.

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Finally, I wish to thank the Society of the Sigma Xi for a much welcomed grant in aid of my research.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>viii</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Location</td>
<td>1</td>
</tr>
<tr>
<td>Scope and Purpose</td>
<td>1</td>
</tr>
<tr>
<td>Previous Work</td>
<td>3</td>
</tr>
<tr>
<td>Regional Geology and Physiography</td>
<td>4</td>
</tr>
<tr>
<td>Regional Climate and Vegetation</td>
<td>11</td>
</tr>
<tr>
<td>Access, Habitation, and Land Use</td>
<td>12</td>
</tr>
<tr>
<td>Research Methods</td>
<td>15</td>
</tr>
<tr>
<td>GEOMORPHIC MAPPING OF THE STUDY AREA</td>
<td>19</td>
</tr>
<tr>
<td>Available Mapping Systems</td>
<td>19</td>
</tr>
<tr>
<td>Geomorphic Symbology for Mass-Wasting Landforms</td>
<td>24</td>
</tr>
<tr>
<td>LANDFORMS OF THE STUDY AREA</td>
<td>31</td>
</tr>
<tr>
<td>The Aquarius Plateau Surface</td>
<td>31</td>
</tr>
<tr>
<td>Plateau Scarp and Talus Slopes</td>
<td>32</td>
</tr>
<tr>
<td>The Landslide Bench</td>
<td>38</td>
</tr>
<tr>
<td>The Landslide-Bench Slope</td>
<td>44</td>
</tr>
<tr>
<td>Debris-Flows</td>
<td>48</td>
</tr>
<tr>
<td>Slow Rock-Fragment-Flows</td>
<td>50</td>
</tr>
<tr>
<td>The Holbys Bottom Earth-Flow</td>
<td>54</td>
</tr>
<tr>
<td>Pediments</td>
<td>63</td>
</tr>
<tr>
<td>Torrential Boulder Deposits</td>
<td>63</td>
</tr>
<tr>
<td>SLOPE STABILITY OF THE STUDY AREA</td>
<td>66</td>
</tr>
<tr>
<td>VEGETATION OF THE STUDY AREA</td>
<td>71</td>
</tr>
</tbody>
</table>
DRAINAGE OF THE STUDY AREA 73

HYPSOMETRIC ANALYSIS OF THE STUDY AREA 75

Hypsographic Curves 75

Analysis of Closed Contours, Number of Landslide Blocks, Depressions, and Relief of the Landslide Bench 83

LAND-USE MANAGEMENT IMPLICATIONS 89

SUMMARY AND CONCLUSION 93

REFERENCES CITED 100
### LIST OF ILLUSTRATIONS

**Plate**

1. Landforms of the study area  
2. Vegetation of the study area  
3. Drainage lines of the study area  
4. The Holbys Bottom earthflow  
5. Stability of slopes in the study area  

**Figure**

1. Location of the study area  
2. Pre-tertiary tectonic features of Utah  
3. Generalized bedrock section in the western Aquarius Plateau area  
4. Location map of the High Plateaus of Utah  
5. Vegetation zones in the Aquarius Plateau area, Utah, and their relation to altitude and precipitation  
6. Geomorphological symbols for mass-wasting deposits  
7. View looking northeast along the central portion of the plateau scarp and talus slope  
8. View looking southwest along the central portion of the plateau scarp and talus slope  
9. Large boulders of the pseudo-protalus rampart  
10. View toward the talus slope from the pseudo-protalus rampart  
11. View across Long Willow Bottom Reservoir to the southern section of the landslide bench  
12. Profiles across the landslide bench  
13. Close-up picture of weathered basalt particles  
14. View over the central portion of the landslide bench
15. View over the central portion of the landslide bench near Yellow Lake

16. View looking east into the vicinity of Griffin Creek and Beck Hollow

17. View of a slow rock-fragment-flow at the head of White Creek

18. View down the landslide-bench slope to the White Creek pediment

19. View of the upper portion of the Holbys Bottom earthflow

20. View down the Holbys Bottom earthflow

21. Photograph of a section of an echelon fracture on the periphery of the Holbys Bottom earthflow

22. View of the head of the Holbys Bottom earthflow

23. View of the active area of slumping near Gates Spring

24. Photograph of the shear zones in the streambank of the stream flowing from Gates Spring

25. Photograph of tree-ring sample taken from the area of active slumping near Gates Spring

26. View of the Beck Hollow pediment

27. Hypsographic Curves Plotted on a Dimensionless Basis for Selected Drainage Basins of Ephemeral Streams East of North Creek

28. Hypsographic Curves Plotted on a Dimensionless Basis for Selected Drainage Basins of Perennial Streams West of North Creek

29. Comparison of the Hypsographic Curves for Twitchell Creek and Beck Hollow

Table 1. Analysis of Closed Contours, Number of Landslide Blocks, Depressions, and Relief of the Landslide Bench
ABSTRACT

A wide variety of geomorphic processes have interacted to produce a complex landscape in the High Plateaus of Utah. This study centers on the high southern slopes of the Aquarius Plateau in the drainage basin of North Creek where the landscape is primarily the result of mass-wasting processes and the subsequent modification of the mass-wasting deposits by fluvial action. The High Plateaus are composed of essentially flat-lying sedimentary strata overlain in places by volcanic rocks and separated by the scarps of high-angle normal faults with the downthrow primarily on the west side. The climate and vegetation associations of the High Plateaus are largely a function of altitude. Access to the study area is provided by one road which follows North Creek to Barker Reservoir. There are no permanent residences in the area and recreation and cattle grazing are the only land uses.

Objectives of the study are primarily to inventory the landforms of the area and discuss the causative geomorphic processes as well as to develop a useful geomorphic mapping technique for mass-wasting phenomena and to apply the technique to aid in the development of a highly unstable area.

Field work was conducted during the months of July and August in 1970. The area was mapped during daily traverses into the various sections and with the aid of aerial photographs obtained from the U.S. Forest Service. An active earth-flow was discovered in Holbys Bottom and was mapped in detail at a scale of 1:2,000 using compass, tape, and Abney level. In the laboratory, slope stability, vegetation,
and drainage were mapped by analysis of aerial photographs aided by recorded field observations. Data for hypsometric analysis and analysis of closed contours, depressions, and relief of the landslide bench was obtained from a topographic map of the area.

The surface of the Aquarius Plateau is bounded by a 17.5 kilometer scarp which is flanked over most of its length by talus slopes. Retrogressive landsliding of large blocks away from the plateau surface has formed a landslide bench below and adjacent to the full length of the scarp. Headward erosion by streams has steepened slopes near the edge of the landslide bench. Saturation of the debris at the edge of the bench by groundwater has resulted in its failure and downslope movement over these slopes until they have become mantled with landslip deposits. This surface is termed the landslide-bench slope and on it are debris-flows, slow rock-fragment-flows, and an active earth-flow. The landslide debris below the landslide bench and bench-slope is continually being reworked by slope wash and channel flow and is being redeposited in some areas as pediment gravels. Torrential boulder deposits are located in the stream bottoms of the major streams.

Slope stability of the study area has been mapped in four classes: 1) active slopes, 2) highly unstable slopes, 3) slopes of questionable stability under present conditions, and 4) slopes which are stable under present conditions.

Vegetation in the study area is primarily associated with climatic factors involved with altitude, slope exposure, and moisture conditions.
On the landslide bench, vegetation associations with surficial materials also exist.

Drainage in the study area reflects the adaption of drainage lines to landslide topography and the subsequent modification of the landslide topography by fluvial erosion.

Two types of hypsometric analysis were conducted in the study area. Hypsographic curves were constructed for stream basins whose morphology was due primarily to landsliding and also for stream basins in which the landslide deposits had been removed by erosion. Analysis of closed contours, depressions, and relief of the landslide bench was undertaken to give quantitative expression to various topographic characteristics of the landslide bench and to provide comparative factors.

Current land use activities in the study area show minor adverse effects but increased intensity of current uses or expansion of the number of land-use activities may have serious adverse effects.
INTRODUCTION

Location

The Colorado Plateau is bounded on the northwestern side by an area of high north-south trending plateaus separated from each other by fault or fault-line scarps and fault-controlled valleys. This area is known as the High Plateaus of Utah. The area in which this study was conducted is located on the eastern side of the High Plateaus in Garfield County (fig. 1). The study centers on the upper portion of the North Creek drainage basin which forms a part of the southern boundary of the Aquarius Plateau, highest of the High Plateaus. The study area is shown at a scale of 1:24,000 on the Barker Reservoir topographic map published by the United States Geologic Survey and covers the portion of the map from 111 degrees, 52 minutes, 30 seconds west longitude, to 111 degrees, 45 minutes west longitude; and from 37 degrees, 52 minutes, 30 seconds north latitude, to 37 degrees, 57 minutes, 30 seconds north latitude.

Scope and Purpose

A number of geomorphic processes acting through time have combined to create a considerable variety of landforms in the North Creek area. Examination of the area is through landform
Figure 1
Location of the Study Area
mapping. The first result of the mapping is the determination of the number of different landforms existing in the area and their spatial relationships. Mass-wasting and fluvial processes have been the major factors in landscape formation in this area. Through map analysis, attempts are made to determine relationships within the various types of mass-wasting and between the mass-wasting and fluvial processes which produced the landforms.

Mapping for the study was done using a new system of geomorphological map symbols recently developed largely in Europe which makes possible the presentation of quantitative and qualitative material not previously possible. The system also permits comparison of the factors which control the development of the landscape. Symbology for use with landforms that have resulted from mass-wasting was insufficient, so several new symbols have been developed for use in this study.

Previous Work

Most of the bedrock geology of the Aquarius Plateau area has been mapped by the U. S. Geological Survey at a scale of 1:24,000. Unfortunately, few of these maps differentiate Quaternary deposits. In 1956, McFall mapped the geology of the Escalante-Boulder area, but divided the Quaternary only into younger and older alluvium and igneous debris. The Quaternary geology of nearby Boulder Mountain has been published by Flint and Denny (1958) and also by Smith, Huff, Hinrichs, and Luedke (1963). These two studies provided considerable insight into the interpretation of landform features
in the present study area. Useful climatic information was provided by Goode (1969) in his appraisal of the ground water resources of the Escalante area. More recently, Fallat (1972) has analyzed rock glaciers of the Aquarius Plateau region and Shroder (1972, 1973) has investigated rock glaciers and slow rock-fragment-flows of the Aquarius and Table Cliffs Plateaus. Several of the features described in their works are within the present study area.

**Regional Geology and Physiography**

Two ancient tectonic features, the Transcontinental Arch and the Wasatch - Las Vegas Line, have influenced the geologic history of Utah through much of geologic time (fig. 2). An ancient band of rocks 1.5 to 2 billion years old has been found which extends from the Lake Superior region to the Mojave Desert. There is evidence that this band of rocks, called the Transcontinental Arch, frequently formed a low barrier between marine invasions flooding the continent from the southeast and northwest. Most of the geologic systems are present north and south of the Arch, while on its summit much of Paleozoic, Mesozoic, and Cenozoic time is represented by unconformities (Stokes and Heylum, 1963, p. 19).

The relationship of the Transcontinental Arch to the Wasatch - Las Vegas Line is not clear, but the Las Vegas Line coincides with, and may be, the northwestern edge of the Arch in southern Nevada and southwestern Utah. However, where the
Las Vegas Line becomes the Wasatch Line, it curves northward into Idaho, Wyoming, and Montana, away from the Transcontinental Arch.

The rise of the Mesocordilleran Highland west of the Wasatch - Las Vegas Line probably occurred in a number of orogenic episodes spread through several geologic periods. Directional properties of sediments in ancient alluvial fans indicate that the area was high enough to supply runoff and sediment during the Mesozoic. By this time, the Mogollon Rim had risen across the Transcontinental Arch in what is now northern Arizona, and with the Transcontinental Arch and Mesocordilleran Highland formed a basin which would accumulate sediment in the southern Utah area through the Mesozoic.

The Tertiary was a time of great structural unrest in Utah and in it began a series of events which overshadowed previous tectonic activity. One of the most violent and intensive periods of vulcanism in western North America began in the late Eocene. During Oligocene and Miocene time, nuées ardentes swept across vast areas piling up great thicknesses of welded tuffs. Extensive lava flows, volcanic mudflows, and blanket deposits of airfall and water-laid tuffs were deposited at this time. Eardley (1962, in Stokes and Heylmun, 1963, p. 21) estimates that at least 30,000 cubic miles of welded tuffs alone can be found in the area. A generalized column of the rock strata found in the area is shown in figure 3.

