Hydrogeology and the Tapeats Amphitheater and Deer Basin, Grand Canyon, Arizona: A study in karst hydrology

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HYDROGEOLOGY OF THE TAPEATS AMPHITHEATER
AND DEER BASIN, GRAND CANYON, ARIZONA:
A STUDY IN KARST HYDROLOGY

by
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# TABLE OF CONTENTS

| LIST OF TABLES | vii |
| LIST OF ILLUSTRATIONS | viii |
| ABSTRACT | x |
| INTRODUCTION | 1 |
| Location | 1 |
| Topography and Drainage | 1 |
| Climate and Vegetation | 2 |
| Topographic Maps | 4 |
| Accessibility | 5 |
| Objectives of the Thesis | 6 |
| Method of Study | 7 |
| Previous Work | 7 |
| ROCK UNITS: LITHOLOGIC AND WATER BEARING PROPERTIES | 10 |
| Definition of Permeability | 11 |
| Precambrian Rocks | 12 |
| Paleozoic Rocks | 13 |
| Tonto Group | 15 |
| Tapeats Sandstone | 15 |
| Bright Angel Shale | 16 |
| Muav Limestone | 17 |
| Temple Butte Limestone | 19 |
| Redwall Limestone | 20 |
| Aubrey Group | 22 |
| Supai Formation | 23 |
| Hermit Shale | 25 |
| Coconino Sandstone | 25 |
| Toroweap Formation | 26 |
| Kaibab Formation | 27 |
| Cenozoic Rocks | 28 |
| Quaternary Slump and Alluvial Material | 29 |
| Stream Gravels | 30 |
| Soil and Debris Mantle | 30 |
| STRUCTURAL GEOLOGY | 31 |
| General Tectonic Pattern | 31 |
| Crazy Jug Monocline-Muav Fault System | 33 |
TABLE OF CONTENTS--Continued

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tapeats Fault</td>
<td>38</td>
</tr>
<tr>
<td>Thunder Fault</td>
<td>40</td>
</tr>
<tr>
<td>Deer Fault</td>
<td>41</td>
</tr>
<tr>
<td>Trail Graben</td>
<td>41</td>
</tr>
<tr>
<td>Upper Deer Fault</td>
<td>42</td>
</tr>
<tr>
<td>Sinyala Fault</td>
<td>42</td>
</tr>
<tr>
<td>Slump Zone in Surprise Valley and West of Deer Creek</td>
<td>44</td>
</tr>
<tr>
<td>Sequence of Tectonic Events</td>
<td>49</td>
</tr>
</tbody>
</table>

HYDROLOGY

- The Infiltration Zone: The Plateau Surface                         | 52   |
- Springs in the Canyon Walls                                        |      |
  - Springs East of Saddle and Crazy Jug Canyons in the Aubrey Group of Tapeats Amphitheater | 56   |
  - Springs in the Aubrey Group in the Northern Portion of Tapeats Amphitheater and Deer Basin | 58   |
  - Springs Below the Aubrey Group                                    | 60   |
- Structurally Controlled Karst Springs in the Muav Limestone         | 62   |
  - General Features                                                   | 62   |
  - Tapeats Spring and Cave                                            | 65   |
  - Thunder Spring and Cave                                            | 67   |
  - Vaughn and Deer Springs                                            | 71   |
- Water Quality Data for the Karst Springs                            | 75   |
- Circulation of Ground Water in the Tapeats-Deer Area                | 75   |
  - The Ground Water Circulation Model                                 | 77   |
    - Case A                                                            | 85   |
    - Example 1                                                         | 87   |
    - Case B                                                            | 87   |
    - Example 2                                                         | 89   |
    - Example 3                                                         | 92   |
    - Case C                                                            | 95   |
- Circulation Model Applied to the Paleozoic Sediments in the Tapeats-Deer Area | 100  |
- Effect of Structural Modifications on Circulation                   | 103  |
- Dynamics of the Tapeats-Deer Ground Water System                    | 105  |
- Evolution of the Present Ground Water System                        | 112  |
- Late Cretaceous Period                                               | 112  |
TABLE OF CONTENTS--Continued

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Cenozoic Era</td>
<td>112</td>
</tr>
<tr>
<td>Faulting in the Tapeats-Deer Area</td>
<td>113</td>
</tr>
<tr>
<td>Hualapai Drainage in the Tapeats-Deer Area</td>
<td>114</td>
</tr>
<tr>
<td>Development of the Modern Colorado River</td>
<td>115</td>
</tr>
<tr>
<td>and Headward Erosion of Tapeats Creek</td>
<td></td>
</tr>
<tr>
<td>Location of Caves at the Base of the Lower Paleozoic Limestones</td>
<td>116</td>
</tr>
<tr>
<td>Surprise Valley Collapse</td>
<td>118</td>
</tr>
<tr>
<td>Present System</td>
<td>120</td>
</tr>
<tr>
<td>Future Evolution</td>
<td>120</td>
</tr>
<tr>
<td>LIST OF REFERENCES</td>
<td>123</td>
</tr>
<tr>
<td>Table</td>
<td>Page</td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>1. Ground Water Discharge into Tapeats and Deer Canyons from Karst Springs in the Muav Limestone</td>
<td>64</td>
</tr>
<tr>
<td>2. Chemical Analysis of Water Samples from Springs in Tapeats and Deer Canyons</td>
<td>76</td>
</tr>
<tr>
<td>3. Estimated Permeability Rank Considering Only Primary Permeability and Secondary Permeability Due to Joints</td>
<td>102</td>
</tr>
<tr>
<td>4. Estimated Permeability Rank Considering Both Primary and Secondary Permeability Factors</td>
<td>102</td>
</tr>
</tbody>
</table>
# LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Topographic Map of the Tapeats Amphitheater and Deer Basin, Grand Canyon, Arizona</td>
<td>Pocket</td>
</tr>
<tr>
<td>2. Tapeats-Deer Area Viewed toward the West</td>
<td>3</td>
</tr>
<tr>
<td>3. Geologic Map of the Tapeats Amphitheater and Deer Basin, Grand Canyon, Arizona</td>
<td>Pocket</td>
</tr>
<tr>
<td>4. Geologic Sections of the Tapeats Amphitheater and Deer Basin, Grand Canyon, Arizona</td>
<td>Pocket</td>
</tr>
<tr>
<td>5. Columnar Geologic Section in the Tapeats-Deer Area, Grand Canyon, Arizona, Showing Lithologic and Hydrologic Properties</td>
<td>Pocket</td>
</tr>
<tr>
<td>6. Cambrian Sediments Deposited against the Precambrian Topographic High along the Granite Narrows Viewed toward the East</td>
<td>14</td>
</tr>
<tr>
<td>7. Muav Fault and Crazy Jug Monocline Viewed toward the South</td>
<td>34</td>
</tr>
<tr>
<td>8. Muav Fault Zone at Big Saddle Viewed toward the North</td>
<td>36</td>
</tr>
<tr>
<td>9. Tapeats Fault and Associated Graben in Tapeats Cave Canyon Viewed toward the North</td>
<td>39</td>
</tr>
<tr>
<td>10. Sinyala Fault Viewed toward the Southwest across Deer Basin</td>
<td>43</td>
</tr>
<tr>
<td>11. Surprise Valley Slump Mass Dissected by Thunder River Viewed toward the South</td>
<td>46</td>
</tr>
<tr>
<td>12. Toreva Block in Surprise Valley Viewed toward the West</td>
<td>47</td>
</tr>
<tr>
<td>13. Tapeats Cave</td>
<td>66</td>
</tr>
<tr>
<td>14. Thunder Spring</td>
<td>68</td>
</tr>
<tr>
<td>15. Thunder Cave</td>
<td>70</td>
</tr>
</tbody>
</table>
## LIST OF ILLUSTRATIONS--Continued

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.</td>
<td>Northward Trending Stream Passage in Thunder Cave</td>
</tr>
<tr>
<td>17.</td>
<td>Vaughn Spring</td>
</tr>
<tr>
<td>18.</td>
<td>Vertical Flow through a Layer</td>
</tr>
<tr>
<td>19.</td>
<td>Head Loss through a Layer</td>
</tr>
<tr>
<td>20.</td>
<td>Elementary Flow Model</td>
</tr>
<tr>
<td>21.</td>
<td>Case A: ( P_2 &lt; P_1 )</td>
</tr>
<tr>
<td>22.</td>
<td>Example 1: ( P_1 &gt; P_2 &gt; P_3 )</td>
</tr>
<tr>
<td>23.</td>
<td>Case B: ( P_1 &lt; P_2 )</td>
</tr>
<tr>
<td>24.</td>
<td>Example 2: ( P_1 &gt; P_3 &gt; P_2 )</td>
</tr>
<tr>
<td>25.</td>
<td>Example 3: ( P_2 &gt; P_3 &gt; P_1 &gt; P_4 )</td>
</tr>
<tr>
<td>26.</td>
<td>Case C: ( P_1 = P_2 )</td>
</tr>
<tr>
<td>27.</td>
<td>Schematic Diagram of the Ground Water Circulation System that Supplies Water to Tapeats and Thunder Karst Springs</td>
</tr>
</tbody>
</table>

Page 72
Page 73
Page 78
Page 82
Page 83
Page 86
Page 88
Page 90
Page 91
Page 93
Page 96
North of the Grand Canyon, water from precipitation infiltrates into the permeable Kaibab Formation which outcrops over the Kaibab and Kanab Plateaus. Water moves vertically downward through a karst drainage network in the Kaibab and Toroweap Formations until it reaches semi-permeable clastic sediments. A portion of the water is perched above these beds and flows toward the west under a gradient imposed on the system by the gentle westward regional dip of the strata. Some of the westward flowing water discharges directly into Tapeats Amphitheater from seeps and small springs but most of it drains into the north-south trending West Kaibab Fault Zone. In the Fault zone, the water encounters large vertical rock permeabilities and readily circulates downward through the otherwise semi-permeable clastic strata to the lower limestone units. At depth, the water is conducted southward to the Grand Canyon in solution tubes which have been dissolved along the fault zone. Within a few miles of the Tapeats Amphitheater, the water is pirated from the Muav Fault of the West Kaibab Fault Zone and moves toward the southwest through solution tubes developed along minor faults in the limestones to discharge points 4000 feet below the plateaus in Tapeats Canyon. To the west, a similar but smaller karst system discharges water into Deer Canyon.
INTRODUCTION

Location

Deer Basin and Tapeats Amphitheater are sub-basins of the Grand Canyon in Coconino County, Arizona. Tapeats Amphitheater lies within the Grand Canyon National Park whereas Deer Basin, the Kaibab Plateau and the Kanab Plateau are in the Kaibab National Forest. The area considered in this report includes about 60 square miles bounded on the south by Tapeats Terrace and the Colorado River, on the west by the plateau separating Deer Canyon from the next canyon to the west, on the north by Indian Hollow and on the east about 3 miles east of Big Saddle, Crazy Jug Canyon and Saddle Canyon. See Figure 1.

Topography and Drainage

The land surface ranges from 2000 to 8000 feet in elevation above sea level from the floor of the Granite Narrows along the Colorado River to the Kaibab Plateau 12 miles to the east. On a regional basis, Big Saddle is the arbitrary division between the Kaibab Plateau to the east and the Kanab Plateau to the west. In this area, the Colorado River has eroded its northernmost meander into the plateaus in the Grand Canyon region. Tapeats and Deer Canyons are large tributary canyons of the Colorado River, both situated north of the river. The northern and eastern
boundaries of Tapeats Amphitheater and the northern boundary of Deer Basin form a physiographic divide between the plateaus and the step-bench topography of the Grand Canyon. Surface drainage on the Kaibab and Kanab Plateaus is from the east to the west. Deer Basin drains predominantly southward whereas Tapeats Amphitheater drains both southward and westward. See Figure 2.

**Climate and Vegetation**

Climatic conditions vary considerably over the Tapeats-Deer area due to the large relief of about 6000 feet between the high plateaus and Grand Canyon. The vegetation ranges from desert plants, including cottonwood trees and cacti, in the Grand Canyon to lush pine forests on the Kaibab Plateau. The high parts of the Kaibab Plateau are covered by Ponderosa pine forests supported by 15 to 25 inches of annual precipitation. In the deep valleys of the Kaibab Plateau scenic groves of aspen are found separated by grassy meadows. The Kanab Plateau receives 10 to 20 inches of annual precipitation which supports juniper and pinon forests. Oak woodlands and scattered chaparral grow on the Kanab Plateau near the canyons and in several low areas. Along the walls of the Grand Canyon, vegetation changes to desert types that exist on a meager rainfall of less than 10 inches per year. Where water is available in the deep canyons, cottonwoods grow but generally scattered desert shrubs and cacti are the only perennial plants.
Tapeats Canyon is the deep gorge in the foreground. The Colorado River flows in the Canyon behind Steamboat Mountain (center of left margin) and on the left side of Surprise Valley (center, below lower set of cliffs).
In the Grand Canyon, temperatures range from an average of 45°F in January to over 90°F in July, whereas on the Kaibab Plateau temperatures range from 20°F in January to over 65°F in July (Green and Sellers 1964). Precipitation occurs in two seasons, widespread cyclonic storms in winter and thunderstorms in summer. Most of the winter precipitation falls as snow that may total as much as 10 feet during the season. More than half of the annual precipitation falls in July and August and usually occurs as late afternoon thundershowers that build up to the west and slowly move eastward. Most showers fall just north of the Tapeats Amphitheater and Deer Basin on the Kanab and Kaibab Plateaus.

**Topographic Maps**

Topographic maps prepared by the Army Map Service and the United States Geological Survey are available. Army Map Service Quadrangles were not useful because of the smallness of scale. United States Geological Survey 15 minute quadrangles, scale 1:62,500, include coverage for the entire area and provided adequate topographic control. The entire Tapeats Amphitheater and eastern portion of Deer Basin are shown on the Powell Plateau, Arizona Quadrangle. Western Deer Basin appears on the Kanab Point, Arizona Quadrangle. Both of these quadrangles appear as Figure 1 in this paper. Various United States Forest Service maps outline roads in the Kaibab and Kanab Plateaus but these maps omit topographic control. Aerial photographs having a scale of
approximately 1:37,500 are available from the United States Geological Survey for the entire area.

**Accessibility**

A good network of dirt roads maintained by the United States Forest Service exists on the Kaibab and Kanab Plateaus. Every major point overlooking the Tapeats Amphitheater can be reached by roads and a road down Indian Hollow provides access to Deer Basin. With care, these roads can be traversed by automobiles.

The interior portions of the Grand Canyon are accessible only by trails or by raft via the Colorado River. Only one trail leads into the deeper portions of Deer and Tapeats Canyons. This trail, known as the Thunder River Horse Trail, descends the north wall of Deer Basin and follows a wide bench around the eastern portion of the basin before descending into Surprise Valley. In Surprise Valley, the trail forks. One ill-defined branch leads westward into lower Deer Canyon and finally southward to the Colorado River, the other trends eastward to the bottom of Thunder River past Thunder Spring.

Three rough unmaintained routes and trails descend the north wall of Tapeats Amphitheater. An old trail descends through a break in the wall east of Big Saddle and divides at the head of Crazy Jug Canyon. The eastern branch follows Crazy Jug Canyon and Saddle Canyon above a set of high limestone cliffs to Muav Saddle. The west branch of
this trail follows Tapeats Canyon above the high limestone cliffs and is joined by a second poorly defined trail that descends the north wall of Tapeats Amphitheater between Crazy Jug and Monument Points. The combined trail joins the Thunder River Horse Trail southwest of Bridger's Knoll. A route exists down the southern divide of Monument Point and joins the Thunder River Horse Trail west of Bridger's Knoll but this route requires difficult climbing. The remainder of the Tapeats Amphitheater and Deer Basin is accessible only by cross-country walking.

Objectives of the Thesis

Over 4000 feet of gently dipping Paleozoic rocks are exposed in the Tapeats-Deer area. Hydrologically, these rocks may be classified into 4 groups. From the top of the section the groups are: (1) the upper limestones, top 700 feet, (2) upper insoluble clastics, 1700 feet, (3) lower limestones, 1300 feet, and (4) lower insoluble clastic rocks that rest on a Precambrian basement. In general, the primary permeability of the rocks decreases with depth which implies that most ground water circulation should occur near the top of the section. In fact, however, most ground water discharges into the Tapeats-Deer area from the base of the lower limestones which lie 3700 feet below the nearest plateaus. Furthermore, the Kaibab and Kanab Plateaus to the north are characterized by negligible amounts of surface runoff even though they receive abundant precipitation. The
purpose of this report is to analyze the ground water flow system that is operating in the Paleozoic section in the Tapeats-Deer area in order to explain these anomalous hydrologic facts.

Method of Study

In order to develop an adequate understanding of the ground water flow system, the geology of the Tapeats-Deer area was mapped to determine the structural and lithologic properties of the rocks. These field studies provided a sound basis for postulating a theoretical model describing ground water circulation in the region. The portions of the flow model that were not directly amenable to field observation were inferred from geologic or hydrologic evidence.

Previous Work

The Grand Canyon is a classical study area for geologists interested in Paleozoic and Precambrian rocks. The literature is replete with lithologic descriptions of the rock formations. Of particular interest to this study are the works of McKee on the Kaibab and Toroweap Formations, (1938), the Redwall Limestone (in Preparation) and unpublished measured sections of the Supai and Hermit Formations in the Tapeats-Deer area. Noble's work in the Shinumo Amphitheater (1914) was relevant due to the close proximity of his area to Tapeats Amphitheater. Many studies of the
structural geology of the Grand Canyon region have also been made but no detailed work has been conducted in the Tapeats-Deer area. Powell (1873), Gilbert (1875b) and Dutton (1882), in their classic works on the Grand Canyon area, reported on the Muav Fault. Dutton observed both the Muav Fault and Crazy Jug Monocline at Muav Saddle south of Tapeats Amphitheater. Detailed work on the Muav Fault was carried out by Noble (1914) in Muav Canyon south of Muav Saddle and is of great interest because Muav Canyon offers the deepest exposure of the Muav Fault in Grand Canyon. Babenroth and Strahler's (1945) work on the East Kaibab Monocline yields the only post-Paleozoic dates on structural events in the Grand Canyon region. Strahler (1948) treated the West Kaibab Fault Zone in detail; however, Tapeats Amphitheater did not receive close scrutiny. He mentioned Tapeats Fault but did not name it.

Unlike the geological studies, the hydrologic aspects of the Grand Canyon region have received virtually no attention. Metzger (1961) discussed the geohydrologic aspects of the South Rim water supply; however, he did not describe in detail the ground water circulation system in the Paleozoic section. Johnson and Sanderson (1968) have compiled water quality data on springs discharging into the Colorado River and they have included data on the major springs of the Tapeats-Deer area. The United States Geological Survey has obtained intermittent discharge measurements from the
Tapeats-Deer area springs which are invaluable. The general climatic characteristics of the Kaibab Plateau region are summarized by Green and Sellers (1964).
ROCK UNITS: LITHOLOGIC AND WATER BEARING PROPERTIES

The Tapeats Amphitheater and Deer Basin have been eroded from thick sequences of Paleozoic and Precambrian rocks. The Paleozoic rocks have a total thickness of over 4125 feet and dip gently westward at less than 2°. Locally, they are tectonically disturbed. The Colorado River and Tapeats Creek have dissected the entire Paleozoic section and in places have cut over 400 feet vertically into the Precambrian basement which consists of faulted and tilted sedimentary and metamorphic units. The outcrops of the rock units in the study area are shown on Figure 3. Figure 4 contains three structural cross sections. The columnar section shown on Figure 5 summarizes the geologic and hydrologic properties of the stratigraphic units.

From a hydrologic point of view, the Paleozoic section may be considered as 4 alternating layers of soluble and clastic insoluble rocks. The Kaibab and Toroweap Formations have a combined thickness of over 650 feet and form the upper soluble group at the top of the section. The upper insoluble clastics including the Coconino Sandstone, Hermit Shale and Supai Formation have a combined thickness of about 1700 feet. The Redwall, Temple Butte and Muav Limestones, 1400 feet thick, compose the lower soluble group. The Bright Angel Shale and older rocks form the lower
insoluble clastic group. Roughly, the clastic insoluble groups decrease in permeability from top to bottom whereas the permeability of the soluble groups increases. This permeability zonation has a profound effect on spring occurrences in the canyon walls.

**Definition of Permeability**

The permeability of a given lithologic unit depends on both the primary and secondary permeability characteristics of the rock. For the purposes of this paper, primary permeability is defined as the ability of a rock unit to transmit water through its intergranular or intercrystalline pore spaces. Therefore primary permeability depends on the size and interconnection of pore spaces and the degree of cementation between the solid grains. The secondary permeability of a rock unit is defined as the permeability resulting from physical modification of the grain-pore matrix of the rock. Secondary permeability is, therefore, a function of all tectonic deformations of the rock such as jointing and faulting and solutional modifications of the matrix.

In the case of the Paleozoic rocks in the Grand Canyon, the primary permeability of the clastic insoluble rocks is much greater than that of the soluble units. However, tectonic and solutional modifications, while affecting all units, have had a greater effect on the soluble members and, as a result, the gross permeability of the soluble rocks exceeds the gross permeability of the clastics.
Unfortunately, the hydrological parameters: permeability, transmissibility, and storage have not been determined for the rocks of the Grand Canyon in this area because test wells do not exist. As a consequence, only the relative permeabilities can be estimated. Because numerical values of permeability are not available, the qualitative terms "small" and "large" must be used. In this text, a medium having a small permeability will refer to a medium that transmits water at a rate of less than 1 gallon per day through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot of water per foot at 60°F. Large permeability will refer to mediums that transmit water at rates greater than 1 gallon per day per cubic foot. For rocks in the study area, primary permeabilities rarely exceed 10 gallons per day per cubic foot; however, large permeabilities along fault zones may easily exceed 1000 gallons per day per cubic foot.

**Precambrian Rocks**

Precambrian rocks are exposed along the entire Colorado River in the study area. Tapeats Canyon is floored by Precambrian rocks within a mile of its junction with Crazy Jug and Saddle Canyons. The Precambrian rocks along the Colorado River consist mainly of Vishnu Schist which forms the Granite Narrows. The Precambrian rocks exhumed by Tapeats Creek are primarily clastic sediments that overlie the schist. These sedimentary rocks are tilted and faulted
members of the Unkar Group of Younger Precambrian Age and include red shale and red-brown, medium to coarse-grained quartz sandstone. The sandstones form resistant cliffs whereas the shales form slopes.

A topographic high of the Precambrian surface occurs under Surprise Valley and is exposed both in the Granite Narrows and lower Tapeats Creek. See Figure 6. The relief of this high is on the order of several hundred feet and forms an irregular contact with the Cambrian sediments that subsequently buried it.

The Precambrian rocks in the area have little hydrologic significance because in general they are tight and well cemented. Seeps of negligible discharge occur along bedding planes of the sandstones and minor springs flow from fault zones; however, these account for an insignificant amount of the total ground water discharge into Tapeats Amphitheater.

**Paleozoic Rocks**

The sequence of the Paleozoic rocks in Grand Canyon has been studied in detail by several authors. As the literature is replete with detailed lithologic descriptions, the following is a brief resume of the lithologic characteristics found in the Tapeats-Deer area. From oldest to youngest, the Paleozoic formations are: Tapeats Sandstone (Cambrian), Temple Butte Limestone (Devonian), Redwall Limestone (Mississippian), Supai Formation (Pennsylvanian-
FIGURE 6. Cambrian Sediments Deposited against the Precambrian Topographic High along the Granite Narrows Viewed toward the East

Photograph taken from the mouth of Deer Creek.
pC, Precambrian rocks; Ct, Tapeats Sandstone; Cba, Bright Angel Shale. Notice that the Tapeats Sandstone is missing above most of the Precambrian outcrop.
Permian), Hermit Shale (Permian), Coconino Sandstone (Permian), Toroweap Formation (Permian), and Kaibab Formation (Permian).

Tonto Group

Gilbert (1874) first applied the term Tonto Group to the Lower and Middle Cambrian sediments of northern Arizona. The Cambrian outcrops in Grand Canyon, all of Middle Cambrian Age, were subdivided by Noble (1914) into three conformable stratigraphic units. In ascending order these are: (1) the Tapeats Sandstone, named for Tapeats Creek, (2) Bright Angel Shale, named for Bright Angel Canyon, and (3) Muav Limestone, named for Muav Canyon. Later, Noble (1922) redefined the contact between the Bright Angel Shale and Muav Limestone by relegating approximately 60 feet of shales in the lower Muav Limestone to the upper Bright Angel Shale. McKee and Resser (1945) conducted an extensive study of the Tonto Group and concluded that the Cambrian Sea that deposited the sediments was transgressing slowly eastward. Consequently, these units transgress time to the east.

Tapeats Sandstone. Where Tapeats Sandstone exists, there is an irregular angular unconformity between it and the Precambrian rocks. In the Granite Narrows between Deer and Tapeats Canyons and also in Tapeats Canyon below Thunder River, the Tapeats Sandstone did not bury the Precambrian topographic high and is missing completely. The resistant Tapeats Sandstone is a cliff former consisting of brown,
slabby, crossbedded, coarse-grained quartz sandstone, well cemented with silica. Conglomerate lenses of rounded pebbles occur within the unit. In this area the Tapeats Sandstone ranges from 0 to more than 200 feet thick. The upper contact with the Bright Angel Shale is arbitrarily chosen as the uppermost beds of coarse-grained, red sandstone.

The Tapeats Sandstone is unimportant hydrologically because (1) it is overlain by the Bright Angel Shale, an effective aquiclude and (2) its permeability is very small due to the high degree of quartz cementation. Small quantities of water seep along joints and faults. A spring occurs in the Tapeats Sandstone where the Tapeats Fault crosses Tapeats Canyon but this spring yields only a few gallons per minute during wet seasons.

**Bright Angel Shale.** The Bright Angel Shale lies conformably over the Tapeats Sandstone where present but has an angular discordance with the Precambrian topographic high where the Tapeats Sandstone is missing in lower Tapeats Canyon and the Granite Narrows of the Colorado River. Where the section appears complete east of Thunder Spring, the Bright Angel Shale is about 425 feet thick. Except for a 40 foot cliff of limestone and sandstone that lies midway between the upper and lower contacts, the Bright Angel Shale is a slope former. Its upper contact is gradational from greenish-gray, micaceous, thin-bedded siltstone interbedded with limestone lenses to the thin-bedded limestone of the
Muav Formation. The upper half of the formation is composed of thin-bedded, buff and gray siltstones and shales which form minor ledges. Near the center, a resistant unit is capped by about 7 feet of rounded pebbles of gray limestone up to 3/4 inch in diameter cemented in a matrix of brown limestone. Immediately below this bed, fine-grained, thin-bedded, slope forming sandstones occur on top of a 40 foot sequence of massive, thick-bedded, red-brown, resistant sandstones. Vertically, the resistant sandstone grades into shale and siltstone and the lower half of the formation contains interbedded shale, silt and fine-grained sandstone of vermillion or greenish-gray color.

Hydrologically, the Bright Angel Shale is almost impervious and effectively retards downward movement of ground water. Seeps occur along some bedding planes but have such small discharges that they barely sustain desert plants. Faults that cut the formation appear to be clogged with impermeable gouge that is not conducive to the development of springs larger than mere seeps. Although the formation is not a water producer, it has a profound effect on ground water circulation in the overlying limestones. As the shale acts as an aquiclude, water moving downward through the Paleozoic section must drain laterally through the overlying limestones to canyon outlets.

Muav Limestone. The Muav Limestone lies conformably on the Bright Angel Shale and is about 417 feet thick in
this area. The upper contact of the Muav is a smooth, flat erosion surface where the section was measured in Deer Canyon. As a unit, the Muav Limestone is composed of mottled bluish-gray, thin-bedded limestone and dolomite. The upper half of the formation is a slope former that is composed of shaly, silty limestone that grades vertically into a more pure, shaly limestone. Lenses and beds up to 3 feet thick of sandy limestone are interbedded with the limestone. The lower portion is composed of thin-bedded, shaly limestone that forms a cliff. The limestone grades into the Bright Angel Shale within a few feet of the base of this cliff.

The primary permeability of the Muav Limestone is as small as the Bright Angel Shale; however, the secondary permeability is extremely large because the Muav is soluble and where fractured, solution tubes have developed. The structurally controlled solution tubes that occur along joints and more importantly along faults attain sizes from small filaments to over 25 feet in diameter. Due to solutioning, the Muav is the most permeable formation in the section in the Tapeats-Deer area on a megascopic scale; however, solutioning is controlled by fractures so there is a great lateral variation in permeability determined by the proximity of fractures. Consequently, springs range from insignificant seeps along bedding planes like those found in the Bright Angel Shale to huge fracture controlled karst springs that have peak discharges in excess of 150 cubic
feet per second. The impermeable Bright Angel Shale prevents downward circulation of ground water below the Muav Limestone and is directly responsible for lateral flow of water through the Muav Limestone to the canyon walls.

Temple Butte Limestone

The Devonian Period is represented by the Temple Butte Limestone which was first recognized as a discontinuous unit in eastern Grand Canyon by Walcott (1883) who separated it from the Redwall Limestone as defined by Gilbert (1875a). Darton (1910) named the formation after Temple Butte 3 miles south of the junction of the Colorado and Little Colorado Rivers. In the Tapeats-Deer area, the Temple Butte Limestone forms a continuous rock unit whose upper contact is an erosion surface with relief exceeding 50 feet where measured in Deer Canyon. The lower contact appears flat and sharp on the top of the Muav Limestone of Cambrian Age. The average thickness of the Temple Butte Limestone is about 293 feet and forms a steep cliff in the canyon walls. The upper portion of the formation is composed of purple, thin-bedded, platy, sandy limestone and fine-grained sandstone. Within a few tens of feet of the upper contact, the sandy limestone grades into a light-gray dolomite with beds up to 6 inches thick. Purple, silty lenses that exhibit depositional deformation are interbedded locally in the dolomite. The lower portion of the formation
consists of a uniform sandy, reddish dolomite. The lowest 5 feet is a shaly and silty, thin-bedded dolomite.