The volcanic caprock which surfaces the Aquarius Plateau is composed primarily of porphyritic basalt, basaltic andesite,
### Generalized Bedrock Section in the Western Aquarius Plateau Area

<table>
<thead>
<tr>
<th>System</th>
<th>Group and Formation</th>
<th>Thickness (meters)</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>Alluvium, colluvium, terrace gravel, landslides, pediment gravel.</td>
<td>0-21</td>
<td>Clay, silt, sand, and gravel in alluvium and colluvium; pediment and terrace gravels include some sand; landslides commonly bouldery or gravelly.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unconformity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tertiary</td>
<td>Volcanic rocks.</td>
<td>153+</td>
<td>Chiefly flows with interbedded tuffaceous sediments.</td>
</tr>
<tr>
<td></td>
<td>Unconformity</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flagstaff Formation</td>
<td>61+</td>
<td>Limestone, clay, conglomerate sandstone, tuff, and tuffaceous sediments.</td>
</tr>
<tr>
<td>Cretaceous</td>
<td>Mancos Shale</td>
<td></td>
<td>Not exposed.</td>
</tr>
<tr>
<td></td>
<td>Dakota Sandstone</td>
<td></td>
<td>Not exposed.</td>
</tr>
<tr>
<td></td>
<td>Unconformity</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Morrison Formation</td>
<td>107+</td>
<td>Conglomeratic sandstone, sandstone, siltstone, claystone.</td>
</tr>
<tr>
<td>Jurassic</td>
<td>Summerville Formation</td>
<td>Unconformity</td>
<td>Siltstone.</td>
</tr>
<tr>
<td></td>
<td>Entreda Sandstone</td>
<td>549+</td>
<td>Earthy sandstone.</td>
</tr>
<tr>
<td></td>
<td>Carmel Formation</td>
<td></td>
<td>Limestone, siltstone, gypsum.</td>
</tr>
<tr>
<td></td>
<td>Unconformity</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kayenta Formation</td>
<td>107+</td>
<td>Sandstone, conglomeratic sandstone, shades of red and white.</td>
</tr>
<tr>
<td></td>
<td>Unconformity</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wingate Sandstone</td>
<td>101+</td>
<td>Crossbedded sandstone, red.</td>
</tr>
<tr>
<td></td>
<td>Unconformity</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chine Formation</td>
<td>137+</td>
<td>Siltstone, claystone, sandstone; variegated.</td>
</tr>
<tr>
<td></td>
<td>Shinarump Conglomerate</td>
<td>Unconformity</td>
<td>Sandstone, conglomeratic sandstone, claystone.</td>
</tr>
<tr>
<td>Triassic</td>
<td>Moenkopi Formation</td>
<td>275+</td>
<td>Siltstone, sandstone, limestone; chiefly red.</td>
</tr>
<tr>
<td></td>
<td>Unconformity</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kaibab Limestone</td>
<td>107+</td>
<td>Limestone, sandstone, calcareous siltstone; white.</td>
</tr>
<tr>
<td></td>
<td>Coconino Sandstone</td>
<td>244+</td>
<td>Crossbedded sandstone, white.</td>
</tr>
</tbody>
</table>

and porphyritic andesite (Smith, Huff, Hinrichs, and Luedke, 1963, p. 40; McGookey, 1960, p. 613; Williams and Hackman, 1971). The volcanic caprock overlies the Flagstaff Formation which consists of interbedded limestone, tuff, sandy tuff, and tuffaceous sandstone, sandstone, siltstone, claystone, and conglomerate. The varied lithology and small exposures of incomplete sequences have caused difficulties in defining the characteristics of the Flagstaff Formation (Smith Huff, Hinrichs, and Luedke, 1963, p. 35).

In the study area, the caprock is approximately 100 meters thick and directly overlies beds of calcareous tuff and tuffaceous limestone. Farther downslope, exposures of conglomerate and white limestone are present.

Widespread subsidence in the area west of the Wasatch - Las Vegas Line has given the area an appearance similar in many ways to a giant collapse caldera. Two possible explanations for this subsidence have been presented. Continued volcanic extrusions may have caused a loss of support within the earth's crust through the Oligocene and Miocene which resulted in subsidence and collapse (Stokes and Heylmun, 1963, p. 21). The other explanation is that the westward-moving North American continental plate may have overridden a subduction zone and caused formation of a new one farther west. Subsequent overriding of this second subduction zone and then of the spreading center associated with it resulted in release of compression stresses on the western portion of the plate which were expressed on the surface by the block faulting which produced the basin and range topography (Shroder, personal communication).
The area surrounding the Wasatch – Las Vegas Line forms a 50-mile-wide transition zone between the more stable area to the east and the subsided region to the west. This area contains features which are the result of distension of the earth's crust adjacent to the western region of subsidence. The High Plateaus are contained within this zone. The High Plateaus are composed of essentially flat-lying sedimentary strata overlain in places by volcanic rocks and separated by the scarps of high-angle normal faults with the downthrow primarily on the western side. Locally, however, there are numerous normal faults with upthrown western blocks, and minor horsts and grabens are common. Altitudes of the plateaus increase in step-fashion from approximately 2,700 meters at the western edge, to over 3,300 meters at the eastern edge (Thornbury, 1965, p. 421). Three major faults, the Hurricane, Sevier, and Paunsaugunt, divide the High Plateaus into three north-south trending groups. The plateaus of the western group from north to south are the Gunnison, Pavant, Tushar, and Markagunt. The Sevier and Paunsaugunt form the middle section, and the Wasatch, Fish Lake, Awapa, and Aquarius Plateaus form the eastern group (fig. 4).

The transitional nature of the High Plateaus is illustrated by examining the geologic structures in the Colorado Plateau and comparing them with Basin and Range structures. The folds of the Colorado Plateau are simple and the faults are normal, and over wide areas the rock strata are essentially horizontal. Structure in the Basin and Range area is much more complex, having resulted from compressive
Figure 4

Location Map of the High Plateaus of Utah

Adapted from: Bowman, 1911; Thornbury, 1965
movements followed by block faulting. This process has produced short mountain ranges separated by basins which accumulate sediment from the surrounding ranges. The structure and topography of the High Plateaus combine features of both of these areas. Plateau topography is dominant, but the structures are more like those found in the Basin and Range areas than those of the Colorado Plateau. The fault and fault-line scarps of the High Plateaus, which are typical of Basin and Range structure, combine with receding cliffs and erosional features typical of the Colorado Plateau to give the High Plateaus a composite topography exemplary of their transitional nature (Spieker, 1949, in Thornbury, 1965, p. 424).

**Regional Climate and Vegetation**

The climate and vegetation associations that occur in the High Plateaus area are largely a function of altitude. The lower areas, at or below 1,800 meters, are desert. Precipitation in these areas ranges from 13 centimeters to 30 centimeters with approximately half of the total amount occurring as thunderstorms from May to September. Other than the vegetation growing along stream channels and flood plains, the precipitation is incapable of supporting anything but desert shrubs and grasses. The subalpine climates found on the plateau tops are a great contrast to the desert areas a few kilometers away. In the areas above 3,000 meters, the precipitation may exceed 75 centimeters per year, about 75 per cent of which is snow falling
from October to April. In these areas, trees, bushes, and grasses form an almost continuous ground cover (Goode, 1969, p. 14; Smith, Huff, Hinrichs, and Luedke, 1963, p. 6). The individual associations of vegetation with altitude and precipitation are shown in figure 5. Detailed discussion of the vegetation associations found in the study area are contained in a separate section of this study. Evidence that former climates were cooler and more humid is shown by the existence of glacial and periglacial features on the Boulder Mountain section of the Aquarius Plateau (Flint and Denny, 1958, P. 115).

Access, Habitation, and Land Use

Access to the North Creek drainage by road is rather limited. A dirt road, which was being rebuilt in August of 1970, branches from the Main Canyon road about 200 meters from its junction with Utah highway 54, eight kilometers west of Escalante and follows North Creek approximately 27 kilometers to Barker Reservoir. This is the only road into the North Creek drainage and is maintained by the Forest Service for recreational access and fire control. Parts of the upper section of the drainage are traversed by Forest Service pack trails, but at the time field work was being conducted they were not maintained. They are usable for travel on foot, but the use of pack animals would be very difficult. The plateau surface above North Creek may be reached by following the Main Canyon road to its junction with the Griffin Top road and then travelling north on the Griffin Top road. Approximately 7 kilometers from the junction,
Figure 5
Vegetation Zones in the Aquarius Plateau Area, Utah, and their Relation to Altitude and Precipitation

<table>
<thead>
<tr>
<th>Vegetation zone</th>
<th>Altitude limits (meters)</th>
<th>Precipitation (cm. per year)</th>
<th>Common names of dominant vegetation species</th>
<th>Common names of subordinate vegetation species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subalpine</td>
<td>2900+</td>
<td>50-63.5</td>
<td>Grasses in meadows; sedges and rushes around swamps and ponds; Engelmann spruce on ridges.</td>
<td>Alpine fir</td>
</tr>
<tr>
<td>Mountain forest</td>
<td>2680-3050</td>
<td>50-75</td>
<td>Douglas fir, white fir, aspen, blue spruce.</td>
<td>Dense fir forest with some grassy meadows and aspen groves.</td>
</tr>
<tr>
<td>(aspen-fir)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pine forest</td>
<td>2220-2750</td>
<td>25-50</td>
<td>Ponderosa pine, juniper, scrub oak (Gambel oak), spruce, fir, other pines.</td>
<td>Willows and narrow-leafed cotton woods along streams; Douglas fir near seeps; pines on ridges; mountain mahogany.</td>
</tr>
<tr>
<td>(yellow pine-oak)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semidesert</td>
<td>1700-2300</td>
<td>20-25</td>
<td>Pinyon pine, Utah juniper, one-seed juniper; sagebrush and grasses in open glades.</td>
<td>Willows and narrow-leafed cottonwoods along streams; isolated groups of Ponderosa pines near seeps or springs.</td>
</tr>
<tr>
<td>(pinyon-juniper)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Desert</td>
<td>1900-</td>
<td>20</td>
<td>Sagebrush, shadscale, rabbit brush, grasses, Mormon tea, herbaceous plants.</td>
<td>Low cactus and yucca, saltbush; broad-leafed cottonwoods along streams.</td>
</tr>
<tr>
<td>(northern desert shrub)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Adapted from: Smith, Huff, Hinrich, and Luedke, 1963, p. 6
<table>
<thead>
<tr>
<th>Common Name</th>
<th>Scientific Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinyon pine</td>
<td>Pinus edulis</td>
</tr>
<tr>
<td>Ponderosa pine</td>
<td>Pinus ponderosa</td>
</tr>
<tr>
<td>Utah juniper</td>
<td>Juniperus osteosperma</td>
</tr>
<tr>
<td>One-seed juniper</td>
<td>Juniperus monosperma</td>
</tr>
<tr>
<td>Douglas fir</td>
<td>Pseudotsuga menziesii</td>
</tr>
<tr>
<td>Subalpine fir</td>
<td>Abies lasiocarpa</td>
</tr>
<tr>
<td>White fir</td>
<td>Abies concolor</td>
</tr>
<tr>
<td>Blue spruce</td>
<td>Picea pungens</td>
</tr>
<tr>
<td>Engelmann spruce</td>
<td>Picea engelmannii</td>
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<tr>
<td>Aspen</td>
<td>Populus tremuloides</td>
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<tr>
<td>Cottonwood</td>
<td>Populus spp.</td>
</tr>
<tr>
<td>Scrub oak (Gambel oak)</td>
<td>Quercus gambelii</td>
</tr>
<tr>
<td>Mountain mahogany</td>
<td>Cercocarpus ledifolius</td>
</tr>
<tr>
<td>Sagebrush</td>
<td>Artemisia tridentata</td>
</tr>
<tr>
<td>Shadscale</td>
<td>Atriplex confertifolia</td>
</tr>
<tr>
<td>Saltbush</td>
<td>Atriplex spp.</td>
</tr>
<tr>
<td>Rabbitbrush</td>
<td>Chrysothamnus nauseosus</td>
</tr>
<tr>
<td>Mormon tea</td>
<td>Ephedra virdis</td>
</tr>
<tr>
<td>Yucca</td>
<td>Yucca spp.</td>
</tr>
</tbody>
</table>
it passes within 1 kilometer of the scarp which separates the plateau top from the drainage basin of North Creek. During the months of July and August, severe thunderstorms occur practically every day. The associated downpour quickly saturates the road surfaces which are primarily composed of sand and clay and results in a muddy, slippery surface that is impassable to all but light all-wheel drive vehicles.