The primary permeability of the Temple Butte Limestone approaches zero; however, secondary permeability is large due to joints, faults and vertically developed solution channels. Where springs occur in the Temple Butte in the Tapeats-Deer area, they are small and issue from joints and tiny solution tubes along beds, usually near the heads of canyons or in the immediate proximity of faults. At most, these springs discharge a few gallons per minute during wet seasons. The overall permeability of the Temple Butte is probably lower than the Muav or springs would form near its lower contact. Like the Muav, the lateral permeability has great variability and increases to a maximum in the immediate proximity of fractures.

Redwall Limestone

The Redwall Limestone of Mississippian Age was first defined by Gilbert (1875a). He included in the unit the lower portion of the Supai Formation which contains limestone beds separated by redbeds, and the entire Temple Butte Limestone. Noble (1922) redefined the Redwall Limestone by separating out the Devonian Temple Butte Limestone as defined by Walcott (1883) and Darton (1910). He also divided out the lower limestones of the Supai Formation on the basis of an unconformity that exists between them and the top of the massive limestone unit of Gilbert's Redwall. The Redwall
Limestone lies unconformably on the Temple Butte Limestone and was determined to be 644 feet thick by Mc Kee (in Preparation) in Surprise Valley. It outcrops as a high, sheer cliff along all of the deep canyons. The upper contact is an erosion surface with a relief of up to 5 feet where measured along a tributary to Deer Canyon. A veneer of chert covers most of the upper contact. Underlying the chert and extending to the lower contact is a relatively uniform, massive, thick-bedded, olive-gray, crystalline limestone containing occasional chert lenses. The exposed surfaces are usually stained red by surface runoff from overlying red beds.

The Redwall Limestone would be impermeable were it not for fracturing and solutional modifications. A post-Mississippian karst developed in the upper quarter of the limestone left solution tubes and sinkholes that were later filled by red beds of younger age (Mc Kee in Preparation). These features appear to be subdued in the Tapeats-Deer area although small solution tubes are exposed at the heads of most canyons in the upper Redwall. Although not essential to the present hydrologic regime, these paleo-solution features help increase the permeability of the upper part of the formation. Subsequent faulting and fracturing has aided vertical solutional development to such an extent that the Redwall is not an effective barrier to downward circulation of ground water to the Temple Butte and Muav Limestones. A
few seeps occur near the upper contact at the base of the Supai Formation where the Redwall is unfractured and essentially impermeable.

Aubrey Group

The Aubrey Group overlies the Redwall Limestone and forms the upper part of the Kaibab Plateau. This sequence, in ascending order, includes the Supai Sandstone (Pennsylvanian-Permian), Hermit Shale (Permian), Coconino Sandstone (Permian), Toroweap Formation (Permian), and Kaibab Formation (Permian). Gilbert (1875a) defined the term Aubrey Group as the sequence of rocks outcropping along the eastern wall of Aubrey Valley from the top of the Redwall Limestone to the top of the Kaibab Formation. Darton (1910) defined the Supai Formation, naming it for outcrops near Supai Village in Havasu Canyon, and included in the unit a thick sequence of shale overlying sandstone beds. Noble (1922) separated the thick sequence of shales from Darton's Supai Formation on the basis of an unconformity between the shale and uppermost sandstone beds. He named the shale unit the Hermit Shale after Hermit Basin. Noble also redefined the Supai Formation to include the upper part of Gilbert's Redwall Limestone which was a series of interbedded limestones and redbeds lying above an unconformity at the top of the massive Redwall Cliff. The Coconino Sandstone was named by Darton (1910). McKee (1938) considered the Coconino Sandstone in further detail and McNair (1951) defined the Aubrey
Valley outcrops as the type section. The Kaibab Formation was first named by Darton (1910) as the sequence of Permian limestones and redbeds overlying the Coconino Sandstone. Noble (1927) designated the outcrops of this unit in Kaibab Gulch, Utah, as the type section. On the basis of an unconformity, McKee (1938) separated a massive limestone unit lying in between 2 redbed sequences from the lower portion of the Kaibab Formation. He named this lower unit the Toroweap Formation and designated the type section as the outcrops of the unit along the eastern wall of Toroweap Valley.

Supai Formation. Burying the Redwall and filling the solution tubes and sinkholes in the ancient Redwall karst are the thick series of alternating siltstone, mudstone and fine-grained sandstone redbeds of the Supai Formation of Pennsylvanian and Permian Age. McKee (personal communication 1967) determined the Supai Formation to be 719 feet thick measured along the Thunder River Trail in Deer Basin. In the Tapeats-Deer area, a bench up to 2 miles wide has developed on the Supai Formation where the less resistant overlying Hermit Shale is stripped away. This bench has not developed south of the Colorado River near the study area. The upper contact is a channelled unconformity with the Hermit Shale. The Supai Formation is composed of alternating red-brown, thin to thick beds of siltstone and fine-grained, cross-bedded sandstones. This sequence of alternating resistances yields a bench-slope topography. The basal portion of the
formation contains beds up to 4 feet thick of crystalline, blue-gray limestone containing chert lenses. These limestones are separated by thick-bedded, red mudstones.

As the Supai is composed of different rock types with a wide range of primary permeabilities, the formation is complex hydrologically. Secondary permeability is best developed along major faults where displacements have destroyed the stratigraphic continuity of small permeable beds. Small displacement faults and joints have only token significance on permeability because displacements are not large enough to disrupt the continuity of the small permeable beds.

In the case of faults having displacements of less than 5 feet in the Redwall Limestone, the displacements are taken up by small folds in the Supai. Although the folding has often shattered the beds, it is not as effective as a true break in increasing vertical permeability.

Several of the Supai beds are less permeable than the beds of the overlying Hermit Shale. Consequently, a portion of the downward flowing ground water becomes perched and escapes laterally along more permeable beds to fault zones or canyon walls. Small seeps and springs issue from the top of some small permeable beds where ground water gradients exist toward the canyon walls such as along the west facing exposures in the Tapeats Amphitheater. Otherwise, seeps do not occur unless the system is charged with unusually high amounts of water from rainfall. It is evident that fault
zones carry considerable quantities of water through the Supai Formation because the major springs in Grand Canyon lie below this unit.

**Hermit Shale.** The Permian Hermit Shale is 787 feet thick along the Thunder River Trail in Deer Basin as measured by Mc Kee (personal communication 1967). The formation is bounded on the top by a sharp, flat unconformity beneath the Coconino Sandstone. The formation is composed primarily of crumbly, red, sandy shale. In the upper portion of the unit, thin to thick beds of fine-grained sandstone are interbedded with the shale. The Hermit Shale forms a slope everywhere in the area.

The shale has a small permeability, although it is not as complete an aquiclude as the Bright Angel Shale. Seeps are found throughout the unit during wet seasons. Secondary permeability is dependent primarily on small scale jointing and large scale faulting. The faults are of greatest importance as conduits for the water that moves vertically through the shale. Seeps and springs that sustain vegetation are found at the upper contact at the more permeable Coconino Sandstone, particularly along the west facing slopes of Tapeats Amphitheater.

**Coconino Sandstone.** The Coconino Sandstone is 178 feet thick at the south end of Monument Point and is Permian in age. Its upper contact with the Torowep Formation is unconformable and consists of a planar surface that truncates
large, underlying crossbeds. The formation is a uniform, pale-orange to white, very fine to medium-grained, well-sorted quartz sandstone with large cross beds lying in sets up to 10 feet thick. The Coconino Sandstone forms a prominent cliff where it is not fractured.

**Toroweap Formation.** The Toroweap Formation of Permian Age contains several rock types and was found to be 316 feet thick at the south end of Monument Point. The upper contact with the Kaibab Formation is an unconformity characterized by shallow erosion channels filled with sandy shale. Less than 10 feet of thin beds of yellow-orange, sandy shale lie below the contact. The remainder of the upper portion of the formation consists of gypsum beds interbedded with lenses of siltstone that weather to a slope. Below the gypsum is a short sequence of bench-slope forming thin-bedded limestones. These rest on top of a sequence of buff to gray limestones with beds from 1 to 10 feet thick which form a vertical cliff 75 feet high. Below the cliff lie massive, sandy limestones interbedded with siltstone and gypsum. The bottom 10 feet of the formation consists of redbeds of reworked Coconino Sandstone.

The Toroweap is complex hydrologically due to its many different lithologies. Primary permeabilities are all small but have been enhanced by jointing of the limestones and solution of both the limestone and gypsum beds. As in the lower limestone group, solutioning is mainly vertical
along fracture zones. Lateral flow along the more permeable beds is significant where these beds are underlain by tight rock sequences. Almost continuous bands of vegetation grow on portions of the slope of the upper half of this unit. These seeps result from lateral flow and are concentrated along the west facing slopes in response to the regional ground water gradient imposed by the westward dip of the strata. Faults conduct appreciable quantities of water vertically through the Toroweap Formation, probably along solution tubes developed in the soluble members and collapse zones in the silty portions.

Kaibab Formation. The Permian Kaibab Formation caps the Paleozoic section in Grand Canyon and forms most of the surface of the Kaibab and Kanab Plateaus. At Monument Point, the Kaibab Formation is 351 feet thick from the highest outcrop on the Kaibab Plateau to the unconformity separating it from the Toroweap Formation. Strahler (1948) assumes the present erosion surface on the Kaibab Plateau is the top of the B member of the Kaibab Formation as defined by McKee (1938) because this unit is very resistant. In general, the Kaibab Formation in this region is a magnesian limestone of yellow-gray, pale-orange or light-gray color. The uppermost beds consist of cherty limestone underlain by sandy limestone. The lower portion of the formation is composed of thick sequences of massive limestones that contain continuous layers of chert up to 2 inches thick. Spires that
stand out from steep slopes erode from the lower cherty member whereas the more resistant overlying sandy limestones form steps and benches.

Water from precipitation falling on the Kaibab and Kanab Plateaus readily infiltrates the Kaibab Formation because this unit has a large secondary permeability. The unit is highly jointed and contains a well integrated karst system. The karst is expressed on the surface by wide basin-like dolines that feed water into vertical joints or small vertically or laterally developed solution tubes. Lateral tubes from dolines to valley walls account for many springs in the plateau area and represent flow paths caused by highly localized perching of water over tight Kaibab or Toroweap beds. Springs of this type are minor in the walls of the Tapeats and Deer Basins. Faults markedly alter ground water flow through the Kaibab Formation because they function as flow sinks that induce laterally moving water to drain downward through the section.

Cenozoic Rocks

The Cenozoic rocks have little effect on the hydrologic regime of the underlying Paleozoic system. These rocks may be divided into 3 general groups: (1) Quaternary slump debris and related alluvial material in closed basins, (2) stream gravels, and (3) soil and surface mantle of debris.
Quaternary Slump and Alluvial Material

In the Surprise Valley region between Thunder River and Deer Creek and in the area west of Deer Creek and immediately north of the Colorado River, enormous collapses of the canyon walls involving about 1-1/2 cubic miles of rock are found below the present Redwall Cliff. These slumps postdate portions of Tapeats Canyon and involve a sequence of about 2000 feet of rocks from the middle of the Bright Angel Shale to the upper portions of the Supai Formation. Large portions of the section are preserved as Toreva blocks in the slump zones. At least 2 partially buried rows of these Toreva blocks occur in Surprise Valley. Recent erosion has buried a large amount of the slump debris and filled closed basins with alluvial fans and alluvial outwash. One large basin, approximately 1/4 square mile in area, lies immediately west of Deer Creek and is still in the process of filling; however, all others have now been filled or breached.

These highly disturbed rocks have large permeabilities but are unimportant hydrologically because they are well drained on their flanks and insignificant quantities of water are available to them. Their water retention is so small, in fact, that only the hardiest of desert plants grow from the thin soils that mantle the debris. Some springs issue from the base of these debris along the Colorado River west of Deer Canyon but this water is simply seepage through
the base of the collapse from Deer Canyon.

Stream Gravels

Stream gravels, primarily chert and limestone cobbles, blanket the valleys of the Kaibab and Kanab Plateaus. Although the permeabilities of the gravels are large, they are not thick enough to form useful aquifers so they are hydrologically unimportant.

Soil and Debris Mantle

A soil and debris mantle is found over most slopes of the canyon walls in the Grand Canyon and contains small amounts of vegetal matter, silt, rock fragments, talus and minor slumps. Aside from supporting transpiring plants that grow on the slopes, this mantle has little hydrologic significance.

The soils developed on the Kaibab and Kanab Plateaus are rich in vegetal debris and support a pine forest. They range from thin mantles to very deep profiles in low areas. A part of the water flowing through the soil is retained and is readily evaporated or transpired. Evapotranspiration losses probably amount to a significant portion of the precipitation falling on the plateaus annually. All sinkholes and dolines are plugged by deep soil accumulations that retard downward movement of water.
STRUCTURAL GEOLOGY

The structural geology of the Tapeats-Deer area has not been treated in detail prior to this work. The locations of the structures described below are shown on Figure 3. Figure 4 contains 3 structural sections that are indexed on Figure 1.

General Tectonic Pattern

The Tapeats-Deer area lies in the transition zone between the Kaibab and Kanab Plateaus. North of Tapeats Amphitheater the plateaus are separated by an abrupt topographic break in the land surface caused by the West Kaibab Fault Zone which displaces the Kanab Plateau down relative to the Kaibab Plateau. This fault zone was named by Powell (1873) and further studied by Gilbert (1875b), Dutton (1882) and Strahler (1948). Its scarp is especially pronounced 10 miles north of the Tapeats Amphitheater where the displacement along the fault zone reaches a maximum vertical displacement of about 1500 feet. Southward from the area of maximum displacement, the fault zone branches and the displacement decreases. In the Tapeats Amphitheater at Big Saddle, the Muav Fault, a segment of the West Kaibab Fault Zone, displaces the Kanab Plateau down about 500 feet relative to the Kaibab Plateau. As a further complication, a monoclinal flexure associated with the fault folds the
section up to the west about 500 feet. As the displacements along the monocline and fault are opposite in sense, the physiographic break between the Kanab and Kaibab Plateaus in the Tapeats Amphitheater is subdued. In the Tapeats-Deer area, a regional dip of about 2° to the west reduces the elevation of the land surface about 1500 feet in a distance of 10 miles.

Tectonic structures found in the area are of both deep seated and gravity origin. Deep seated tectonic structures include several high angle normal faults and 1 monocline. Gravity collapses in the form of slump zones and Toreva blocks have been important in shaping the landscape. Vertical displacements along the faults are commonly less than 50 feet except in the case of the Muav Fault where the displacement is about 500 feet. The monocline has a displacement of about 500 feet. Displacements on some Toreva blocks exceed 1400 feet.

Two distinct structural trends exist in the area: (1) structures parallel to the north-south orientation of the Crazy Jug Monocline such as the Muav and Tapeats Faults, and (2) structures with a northeast-southwest orientation including the Thunder, Deer, Upper Deer and Sinyala Faults. The northeast-southwest structures, without exception, die out as they are traced northeastward into the north-south structures.

Dating of the tectonic features is difficult because
all rocks younger than the structures have been stripped away and no volcanism is associated with the faulting. Strahler (1948) assumed the major structures, including the Crazy Jug Monocline, Muav Fault and Tapeats Fault, to be Laramide in age to be consistent with the dates determined from stratigraphic evidence in Utah that Babenroth and Strahler (1945) developed for the East Kaibab Monocline.

Crazy Jug Monocline-Muav Fault System

The Muav Fault, named by Noble (1914) for Muav Canyon, forms part of the western boundary of the Kaibab Plateau. It can be discerned north of Ryan and trends about 25 miles south to Tapeats Amphitheater. The fault can be traced into the Grand Canyon at Big Saddle, along Crazy Jug Canyon, across the head of Tapeats Canyon and along Saddle Canyon to Muav Saddle. See Figure 7. South of Muav Saddle, the fault continues for another 10 miles into Shinimo Amphitheater before it dies out. The maximum displacement of Paleozoic rocks by the fault in Tapeats Amphitheater is 500 feet, west downward, at Big Saddle. The displacement decreases southward.

A valley occurs along the fault north of Big Saddle. At Big Saddle, the total displacement is taken up along 2 normal slip planes that bound a wedge shaped fault block about 900 feet wide that lies midway in elevation between the 2 limbs. This fault block is slightly tilted toward the west and is highly fractured. It tapers downward and pinches
FIGURE 7. Muav Fault and Crazy Jug Monocline Viewed toward the South

The fault is indicated by the line. U, upthrown limb; D, downthrown limb. Notice the monoclinal flexure to the west of the fault. Crazy Jug Canyon is at lower left, Saddle Canyon is left of center and Muav Saddle is the gap formed by the fault along the horizon.
out about 900 feet below the canyon rim. The fault planes are replete with gouge, breccia and slickensides and the surrounding rock is highly fractured. See Figure 8.

In the Tapeats-Deer area, a monoclinal flexure lies parallel to the Muav Fault and is herein named the Crazy Jug Monocline for Crazy Jug Point. Immediately to the east of the fault at Big Saddle, the country rock is folded upward toward the fault plane with a dip of about 10°E. The folding of the rock to the east of the fault is exactly opposite to the movement along the fault and cannot be associated with drag between the limbs. Within a few hundred yards east of the fault plane, the dip of the beds is reversed and attains the regional 2° dip toward the west. West of the fault there is a gentle dip less than 10° toward the east. Within a mile west of the fault zone, this eastward dip reverses so that west of Crazy Jug Point the rocks assume the normal regional dip of 2°W. This monocline flexed the strata up to the west approximately 500 feet. Consequently, there is virtually no displacement across the fault-monocline system in the Big Saddle area.

In Crazy Jug Canyon, the fault is a single, brecciated plane that lies just off the east flank of the monocline. At the head of Tapeats Canyon, where the fault is exposed in the Muav Limestone and Bright Angel Shale, the monocline dips eastward into the fault plane. In Tapeats Canyon, the Redwall, Muav and Bright Angel Formations are highly disturbed
FIGURE 8. Muav Fault Zone at Big Saddle Viewed toward the North

Faults are indicated by the lines. Arrows show relative movement. Pk, Kaibab Formation; Pt, Toroweap Formation; Pc, Coconino Sandstone; Ph, Hermit Shale. Notice the upturned beds on the eastern side of the fault zone.
in a brecciated zone a few hundred feet wide. Aside from breccia, there is gouge and large eastward dipping blocks of country rock are torn from the walls. In Saddle Canyon, the displacement along the fault is restricted to a single highly disturbed zone and the monocline dips into the fault plane. The displacement along the Crazy Jug Monocline remains at about 500 feet, west limb downward, through this area but the displacement of the Muav Fault is slightly less. Consequently, the net displacement across the fault-monocline system increases southward from Big Saddle. Where the fault-monocline system passes through Muav Saddle at the head of Saddle Canyon, the western block is displaced upward approximately 100 feet.

Folding on both sides of the fault at Big Saddle suggests a faulted monocline. Noble (1914) came to this conclusion; however, folded beds east of the fault plane were not present in Muav Canyon where Noble studied the Muav Fault south of Tapeats Amphitheater. A faulted monocline suggests that there were 2 stages of tectonic events. Strahler (1948) did not have the fault-monocline evidence at Big Saddle at his disposal so he concluded, in contrast, that the downwarping of the western limb was contemporaneous slumping with faulting. Consequently, Strahler concluded that there was only 1 stage of tectonic activity.
Tapeats Fault

Tapeats Fault, herein named for Tapeats Spring, lies about 2 miles west and parallel to the Muav Fault. It can be traced from just north of Indian Hollow southward across the Kanab Plateau to the canyon wall and along the floor of Tapeats Cave Canyon above the Redwall Cliff. Below the Redwall Cliff, the fault is a single fracture that lies east of the canyon floor under cover in the Bright Angel Shale. It occurs in Tapeats Canyon as a 3 foot wide zone in the Tapeats Sandstone but dies out as 2 highly fractured but slightly displaced limbs 1/2 mile south of Tapeats Creek. The net displacement is at most about 5 feet, west side upward, where the fault is seen as a single trace in Tapeats Canyon.

Two wedge shaped graben blocks have been broken from the walls of the fault and have slipped downward. One of these, shown in Figure 9, is well exposed at the head of Tapeats Cave Canyon and is about 3/4 of a mile long with a maximum width of about 700 feet at the top of the Redwall Limestone. The block tapers downward between 2 normal faults that converge in the lower Muav Limestone. Both bounding faults are narrow zones in the limestones from less than 6 inches to 3 feet wide that are filled with brecciated country rock cemented by calcite gouge. The displacements on the eastern and western bounding faults of the graben are 35 and 40 feet respectively. The second graben block in the fault zone lies slightly north of the first, is up to 700 feet wide
Figure 9. Tapeats Fault and Associated Graben in Tapeats Cave Canyon Viewed toward the North

Faults are indicated by the lines. Arrows show relative movement. Mr, Redwall Limestone; Dtb, Temple Butte Limestone; Cm, Muav Limestone; Cba, Bright Angel Shale. Tapeats Spring discharges from the base of the graben block.
and extends into the Kanab Plateau before it is buried by cover. Displacements along the bounding faults are on the order of 40 feet each.

Northwest of Monument Point, where Deer Canyon dissect the Aubrey Group, a small fault with more than 10 feet of displacement, west side upward, occurs in the canyon wall on both sides of upper Deer Canyon. This fault is obscured by cover both on Monument Point and in the Kanab Plateau. Immediately to the east of this minor fault, about 4 small folds with a maximum wave length of 100 feet and amplitude of 10 feet are dissected by Deer Canyon in the Kaibab Limestone.

Thunder Fault

Thunder Fault, named herein for Thunder Spring, lies about 100 feet west of Thunder Spring. It consists of several fractures in the Muav, Temple Butte and Redwall Limestones spaced from 3 to 75 feet apart, each having a displacement of less than a foot. The west side is displaced upward a total of slightly more than 3 feet. A gouge zone up to 3 feet wide and minor drag folds are associated with a slip plane in the Muav Limestone near Thunder Spring. A notch has eroded at the top of the Redwall Cliff where the fault zone is less than 6 inches wide and trends northward independently of the joint pattern. As the fault is traced vertically through the lower Supai Formation, the deformation is taken up by a small fold and within 400 feet vertically
above the Redwall Limestone-Supai Formation contact, there is no trace of the structure. The fault is assumed to continue laterally northward under the Supai Sandstone as a minor fault in the lower limestones. Thunder Fault is buried in Surprise Valley south of the Redwall Cliff.

Deer Fault

Deer Fault, named herein for Deer Spring, is a northeast-southwest trending fracture whose western side is displaced downward a maximum of 4 feet. The fault appears to die out near Vaughn Spring in Deer Canyon but can be traced to the northeast in the Redwall Limestone and Supai Sandstone before it again dies out in upper Deer Canyon northwest of Monument Point. The maximum displacement is about midway between its terminal points and appears as a shattered zone 20 feet wide in the Supai Sandstone. The fault controls the orientation of several small canyons in Deer Basin.

Trail Graben

Trail Graben, herein named for the Thunder River Horse Trail, trends northwestward from the northernmost part of Surprise Valley until it intersects Deer Fault where both of its bounding faults die out. Toward the southeast, the displacement of both faults increases to a maximum of about 40 feet before they are buried in Surprise Valley. The limb southwest of the graben is displaced slightly downward relative to the northeast limb. Fault gouge, breccia and calcite
Upper Deer Fault

Upper Deer Fault, herein named after Deer Canyon, trends northeast-southwest along the floor of a large tributary canyon that joins Deer Canyon from the east. The fault can be traced across Deer Canyon and into the Supai bench lying to the west where it apparently dies out. To the northeast, the fault dies out in the tributary canyon about 1/2 mile upstream from its junction with Deer Canyon. On the west wall of Deer Canyon, the fault is well exposed with the total displacement of 5 feet, west side down, taken up along several closely spaced slip planes.

Sinyala Fault

Sinyala Fault is named for Mount Sinyala, a lone butte near Havasu Canyon. It is possible that this fault was named Kanab Fault by Powell (1873) who described a structure near the mouth of Kanab Canyon as having a displacement of 100 to 200 feet, west side downward, and a lateral extent of 30 miles. Unfortunately, his description is too vague for positive identification. The Sinyala Fault can be traced 18 miles from the western side of Havasu Canyon, across the Colorado River and into Deer Basin where it dies out against the Kanab Plateau. In Deer Basin, the displacement does not exceed 5 feet. As shown in Figure 10, this fault zone controls headward erosion in every canyon it crosses.
FIGURE 10. Sinyala Fault Viewed toward the Southwest across Deer Basin

Notice the fault control of the canyons in the area. Deer Canyon is in lower left portion of the picture.
and is one of the most striking topographic features in the Grand Canyon.

**Slump Zone in Surprise Valley and West of Deer Creek**

An enormous mass of brecciated rocks and Toreva blocks involving approximately 1-1/2 cubic miles of material lies in Surprise Valley and the area west of Deer Canyon between the Redwall Cliff and the Colorado River. The collapse material is composed of about 2000 feet of the Paleozoic strata from below the resistant sandstone layer of the Bright Angel Shale up through the middle of the Supai Formation. The mass is bounded on the north by the Redwall Cliff and on the east by Tapeats Canyon. To the south, an irregular contact exists between the disturbance and the Bright Angel Shale in Bonita Canyon. The Colorado River forms the western and southern limit of the disturbance west of Deer Creek. Cogswell Butte and the surrounding hills of Redwall Limestone appear to be highly shattered in places; however, Cogswell Butte does not appear to be displaced because the Redwall Limestone and overlying Supai Sandstone lie in situ relative to the surrounding Paleozoic rocks and have normal westward dips.

Thunder River has eroded through a portion of the slump debris and has exposed a slip plane tangent to the face of the Redwall Cliff which curves southward and flattens out in the Bright Angel Shale south of Thunder Spring. The rock immediately above the slip plane is highly
pulverized and is cemented into a coarse breccia. Higher above the slip plane, the rocks are more intact and bedding can be discerned. Toreva block structures are evident in the higher portions of the collapse zone and dip toward Thunder Spring as shown in Figure 11. In Surprise Valley, at least 2 rows of Toreva blocks are exposed, all dipping north at about 23°. The row closest to the Redwall Cliff is well exposed and is composed of Redwall Limestone capped by Supai Sandstone. One of the Toreva blocks in this row is shown in Figure 12. A second row parallel to the first but closer to the center of the valley is almost buried by alluvium. The caps of Supai Sandstone that are exposed indicate that the blocks have been displaced downward about 1400 feet. These slump features continue westward between Cogswell Butte and the Redwall Cliff but become almost totally buried near Deer Canyon. The east wall of Deer Canyon is almost obscured by cover; however, the rocks that are exposed are highly shattered and tilted. Immediately south of Vaughn Spring, a vertical fault truncates the normal Paleozoic rocks to the north and slump debris lie to the south. This may be the Deer Canyon counterpart of the slip plane seen at Thunder River. Cogswell Butte is entirely surrounded by debris which obscures all the Paleozoic contacts between the Redwall Limestone and the Bright Angel Shale. Where small tributaries have cut northward into this disturbance from the Colorado River, the section below the
FIGURE 11. Surprise Valley Slump Debris Dissected by Thunder River Viewed toward the South

The Surprise Valley slip plane is between the slump debris (Q) and the Bright Angel Shale (Gbba) as indicated by the line. Notice the bedding planes that face the viewer in the upper right portion of the slump material. These beds are parts of Toreva blocks that have slumped downward to the south and now dip toward the viewer at 23°N.
FIGURE 12. Toreva Block in Surprise Valley Viewed toward the West

The Redwall Cliff, capped by Supai Sandstone, forms the background. The Toreva block in center is dipping 23°N and is composed of Redwall Limestone and Supai Sandstone. Trail Graben forms the slight gap in the Redwall Cliff.
middle of the Bright Angel Shale is found to be undisturbed. For the most part, contacts between the Bright Angel Shale and the overlying debris are buried by superficial debris.

The slump area west of Deer Creek is totally brecciated and no Toreva block structures are evident. No well defined lower contacts are found along the western side of Deer Canyon nor along the Colorado River of which the debris forms the northern bank. A large closed basin that is 1/4 of a mile long and 1/8 of a mile wide was created by the collapse of the Redwall Cliff west of Deer Creek. Presently this basin is filling with alluvium.

The writer postulates that at one time Tapeats Canyon was oriented east-west through Surprise Valley immediately north of Cogswell Butte in line with the upper 3 miles of the present canyon. This canyon discharged into the Colorado River near or west of the present mouth of Deer Creek and must have been narrow and eroded well into the Bright Angel Shale. Under the influence of gravity and lubricated by the spring water in Tapeats and Deer Canyons, the steep northern walls of the canyon collapsed from Thunder River to about 1-1/2 miles west of Deer Creek in a series of enormous landslides that triggered smaller scale slumps from both sides of Cogswell Butte. Water that flowed down Tapeats Canyon was dammed and discharged southward through a topographic low east of Cogswell Butte and subsequently cut lower Tapeats Canyon as seen today. Similarly, Deer Creek
breached the debris blocking its mouth and flowed to the south into the Colorado River. This is the simplest arrangement of canyons that would account for the present topography and distribution of debris although other configurations are possible.