There are two types of land-use activities currently active within the North Creek drainage. Cattle are released into the area in the spring and graze freely throughout the summer. They are picked up in the valley bottom in the fall when the snow has forced them down from the higher elevations. The other land-use activity in the area is recreation. Several small reservoirs have been constructed in the upper part of the area and are stocked with trout. A campground is maintained at Barker Reservoir and individual unimproved campsites are available at the other reservoirs. Only Barker and Lower Barker Reservoirs are readily accessible by conventional two-wheel drive vehicles. To reach the other reservoirs, an average hike of about 1.6 kilometers is necessary. Deer and small game abound in the area and in season are pursued by hunters.

Research Methods

Research began with a survey of the literature to determine the extent of the work previously done in the area or in similar areas. Literature concerning geomorphological mapping was also
surveyed and various systems of symbols were recorded for use in field mapping. A search was also made for articles dealing with topographic analysis and data collection methods to determine the types of data which might be collected in the field to be subjected to analysis in the laboratory after field research had been completed.

Field work was conducted during the months of July and August in 1970. A base camp was established at Barker Reservoir and daily traverses into various parts of the area were conducted from there. Most of the study area was accessible by a hike of two hours or less from the nearest point on the road, but some of the more remote areas near the east and south borders of the study area required hikes of up to 6.5 kilometers and required considerably more time to reach. Field work began with an initial reconnaissance of the area to determine the magnitude of the variety of landforms present and to form a sort of time schedule for detailed study of individual areas. The study area was then divided into smaller units in which the landforms were somewhat similar and mapping was begun using the Barker Reservoir topographic map as a base map. It was at this time that it became apparent that due to the complexity of the area and the wide variety of landforms present, detailed geomorphic mapping of the area would consume practically all of the time available for field work. Each section of the area was examined beginning with the plateau scarp and moving outward over the landslide bench and down the landslide-bench slope. Landforms were mapped by comparison of the ground surface to topographic maps and aerial photographs. The aerial photographs used in the study
were obtained from the regional office of the Intermountain Region of the U. S. Forest Service at Ogden, Utah, and were made June 23, 1960. Distances were measured by scaling from maps or, where shorter distances were involved, by actual point to point measurement on the ground. Generally, features less than 100 meters in length were measured with a tape. Lengths of the slow-rock-fragment flows were obtained from other workers. Precise locations were determined by compass resection. Slope angles were measured with either the clinometer contained within the Brunton compass or the Abney level. Whenever possible unusual or exemplary features were documented with photographs. An active earth-flow was discovered in Holbys Bottom and was mapped in detail at a scale of 1:2,000 using compass, tape, and Abney level. Tree-ring samples were taken in the area to provide information concerning its movement, and since the road passed through the upper end of the earth-flow and had been rerouted several times, the local forest ranger was also able to provide information on the activity of the flow.

Field work was concluded with final field checks, additional visits to areas of particular interest, and a few last attempts to get photographs which had previously been passed because of poor lighting or weather conditions. Camp was dismantled and the return trip to Omaha began on August 16, 1970.

In the laboratory, final drafts of field maps were completed, and vegetation and slope stability maps were constructed from aerial photograph interpretation and examination of field data. In order
to provide slope values for the stability classes, a one inch grid was laid over a topographic map of the study area and each intersection of grid lines was taken as a sample point. This provided 165 sample points. The slope of the ground was then calculated along a line through the intersection point and perpendicular to the contours from the index contour above the intersection to the index contour below the intersection point. In cases where either the top of the slope or the toe of the slope were reached before an index contour, the slope measurement was terminated at that point. Mean, median, and mode values were calculated and are shown on plate 5. Because of the relatively small size of the actively moving slopes, the slope value for each area of movement was calculated individually.

Hypsographic curves were prepared for selected drainage basins in the study area to compare the roles of mass-wasting and fluvial erosion. Necessary area measurements were computed with an electronic graphics calculator courtesy of the U.S. Forest Service. In order to quantitatively compare differing sections of the landslide bench and to permit comparison with similar features elsewhere, a method of topographic map analysis using closed contours, number of landslide blocks, depressions, and relief of the landslide bench was developed.
GEOMORPHIC MAPPING OF THE STUDY AREA

Available Mapping Systems

The current concept of geomorphological mapping originated in Europe in the mid-nineteen fourties. Prior to that time maps concerned with landforms were presented primarily as supplementary material with written reports and dealt with only a single landform or a few landforms, leaving the major portion of the map blank. These maps were of the physiographic-pictorial type and were designed to support the conclusions of the author (Verstappen, 1970, p. 85). Since 1950, several different geomorphological mapping systems have been developed. These systems differ widely and prevent comparison of data mapped in different areas. The Subcommission on Geomorphological Mapping of the International Geographical Union has attempted to standardize the mapping legends, and has recently published a unified key for detailed geomorphological mapping of the world (Demek, 1972).

The mapping systems currently in use emphasize four primary types of information (Verstappen, 1970, p. 86):

Morphographic - The landforms are identified from a geomorphic point of view using geomorphological terminology.
Morphogenetic - Information concerning the origin and development of the landform is presented and also information relating to the processes responsible for their formation and modification.

Morphometric - Cartographic representation of the dimensions of the landforms mapped is essential and is commonly done by superimposing the geomorphic symbols over the contour lines of a topographic map.

Morphochronologic - Since each landform reflects the time of its origin, it is important to distinguish landforms of differing ages, particularly between those which have been recently formed and fossil landforms which were created under different environmental conditions.

The inability to compare data mapped in different areas results from the extremely varied and complex ways in which these four types of information are presented cartographically by various authors. The following examples are presented to indicate the complexity of the problem:

The legend developed by the Division of Geography of the Polish Academy of Sciences distinguishes between three periods of time (Neogene, Pleistocene, and Holocene) and three slope
values (less than 4 degrees, 4 to 20 degrees, and greater
than 20 degrees) by using different shades of color. Neogene
landforms are shown in gray. Pleistocene erosion-denudation
forms are shown in orange and construction-sedimentation forms
are shown in green. Holocene erosional forms are shown in
red and sedimentation forms in blue. Ridges, summits, and similar
features, are shown in black. The resulting maps are easily
read but are limited in the total amount of information presented
(St. Onge, in Fairbridge, 1968, p. 390).

In Russia, Baszenina and others have worked out a legend
which contains over 500 symbol-color combinations. The legend
is divided into two sections, one of which deals with families
of landforms and the other with individual landforms. The
families of landforms are differentiated by various shades
of individual colors which are sometimes difficult to distinguish.
The ages of these families are indicated by the pattern in
which the color is printed. Individual landforms are identified
by symbols and the color of the symbol indicates genesis.
Lithology is shown by gray symbols superimposed over the other
information and morphometric data is absent. The maps produced
by this system are highly complex and difficult to read (St. Onge,
in Fairbridge, 1968, p. 399).

Two mapping legends have been developed in Belgium. Macar
has presented a system which emphasizes morphometric information.
He classifies slope steepness and distinguishes the various
classes by the use of colored area symbols. A similar system
emphasizing slopes has been constructed by Gullentops. In this legend slope steepness is indicated by varying the density of the hachures which indicate slope. Individual landforms are indicated by symbols only when the scale of the map prevents breaking the landforms into slope elements. Genesis of landforms is shown by using different colors for various processes. The age of the landform is indicated by using various shades of the color used for genesis. The variation in the density of hachures and many shades of color used tend to make this type of map difficult to draw and to print (St. Onge, in Fairbridge, 1968, p. 401; Verstappen, 1970, p. 88).

The Geographical Institute of the Czechoslovakian Academy of Sciences has developed a legend based on landform genesis. Landforms are divided into four main groups: structural, erosion-denudation, accumulation, and anthropogenic. Colors are used to indicate genesis. Volcanic landforms are shown in violet and karst landforms are shown in red. All accumulation forms are depicted with shades of blue. Chronology is indicated by printing a pattern over the color. Individual landforms are shown either by lined patterns or symbols. No provision is made to include morphometric information (St. Onge, in Fairbridge, 1968, p. 401).

St. Onge has presented a legend in Canada in which slope values are shown by lines of varying thickness. Individual landforms are depicted by symbols whose color indicates their origin. In the original usage of this system all of the landforms
mapped were Pleistocene in age and no chronological differentiation was necessary. Lithology was shown on an accompanying inset map (St. Onge, in Fairbridge, 1968, p. 402).

In France, Tricart has presented a legend which includes over 250 symbols and uses color to show lithology. Landforms are shown by symbols which are printed over the lithological colors. The color of the symbols indicates the age of the landform. Problems have arisen with this system because of the necessity of printing one color over another. The symbols do not stand out from the solid lithological color and are difficult to read (St. Onge, in Fairbridge, 1968, p. 401; Verstappen, 1970, p. 87).

A somewhat different mapping technique has been presented by Savigear (1965, p. 514). This method separates slopes into units and maps breaks and changes of slope by means of lines ornamented with symbols. The resulting maps indicate the shape of the land and permit morphometric analysis, but no attention is given to identification of landforms, their genesis, or chronology. These maps are highly complex and are very difficult to read unless the user has a thorough familiarity with all aspects of the system.

Verstappen, after reviewing previous systems, has recently presented a mapping system which utilizes different types of special-purpose geomorphic maps. The general-purpose map stresses morphogenesis and chronology. Major genetic landform types are shown with colored area symbols. Lithology is shown in gray. Processes are indicated by line symbols printed in black and chronology is shown in black lettering. The morpho-conservation
map emphasizes slope classification and uses colors for slope classes. Vegetation is shown in green and active processes are shown in red to distinguish them from fossil processes. The hydro-morphological map for use in hydrological studies uses colored area symbols for hydro-morphological units which are delineated by their infiltration-runoff ratio. Information concerning stream order and drainage divides is also included. Other special purpose maps are constructed as needed.

Geomorphic Symbology for Mass-Wasting Landforms

The landforms of the study area have resulted primarily from mass-wasting processes and the subsequent modification of the mass-wasting deposits by fluvial action. None of the currently available mapping systems contain symbology to permit detailed mapping of this type of terrain at a large scale. For this reason, the following symbol system was developed to permit detailed mapping of the landforms described in mass-wasting classifications by Sharpe (1938), Varnes (1958), Hutchinson (1968), Savage (1968), and Shroder (1971), (Shroder and Putnam, 1972). The object of the system is to put as much information as possible about each landform on a single, easily readable map. Because all mass-wasting landforms are the result of various combinations of a relatively small number of genetic components, these components have been assigned individual symbols and the landform is mapped as a composite of these individual symbols. In this
way many landforms can be mapped with a minimum of different symbols. The symbols were designed with the intent that they would create a mental picture of the actual landform in the mind of the viewer and thereby avoid the problem of constant referral to an extensive legend in order to interpret the map. Many of these symbols are commonly used in other systems and will be readily identified by anyone viewing the maps. Symbology for the system is based on the following four genetic components:

1). The type of material moved.
2). The type of movement.
3). The rate of movement.
4). The water and ice content of the material moved.

Type of Material

Three types of material are involved in mass-wasting: rock, earth, and debris.

Rock - The symbol chosen to represent rock is common to many symbol systems and consists of small closed polygons to represent rock fragments. The roundness or angularity of the fragments in the field may be reflected in the symbols.

Earth - Randomly spaced dots are used to represent earth. This symbol is also common to many systems.
Debris - Since debris is a combination of rock and earth materials, the symbol representing debris is a combination of the rock and earth symbols.

Type of Movement

Four types of movement are included in the system: fall, slide, flow, and creep. Variations of the most common symbol used to indicate direction and motion, the arrow, are used to indicate the type and direction of movement. The shaft of the arrow indicates the type of movement and the head indicates the direction.

Fall - Falling motion is indicated by an arrow with a straight, solid shaft.

Slide - To indicate sliding motion, the shaft of the arrow is segmented.

Flow - Flowing motion is indicated by using a sinuous line for the shaft of the arrow. In cases where the flowage is extremely slow, a combination of the flow and creep symbols may be used.
Creep - The imperceptible downslope movement of surficial material is shown by an arrow whose shaft consists of short parallel dashes normal to the direction of movement.

To use this system in mapping landslide blocks, large unitary masses which move without disintegrating, an addition to the slide symbol is necessary. A letter indicating the type of landslide block mapped is placed between the segments of the slide symbol.

- Slump-block - Landslide block which has reverse rotation in the direction of movement.

- Tilt-block - Landslide block which has forward rotation in the direction of movement.

- Glide-block - Landslide block with non-rotational movement along a planar surface.

- Ridge-block - Landslide block having non-rotational downward movement due to the removal of underlying material.
Rate of Movement

Since the rate of movement of mass-wasting phenomena may vary from imperceptibly slow to very rapid, this information may be included if known. At this time, no velocity values have been established which would define a particular landslide as occurring at a slow, rapid, or very rapid rate. However, a useable differentiation might be to consider velocities too slow to be discerned by the unaided eye as slow, and discernable movement as rapid. The rate of movement is indicated by varying the length of the segments in the shaft of the arrow used to indicate the type of movement. Falling motion and creep are not included since falling is a constant factor and creep is defined as being imperceptibly slow movement.

<table>
<thead>
<tr>
<th>Slow</th>
<th>Rapid</th>
</tr>
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<tbody>
<tr>
<td>Slide</td>
<td></td>
</tr>
<tr>
<td>Flow</td>
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</table>

Water and Ice Content

Since the water and ice content of the material can greatly effect the mass-wasting processes, this information should also be provided. The primary distinctions are between materials which are dry, wet, frozen, or partially frozen.

**Water** - The symbol for water is common to several mapping systems and consists of a short doubly-curved line.
Ice - The asterisk (*) is used to represent ice and has been selected because of its resemblance to the six-sided crystal pattern of snowflakes.

The mass-wasting features that can be mapped by using various combinations of these symbols are shown in figure 6, and those which were applied in the mapping of the study area are contained within the legend of plate 1.
### Geomorphological Symbols for Mass-Wasting Deposits


<table>
<thead>
<tr>
<th>MOVEMENT</th>
<th>SYMBOL</th>
<th>MATERIAL</th>
<th>ROCK</th>
<th>DEBRIS</th>
<th>EARTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Falls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Few units</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slides</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Many units</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry med.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freeze-thaw</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isolated unit falls and slides</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table Legend**
- **Type**: Type of movement
- **Symbol**: Symbol representing the movement
- **Rock**: Symbol for rock
- **Debris**: Symbol for debris
- **Earth**: Symbol for earth

**Diagram**
- **Block slides**
- **Sand-run Loess-flow**
- **Solifluxion**
- **Talus**
- **Colluvium**
LANDFORMS OF THE STUDY AREA

The landforms of the study area lend themselves to division into five groups: 1) the Aquarius Plateau surface; 2) the scarp and talus slopes which bound the Aquarius Plateau; 3) the numerous and varied landslide (landslip) blocks which make up the landslide (landslip) bench; 4) the earth-flows, debris-flows, and slow rock-fragment-flows of the landslide (landslip)-bench slope; and 5) the pediments, torrential boulder deposits, and reworked landslip bebris which make up the lower slopes.

The Aquarius Plateau Surface

The surface of the Aquarius Plateau in the study area consists of gently undulating uplands separated by broad, shallow valleys. Because the study centers on the landslide deposits on the high southern slopes of the plateau, only aspects of the plateau surface which might effect the landslipping on the surrounding slopes were studied. The lack of an integrated drainage system on the plateau surface indicates the importance of the movement of water down through the volcanic caprock. The rocks of the plateau surface are highly jointed and faulted and the water apparently infilts down through these fractures to the underlying strata and then moves horizontally to where it emerges in springs on the landslide bench and landslide-bench slope. Two northeast-trending normal faults form a small graben on the plateau surface.
west of Round Willow Bottom Reservoir (plate 1). The southernmost of the two faults has fault-line sinks along the base of the fault scarp which further emphasize the movement of groundwater downward through the caprock. The downward movement of groundwater through the caprock and out onto the landslide bench may be one of the primary causative factors of landslipping in the area.

Plateau Scarp and Talus Slopes

The scarp which separates the plateau surface from the landslide bench is 17.5 kilometers long and ranges from 30 meters to 100 meters in height. It fits Schumm and Chorley's classification of a compound scarp (1966, p. 18) since it is formed by relatively weak strata overlain by a more resistant caprock. The portion of the scarp bordering Griffin Top is broken by two parallel northeast-trending faults. An intermittent stream flowing along the outcrop of the southern fault has cut a notch into the scarp, but there is no expression of the northern fault on the scarp face. A north-south-trending fault crosses the scarp approximately 2.5 kilometers east of the Gap. This fault also is not visible on the face of the scarp.

The scarp is flanked by talus slopes over most of its length. The nature and slope of the talus varies with its position along the scarp. Along the southern-most one-third of the scarp, where landsliding has been most recent, the talus slopes
are discontinuous, poorly developed, and contain a considerably smaller volume of talus. Slope angles in this area are quite steep averaging 40 to 45 degrees. The slope angles reflect the large size of the boulders which form the slopes (average 1 to 3 meters) and may have resulted from collapse of fractured rock in the cliff face immediately subsequent to landsliding. Uncommonly, lichen-free boulders are located near the top of the slopes indicating that some rock-falls and possibly small rock-avalanches are still taking place. The only vegetation on these slopes consists of scattered spruce trees which grow in places where enough fines have accumulated to support a single or at most a few trees.

The central portion of the scarp, which extends from 3 Springs to a point approximately 2.5 kilometers east of the Gap, is flanked by a continuous, well developed talus slope. Slope angles in this section are in the 30 to 35 degrees range and the top of the talus slope in most places is only about 10 meters from the top of the scarp (fig. 7). At first observation, these talus slopes appear to have well formed protalus ramparts composed of large boulders up to 9 meters in length (figs. 8, 9). Closer inspection, however, reveals that the large boulders have piled up against the backs of landslide blocks a short distance from the base of the scarp. It is possible that some subsequent movement of the toe of the talus has been caused by additional landslip activity or by freeze and thaw in the manner
Figure 7. View looking northeast along the central portion of the scarp and talus slope. Slope angle of the talus in this area is approximately 30 degrees. Vegetation on the talus slope is aspen while that on the plateau top above and on the debris of the landslide bench below is primarily spruce. The lighter colored area of talus in the center of the picture indicates more recent activity there than on the remainder of the slope.
Figure 8. View looking southwest along the central portion of the scarp and talus slope. The extremely large boulders in the lower right portion of the picture appear to form a sizeable protalus rampart but they are actually piled up against the backs of small landslide blocks which are only a short distance from the base of the scarp. The upper left portion of the picture shows part of the largest landslide block found on the landslide bench. Note the vegetation association with the surficial materials on the block. The downslope side where the surficial materials are derived from tuff and limestone is covered with dense stands of aspen while the upslope side which has surface materials derived from volcanic rocks supports an almost pure stand of spruce.
Figure 9. Large boulders of the pseudo-protalus rampart. The largest one against which Dr. John F. Shroder stands was measured at slightly over 9 meters in length. The light colored spots on the rocks are lichen colonies.
Figure 10. View looking toward the talus slope from the pseudo-protalus rampart. The size gradation of the clasts is quite noticeable. The boulders in the foreground are probably Pleistocene and the smaller clasts up the slope neo-glacial to modern.
described by Richmond (1962, p. 20) in his discussion of protalus lobes. These boulders are dark gray in color, contain numerous solution pits, and support considerable lichen growth. There is a decreasing size gradation up the talus slope and the color of clasts is lighter. The large boulders of the pseudo-protalus rampart may be Pleistocene in age and the slopes above are probably largely Holocene (fig. 10) (Shroder, personal communication). A continuous stand of aspens covers the upper two-thirds of the slopes and is advancing toward the foot of the slopes (figs. 7, 8, 10). For the most part, these slopes have been inactive for a considerable period of time, but a few sections contain finer grained and lighter colored rocks which indicate more recent activity.

The remaining portion of the scarp and talus slopes east to the boundary of the study area is the oldest section. Slope angles vary from 20 to 30 degrees and stands of aspen mixed with spruce vegetate the entire slopes. The upper part of the scarp has been rounded by weathering to the point that in most places there is no vertical cliff remaining and the talus slope appears to extend to the top of the scarp.

The Landslide Bench

Retrogressive landsliding of large blocks has resulted in a chaotic surface of ridges and depressions adjacent to and below the full length of the scarp. This type of feature
has been termed a landslide bench by Yeend (1969, p. 30) in his study of the Grand and Battlement Mesas area in Colorado, and has been applied to similar features in Utah by Shroder (1971, p. 4). Shroder now, however, prefers to use the term landslip because it does not imply a particular type of movement (Shroder, personal communication). The two terms are used interchangeably in this study. The landslide bench in the study area varies from 200 meters in width at the eastern boundary of the study area to 3.8 kilometers at the widest point south of Twitchell Creek (plate 1). The landslide blocks which, with associated debris, make up the landslide bench vary in size from those approximately 100 meters in length and a few meters in height to the largest block which is 1.6 kilometers long and 75 meters high. The recency and frequency of the landsliding which produced the bench are extremely varied; but the physical characteristics of the bench surface indicate three general periods of landsliding.

The most recent landsliding has occurred in the area south of Round Willow Bottom Reservoir. The greatest concentration of blocks is found in this area and they are generally shorter in length and closer together than those in the other sections of the bench. Near the scarp the crests of the blocks are extremely angular and the blocks further from the scarp have more rounded crests, a reflection of longer exposure to weathering. The surfaces of all the blocks are entirely mantled with volcanic
rubble. The rotational movement of the blocks at the time they were placed is impossible to determine because of the profusion of boulders. The angularity of the surface is illustrated by figure 11 and by profiles a, b, and c, of figure 12. (The location of the profiles of figure 12 is shown on plate 5.) Weathering processes are beginning to disintegrate the boulders (fig. 13) and Douglas fir, spruce, and Alpine fir are growing where enough fines have accumulated to support their growth.

The landsliding in the central portion of the landslide bench from Round Willow Bottom Reservoir to North Creek occurred sometime before that in the southern portion of the bench. The landslide blocks of the central section are generally larger than in the southern area, but reflecting their longer duration of exposure to weathering, the crests of all the blocks are rounded except those very near the scarp. The largest blocks on the landslide bench are found near the scarp in this section. They are 1.6 kilometers and 1.2 kilometers in length and both are approximately 70 meters in height. These are the only two blocks on the bench in which rotation during movement can be determined and they are both slump blocks (Toreva blocks of Reiche, 1937). The volcanic caprock has remained essentially intact during movement and is found on the scarp side of both blocks. The downslope sides of these two blocks are the only places on the landslide bench where sizeable outcrops of tuffaceous limestone can be found. The largest block may owe its size to sliding along a pre-existing fault line. The area along
Figure 11. View across Long Willow Bottom Reservoir to the southern section of the landslide bench. The coarseness and angularity of the landslide blocks in the area is apparent from the picture. The stands of spruce also reflect the predominance of volcanic rubble in the surficial materials.
Figure 12
Profiles Across the Landslide Bench
Key to profile location contained on plate 5

**Southern Section**

a

b

c

**Central Section**

d  Long Willow Bottom Reservoir

e

f  Barker Reservoir

**Eastern Section**

g

h

i

Vertical mark in each profile indicates the edge of the landslide bench
Figure 13. Weathering of the basalt boulders results in a kind of granular disintegration. The hardiness of the vegetation in the area is indicated by the grasses which have already begun to grow in the gravel sized basalt particles.
the scarp from which the block came lines up almost perfectly with a north-east trending fault which approaches the scarp near the southwest corner of Section 24, Township 33 South, Range 1 West (plate 1). The blocks further out on the bench show considerable modification by weathering. The crests of the blocks have been smoothed and rounded and the volcanic boulders are almost black in color. The voids between the boulders have been completely filled with fines and the areas between the blocks have accumulated fines to such depths that all of the boulders have been buried and smooth floors have been formed. Views over the landslide bench in this area are shown in figures 14 and 15, and cross-sections through it are shown by profiles d, e, and f of figure 12.