**Sequence of Tectonic Events**

Although specific dates for each tectonic event in the Tapeats-Deer area are not available, a natural relative sequence is suggested from the foregoing field relationships. A great deal of Precambrian folding and faulting is evident, including Precambrian movements along the Muav Fault (Noble 1914). Throughout Paleozoic time, tectonic deformations did not occur in the Tapeats-Deer area. The first post-Paleozoic deformation appears to have been the Crazy Jug Monoclinal flexure that trended north-south through Tapeats Amphitheater and uplifted the section to the west. It is assumed by Noble (1914) and Strahler (1948) that the monoclinal flexing occurred during the interval in which the Paleozoic section was buried under a considerable thickness of Mesozoic rocks; otherwise, they believe that faulting would have occurred. The monoclinal flexing has been assumed as Laramide in age by Strahler (1948) to be consistent with flexing dated along the East Kaibab Monocline (Babenroth and Strahler 1945). These conclusions are accepted by the present writer. Strahler (1948) felt that regional faulting was contemporaneous with folding and the flexure was caused by
sagging of the western limb of the fault. In contrast to the ideas of Strahler and based on the presence of upturned beds on the eastern fault block at Big Saddle, the present writer agrees with Noble that the flexure is a monocline that was subsequently faulted.

Subsequent faulting of the Crazy Jug Monocline implies at least 2 post-Paleozoic tectonic episodes in the Tapeats-Deer area. Noble felt that faulting followed the removal of the Mesozoic cover; otherwise, he infers that the second deformation would have been refolding of the section in an opposite sense. This writer does not feel that removal of the Mesozoic cover is a necessary prerequisite for the faulting. As the faults are normal, a tensional stress regime is implied. This tensional regime is different than the tectonic processes that caused the vertical uplift of the plateau to the west with folds as the mode of deformation. Consequently, it is reasonable to assume that if 2 deep-seated tectonic regimes operated in this region after the Paleozoic Era, the respective modes of deformation would logically be different regardless of the amount of overburden.

The minor normal fault structures in the Tapeats-Deer area are thought to represent faulting contemporaneous with or slightly subsequent to the faulting of the Crazy Jug Monocline. Most likely, these faults all occurred during the early Cenozoic Era before the Colorado River started to dissect the Kaibab Limestone. The normal faults west of the
Muav Fault are probably minor adjustments in the equilibrium of the plateau that responded to the major deformations along the Muav Fault or deformations outside the area.

It is curious that the northeast-southwest normal faults do not cut across the north-south structures, but rather they die out against them. It is possible that all of these structures are contemporaneous and this area represents the transition zone between a dominant north-south structural pattern and a weaker northeast-southwest pattern lying to the west. Likewise, it would also be reasonable to interpret the north-south pattern as being older than the northeast-southwest structures and that the latter simply died out against the existing structurally resistant north-south grain. Regardless of the complexity of the normal fault structures, evidence implies that they occurred after the monoclinal flexure.

The Surprise Valley Slump Zone and the slump zone west of Deer Creek represent gravity tectonic deformations subsequent to deep entrenchment of the Colorado River and its tributaries and as such, these structures are relatively young. Deep-seated processes that could have triggered the slumps are not suggested by known field relationships.
HYDROLOGY

The primary concern of this paper is the mechanics of the hydrologic system in the Tapeats-Deer area. As in any physical system, an understanding of the whole requires foreknowledge of the component parts. The geologic framework and some of the basic hydrologic properties of that framework have been described above. It is the purpose of this section to first analyze the individual hydrologic components of the Tapeats-Deer area and then formulate a model that integrates these individual facets into a coherent system.

The Infiltration Zone: The Plateau Surface

Both the Kaibab and the Kanab Plateaus function as the recharge area for water pulsing the hydrologic system in the Paleozoic rocks. In the study area, the plateau surface ranges from 6500 to 8000 feet above sea level and 4000 feet above the canyon floors in Grand Canyon. The surfaces of the plateaus are immediately underlain by the Kaibab Formation except for insignificant areas in deep valleys. Soil mantles range from thin profiles that barely cover outcrops to soil and gravel sequences up to several tens of feet thick. The latter are primarily found in low areas or in deep solutional depressions. On the Kanab Plateau, a juniper forest is supported by the soil but as the surface rises toward the east and more precipitation is available, these
desert plants grade into a rich pine forest that supports a large lumber industry.

The most noticeable feature of either of the plateaus is the lack of surface runoff regardless of the time of year. Furthermore, it is noticed that at higher elevations, dolines or "sinkholes" pockmark the surface. These depressions range from a few tens of feet in diameter with steep sides to wide, shallow basins several hundred feet in diameter and up to many tens of feet deep. Characteristically, doline floors are choked by soil, sometimes so impermeable that the depressions hold pools of water for long periods after wet seasons. These depressions occur regardless of the slope of the terrain and can be found on plateaus, valley walls and valley floors. In many areas the depressions are completely filled with debris that is level with the surrounding landscape. The existence of some buried dolines is indicated by local vegetational changes on the surface, such as grass patches or circular brush concentrations that indicate moisture trapped beneath the surface by the impervious soils that surround the sides of the depressions. However, it is reasonable to conclude that most of the buried depressions have not been detected and form the vast majority present.

Writers as early as Dutton (1882) concluded that the depressions were surface karst forms that collected water and transported it to solution channels below the surface. In the parks near the center of the Kaibab Plateau, including
De Motte Park, sinkholes have obliterated the surface drainage network and a karst system drains these areas. In the plateau regions immediately adjacent to the Tapeats-Deer area, solutioning of the limestone has not progressed to this extent; however, surface runoff and movement of stream gravel occurs only with rainstorms of very high magnitudes and intensities. Conspicuously absent from this karst system are caverns large enough for human passage. No extensive caves have been found in the Kaibab Limestone of the Kanab Plateau or the western portion of the Kaibab Plateau.

Characteristically, the Kaibab Formation is highly jointed. Dolines readily form along these joints and channel water downward if the soils at the base of the depressions are permeable. Once in the joints, the water moves vertically to more impermeable strata. Where the total quantity of water moving downward cannot be transmitted through these layers, a portion of the water is perched and moves laterally to more permeable zones or valley walls. Seeps or more rarely small springs that discharge a few gallons per minute are found along valley walls in the Kaibab and Toroweap Formations and attest to the existence of lateral flow along the tops of low permeable beds. In some cases, these springs issue from solution-widened joints. Immediately on discharging from springs, the water drains downhill to more permeable joints or sinkholes where it is again lost to subterranean channels.
It is concluded by the writer that due to the close spacing of joints, the solution tubes that have developed vertically along joints or laterally along joints and bedding planes individually carry such small quantities of water that they have not had enough time to develop into large traversible caverns since the Mesozoic sediments were stripped away. Furthermore, the highly jointed nature of the Kaibab Formation indicates that as the canyons rapidly exposed it from beneath the Mesozoic cover, ground water drained readily to topographic lows. The result was a very short period of total saturation and insufficient duration of ground water circulation to allow large scale solutioning. Consequently the Kaibab Formation now collects precipitation in dolines and joints, loses a portion of this water to transpiration and evaporation and the remainder circulates downward and laterally through small solution tubes and joints. Although a grand karst river system does not exist, the Kaibab Formation efficiently fulfills its function as a ground water collector.

**Springs in the Canyon Walls**

As there are no wells in the Tapeats-Deer area, water conditions must be observed at seeps and springs along the canyon walls. The regional dip of the strata is toward the west with a slight component to the south so it is reasonable to conclude that water moving laterally along bedding planes will flow in response to this gradient and will discharge
from springs along the west facing canyon walls. This assumption is markedly demonstrated in Tapeats Amphitheater because the amphitheater is the first large basin cut northward into the westward dipping rocks of the Kaibab Plateau. Consequently, it intercepts all the westward flowing water in this region. Along all the westward facing slopes of Saddle and Crazy Jug Canyons, perennial seeps and springs occur that have individual discharges of less than 5 gallons per minute. The largest discharge is during the late spring and early summer when the system is pulsed by snow melt waters from the Kaibab Plateau. Due to the nature of the flow system, it is convenient to describe the springs by geographical regions.

Springs East of Saddle and Crazy Jug Canyons in the Aubrey Group of Tapeats Amphitheater

The Aubrey seeps are readily observed by the presence of bands or clumps of vegetation that grow on otherwise sparcely vegetated slopes. None of these springs discharge sufficient water to support flowing streams for any long-distance over the surface. Most of the water is evaporated or transpired by plants growing on the outcrops adjacent to seeps, particularly in summer.

Very little ground water discharges from the Kaibab Formation due to its high vertical permeability. The same is true of the cliff forming portion of the Toroweap Formation. However, the slope forming members of the Toroweap,
which contain several low permeable beds, are usually blanketed by a lush growth in eastern Tapeats Amphitheater. Crazy Jug Spring, 1 mile east of Big Saddle, discharges about 2 gallons per minute from the upper slope forming part of the Toroweap Formation and due to its proximity to the rim, it was the only spring ever developed as a water supply in Tapeats Amphitheater. Water was piped laterally toward Big Saddle to supply 2 cattle watering tanks which were used until the middle 1950's. Since then, the spring has been abandoned and the piping system and water troughs have deteriorated into uselessness. Further south along the Toroweap Formation, small rivulets can be found but rarely flow over the underlying Coconino cliff.

No water discharges from the upper contact of the Coconino Sandstone and none along the cliff face. However, a band of vegetation follows most of the Coconino Sandstone-Hermit Shale contact as the Hermit is less permeable than the Coconino. Liquid water does not flow on the surface from any of these seeps unless there has been an exceptionally wet season on the Kaibab Plateau.

Seeps occur in the Hermit Shale only during exceptionally wet periods. As a result, little vegetation grows on the Hermit slope. In this area, conspicuous springs or seeps controlled by bedding are rare. Localized seeps have been found at the tops of the most impermeable members of the Supai Formation but they barely wet the surface of the
rocks. One small spring having a discharge of less than 3 gallons per minute issues from a bedding plane in the Supai Formation near the Hermit Shale-Supai Formation contact on the eastern side of Crazy Jug Canyon below the northernmost tip of Parissawampitts Point. Other springs similar to this are assumed to exist to the south but were not observed.

Springs in the Aubrey Group in the Northern Portion of Tapeats Amphitheater and Deer Basin

No perennial bedding plane springs or seeps are known to the writer in the Aubrey Group west of Crazy Jug Canyon in the Tapeats-Deer area. The east-west trending canyon walls in the area intercept virtually no westward flowing water from the Kaibab Plateau. Even the west facing cliffs along the western side of Monument Point were found to be dry. Water seeps from the slope forming portion of the Toroweap Formation or from the Coconino Sandstone-Hermit Shale contact only during the wettest periods. In early June, 1965, following a wet spring season, the writer observed small rivulets of water collecting from seeps in the Hermit Shale below Monument Point. This phenomena has not been observed since.

Three structurally controlled springs are known in the Supai Formation and have discharges that, at most, reach 5 gallons per minute. One occurs at an elevation of about 5800 feet near the head of Crazy Jug Canyon and issues a small stream that flows a few hundred feet on the surface
before sinking into the Muav Fault Zone. It supports a thicket of scrub oaks which transpires the majority of the yield. The remaining 2 springs are located in Tapeats Cave Canyon east of Bridger's Knoll. The smaller of these had a discharge of less than 1 gallon per minute in July, 1967, and occurs along a well defined fracture zone east of and parallel to Tapeats Fault. It is about 5100 feet in elevation 1/4 mile upstream in the first tributary joining Tapeats Cave Canyon from the east approximately 2/5 mile north of the top of the Redwall Cliff. The water from this spring supports a few small shrubs before sinking into the jointed Supai Sandstone downstream from its source. The other spring is located at the junction of Tapeats Cave Canyon and the second tributary to the east 1/2 mile north of the Redwall Cliff. This spring flows from the Tapeats Fault Zone near the Supai Sandstone-Redwall Limestone contact at an elevation of about 5000 feet and had a discharge of about 5 gallons per minute in July, 1967. It supports a lush pocket of vegetation including cottonwood trees before the water sinks into the Tapeats Fault Zone a few hundred feet downstream.

No springs are known to the writer in the Aubrey Group in Deer Basin. Likewise no springs were found in the Aubrey Group on the flanks of Steamboat Mountain south of Tapeats Canyon.
Springs have not been found along the Redwall or Temple Butte Limestone cliffs in Deer Basin, Surprise Valley or the north and south facing walls of Tapeats Canyon. However, along the west facing exposures of the Temple Butte Formation in Stina Canyon, seeps from bedding planes fed a rivulet of water that discharged less than 10 gallons per minute in June, 1967. This water sinks into the streambed on reaching Saddle Canyon.

Seeps along bedding planes in the Muav Limestone exist and usually occur in the portions of the unit immediately above the Bright Angel Shale contact. All of these springs observed have discharges of less than 3 gallons per minute and can be detected by clumps of vegetation or damp travertine deposits on the walls of the canyons. In the summer months surface discharges rarely occur because the water evaporates quickly from the seep faces or is transpired by surrounding vegetation. Three Muav Limestone springs of this type are known in Tapeats Canyon as follows: (1) a spring at about 4000 feet elevation immediately east of the Tapeats Fault where the fault cuts into Tapeats Terrace on the south wall of the canyon, (2) a small seep on the downthrown side of the Muav Fault that lies at about 4000 feet in elevation on a west facing exposure of Muav Limestone in Saddle Canyon a few hundred feet upstream from its junction with Crazy Jug Canyon, and (3) a small spring that lies at
approximately 3700 feet in elevation at the head of an amphitheater 3/4 of a mile east of Thunder Spring on the north wall of the canyon. Other very weak seeps can be detected on close examination in portions of Tapeats Canyon. No large bedding plane seeps or springs are known in the Muav Limestone in Deer Basin.

The Bright Angel Formation, Tapeats Sandstone and some Precambrian rocks contain minute bedding plane seeps in Tapeats and Deer Canyons; however, these seeps barely support grass and other small plants. The only large seep in the Bright Angel Shale is indicated by a group of cottonwood trees growing in the floor of Tapeats Canyon at an elevation of about 3750 feet 1/3 of a mile downstream from the confluence of Saddle and Crazy Jug Canyons. No water discharges to the surface from this spring.

Water rises from the stream bed of Tapeats Canyon at the point where Tapeats Fault crosses the stream in the Tapeats Sandstone. Westward from this point, a small stream exists that supports cottonwood trees and other growth. In June, 1967, this stream had a discharge of about 1/2 cubic feet per second. The water undoubtedly represents flow through the porous stream bed that is brought to the surface by a slight bedrock rise west of Tapeats Fault. A small amount of this water may seep along Tapeats Fault from Tapeats Spring.
Structurally Controlled Karst Springs

in the Muav Limestone

Four karst springs discharge from the base of the Muav Limestone and transform Tapeats and Deer Canyons into scenic paradises. These fault controlled springs have individual base flows that range from 5 to more than 35 cubic feet per second and support a thick carpet of foliage that covers the floors of the canyons. Thunder and Vaughn Springs discharge from orifices in the face of the Muav cliff creating spectacular and scenic waterfalls.