The portion of the landslide bench east from North Creek to the border of the study area is the oldest section of the bench. Where individual blocks can still be recognized they are low rounded ridges whose lateral dimensions are difficult to delineate. Headward erosion by streams is continually reducing the width of the bench in this area. At the heads of Griffin Creek and Beck Hollow the width of the bench has been reduced to just over 200 meters (profiles g, h, i of fig. 12; and fig. 16).

The Landslide-Bench Slope

Headward erosion by streams into the area of the landslide bench has resulted in a considerable slope break and steepened
Figure 14. View over the central portion of the landslide bench. The rounding and generally subdued topography is in considerable contrast to the southern portion of the bench shown in figure 11. In this view looking northeast, the decreasing presence of conifers and increasing presence of aspens is quite apparent.
Figure 15. View south over the central portion of the landslide bench near Yellow Lake. This area is the wettest part of the landslide bench. Springs and small swampy ponds are common between the landslide blocks. The dense stands of almost pure aspen are also indicative of the wet conditions.
Figure 16. View looking east into the vicinity of Griffin Creek and Beck Hollow. The landslide bench at the heads of these two drainages has been reduced to approximately 200 meters in width. The zonation of vegetation with altitude is apparent in this picture. At the top, near the scarp the vegetation is primarily spruce. Below this is a band which is almost entirely aspen and below that the vegetation is almost entirely Ponderosa pine.
slopes at the outer edge of the bench. The steepened slopes and saturation of the debris at the edge of the bench by groundwater has resulted in failure of the debris and its movement down over the adjacent slopes. These slopes adjacent to the landslide bench and mantled with landslide deposits are collectively termed the landslide (landslide)-bench slope by Shroder (personal communication).

In the study area, a landslide-bench slope has been formed below the southern and central portions of the landslide bench. The landslide-bench slope ranges from 100 meters to 1 kilometer in width and extends down to approximately the 9,000 foot (2745 meter) contour line. On this surface, debris-flows, slow rock-fragment-flows, an active earth-flow, and an active area of slumping have been identified and mapped. These features are discussed in the following sections. Below the eastern section of the landslide bench, any evidence of a landslide-bench slope which may have existed has been removed by erosion.

Debris-Flows

Debris-flows are downslope movements of mixtures of rock-fragments and fine clastics with varying amounts of water. They move at velocities ranging from slow to very rapid and their form during movement is similar to that of viscous liquids. The debris-avalanche results from the failure of steep slopes overloaded by saturation from intense rains. Debris-avalanches
primarily involve materials above bedrock which flow down a stream channel or depression on the hillslope. The rapid debris-flow is similar to the debris-avalanche but has a greater water content and occurs on less steep slopes. The slow debris-flow is the very slow downslope movement of bedrock-derived debris with varying amounts of water. The slow debris-flows are much larger than the debris-avalanches or rapid debris-flows and have a greater viscosity. They originate from the slow failure of fine grained clastic bedrock which flows down valley or spreads out over a slope disrupting the original drainage and forcing it to flanking positions (Shroder, personal communication).

Three slow debris-flows and two other landforms which are quite probably slow debris-flows have been mapped on the landslide-bench slope in the study area (plate 1). These flows have resulted from the saturation of debris at the edge of the landslide bench by groundwater. This saturation decreases the internal cohesion of the debris to the point where it begins to flow downslope like a viscous liquid. The toe of the largest debris-flow is 1.2 kilometers from the edge of the landslide bench in North Creek and rests at about the 8520 foot (2600 meter) contour. The debris-flow has displaced North Creek so that it now flows along the contact between the debris-flow and the valley side. North Creek is actively downcutting into the debris-flow and active small scale slumping is occurring on the stream banks. Average slope of this debris-flow is 9 degrees. The surface consists of well rounded volcanic boulders which range
in size up to 2 meters in a matrix of fines. Fragments of tuffaceous limestone also occur and range in size up to 30 centimeters. The debris-flow is vegetated over its entire length by aspen, Douglas fir, Ponderosa pine, and near the toe, scrub oak. A low ridge on the north side of the debris-flow near the upper end may be the remnant of a landslip levee (Shroder, 1971, p. 4) but erosion has modified it to the point where definite identification is not possible. The second-largest debris-flow is on the north side of Twitchell Creek and has moved approximately 700 meters downslope from the landslide bench at an average slope of 14 degrees. Vegetation on this flow consists of a scattered covering of scrub oak. The other debris-flows are considerably smaller, 400 meters or less, and are associated with the slow rock-fragment-flows.

**Slow Rock-Fragment-Flows**

Along the southern section of the landslide-bench slope are a group of landforms which upon first inspection in 1970 were thought to be rock glaciers. They exhibited features such as shear zones from differential rates of movement and lateral ridges which are common to rock glaciers, and there were no other boulder deposit landforms recognized at that time which would have caused them to be classified as anything else. Detailed research the following year, however, by Fallat and Shroder on the rock glaciers of the Aquarius and Table Cliffs
Plateaus revealed that these features did not exhibit some of the classic features of true rock glaciers such as a steep front at the angle of repose and a sharp angle between the front and the top surface of the deposit, which Wahrhaftig and Cox (1959, p. 397) have pointed out are exemplary of rock glacier movement. Subsequent research by Shroder (1973) on the nearby Table Cliffs Plateau has revealed that it is not likely that these deposits were ever ice cored or contained sufficient interstitial ice to cause movement throughout the length of the deposits. However, the presence of near freezing water flowing from one spring at the head of White Creek indicates that minor deposits of interstitial ice may be present and contribute locally to movement. Shroder has found these deposits to be primarily the product of water-induced failure of underlying fine-grained clastics or debris which has resulted in basal shearing, a landslip type of movement. He has termed these previously unrecognized features slow rock-fragment-flows and presents the following definition: "Tongue-like or lobate veneer accumulation of rock fragments resulting from slow downslope movement caused by shear within underlying fine clastics or debris." The slow rock-fragment-flows in the study area (figs. 17, 18) range in length from 311 meters to 640 meters; in slope from 15 to 26 degrees; and in average clast size from 31.1 centimeters to 57.4 centimeters. Individual clasts up to 3 meters in length are common in some of these flows and one individual clast 6 meters in length was observed. For the most part these features are presently dormant, but recent localized internal
Figure 17. View of the slow rock-fragment-flow at the head of White Creek. This is the largest slow rock-fragment-flow on the landslide-bench slope and is 568 meters long and has an average clast size of 48.9 centimeters. In the left center of the picture is an area where soil creep is occurring at a rapid enough rate that aspens have been prevented from growing. The soil is probably moving on the same surface that the slow rock-fragment-flow moved on and lacks only the veneer of boulders to be the same type of feature.
Figure 18. View down the landslide-bench slope across a slow rock-fragment-flow to the White Creek pediment. The lateral ridge in the right center of the picture is caused by differential flow in the rock-fragment-flow and is similar to those produced by rock glaciers.
movements have taken place (Fallat, 1972, p. 80-106; and personal communication). Enough movement is taking place in the surficial materials adjacent to some of the slow rock-fragment-flows to prevent the growth of aspens (fig. 17).

The Holbys Bottom Earth-flow

An actively moving earth-flow has been mapped in Holbys Bottom, east of Barker Reservoir (plate 4, figs. 19, 20, 21). It is analogous to the previously described slow rock-fragment-flows in that its movement is due to water-induced shear of the substrata. The flow is moving over a distance of approximately 700 meters and tapers from a width of 265 meters near the head to about 50 meters at the toe. The toe of the earth-flow is in the stream which flows from Gates Spring and the stream is removing the earth as it arrives. This is undoubtedly contributing to the continued movement of the earth-flow. Streams flow onto the surface of the earth-flow in six different places and insure a plentiful supply of water to keep the earth saturated. Ponded water and areas of swampy grasses are common over most of the surface. Irregularities in the slip surface have resulted in a series of scarps and benches down the length of the flow and the entire surface is laced with ruptures. Saturation of the surface of one scarp by streams has caused a small mudflow to run down the surface of the scarp and into an area of ponded water (plate 4). Aspens which were growing on the earth-flow before movement
Figure 19. View of the upper portion of the Holbys Bottom earth-flow. Movements of the earth-flow are tilting aspens and small scarps and ruptures cover its surface.
Figure 20. View looking down the Holbys Bottom earth-flow. Streams are cutting deep channels into the surface of the earth-flow as it moves downslope.
Figure 21. En echelon fractures are found along both sides of the earth-flow. In the picture, the right side of the fracture is stable and the left side is moving straight away from the viewer.
Figure 22. View of the head of the Holbys Bottom earth-flow. The road to Barker Reservoir still crosses the earth-flow and movements in the area will eventually require relocation or extensive reconstruction of the road.
began have been tilted in all directions and some have been in their current positions long enough to have begun to straighten themselves which indicates relatively slow movement or at least temporary cessation of movement in some areas. In one area near the toe of the flow, the aspens have been doubly curved and have managed to straighten themselves again. The location of this earth-flow is particularly significant for two reasons. The road to Barker Reservoir crosses its surface and has had to be relocated twice since 1960 because of movement of the earth-flow (Sonny O'Neil, personal communication). The present location of the road still crosses a small section at the head of the earth-flow and movements in this area will require either extensive reconstruction or further relocation of the road (fig. 22). The earth-flow is located near several small reservoirs which were constructed in the early 1960's which is the same time at which the earth-flow began to move. The reservoir construction has apparently increased the groundwater flow in the area sufficiently to initiate or strongly contribute to the movement of the earth flow (Shroder, and Putnam, 1972, p. 1085).

A short distance from Holbys Bottom, near Gates Spring, is an area of active slumping caused by downcutting of the stream into the debris (fig. 23). Visible in the stream banks are shear zones which reveal at least three episodes of movement since the one which originally formed the landslide bench in this area (fig. 24). A tree-ring sample taken from this area (fig. 25) indicates that active movements were occurring in this area up to 70 years ago.
Figure 23. View of the area west of Holbys Bottom where downcutting by the stream flowing from Gates Spring is causing slumping into the stream channel.
Figure 24. Downcutting by the stream flowing from Gates Spring has exposed shear zones in the debris near the edge of the landslide bench which indicate that several movements have taken place since the original formation of the bench. Dashed ink lines indicate the shear zones.
Figure 25. Tree-ring sample taken from the area of slumping near Gates Spring. Pins have been placed at 10 year intervals in the growth rings. The elliptical shapes of the growth rings indicate that the tree has been tilted twice; the first time about 75 years ago and then again about 40 years ago. When the sample was taken the tree was in the area which is actively slumping and had recently been moved a third time.
Pediments

The slopes below the landslide bench and landslide-bench slope in the study area contain several relatively planar surfaces which resemble remnants of a dissected pediment (figs. 18, 26). The individual surfaces all have slopes between 4 and 7 degrees, but vary in length from 250 meters near Whites Cove to 2.2 kilometers in White Creek. A considerable variance in altitudes prevents these features from being remnants of a single pediment. The tops of the surfaces range in altitude from 2400 to 2600 meters and adjacent surfaces may be as much as 100 meters apart in elevation. The mass-wasting deposits and other colluvial materials of the landslide-bench slope are constantly being regraded by slope wash and channel flow. Some of these deposits become pediment gravels. These pediments are dissected by numerous ephemeral streams many of which are in states of recent or incipient headwater capture. Many small alluvial plains are formed by the resultant cross grading. Continued downcutting by the surrounding streams isolates these alluvial plains creating the multi-level pediment remnants.

Torrential Boulder Deposits

In the bottom of North Creek, and to a lesser extent in the bottoms of all of its tributary streams, are boulder deposits
Figure 26. This view over the Beck Hollow pediment indicates the relatively planar surfaces being formed by the deposition of reworked landslide debris by the streams in the lower parts of the study area.
whose individual members are much too large for the streams
to move at their normal rate of flow. In the months of July
and August, however, precipitation comes in the form of cloudbursts
and runoff is extremely rapid. In a very short time North
Creek changes from a small clear stream to a raging turbid torrent.
It is during these times that the large boulders located in the
stream bottom are moved into their present positions.
SLOPE STABILITY OF THE STUDY AREA

Any discussion of the stability of the slopes in the study area must be tempered by the knowledge that the entire periphery of the plateau area at one time or another has been subject to large scale landsliding and since all of the basic components which were involved in landsliding are still present, the entire area must be considered to a degree potentially unstable. However, varying degrees of instability may be recognized and it is these degrees which have been mapped (plate 5). Slope stability has been divided into four classes which are essentially the same as those used by Bailey (1971, p. 3) in working with landslides in the Teton National Forest of Wyoming. These slope classes are: 1) active slopes; 2) highly unstable slopes; 3) slopes of questionable stability under present conditions; and 4) slopes which are stable under present conditions. The criteria used in mapping these classes are as follows:

1) Active slopes
   a) Slopes which are actively moving.