General Features

From east to west the springs are Tapeats Spring, Thunder Spring, Vaughn Spring and Deer Spring.1 Each discharges from the base of the Muav Limestone at elevations of approximately 3700, 3500, 2800 and 2700 feet respectively. The decrease in elevation is due to the westward regional dip of the Paleozoic rocks and with the exception of Vaughn Spring, which ceases to flow during the dry season, the quantity of water discharged by the springs decreases respectively from east to west. The entire discharge record to date (United States Geological Survey Miscellaneous Measurements) is shown in Table 1. In all cases, these springs

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1. On the Kanab Point, Arizona Topographic Quadrangle of the United States Geological Survey, Deer Springs is shown at the location of Vaughn Spring and Vaughn Spring is shown almost 2 miles further north of the correct location of Deer Spring. These errors are corrected on the maps included with this paper.
are fault controlled and issue from solution channels in the Muav Limestone. Their elevations are maintained on the top of the Bright Angel Shale because this formation is insoluble.

Although continuous stream gauges have never been in operation at any of these 4 springs, the following general facts are supported by field observations. Peak flows occur during the spring from March to June depending on the snow melt period on the Kaibab Plateau. A gradual recession follows through the summer months pulsed by summer storms that occur over the plateau regions. Minimum flows occur during the winter months.

During the first week of April, 1961, the writer observed a heavy snowfall in excess of 2 feet melt on the western Kaibab Plateau in a period of 4 days. Surface runoff from this storm was negligible; however, on the fourth day after melting commenced, the discharge from Thunder Spring was observed to increase on the order of 30 per cent over a period of 24 hours. It is obvious that although these springs lie at considerable depths below the plateau rims and many miles from most of the source areas, the drainage systems are sensitive and respond quickly. Due to the lack of stream gauging data, no information is available that shows the time lag between the hydrologic pulses on the rim and peak discharges at the springs or the recession characteristics of the flows.
TABLE 1. Ground Water Discharge into Tapeats and Deer Canyons from Karst Springs in the Muav Limestone

<table>
<thead>
<tr>
<th>Spring</th>
<th>Date of Measurement</th>
<th>Discharge (cubic feet per second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tapeats Spring²</td>
<td>June 27, 1951</td>
<td>37.3</td>
</tr>
<tr>
<td></td>
<td>May 28, 1952</td>
<td>156</td>
</tr>
<tr>
<td></td>
<td>May 29, 1952</td>
<td>149</td>
</tr>
<tr>
<td></td>
<td>May 19, 1953</td>
<td>46.5</td>
</tr>
<tr>
<td></td>
<td>April 26, 1954</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>May 29, 1955</td>
<td>42.4</td>
</tr>
<tr>
<td>Thunder Spring³</td>
<td>June 27, 1951</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>May 28, 1952</td>
<td>127</td>
</tr>
<tr>
<td></td>
<td>May 19, 1953</td>
<td>15.3</td>
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<tr>
<td></td>
<td>April 26, 1954</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>May 29, 1955</td>
<td>14.4</td>
</tr>
<tr>
<td>Tapeats and Thunder Springs Combined⁴</td>
<td>June 9, 1923</td>
<td>93.9</td>
</tr>
<tr>
<td></td>
<td>June 9, 1953</td>
<td>55.6</td>
</tr>
<tr>
<td></td>
<td>June 18, 1960</td>
<td>51.4</td>
</tr>
<tr>
<td></td>
<td>June 25, 1966</td>
<td>79.8</td>
</tr>
<tr>
<td>Deer and Vaughn Springs Combined⁵</td>
<td>Sept. 10, 1923</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>June 10, 1953</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>June 19, 1960</td>
<td>5.44</td>
</tr>
<tr>
<td></td>
<td>June 25, 1965</td>
<td>8.6</td>
</tr>
</tbody>
</table>

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2. Flow measured in Tapeats Creek above junction with Thunder River.

3. Flow measured in Tapeats Creek above junction with Thunder River is subtracted from flow measured in Tapeats Creek below junction with Thunder River.

4. Flow measured in Tapeats Creek below junction with Thunder River or at mouth of Tapeats Creek and the Colorado River.

5. Flow measured at the mouth of Deer Creek and the Colorado River.

Tapeats Spring and Cave

Tapeats Spring flows from the floor of Tapeats Cave Canyon near the base of a wedge-shaped graben block that is developed above the Bright Angel Shale in the Tapeats Fault Zone. Measured discharges from the spring have ranged from 37.3 to 156 cubic feet per second. Consequently, this is the largest karst spring in the Grand Canyon National Park.

East of the spring, about 100 feet west of the eastern fault that bounds the graben block, a cavern chamber 70 feet wide, 30 feet high and over 150 feet long occurs in the canyon wall. Several solution tubes which attain maximum diameters of 10 feet join the room from the north. Water flows from these tubes only during extreme floods in the system, otherwise they remain dry. They can be traced northward 700 feet before they intersect the main flow channel which is a tube that is at least 30 feet in diameter. All of the water that discharges from Tapeats Spring flows along the floor of the main passage over rubble which has collapsed from the ceiling. In places sand dunes and sand bars of fine-grained quartz sand cover the rubble and attest to sediment transport through the karst system. This large passage extends about 3/4 of a mile to a point where it has been sealed by a large ceiling collapse. Two thousand feet of Tapeats Cave were mapped from its mouth with a Brunton compass and steel tape and it was found to be aligned with the Tapeats Fault Zone. See Figure 13. Small fault displacements were
FIGURE 13.
TAPEATS CAVE

Planimetric Map of the Entry Portion of the Principal Passage

Brunton Compass - Steel Tape Traverse
detected along fractures in the ceilings of many passages trending north-south. All other passages have developed along prominent joints. Wide gouge zones and large displacements along slip planes were not observed in the 2000 feet of passageway mapped. Consequently, it is doubtful that the explored cavern follows a major fault plane associated with the graben. It was evident from bedding in the walls of the cave that the passages follow the dip of the limestone; therefore, their gradients are low.

Thunder Spring and Cave

Thunder Spring has issued discharges measured at 14.4 to 7 cubic feet per second and is the most scenic of the springs in the Grand Canyon. As Figure 14 indicates, the water from the spring cascades over several cliffs and down a half mile long canyon to a junction with Tapeats Creek. Most of the water discharges from 2 joint controlled passages spaced 10 feet apart in the face of a sheer cliff that extends to the top of the Redwall Limestone. Other smaller springs discharge from small tubes eroded along joints in the underlying Bright Angel Shale. To the east of the main orifice many joints are dissolved out perpendicular to the cliff face and indicate older outlets now pirated by the present spring. One hundred feet west of Thunder Spring, the Thunder Fault trends northward in the limestone cliffs. In the lower Muav cliff, one solution passage 7 feet in diameter and a few smaller tubes that trend northward are
The contact between the Muav Limestone (Cm) and Bright Angel Shale (Cba) is indicated by the line.
exposed along the fault zone but are choked with breccia and finer fill. Also exposed are similarly filled solution tubes developed along east-west trending joints. The east-west lineation is parallel to the slip plane of the Surprise Valley Slump which rests along the limestone cliff in this area. These filled tubes are thought to represent discharge channels developed along the fault prior to the collapse of Surprise Valley.

Thunder Cave is entered through the spring orifice. Approximately 2700 feet of passageways were mapped using a Brunton compass and steel tape. See Figure 15. An entrance complex of sinuous joint controlled passages having maximum widths of 5 feet and heights of 10 feet lead northward to a spacious east-west trending passageway that has maximum dimensions of 20 feet wide and 50 feet high. This passage is also joint controlled and lies parallel to the cliff face. The Thunder Spring water flows from the west along this large passage and is pirated by the entrance joint complex. To the east of the entrance complex, the large passage is dry and extends 1600 feet to a collapse zone that plugs it. About 2000 feet east of Thunder Spring a collapse of the cliff face exposes an additional segment of this same east-west trending passage which can be followed toward the west to the blockage observed in Thunder Cave.

The large east-west trending passage contains water west of the entrance complex. Within 200 feet along this
5.
CAVE

Plan II Portion
Bruno

the Entry
Principal Passage
Tape Traverse

200

Dry Passage

Thunder Spring and Entrance

Entrance

P.W.H. 1958
passage, the cave turns northward and from this point the water flows from the northeast through a network of north-south and east-west trending passages. Sand bars line the passages and ceiling collapses have occurred in the wider chambers. As shown in Figure 16, displacements on the order of a few inches are evident along the controlling fractures of every north-south trending passage but no displacements occur along the joints that control the east-west passages. It is important to notice that only about 1/4 of the known cave follows fault controlled solution tubes. The remaining passages lie along fractures aligned with the east-west slip planes of the Surprise Valley Slump Zone.

Vaughn and Deer Springs

Vaughn and Deer Springs have had recorded combined discharges of 5.4 to 8.2 cubic feet per second and are considered to be a single hydrologic unit. See Table 1. Both springs lie in close proximity to, but west of Deer Fault, a northeast-southwest trending structure with a displacement of no more than 4 feet west side downward. Deer Spring discharges perennially from the base of talus that covers the eastern wall of Deer Canyon. As a result, the cavern from which the water flows is buried and cannot be entered.

Vaughn Spring issues from an orifice above a travertine apron 8 feet above the floor of an overhanging amphitheater that is eroded from the Muav and Bright Angel Formations. See Figure 17. No measurements have been made of the individual flows
FIGURE 16. Northward Trending Stream Passage in Thunder Cave

Notice the small fault in the arch above the raft that controls the passage.
Notice the fracture control of the solution tube that discharges water. This spring ceases to flow in dry periods.
from these springs; however, Vaughn Spring always contributes the smaller proportion. During dry periods, Vaughn Spring ceases to flow entirely, a unique occurrence for a karst spring in the Muav Limestone.

The cave at Vaughn Spring was entered by scaling the cliff face but it was too narrow for human passage beyond 100 feet. In the amphitheater surrounding the springs, several small joint controlled, dry solution tubes are exposed; however, none of these provided access to an extensive cavern system.

The locations of Deer and Vaughn Springs are thought to postdate the Surprise Valley collapse. The cavernous fractures at Vaughn Spring have 2 predominant trends, an east-west set parallel to the slip plane of Surprise Valley and a north-south set. Joints and fractures in the Muav Limestone at Deer Spring have the same orientations. It is assumed that water flows through solution channels dissolved along the Deer Fault Zone. This water finds outlets from the fault to Deer Canyon through fractures that cross the fault and trend parallel to the slip planes of the Surprise Valley Slump. The water pirated by these west trending fractures finds a topographically lower outlet in Deer Canyon at Deer Spring. As these younger east-west fracture channels are not as large as the conduits developed along Deer Fault, they do not have the capacity of the older channels. Consequently, if the quantity of water flowing along Deer Fault from the
northeast exceeds the capacity of the Deer Spring conduit, the excess water continues to flow along the fault to Vaughn Spring. During low flow periods, the Deer Spring fractures can accommodate the entire flow and Vaughn Spring dries up.

Water Quality Data for the Karst Springs

Water quality data for the Tapeats-Deer karst springs have been collected by the United States Geological Survey and are tabulated from open file reports by Johnson and Sanderson (1968). These data are reproduced in Table 2. It is obvious that the water discharging from Tapeats and Thunder Springs is almost identical. The water in Deer Canyon, that represents the combined samples of Deer and Vaughn Springs, is slightly different. These data are presented here as evidence that the springs are discharging from approximately the same ground water body. In the case of Deer and Vaughn Springs, the slight variance is evidence that the source of water for these springs is a portion of the plateau slightly west of the geographic area that Thunder and Tapeats Springs drain jointly. Deer and Vaughn Springs probably drain a large portion of the Kanab Plateau west of Muav Fault whereas Thunder and Tapeats Springs derive most of their water from the Kaibab Plateau east of the Muav Fault.

Circulation of Ground Water in the Tapeats-Deer Area

The ground water circulation model developed in this section describes ground water flow through a multilayered
## TABLE 2. Chemical Analysis of Water Samples from Springs in Tapes and Deer Canyons

<table>
<thead>
<tr>
<th>Source</th>
<th>Location Sample Collected</th>
<th>Date</th>
<th>Discharge (cfs)</th>
<th>Temperature (°F)</th>
<th>Ca</th>
<th>Mg</th>
<th>Na</th>
<th>K</th>
<th>HCO₃</th>
<th>CO₂</th>
<th>SO₂</th>
<th>Cl</th>
<th>F</th>
<th>NO₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peaks Spring</td>
<td>Tapes Creek Shoal Junction with Thunder River</td>
<td>6-27-51</td>
<td>373</td>
<td>57</td>
<td>44</td>
<td>19</td>
<td>-</td>
<td>-</td>
<td>206</td>
<td>0</td>
<td>4.7</td>
<td>2.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Under Spring</td>
<td>Mouth of Thunder River above junction with Tapes Creek</td>
<td>6-27-51</td>
<td>16.5</td>
<td>56</td>
<td>44</td>
<td>19</td>
<td>-</td>
<td>-</td>
<td>205</td>
<td>trace</td>
<td>3.3</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Per and Vaughn Springs</td>
<td>Mouth of Deer Creek</td>
<td>6-20-60</td>
<td>8E</td>
<td>61</td>
<td>47</td>
<td>14</td>
<td>2.0</td>
<td>1.0</td>
<td>208</td>
<td>0</td>
<td>10</td>
<td>2.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

- **Cl** | **F** | **NO₃** | **Dissolved Solids (milligrams/liter)** | **Sulfate** (mg/l) | **Hardness as CaCO₃ (mg/l)** | **% Na** | **Sodium Absorption Ratio** | **Specific Conductivity (microsiemens at 25°C)** | **pH**
- 2.0 | 0  | 0  | - | - | 186 | 19 | - | 0.3 | 318 | - |
- 1.0 | 0  | 0  | - | - | 186 | 20 | - | 0.3 | 311 | - |
- 2.1 | 0.1 | 0.1 | 179 | 0.24 | 175 | 5 | 2 | 0.1 | 340 | 7.1 |

---

a. Data from Johnson and Sanderson (1968)
system in which the boundary conditions are well defined. As such, it is not an analytical device that predicts hydraulic variables given an input of certain hydrologic parameters; rather, it is a general qualitative description of ground water circulation through a sequence of stratum in which permeability is a variable. Because permeability is a function of lithology and tectonic fabric, the model can be used to illustrate the hydromechanics of the aquifers that drain into the Grand Canyon. The model will be developed by first considering the flow system in the Paleozoic rocks as affected by the primary permeability and the permeability due to jointing of the individual stratum. Next, the additional structural features that affect permeability, such as faulting and solutional modification, will be superimposed on the simpler system. Finally, in qualitative terms, the Tapeats-Deer area ground water system will be analysed as a functioning hydraulic unit.

The Ground Water Circulation Model

Consider a saturated, homogeneous, horizontal bed of porous rock of thickness \( s \) through which water flows vertically and discharges from the base at atmospheric pressure \( p_a \). To maintain saturation, a very thin film of water is maintained on the upper surface. See Figure 18. Darcy's Law for flow through a porous media reads throughout the layer.
FIGURE 18. Vertical Flow through a Layer
if and only if it is saturated.¹

\[ V = \frac{Ph_s}{l} \]

where: \( V \) = velocity,
\( P \) = constant of permeability dependent on the properties of the rock,
\( l \) = length of flow path,
\( h_s \) = the loss in hydraulic head along a flow path of length \( l \).

In the vertical flow case

\[ l = s \]

or

\[ \frac{h_s}{s} = \frac{h_s}{s} \]

Multiplying through by the cross sectional area of flow,

\[ Q = VA = \frac{Ph_sA}{s} \]

where: \( A \) = cross sectional area perpendicular to the flow direction,
\( Q \) = quantity of water passing through \( (A) \) per unit time.

The quantity \( h_s/s \) can be evaluated with the aid of the Bernoulli equation:

¹ Darcy's Law appears to hold in unsaturated flow cases if the constant \( P \) is replaced by \( P(0) \), a variable function dependent on the per cent saturation. For the purpose of this discussion, this form of Darcy's Law will be neglected.
\[ \frac{P_i + \frac{V_i^2}{2g} + z_i}{\gamma} = \frac{P_j + \frac{V_j^2}{2g} + z_j + h_s}{\gamma} \]

where: the subscripts (i) and (j) denote the elevation of points measured from a datum plane. For convenience, datum will be taken at a level lying below the layer considered.

- \( P_i \) = pressure on the fluid at a point (i),
- \( \gamma \) = specific weight of the fluid; in this case, water,
- \( V_i \) = velocity of the fluid along a streamline at a point (i),
- \( z_i \) = elevation at the point (i) measured vertically from the datum plane,
- \( g \) = acceleration of gravity,
- \( h_s \) = the head loss between elevations (i) and (j).

In ground water circulation, the velocity of flow through porous media is very small so the term \( \frac{V_i^2}{2g} \) becomes negligible and can be dropped from the equation without appreciable error. Therefore,

\[ \frac{P_i + z_i}{\gamma} = \frac{P_j + z_j + h_s}{\gamma} \]

or rewriting,
\[ h_s = \frac{P_i - P_j + (z_i - z_j)}{\gamma} \]

Let \((i)\) and \((j)\) be respective points on the upper and lower surfaces of the layer, as in Figure 19, then

\[ h_s = \frac{P_a - P_a + (z_o + s) - z_o}{\gamma} \]

or

\[ h_s = s. \]

As \((P_a)\) varies with elevation, a slight error is introduced if \((s)\) is large, but this error is less than 0.1 per cent in all cases that will be considered and will be neglected. Consequently, under the vertical flow conditions assumed, the Darcy Equation:

\[ Q = \frac{Ph_A}{s} \]

simplifies to

\[ Q = PA. \]

Now consider the vertical flow case shown in Figure 20 where two homogeneous, horizontal layers of rock having permeabilities \((P_1)\) and \((P_2)\) are such that the upper surface, one side and the bottom are open to atmospheric pressure \((P_a)\), the opposite side is impermeable and at least the upper surface transmits water under saturated conditions. Darcy's Law holds throughout the saturated portions of the model. Assume for the present that \(h_s/s = 1\) so that the simplified form of Darcy's Law can be used:

\[ Q = PA. \]
FIGURE 19. Head Loss through a Layer
Figure 20. Elementary Flow Model
Consider a slab of the model having unit width. It is seen that

\[ A = LW \]

where: \( A \) = area,

\( L = \) length, the horizontal dimension perpendicular to the impermeable boundary,

\( W = \) width, the horizontal dimension parallel to the impermeable boundary,

but if a unit width is taken,

\( W = 1 \).

Hence

\[ A = L \]

and Darcy's Law further simplifies to

\[ Q = PL. \]

Given an area of unit width on the top of layer 1 through which a quantity (Q) is passing, Darcy's Law yields a relationship that specifies the area on the top of layer 2 required to transmit the same quantity of water. That is,

\[ Q = P_1L_1 = P_2L_2 \]

or rewriting,

\[ L_2 = \frac{P_1L_1}{P_2}. \]
Case A. Consider the case where $P_1 > P_2$. From Darcy's Law,

$$L_2 = \frac{P_1 L_1}{P_2}$$

but if

$$P_1 > P_2$$

then

$$L_2 > L_1.$$ 

That is, more area will be required on the second layer to transmit the quantity $(Q_1)$ than on the upper layer. If the flow lines that bound the area $(L_1)$ are defined, it is seen that they will of necessity be displaced outward from the impermeable boundary as they reach the second layer. See Figure 21. It is also noticed that when $(L_1)$ becomes larger, $(L_2)$ will increase at a faster rate and displace the flow lines on the lower layer further and further out from their respective points of origin on the upper layer. When area $(L_1)$ has covered the entire upper surface, $(L_2)$ has extended into space. The amount of $(L_2)$ hanging in space represents the amount of water moving through layer 1 that cannot pass through layer 2. Consequently, this water is discharged as a spring at the contact between layers 1 and 2. It can be

---

1. The term case will be used to specify each of the 3 unique stratigraphic-permeability relationships that can exist between 2 strata in this model. The term example will be used to designate problems illustrating the application of the theory.

spring discharge  impermeable boundary
seen that the amount of water discharged from the spring is a function of the difference in permeabilities between the two layers. Also it is evident that both layers transmit water under saturated flow conditions and Darcy's Law is satisfied everywhere.

Unfortunately, the simplified Darcy Equation:

\[ L_2 = \frac{P_1 L_1}{P_2} \]

fails with distance from the impermeable boundary because the ratio

\[ \frac{h_s}{L} = \frac{h_s}{s} = 1 \]

is no longer true. This qualification must be made because as the flow lines bend further from the normal away from the impermeable boundary, \( l \) is no longer equal to \( s \) but rather \( l > s \). Although the mathematical relationships are not satisfied away from the boundary, this simple analysis gives excellent qualitative insight into the mechanism of water passage from a large permeable stratum to a smaller permeable stratum.

**Example 1.** Consider the situation shown in Figure 22 where 3 strata exist under the assumed conditions such that \( P_1 > P_2 > P_3 \). Case A will hold between each pair of layers and the flow paths will be displaced outward from the impermeable boundary at each contact.

**Case B.** If \( P_1 < P_2 \), then by Darcy's Law, \( L_2 < L_1 \) or less area will be required on the second layer to transmit
FIGURE 22. Example 1: $P_1 > P_2 > P_3$
the quantity \( Q_1 \). This does not mean that flow lines will be displaced toward the impermeable boundary as they approach the second layer because the gradient still remains vertical. What actually occurs is that flow lines continue straight down but on reaching the more permeable material flow becomes unsaturated as shown in Figure 23. Consequently, the relationship derived from Darcy's Law fails, \( L_1 = L_2 \), and no spring forms at the contact. In this special case, Darcy's Law does not hold in the second layer because this layer is transmitting water under unsaturated conditions.

**Example 2.** If \( P_1 > P_3 > P_2 \), Case A will hold at the contact between layers 1 and 2 but Case B will hold between layers 2 and 3 so \( L_1 < L_2 = L_3 \). A spring forms at the contact between layers 1 and 2, but layer 3 is transmitting water under unsaturated conditions. See Figure 24.

Difficulties arise in Case B problems because Darcy's Law as written is not valid in the unsaturated portions of the flow system. For this reason, if Darcy's Law is applied between layers transmitting water under unsaturated conditions, erroneous results may be obtained. These difficulties can be circumvented by realizing that the smallest permeable layer in a section governs the quantity of water per area that is transmitted downward below it as shown by the analysis of Case B. In essence, this means that any large permeable layers underlying a small permeable layer have no effect on the flow lines; that is, no deflection of flow lines
FIGURE 23. Case B: $P_1 < P_2$
FIGURE 24. Example 2: $P_1 > P_3 > P_2$
will occur in the unsaturated zones. For all practical purposes then, the unsaturated layers can be neglected in the mathematical analysis and Darcy's Law can be applied directly between the small permeable member and each successive underlying member until one of these has an even smaller permeability. An example will serve to illustrate this point.

Example 3. Consider four successive strata such that

\[ P_2 > P_3 > P_1 > P_4 \]

so that above the fourth layer, layer 1 has the lowest permeability. See Figure 25. Since \( P_1 < P_2 \), Case B holds at the contact between layers 1 and 2 so \( L_1 = L_2 \) and flow is unsaturated in the second layer. If we neglect the fact that Darcy's Law is invalid in layer 2, we find on applying it to the contact between layers 2 and 3 that Case A holds here; that is,

\[ P_3 < P_2 \]

and

\[ L_3 = \frac{P_2L_2}{P_3} \]

so

\[ L_3 > L_2. \]

From above, it was found that \( L_2 = L_1 \), consequently

\[ L_3 > L_1. \]

This is obviously an erroneous result because \( P_1 < P_3 \).

Now, if this problem is approached correctly, Case B holds at the contact between layers 1 and 2 as before
FIGURE 25. Example 3: $P_2 > P_3 > P_1 > P_4$
yielding

\[ L_1 = L_2. \]

Realizing that water in layer 2 is percolating under unsaturated conditions and Darcy's Law is invalid at the contact between layers 2 and 3, we can omit layer 2 from the analysis and test Darcy's Law directly between layers 1 and 3. As \( P_3 > P_1 \), Case B also holds between these layers; consequently, \( L_3 = L_1 \), and \( L_1 = L_2 = L_3 \). The water in layer 3 is also percolating under unsaturated conditions even though \( P_3 < P_2 \).

As the water in both layers 2 and 3 is flowing under unsaturated conditions, layer 4 must be tested directly against layer 1. Applying Darcy's Law again, we find Case A holds between layers 1 and 4 because \( P_1 > P_4 \), consequently \( L_4 > L_1 \). Now that layer 4 has the smallest permeability in the section, all underlying layers must be tested against it until a layer having even smaller permeability is found.

It will be noted that even though the water in layers 2 and 3 is percolating under unsaturated conditions, the quantity of water delivered to the upper contact of layer 4 through an area \((L_1)\) will exceed the ability of the 4th layer to transmit that water. As a result, the water in layer 4 will flow under saturated conditions and the flow lines will be deflected at its upper contact.

From this analysis, it is seen that a spring will never form at the upper contact of any layer unless the
permeability of that layer is lower than the permeability of every overlying layer.

Case C. In the trivial case where \( P_1 = P_2 \), Darcy's Law shows that \( L_1 = L_2 \). The flow lines continue vertically through the lithologic boundary, no springs form and both layers remain saturated. Darcy's Law holds throughout the system. See Figure 26.

It is now appropriate to consider the effect of decreasing the flow through the layers. Given that layer \((k)\) lies anywhere below layer \((i)\), in Cases B or C where \( P_i < P_k \), there is no effect on \((L_k)\) when the flow is decreased because \((L_k)\) will always equal \((L_i)\). However, in Case A where \( P_i > P_k \) there is a profound effect. If we consider layer \((i)\) under saturated conditions, it is transmitting at its maximum capacity. However, if water is introduced onto its upper surface at a rate slower than the layer can transmit this water, the flow in the layer will become unsaturated. Layer \((k)\) will still transmit at its maximum capacity but now it can accommodate a larger proportion of the water introduced onto its upper surface. Consequently, less water will have to be discharged from the spring at the contact and \((L_k)\) will shorten toward the impermeable boundary. As less and less water is introduced onto the upper layer, there is a point at which the spring will cease to flow.

From the simplified form of Darcy's Law we have

\[
Q = P_k L_k.
\]
FIGURE 26. Case 3: $P_1 = P_2$
If we are interested in the quantity of flow when the spring at the contact between the layers dries up, the area through which the flow is passing must be equal in both layers; that is,

$$L_k = L_i.$$  

Hence, the spring ceases to exist when

$$Q = P_k L_i.$$  

It is obvious that if the flow diminishes below this value, the second layer will also transmit water under unsaturated conditions. It follows that as long as

$$Q \leq P_k L_i$$

no spring will form at the contact between the two layers.

In summary, the following general results may be stated. If a quantity of water (Q) reaches the upper contact of the (i)th layer down from the top of a section, the surface area ($L_i$) of that layer required to transmit the quantity (Q) will be as follows:

1. if $P_i < P_{\text{min}}$, $L_i = \frac{L_{\text{min}} P_{\text{min}}}{P_i}$

where: $P_{\text{min}}$ = permeability of the layer having the lowest permeability that overlies the (i)th layer,

$L_{\text{min}}$ = area on the upper contact of the minimum permeable layer required to transmit (Q).
A spring will form at the top of the \((i)\)th layer if \(Q > P_i L_{\text{min}}\).

2. If \(P_{\text{min}} \leq P_i\), \(L_i = L_{\text{min}}\) and a spring will not form at the top of the \((i)\)th layer.

Qualitatively, these results may be stated as follows:

1. If the permeability of the \((i)\)th layer below the surface layer is less than every other layer above it, a spring will form at its upper contact when the amount of water entering the section exceeds the transmission capacity of the \((i)\)th layer.

2. If the permeability of the \((i)\)th layer down from the top is greater than or equal to any layer above it, no spring will form at its upper contact.

In order to facilitate the use of these results, the following steps will indicate where springs will occur in multilayered sections if the relative permeabilities are known.

1. Number the layers from the top of the section downward.

2. Using these numbers as subscripts for the permeabilities of their respective layers, order the relative permeabilities from greatest to smallest.

For example, \(P_1 > P_3 > P_2\) means that the permeability of the first layer, the highest layer in the section, is greater than the
permeability of the third layer which is in turn greater than the permeability of the second layer.

3. After the permeabilities of the layers are ordered, a spring will occur at the upper contact of any layer if its subscript has a lower numerical value than the subscript of each less permeable layer or if the layer has the lowest permeability in the section.

If two or more layers in the section have the same permeability and the analysis indicates that a spring will form at the upper contact, it will form only at the upper contact of the highest of the layers in the section.

If the analysis indicates that a spring will form at the top of the first layer, this result is trivial and can be neglected.

In the example $P_1 > P_3 > P_2$, a spring will form at the upper contact of layer 2 because it has the lowest permeability in the section. No spring will form at the upper contact of layer 3 because the subscript 3 is greater than 2, which is the subscript of a layer having lower permeability.
Circulation Model Applied to the Paleozoic Sediments in the Tapeats-Deer Area

The application of this theoretical model to the Paleozoic sediments in the Tapeats-Deer area yields significant results. The validity of the model is made possible due to the following similarities between the model and field conditions. (1) In general, the strata dip only 1 or 2 degrees from the horizontal plane and can be considered approximately level. (2) The water in the form of precipitation that is introduced onto the top of the section approaches uniform distribution on a megascopic scale. (3) Due to symmetry, the impermeable boundary assumed in the model can be replaced by a ground water divide that exists in the Kaibab Plateau. (4) The canyons of the Colorado River form the open face along which springs may occur. (5) Atmospheric pressure exists along the plateau surface and canyon walls and due to open karst systems close to the base of the section, atmospheric pressure can be assumed there without appreciable error.