2) Highly unstable slopes
   a) Presence of surface water and evidence for considerable ground water movement.

   b) Presence of fast growing species such as aspen which reproduce by root buds and the lack of slow growing species such as conifers which require stable soils.
c) Presence of recently active landslips (slow rock-fragment-flows and debris-flows) on steeper slopes.

3) Slopes of questionable stability
   a) Presence of surface water and evidence for considerable ground water movement.
   
   b) Presence of fast growing species such as aspen which reproduce by root buds and the lack of slow growing species such as conifers which require stable soils.

4) Slopes which are stable under present conditions
   a) Slopes with well integrated drainage systems.
   
   b) Presence of vegetative species which require more stable soils such as conifers or species such as juniper and scrub oak which indicate dry conditions.
   
   c) Evidence that a considerable amount of time has elapsed since any active landslide movements have taken place.

All of the active landslips as well as the slopes classified as highly unstable are found on the landslide-bench slope. The steepness of the slopes, abundance of water, and presence of landslide landforms either active or having physical characteristics which indicate recent activity, all reflect the instability of the area.

The area in the central portion of the landslide bench has been designated as having questionable stability because
it is showing signs which may indicate decreasing stability.

This area is the wettest part of the bench with dense stands of aspen, swampy ponds, and springs occurring throughout the area. The landslide-bench slope below the area is currently the site of actively moving landslips. The construction of several small reservoirs on the landslide bench above the active landslips may be increasing the flow of groundwater in the area and may be the initiating cause of the movement. The construction of the reservoirs in the early 1960's closely coincides with the increased activity of the landslips. Close observation of this area should be maintained in the ensuing years to determine if the area is actually losing stability and to determine if major mass movements may be expected. The southern portion of the landslide bench has also been placed in the questionable stability category because it contains the most recent landsliding on the landslide bench and it is relatively narrow and adjacent to the highly unstable slopes of the landslide-bench slope.

The eastern portion of the landslide bench appears to be stable because of the lack of water in the area and also the apparent length of time since any landsliding has taken place. The slope aspects in the area are south and southwest which seems to be one of the controlling factors in the landsliding of this area. In studying landslides over the entire state of Utah, Shroder (1971, p. 8) found the least number of landslides were on slopes with south and southwest aspects. All other slope aspects contained a far greater number of landslides.
The compliance of the study area with these findings may be coincidental because of its relatively small size, but the implication is strong.

Another possible explanation for the distribution of landslides in the area might relate to possible permafrost distribution at the end of the Pleistocene. During interglacial periods, water could move downward through the plateau surface along numerous faults and fractures and through fault-line sinks. With the onset of glaciation, the shaded north and east facing slopes of the landslide bench were probably first to develop permafrost conditions. During the full glacial periods, probably all but south or southwest facing slopes became permanently frozen stopping any water movement. This resulted in blockage of the lateral outlets for groundwater from the plateau surface. Continued freezing extended the permafrost conditions onto the plateau surface and associated ice expansion disrupted the rock. Subsequent thawing during interglacials and interstadials could have then produced profuse landslip activity in the former areas of permafrost whereas the south-facing, possibly unfrozen slopes, might have merely undergone a continuation of surficial colluvial and fluvial processes without a great deal of change. This could account for the great difference in landform genesis, type, and age in the area (Shroder, personal communication).

The slopes below the landslide bench east of North Creek and below the landslide-bench slope west of North Creek are considered to be stable because drainage through these areas is in well developed channels and no significant ground water
movement is apparent. The vegetation in the area is primarily Ponderosa pine and juniper which indicate dry conditions and there is no evidence of recent landslip movements. If any landslip movements have occurred in the past in these areas, they have been removed by erosion or so modified that they are unrecognizable.

Mean, median, mode, and range slope values have been established through a sampling procedure (see p. 17) for each of the stability classes except the active slopes which were measured individually. These values are shown on plate 5. Because of the extremely hummocky nature of the topography of the area which has resulted in a wide range of values within each stability class, the mean, median, and mode values are felt to be useful only in making general comparisons between the stability classes. Throughout the study area, the presence of water is at least as important as the slope steepness in determining slope stability and in some areas such as the Holbys Bottom area, the presence of water may be the decisive factor.
VEGETATION IN THE STUDY AREA

The vegetation in the study area is primarily associated with the climatic factors involved with altitude, slope exposure, and moisture conditions. On the landslide bench, association of vegetation with surficial materials also occurs (plate 2).

The vegetation of the plateau surface reflects the greater than 3000 meter elevation. The area is in the subalpine zone and consists of Engelmann spruce and Alpine fir forest on the uplands and grasses in the valleys.

The stands of spruce and aspen on the landslide bench strongly reflect the surficial materials and moisture conditions where they are located. The surface of the southern portion of the landslide bench is covered with volcanic rubble and the vegetation in the area is dominated by Engelmann spruce. Toward the central portion of the landslide bench, where weathering and erosion have removed much of the volcanic debris, there is a transition from spruce forest to stands of aspen. The best example of vegetative association with surficial materials is shown on the largest landslide block on the landslide bench in this area (fig. 8). The volcanic caprock on the block remained essentially intact during movement and is found on the upslope side of the block. Vegetation on this side of the block is Engelmann spruce with an occasional Douglas fir or Alpine fir. The downslope side
of the block shows several outcrops of tuffaceous limestone and is vegetated almost exclusively by aspen. The presence of spruce in the areas where the surficial materials are primarily derived from volcanics may reflect soil pH, but this factor was not studied and remains a problem. The central portion of the landslide bench is also the area of major groundwater movement and the density of the aspen stands in the area reflect the wet conditions (fig. 15). The eastern section of the landslide bench is almost entirely vegetated with aspen groves. There are a few small areas near the scarp, however, where there are spruce mixed with the aspens, reflecting the presence of volcanic debris.

Below the landslide bench, the vegetation reflects altitude zonation, slope aspect, and moisture conditions. The landslide-bench slope is primarily vegetated with aspens partly because of the instability of the slopes (Bailey, 1971, p. 5) and partly because of the high groundwater content. the zone of elevation from 2700 meters (9,000 feet) down to 2500 meters (8,200 feet) is Ponderosa pine forest. Aspens grow in the drainage ways, and on the south and southwest slopes mixtures of scrub oak, juniper, and grasses with the Ponderosa pines reflect the drier conditions. Below 2500 meters (8200 feet) juniper is codominant with Ponderosa pine and on the south and southwest slopes juniper is the dominant specie.
DRAINAGE IN THE STUDY AREA

The drainage patterns in the study area reflect the adaption of drainage to landslide topography and the subsequent modification of the topography by stream erosion (plate 3).

Surface drainage in the southern section of the landslide bench is completely controlled by the position of the landslide blocks. Because the crests of the blocks and the depressions between them are for the most part parallel to the scarp, the lines of drainage are either parallel to the scarp or perpendicular to it where the flow is between the blocks away from the scarp. This has resulted in a drainage pattern which is quite rectangular. Most of the stream junctions are at nearly right-angles and most drainage ways contain right-angle bends along their courses.

The drainage pattern in the central portion of the landslide bench is also controlled by the position of the landslide blocks in most instances, but the angularity of the stream courses has been considerably reduced and in the area where Twitchell Creek and North Creek cross the outer edge of the landslide bench, the stream pattern is becoming dendritic. Three lakes occur naturally in this portion of the landslide bench and six more have been created by building dams across the streams as they flow through depressions between the landslide blocks. Channels have been constructed in several places to direct the outflow from each reservoir to the next one downslope. The construction of these reservoirs has apparently altered the groundwater flow significantly.
and may be causing landslip movements on the landslide-bench slope adjacent to this portion of the landslide bench.

No perennial streams currently cross the eastern section of the landslide bench, but drainage ways have been established which show only minimal influence by landslide blocks. Headward erosion by streams has extended the dendritic stream pattern in the area below the landslide bench across the bench to the base of the scarp.

The slopes in the study area below the landslide bench are mantled with colluvial debris which is constantly being reworked by sheetwash and channel flow. A uniform dendritic drainage pattern has been established over these slopes. In the vicinity of Whites Cove, streams which originate on lower slopes of the plateau are eroding headward into the white limestone of the Flagstaff Formation which underlies the colluvial debris on the lower slopes. This has resulted in the close spacing and short lengths of the drainage ways which occur in that area.
HYPSOMETRIC ANALYSIS OF THE STUDY AREA

Two types of hypsometric analysis have been conducted in the study area. Hypsographic curves have been constructed for seven drainage basins within the area to compare the roles of mass-wasting and fluvial erosion in the study area. Analysis of closed contours, depressions, and relief of the landslide bench has been undertaken in order to quantitatively compare differing sections of the bench and to permit comparisons with similar features in other areas.

Hypsographic Curves

The hypsographic curve indicates the proportion of a given area of earth surface which is found above a certain elevation. Strahler (1952) has modified the hypsographic curve so that it may be used for comparative purposes between drainage basins. In order to permit comparison, the units used to plot the data must be dimensionless and should be reduced to percentage proportions of the total basin. In this way, the values of the data for all basins will range between 0 and 1 along the axes of the graph. Analysis of this type "forms a useful preliminary step in the study of the dynamic quantitative development of the landscape by river action and mass-movement" (King, 1966, p. 244).
Construction of this type of hypsographic curve involves the following steps:

1) The boundaries of the drainage basin are drawn on the map and the areas between the contours are measured. In this study the 200ft. index contours were used and the areas between them measured by outlining the areas on tracing paper and then using an electronic graphics calculator to compute the areas. For use as an example a small drainage basin on the east side of North Creek has been selected. It is designated as number 1 on plate 5.

In the example area the contours and the areas between them are:

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<th>Contour</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>8400-8600</td>
<td>1,812,500 sq.ft.</td>
</tr>
<tr>
<td>8200-8400</td>
<td>1,500,000 sq.ft.</td>
</tr>
<tr>
<td>8000-8200</td>
<td>593,750 sq.ft.</td>
</tr>
<tr>
<td>7870-8000</td>
<td>375,000 sq.ft.</td>
</tr>
</tbody>
</table>

\[ A = 4,281,250 \text{ sq.ft.} \]

The total area of the basin \((A)\) is the sum of the areas between the contours.

2) The area of the drainage basin above each contour \((a)\) is found by beginning with the highest contour and adding the area of each lower contour to that value.

<table>
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</tr>
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<tr>
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<tr>
<td>8000</td>
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</tr>
<tr>
<td>7870</td>
<td>375,000</td>
<td>4,281,250</td>
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</table>
3) The relative area above each contour (a/A) is found by dividing the area above each contour by the total area of the basin.

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<th>a/A</th>
</tr>
</thead>
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<td>.92</td>
</tr>
<tr>
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<td>1.00</td>
</tr>
</tbody>
</table>

4) The height (h) of each contour is the distance between that contour and the lowest contour, and the total height (H) is the distance between the lowest and highest contour.

<table>
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<tr>
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<tr>
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</tbody>
</table>

5) The relative height of each contour (h/H) is found by dividing the height of each contour by the total height of the basin.

<table>
<thead>
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<th>Contour</th>
<th>h</th>
<th>h/H</th>
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<td>.18</td>
</tr>
<tr>
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</tr>
</tbody>
</table>

6) The relative area (a/A) is then plotted on the x axis of the graph against the relative height (h/H) on the y axis and the result is the percentage hypsographic curve.
The hypsometric integral is equal to the ratio of the area under the hypsometric curve to the area of the entire square. It is expressed in percent and provides further information for comparison of drainage basins.

Percentage hypsographic curves have been constructed for seven drainage basins within the study area (figs. 27, 28) to compare the areas where landsliding is an important factor in the present morphology of the drainage basins, and the areas in which fluvial erosion has removed practically all of the landslide deposits to the extent that landslide topography exerts only minimal influence on the morphology of the drainage basins.

The curves of figure 27 represent the drainage basins of the ephemeral streams east of North Creek where the longest span of time has occurred since any active landsliding has taken place. Figure 28 shows the curves for the area west of North Creek which contains the most recent and presently active landslide deposits.

Strahler (1952, p. 1130) points out that hypsometric curves reflect only two major stages in the development of drainage basins. First, there is an inequilibrium stage of early development in which slope transformations are taking place rapidly as the
Figure 27
Hypsographic Curves Plotted on a Dimensionless Basis for Selected Drainage Basins of Ephemeral Streams East of North Creek in the Study Area

Boundaries of drainage basins selected are shown on plate 5.

Drainage basins of unnamed ephemeral streams are designated by numbers.
Hypsographic Curves Plotted on a Dimensionless Basis for Selected Drainage Basins of Perennial Streams in the Study Area

Boundaries of drainage basins selected are shown on plate 5.

<table>
<thead>
<tr>
<th>Creek</th>
<th>Integral</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Creek</td>
<td>.68</td>
</tr>
<tr>
<td>Twitchell Creek</td>
<td>.78</td>
</tr>
<tr>
<td>White Creek</td>
<td>.54</td>
</tr>
</tbody>
</table>
drainage system expands into the upland surface. The hypsometric curve which represents this stage is commonly convex over much of its length and has a high integral value. Strahler defines the integral of the inequilibrium stage as being greater than 60 per cent. In the second, or equilibrium, stage, the drainage basin has reached its maximum extent and the forces of erosion are slowly and steadily decreasing relief. The hypsometric curve which represents this stage is commonly concave over the upper half of its length and convex over the lower half. These curves have integrals ranging from 40 to 60 per cent (Strahler, 1952, p. 1130).

The hypsometric curve for Twitchell Creek (fig. 29) with its convexity and integral of 78 per cent is highly representative of a drainage basin in the initial stage of development. The decreasing slope of the upper portion of the curve indicates the area of the landslide bench and plateau surface into which Twitchell Creek is extending its basin. The landslide bench also comprises a considerable portion of the upper part of the drainage basin of North Creek which also has a convex curve. Most of the landslide bench has been removed by fluvial erosion in the drainage basins of Griffin Creek and ephemeral stream 3. The hypsometric curves associated with these areas are less convex and their integrals of 60 per cent indicate that they have almost reached the equilibrium stage of development. The hypsometric curve for Beck Hollow (fig. 29), after the initial steep rise common to
Figure 29

Comparison of the Hypsographic Curves for Twitchell Creek and Beck Hollow

<table>
<thead>
<tr>
<th>h/H</th>
<th>Integral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twitchell Creek</td>
<td>.78</td>
</tr>
<tr>
<td>Beck Hollow</td>
<td>.50</td>
</tr>
</tbody>
</table>
all of the curves, decreases its slope to approximately 45 degrees which remains constant to the top of the curve. This slope represents an even distribution of the area of the drainage basin through most elevations. The drainage basin of Beck Hollow has contacted the drainage basins of other streams on all sides and is no longer expanding. The hypsometric integral of 50% reflects its entry into the equilibrium state. Similar conditions exist in White Creek which has a hypsometric curve similar to that of Beck Hollow.

Analysis of Closed Contours, Number of Landslide Blocks, Depressions, and Relief of the Landslide Bench

In studying the landslide bench, a number of observations concerning the topographic characteristics of the various sections of the bench were made. The landslide blocks which make up the bench appeared to be fewer in number and to have less relief with increasing distance from the plateau scarp. There also appeared to be fewer landslide blocks in the eastern section of the bench than in the central section and fewer in the central section than in the southern section. In order to verify these observations, and to permit future comparison of the landslide bench in this area with similar features elsewhere, it became necessary to develop some form of quantitative expression of the irregularity of terrain and the degree of erosion of the landslide blocks making
up the bench. To provide this information, an analysis of the closed contours, number of landslide blocks, depressions, and relief of the various sections of the landslide bench was undertaken. On a map of the study area, a series of concentric lines were drawn over the landslide bench paralleling the line of the plateau scarp at .5 kilometer intervals. The number of closed contours (representing positive topographic features), landslide blocks, depressions (represented by depression contours), and the relief of the areas between the lines were recorded. The compiled data for each of the sections of the landslide bench are shown on Table 1.

The data of Table 1 shows that, in general, the number of closed contours, number of landslide blocks, and relief decrease with distance from the scarp reflecting the longer period of time the landslide blocks further from the scarp have been subject to weathering. Notable exceptions to this trend occur on the eastern and southern sections of the bench. On the eastern section of the bench, in the area from .5km. to 1km. from the scarp, the number of closed contours increases from 3 to 8 indicating an increase in the irregularity of the surface. On the southern section of the bench, the relief in the area from 1.5km. to 2.5km. from the scarp increases from 200 to 320ft. These apparent exceptions may be explained by the fact that the areas in which these conditions exist are near the outer edge of the landslide bench where the drainage patterns are well established and the streams are removing the unconsolidated material from around the remaining landslide blocks. As the material from
Table 1

Number of Closed Contours, Landslide Blocks, Depressions, and Relief of the Landslide Bench Recorded at .5km. Intervals

C = Number of closed contours representing positive topographic features  
N = Number of landslide blocks  
D = Number of depressions represented by depression contours  
R = Relief of each .5km. wide zone

<table>
<thead>
<tr>
<th>Distance from scarp in kilometers</th>
<th>Southern Section</th>
<th>Central Section</th>
<th>Eastern Section</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>N</td>
<td>D</td>
</tr>
<tr>
<td>0 to .5km</td>
<td>46</td>
<td>45</td>
<td>4</td>
</tr>
<tr>
<td>.5 to 1km</td>
<td>22</td>
<td>21</td>
<td>360</td>
</tr>
<tr>
<td>1 to 1.5km</td>
<td>14</td>
<td>16</td>
<td>200</td>
</tr>
<tr>
<td>1.5 to 2km</td>
<td>3</td>
<td>2</td>
<td>240</td>
</tr>
<tr>
<td>2 to 2.5km</td>
<td>2</td>
<td>1</td>
<td>320</td>
</tr>
<tr>
<td>2.5 to 3km</td>
<td>0</td>
<td>0</td>
<td>160</td>
</tr>
<tr>
<td>Total</td>
<td>87</td>
<td>85</td>
<td>53</td>
</tr>
</tbody>
</table>

Average number of closed contours and landslide blocks per square kilometer for each section

<table>
<thead>
<tr>
<th>C</th>
<th>N</th>
<th>Area</th>
<th>C</th>
<th>N</th>
<th>Area</th>
<th>C</th>
<th>N</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.2</td>
<td>12.9</td>
<td>6.6sq.km.</td>
<td>5.8</td>
<td>7.4</td>
<td>9.2sq.km.</td>
<td>2.7</td>
<td>4.9</td>
<td>4.9sq.km.</td>
</tr>
</tbody>
</table>

Ratio of the average number of closed contours per square kilometer to the average number of landslide blocks per square kilometer for each section of the landslide bench:

<table>
<thead>
<tr>
<th>Southern Section</th>
<th>Central Section</th>
<th>Eastern Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.02</td>
<td>.78</td>
<td>.55</td>
</tr>
</tbody>
</table>
around the blocks is removed, the relief and irregularity of the topography is increased until the remnants of the landslide blocks themselves are removed as the outer edge of the landslide bench retreats toward the plateau scarp.

In order to have a single numerical figure to categorize the topography of each section of the landslide bench, a ratio has been formed of the average number of closed contours (representing positive topographic features) per square kilometer, to the average number of landslide blocks per square kilometer. This ratio indicates the average number of closed contours per landslide block for each section of the bench and thus reflects the average relief of the landslide blocks in the area. Because the effects of erosion reduce the relief of individual landslide blocks, the ratio is also an indirect reflection of the degree of erosion of the landslide blocks. In the southern section of the landslide bench the ratio is greater than 1.0 indicating that the average landslide block is just high enough to be expressed by a closed contour. The average height is therefore slightly greater than the contour interval of the map from which the data were taken (in this instance 40 ft.). The ratio for the central and southern sections is less than 1.0 indicating that the average landslide blocks there are not high enough to be expressed by a closed contour. The ratios also indicate a greater amount of erosion of the landslide blocks of the central and eastern sections of the landslide bench. This type of analysis should provide immediately comparative factors with other areas if the same units of area are used
to collect data and the maps have the same contour interval. If different area units and contour intervals have been used, comparative results can still be obtained by converting the data from one map to area and contour units that are equivalent to those of the other map. For example, to compare a map with a 40ft. contour interval on which the number of closed contours have been counted per square mile with a 10 meter contour interval map on which the closed contours have been counted per square kilometer, the following steps are necessary: First the units of area used to express the number of closed contours must be made comparable. To be comparable, the areas must be expressed in the same units. One square mile contains 27,878,400 square feet. One square kilometer contains 10,764,908 square feet. Dividing the area of one square kilometer into the area of one square mile (27,878,400/10,764,908) reveals that one square mile is 2.59 times larger than one square kilometer. The number of closed contours and landslide blocks per square kilometer should then be multiplied by 2.59 to make them equivalent to the area of one square mile. Because the contour intervals of the two maps are different, a further adjustment of the average number of closed contours is necessary. The 10 meter contour interval is equivalent to an interval of 32.8 feet, which is .82 times as great as the 40 ft. interval. Because the 10 meter contour interval is less than the 40ft. interval, there would be more closed contours to represent the same vertical distance. To make the number of closed contours from the two intervals equivalent, the number of closed contours at the 10 meter contour interval
(already multiplied by 2.59) should be multiplied by .82. The ratio of the number of closed contours to the number of landslide blocks per unit of area for each of the maps is then comparable. Calculation of this ratio in the future for other areas will permit comparison of topographic characteristics which were not previously possible.
LAND-USE MANAGEMENT IMPLICATIONS

The variety of land uses possible in the study area is severely limited by the stability characteristics of the slopes in the area. At the time field research was completed, recreation and cattle grazing were the only two activities in the area. The quantity of cattle which could be supported by the grasses in the area is probably not great enough to have any adverse effect on the stability of the area either by overgrazing or by causing increased downslope movement of soil by continuous traversing of the slopes. The present intensity of recreational use should also have no adverse effects on the stability of the area. However, it should be pointed out that dam and reservoir construction in the early 1960's was apparently sufficient to raise the water table in the area enough to initiate or strongly contribute to the movement of the large Holbys Bottom earth-flow (Shroder and Putnam, 1972, p. 1085). Any developments undertaken to expand recreational use of the area, particularly those which would involve the construction of a road system or more reservoirs should be undertaken with extreme care. The disruption of surface and subsurface water flow by road construction in areas of tenuous slope stability, such as those of the landslide-bench slope and central and southern portions of the landslide bench in the study area, have in other areas in similar situations resulted in activation and reactivation of landslides (Bailey, 1971, p. 101-120).
With the ever increasing demand for lumber in the United States, the possible expansion of the land-use activities in the study area to include logging must be considered. There are two locations within the study area where trees with potential value to the lumbering industry are found. The area on the landslide bench south of Twitchell Creek is forested with stands of spruce with intermixed Douglas fir and the lower slopes of the study area below approximately 3000 meters elevation are forested with stands of Ponderosa pine of varying densities which reflect slope exposure and moisture conditions (plate 2).

Any logging operations at all are deemed inadvisable in the area south of Twitchell Creek. Even if stability were not a consideration, logging this area may be both physically and economically impossible. The potential problems with roads have already been mentioned and the effect of the heavy weights involved with hauling logs would multiply the problems many times because of the added necessity of base stabilization and surfacing. Even if the problems with roads could be overcome, the collection of the logs would still present a major obstacle. Much of the ground surface in this area is bouldery rubble which would make surface skidding of logs practically impossible. Alternative logging systems such as the use of baloons or skylines might provide a solution to the problem but the cost of these operations would probably far outstrip the value of the trees in the area. Helicopter logging would
solve both the roads and skidding problems, but the size of the logs and the distance to a suitable landing would make the use of this system financially impossible. The consideration of slope stability problems further complicates the problem. This area is included within the section of the landslide bench which has most recently undergone landsliding. This in itself makes the present stability of the area questionable. Even if the removal of part of the trees from the area did not result in any movement on the landslide bench, the reduction in transpiration of ground water would result in an increase in the flow to the adjacent portions of the landslide-bench slope which could quite conceivable result in activation and reactivation of large landslips in that area. The beneficial effect of the trees in this area in aiding slope stabilization far outweighs their potential value as lumber.

In the lower parts of the study area where the stands of Ponderosa pine are found, a light harvest by various selective cutting methods may be possible. These areas which are relatively stable with respect to landsliding are, however, extremely susceptible to erosion by running water and any logging operations would have to include precautions to prevent disturbance of the low ground vegetation to the extent that sheet wash and channel flow could damage the soils. In this area, a system which involved lifting the logs instead of dragging them to minimize scarification of the soil would be preferable. Road mileage should be minimized
and alignments should follow the surface topography as much as possible to restrict the size of cut and fill slopes. Provision for adequate drainage of water from roads is essential, and if the runoff is directed down a fill slope it should be troughed to the bottom and the area near the outlet rocked. If the proper precautions are taken, a limited harvest may be made with minimal damage to the area.
SUMMARY AND CONCLUSION

The High Plateaus of Utah are composed of essentially flat-lying sedimentary strata overlain in places by Tertiary volcanics and separated by the scarps of high-angle normal faults with the downhill primarily on the western side. The High Plateaus occupy a position transitional in nature between the geologic structures of the Colorado Plateau and the Basin and Range Province to the west. Plateau topography is dominant, but the fault structures are more like those found in the Basin and Range area than those of the Colorado Plateau. The climate and vegetation of the High Plateaus are largely functions of altitude. The areas below 1,800 meters in elevation are desert and the climatic and vegetational changes with increasing elevation range through Ponderosa pine and spruce-fir forests to the subalpine zone on the plateau surfaces.

Access to the study area in the North Creek drainage on the southern slopes of the Aquarius Plateau by road is limited to a single road which follows North Creek to Barker Reservoir. There is currently no one living in the area and recreation and cattle grazing are the only land use activities.

Geomorphic processes acting through time have resulted in the formation of a complex landscape in the High Plateaus of Utah. The landforms of the study area are primarily the result of mass-wasting processes and the subsequent modification of the
mass-wasting deposits by fluvial action. Study of the area has been primarily through geomorphic mapping of these landforms. At the time the study began, no geomorphic symbols were available for detailed mapping of mass-wasting deposits so a new set of symbols was developed for this purpose. This system is based on a number of genetic components common to all mass-wasting landforms. Symbols have been created for: 1) the types of material moved; 2) the types of movement involved; 3) the rate of movement; and 4) the water and ice content of the material moved. The system has been designed so that the symbols are easily recognized and easy to remember, thus avoiding constant referral to a complicated legend. The system has proved to be a valuable research tool both in the field and in the laboratory.

In this study, the landforms of the study area were divided into five groups: 1) the Aquarius Plateau surface; 2) the scarp and talus slopes bounding the plateau surface; 3) the landslide bench; 4) the landslide-bench slope; 5) the remaining slopes below the landslide bench and landslide-bench slope. The surface of the Aquarius Plateau consists of gently undulating uplands separated by broad shallow valleys. The lack of an integrated drainage system and the presence of sink holes and fault-line sinks indicates the importance of the movement of groundwater down through the highly faulted and jointed caprock to the underlying strata. The scarp bounding the plateau surface in the study area is 17.5 kilometers long and ranges from 30 to 100 meters in height. The scarp is flanked by talus slopes over most of its length.
which vary in nature with their location along the scarp. A large pseudo-protalus rampart has been formed along part of the talus slopes primarily by the piling up of large boulders behind landslide blocks a short distance from the scarp. Some additional movement of the toe of the talus may have been caused by subsequent landslip activity or talus creep.

Retrogressive landsliding of large blocks has resulted in the formation of a landslide bench below the full length of the scarp. The landsliding which formed the bench can be generally divided into three periods. The southern section of the bench contains the most recent landsliding. The blocks in this area are smaller, closer together, and more angular than those on the remainder of the bench. The landsliding in the central portion of the bench occurred sometime before that in the southern portion of the bench. The landslide blocks in the central section are larger, but more rounded reflecting their longer exposure to weathering. The eastern portion of the bench is the oldest. Where individual landslide blocks can still be recognized, they are low, rounded ridges whose lateral dimensions are difficult to delineate. Erosion has reduced the width of the bench in part of this area to just over 200 meters.

A landslide-bench slope has been formed below the southern and central portions of the landslide bench. Slow debris-flows up to 1.2 kilometers in length have been mapped on the landslide-bench slope. Along the southern section of the slope are several features which were originally thought to be rock glaciers, but which have recently been identified as slow rock-fragment-flows. They
exhibit surface features such as shear zones and lateral ridges similar to rock glaciers but lack the steep front characteristic of the rock glacier. Their movement is by basal shearing, a landslip type of movement. An active earth-flow is located in Holbys Bottom east of Barker Reservoir. Its movement is by basal shearing like that of the slow rock-fragment-flows but it lacks the surficial veneer of boulders. Activity of the earth-flow is associated with the construction of several small reservoirs on the landslide bench nearby which are increasing the amount of groundwater flow in the area.

The landslide debris on the slopes below the landslide bench and landslide-bench slope is continuously being reworked by slope wash and channel flow and is being redeposited as pediment gravels. Because of the frequency of channel changes in this area these pediments are simultaneously being created and destroyed. In the stream bottoms are torrential boulder deposits which are placed by flash flooding of the streams caused by cloudbursts during the months of July and August.

Slope stability in the study area appears to be primarily dependent on the presence of ground water and the slope aspect. The south and southwest slopes of the eastern portion of the landslide bench are dry and appear to be stable under present conditions. The southern and central sections of the bench have east and southeast aspects and abundant surface and groundwater flow. Reservoir construction in the central portion of the bench may be increasing the groundwater flow and decreasing stability in that area.
The vegetation in the study area is primarily associated with the climatic factors involved with altitude, slope exposure, and moisture conditions; although on the landslide bench, association of vegetation with surficial materials has been observed. The plateau surface is vegetated with stands of spruce and fir reflecting the high elevation. On the landslide bench, spruce are associated with surficial materials derived from volcanic rubble, and stands of aspen are associated with surficial materials derived from tuffaceous limestone and high ground water content. The landslide-bench slope is vegetated with stands of aspens, grasses and shrubs reflecting the instability of the area and the high groundwater content. Below the landslide bench and bench-slope, the vegetation is a reflection primarily of altitude zonation and slope aspect. Ponderosa pine dominates with juniper, scrub oak, and grasses as subordinate species.

The drainage system of the study area reflects the adaption of drainage lines to landslide topography and the subsequent modification of the landslide topography by stream erosion. In the southern section of the bench the drainage pattern is totally controlled by the position of the landslide blocks which has resulted in the development of a rectangular drainage pattern. Drainage in the central portion of the bench is controlled by the position of the landslide blocks, but the angularity of the stream courses has been considerably reduced. The eastern section of the landslide bench exhibits only minimal influence of the drainage pattern by
landslide blocks and the dendritic pattern found below the landslide bench has been extended up over the bench to the base of the scarp.

Two types of hypsometric analysis have been conducted in the study area. Hypsographic curves were constructed for selected drainage basins in areas whose morphology was due to landsliding, and in areas where fluvial erosion has removed the landslide deposits. In the landslide areas, most of the area of the drainage basins are in the upper elevations. The result of fluvial erosion of these areas appears to be the redistribution of the land area equally throughout the elevation ranges of the drainage basins. Analysis of closed contours, number of landslide blocks, depressions, and relief of the landslide bench was undertaken to give quantitative expression to the topographic characteristics of various portions of the bench and to permit future comparisons with similar features in other areas. The results of this analysis supported the observations that the number of landslide blocks and relief decrease with distance from the scarp and that the landsliding has been most recent in the southern portion of the landslide bench and that the eastern section of the bench is the oldest.

The stability conditions in the study area are very fragile and severely limit the possible land use activities in the study area. The current land use activities of recreation and grazing do not appear to have adverse effects on slope stability, but expansion of recreation usage or the expansion of land use activities to include logging could have serious adverse effects. In addition to stability problems, the high cost of any logging operations undertaken on the landslide bench would make them economically unfeasable. In
the lower areas where slope stability with respect to landsliding is not as serious a problem, a light timber harvest may be possible if adequate precautions to protect the soils are taken.

Any statements made at this time concerning the long range stability of the study area must be speculative in nature. The area of the Aquarius Plateau in the past must have been considerably larger than its present size and landsliding appears to have been an integral part of the slope forming processes of the area. If this is true, then landsliding should also be an integral part of future slope forming processes. The movement of groundwater from the plateau surface down through the caprock to the landslide bench and bench-slope appears to be an important part of the mechanism which induces landsliding. Also, streams which originate on the lower slopes of the plateau are eroding headward and have begun to enter the study area in the vicinity of White's Cove. The resultant steepening of slopes by the advance of these streams may also be a basic component in the process. In any case, a great deal of research lies ahead if the complex of geomorphic systems operating in this area are to be fully understood. It is hoped that this study has made one of the initial steps in that direction.
REFERENCES CITED


Movement of boulder deposits, Table Cliffs Plateau, Utah: Rocky Mountain Section, Geological Society of America, abstracts with programs, 1973, p. 511-512.


SLOPE STABILITY

STABILITY CLASSES

Active Slopes

Highly Unstable Slopes

Slopes of Questionable Stability

Stable Slopes

Plateau Scarp

Boundary of Landslide Bench

Location of slope profiles a-i shown in figure 12

Boundaries of drainage basins for which hypsographic curves have been constructed

Unnamed ephemeral streams east of North Creek have been assigned numbers

SLOPE VALUES FOR STABILITY CLASSES

Active slopes mean 15.88°, median 17°, mode 11°, range 9°-24°

Highly Unstable slopes mean 15.88°, median 17°, mode 11°, range 9°-24°

Slopes of Questionable Stability mean 11.30°, median 11°, mode 8.5°, range 0°-19°

Stable slopes mean 14.18°, median 10°, mode 14°, range 0°-33°

PLATE 5

SLOPE STABILITY

STABILITY CLASSES

Active Slopes

Highly Unstable Slopes

Slopes of Questionable Stability

Stable Slopes

Plateau Scarp

Boundary of Landslide Bench

Lower Boundary of Landslide Bench-Slope

Location of slope profiles a-i shown in figure 12

Boundaries of drainage basins for which hypsographic curves have been constructed

Unnamed ephemeral streams east of North Creek have been assigned numbers

SLOPE VALUES FOR STABILITY CLASSES

Active slopes mean 15.88°, median 17°, mode 11°, range 9°-24°

Highly Unstable slopes mean 15.88°, median 17°, mode 11°, range 9°-24°

Slopes of Questionable Stability mean 11.30°, median 11°, mode 8.5°, range 0°-19°

Stable slopes mean 14.18°, median 10°, mode 14°, range 0°-33°
LANDFORMS

Plateau Scarp
Talus Slopes
Landslide Blocks
angular crests
rounded crests
slump blocks
Boundary of Landslide Bench
Debris on Landslide Bench Slope
Lower Boundary of Landslide Bench Slope
Earthflow
Debris flows
Area of Small Scale Slumping
Slow Rock Fragment Flows
Boulderfields
Reworked Landslide Debris
Soil Creep
Torrential Boulder Deposits
Faults
Fault line Sinks
Piedmonts
Colluvial Slope Deposits
from Weathering of Sedimentary Rocks
Cliffs
Active Landslips Shown in Red
Boundary between sections of the Landslide Bench
PLATE 2

VEGETATION

Dominant species and first major subordinate species have been mapped. Where species are codominant, only the codominant species are shown.

Dominant species are indicated by upper case letters and subordinate species are indicated by lower case letters.

SPECIES MAPPED

Aspen A
Spruce S
Ponderosa pine P
Juniper J
Grasses G
Scrub oak S

Nonvegetated areas N

Mapped from aerial photographs dated 6-23-60

Fuller information on this map and additional copies may be had by writing to:

U.S. Geological Survey
Denver, Colorado 80225
PLATE 3

DRAINAGE LINES OF THE STUDY AREA

Adapted from: KAIPEPENOTZ PEAK Z. UTAH
DIXIE NATIONAL FOREST
U.S.F.S. PLANIMETRIC SERIES, 1961