Consider the circulation model applied to the Paleozoic strata when fault and solutional modifications are neglected. In this case, the permeability of each stratum will be dependent on the primary permeability of the rock and the secondary permeability due only to the joints unrelated to faulting. By thus limiting the model, spring locations can be predicted in regions hydrologically unaffected
by faulting and solution. Also, a basis is established for comparing the effect tectonic modifications have once they are imposed on the ground water system. It is possible to estimate the relative rank of the permeabilities of the various stratigraphic units from the lithologic descriptions. Table 3 shows the permeability estimates when faulting and solutioning are neglected.

Ranking the relative permeabilities from greatest to least using the formation order numbers as subscripts,

\[ P_1 > P_3 > P_2 > P_5 > P_{10} > P_4 > P_8 = P_9 > P_6 = P_7. \]

It is seen from the method developed above that springs are expected at the tops of the most impermeable member of the following formations: 2, 4, and 6, or respectively, the Toroweap Formation, Hermit Shale, and Redwall Limestone. Very little water would move through the Redwall Limestone but the water that does would be expected to drain from springs in the lowest Paleozoic unit exposed. Observations described in this report bear out these conclusions, particularly in the region east of the Muav Fault where fault and solution modifications have very little effect on the westward flowing ground water.

West of the Muav Fault, however, only a fraction of the total ground water discharges above the Redwall Limestone. If it is assumed that the mathematical model has not failed, the huge springs issuing from the base of the Muav Limestone must depend upon permeability factors other than
### TABLE 3: Estimated Permeability Rank Considering Only Primary Permeability and Secondary Permeability Due to Joints

<table>
<thead>
<tr>
<th>Formation</th>
<th>Order from Top</th>
<th>Estimate of Relative Permeability Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaibab Formation</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Toroweap Formation</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Coconino Sandstone</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Hermit Shale</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Supai Formation</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Redwall Limestone</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Temple Butte Limestone</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Muav Limestone</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Bright Angel Shale</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>Tapeats Sandstone</td>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>

### TABLE 4: Estimated Permeability Rank Considering Both Primary and Secondary Permeability Factors

<table>
<thead>
<tr>
<th>Formation</th>
<th>Order from Top</th>
<th>Estimate of Relative Permeability Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaibab Formation</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Toroweap Formation</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Coconino Sandstone</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Hermit Shale</td>
<td>4</td>
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</tr>
<tr>
<td>Redwall Limestone</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Temple Butte Limestone</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Muav Limestone</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Bright Angel Shale</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Tapeats Sandstone</td>
<td>10</td>
<td>8</td>
</tr>
</tbody>
</table>
primary permeability and jointing. Of course, these additional factors include faulting of all units and solutioning of the limestones along fractures. In Table 4, the permeability rank, including all primary and secondary factors, is estimated on the basis of stratigraphic and structural observations.

Ranking the relative permeabilities from greatest to least using the formation order numbers as subscripts,

\[ P_1 > P_4 > P_8 > P_2 > P_7 > P_5 > P_6 > P_{10} > P_3 > P_9. \]

Now applying the method for determining spring locations, it is seen that the major springs would occur at the upper contact of layers 2, 4, and 9 or at the tops of the most impermeable members of the Toroweap Formation, Hermit Shale and Bright Angel Shale which fits closely with field observations west of the Muav Fault.

It should be noted that the model developed for this analysis assumes homogeneity which is fairly well achieved on a megascopic scale; however, faults and solution channels are not uniformly distributed so these general results fail locally. Due to local variations in lithology and structure, small springs are found at contacts other than those predicted by the model.

**Effect of Structural Modifications on Circulation**

At this point, it is appropriate to consider how tectonic structures influence ground water circulation in the Paleozoic system of the Tapeats-Deer area.
The dip of the strata toward the west in the Tapeats-Deer area influences ground water circulation when the water becomes perched above beds having small permeabilities. As the model indicates, the portion of water not able to pass through a given area on the surface of a layer having a small permeability must spread over more area in order to be transmitted. Lateral spreading results from a build up of ground water mound above the contact which imposes a lateral gradient component on the water. If the low permeable layer is dipping, the ground water mound will also be tilted and a gradient will develop in the down dip direction. Consequently, the flow paths will deflect down dip. The stratigraphic dip influences the direction in which flow paths are deflected only in so far as the dip dictates the shape of the ground water mound developed above a layer having a small permeability. It should be noted that the stratigraphic dip does not influence ground water flow if the flow is unsaturated or, in saturated zones, if ground water mounds are not present.

Faults effectively increase permeability as long as large quantities of impermeable gouge are not created and cementing is not effective in clogging otherwise porous zones. Throughout the Tapeats-Deer area, faulting has occurred on a relatively small scale but the rocks are brittle enough that faults are very effective in creating highly permeable zones. It follows, therefore, that faults have
been effective in increasing vertical permeabilities in all the Paleozoic strata, thereby creating hydrologic shortcuts across low permeable beds such as the Hermit Shale and Redwall Limestone. Given outlets at lower elevations, faults provide permeable conduits through the section that intercept laterally flowing water and carry it to lower elevations.

Circulation along faults and related fracture zones is extremely important in the development of secondary permeability in thick limestone strata. With outlets in the deep canyons, limestones are subjected to solution by circulating ground water. Development of solution tubes both vertically and laterally along fault zones has intensified the dominant hydrologic influence of the north-south faulting in the Tapeats-Deer area. Solution voids so created form an efficient, quick responding, interconnected network that carries water rapidly through the lower limestone units from source areas to the canyon walls.

Dynamics of the Tapeats-Deer Ground Water System

In summarizing the ground water circulation system in the Tapeats-Deer area, it is necessary to consider portions of the Kaibab and Kanab Plateaus up to 25 miles north and east of the karst springs because most of the water that discharges from the springs originates in these regions. Figure 17 schematically summarizes the ground water circulation system that supplies water to Tapeats and Thunder Springs.
Recharge takes place in dolines and joints in the Kaibab Formation which concentrate available surface water from small areas into joints and small solution tubes. The water moves vertically by the influence of gravity until it reaches a layer that has a smaller relative permeability than the one through which it is flowing. The fraction of the total quantity of water that does not move through this layer must be spread laterally over enough surface area of the retarding bed so that transmission can be completed.

At such a point in the flow system, the evaluation of a ground water divide becomes important. West of the north-south trending ground water divide assumed to exist near the center of the Kaibab Plateau, vertical flow paths are deflected westward down dip as water moves from a bed having a relatively large permeability to one having a relatively small permeability. Many miles from the divide in the vicinity of the western portion of the Kaibab Plateau, flow paths are deflected to such a magnitude that they are essentially parallel to the dip of the rock.

The fraction of the total quantity of water moving downward through a bed having a small permeability responds identically on reaching beds of even smaller relative permeability. Flow paths are again deflected toward the west. As shown in the previous section, the impermeable beds of the Toroweap Formation, top of the Hermit Shale and top of the Redwall Limestone are the most important retarding units.
They are so effective in deflecting flow to the west that most of the water moving downward in the section is diverted westward before reaching the top of the Redwall Limestone. The minute fraction passing through the Redwall accounts for small bedding plane springs in the Muav and Bright Angel formations in Saddle and Crazy Jug Canyons of eastern Tapeats Amphitheater.

In the absence of a hydrologic discontinuity between the ground water divide and a canyon, the flow paths that are deflected away from the divide form springs along the upper contacts of low permeable beds in the canyon walls. Geographically, Tapeats Amphitheater is the first major canyon that cuts deeply northward into the western Kaibab Plateau. As such, it cuts across a wide area of westward dipping strata and intersects a large amount of water flowing westward from the divide. For this reason, seeps occur east of the Muav Fault in Tapeats Amphitheater as almost continuous bands above the low permeable beds of the Toroweap Formation and at the contact between the Coconino Sandstone and Hermit Shale.

The magnitude of discharge from the bedding plane seeps along eastern Tapeats Amphitheater is determined by the number of flow paths deflected out through the canyon walls. As seen in the model, the number of flow paths deflected at a contact zone depends on the absolute quantity of water flowing through the section as well as the magnitude
of the difference in relative permeabilities of the strata. During dry seasons when the lower permeable beds are able to transmit a larger fraction of the water introduced onto their upper surfaces, the deflection of flow paths is reduced and spring discharge diminishes.

Bedding plane springs are expected along the Toroweap Formation and top of the Hermit Shale in the canyon walls of Deer Basin northwest of Monument Point because Deer Basin cuts further north into the Kanab Plateau than Tapeats Amphitheater and should capture some westward flowing water. The absence of springs along these cliff faces strongly suggests a hydrologic discontinuity east of Monument Point. Of course, the Muav and Tapeats Faults occur in the region east of Monument Point and form hydrologic discontinuities by providing highly permeable zones that shortcut the low permeable beds of the Toroweap, Hermit, and Redwall Formations. In terms of the model, the westward deflected flow paths enter the fault zones and find high capacity routes downward; therefore, the flow moves vertically downward in the fault zone.

Ground water circulation below the Aubrey Group is principally confined to secondary channels such as fractures and solution openings because the primary permeabilities of these underlying units are very small. Water entering fracture zones in these units seeks outlets at lower elevations such as the deep canyons of Tapeats Amphitheater. The Muav
Fault in Big Saddle is the most important ground water conduit in the lower Paleozoic section because it severely fractures the section and is laterally extensive. Because this fault extends northward from Big Saddle for 24 miles, it creates an enormous line sink for westward flowing water. Also, a small amount of water in the Kanab Plateau to the west drains toward the fault. This quantity of water is smaller than the flow from the Kaibab Plateau because there is less water available on the Kanab Plateau due to lower rainfall and the westward dip of the rocks opposes eastward deflection of flow.

The implications of circulating ground water in the Muav Fault are great because the fault allows water to drain deeply into the Paleozoic section below the Redwall Limestone and it turns the flow from west to south, a full 90 degrees. The curious fact remains that although the Muav Fault is a major conduit, no water discharges from it in Tapeats Canyon. Rather, the water appears at Thunder and Tapeats Springs to the west.

The writer postulates that the Muav Fault is hydrologically connected to the Tapeats and Thunder structures by northeast trending fractures. Although the northeast trending faults die out against the dominant north-south structures of Tapeats Fault, Muav Fault, and Crazy Jug Monocline, the northeast structures have fractured the rocks beyond the point where their displacements die out. Consequently, the
faults continue as fracture zones for some distance toward the northeast. Evidence supporting this argument is found in the Aubrey Group of Deer Basin where the Sinyala Fault dies out. Although there is no visible displacement, the Aubrey Cliffs have been cut deeply by erosion where the trace of the Sinyala Fault would pass. This notch indicates fracture weakening of the section beyond the northeastward limit of the Sinyala Fault displacement.

The brittle limestones underlying the Aubrey Group are far more sensitive to stress and fractures in these units are undoubtedly propagated for miles beyond the limits of fault displacements. It is entirely conceivable that many of the northeast trending faults whose displacements die out in the Tapeats-Deer area continue to the northeast as fractures at least as far as the Muav Fault. Such shattered zones in the Redwall, Temple Butte and Muav Limestones would enhance the permeability of these units substantially. Ground water circulation along these fractures from sources along the Muav Fault to the deep canyons would gradually dissolve conduits and further increases the transmission capacity of the minor intersecting structures. Through such a tectonic fabric, the northeast trending structures would hydrologically connect the Muav Fault to the Tapeats and Thunder Faults to the west.

Water quality data indicates that Thunder and Tapeats spring water is almost identical, so it is assumed that these two springs are hydrologically related and their water
originates from the same source. As the Muav Fault is the only structure with sufficient continuity to collect the quantity of water that discharges from these karst springs, it is concluded that a hydrologic connection exists between the Thunder and Tapeats Faults and the Muav Fault; however, a structural connection cannot be proven from evidence on the Kaibab Plateau. If Thunder Fault continues northeastward past Bridger's Knoll as a fracture in the lower limestones, it would form a hydrologic connection with Tapeats Fault. Likewise, Thunder Fault or any other northeast trending fracture could hydrologically connect Tapeats Fault to the Muav Fault. Pirating of the water from the Muav Fault probably occurs within 10 miles of the present canyon rim because several northeast fractures can exist in this region by extension of known faults in the Tapeats-Deer area.

Chemical quality data collected from the Deer Canyon springs indicates that they are not directly connected to the Thunder-Tapeats system. It is possible that at least a small portion of the Deer Canyon water may be derived from the Muav Fault because the northeast trending Deer Fault may connect the systems. Most likely though, the Deer Canyon springs derive most of their water from the Kanab Plateau in the region north of Deer Basin through a karst drainage system very similar but smaller than the Thunder-Tapeats system.
Evolution of the Present Ground Water System

In the Tapeats Amphitheater and Deer Basin certain pertinent questions can be answered if time is rolled back and the evolution of the ground water system is observed. Among these questions are: (1) why do the springs occur at their present locations and elevations, and (2) why are there no large karst springs discharging from the Muav Fault Zone at the head of Tapeats Canyon? The answers to these questions can be best formulated by considering the basic hydrologic properties of the Paleozoic system and the differing effects on ground water circulation as the Tapeats Amphitheater and Deer Basin were eroded into this system.

Late Cretaceous Period

Prior to the Laramide structural developments in the early Cenozoic Era, the Tapeats-Deer area lay buried under approximately 1000 to 3000 feet of Cretaceous rock and 3000 to 5000 feet of Triassic and Jurassic rocks. The top of this Mesozoic cover, from 4000 to 8000 feet thick, was slightly above sea level and had a gentle eastward dip (McKee, Wilson, Breed and Breed 1967). It is obvious that the Paleozoic section was dormant hydrologically because of its low elevation, thick cover and insignificant gradient.

Early Cenozoic Era

The Laramide structural developments produced north-south trending monoclines including both the East Kaibab
Monoclinal of the eastern Kaibab region having 3000 feet of
displacement and the Crazy Jug Monocline of the Tapeats-Deer
area having over 500 feet of displacement. Both of these
structures lifted the land surface progressively higher to
the west a combined total of some 3500 feet. Monoclines
lying further to the east lifted the region even higher.
Consequently, surface drainage was probably eastward off the
Kanab Plateau in the Tapeats-Deer area and the younger Mesozoic rocks were starting to erode. As yet, there was no significant ground water circulation in the Paleozoic sediments because no outlets for this water were developed through the still thick overlying Mesozoic sediments.

Faulting in the Tapeats-Deer Area

Following the monoclinal uplifts of the Laramide, normal faulting occurred in the Tapeats-Deer area. The Muav Fault along the Crazy Jug Monocline dropped the western limb a vertical distance equivalent to but opposite in sense to the monoclinal flexure of about 500 feet. Tapeats Fault probably originated during this tectonic pulse and possibly the minor northeast-southwest trending faults of the western portion of the area. The exact dates of the faults remain unknown but they may have occurred with the culmination of the Laramide in the late Palocene or followed the Laramide during the Eocene. By this time the Kaibab Plateau was fully uplifted and a gentle, westward regional tilt was imposed on the Tapeats-Deer area. The Mesozoic cover was being
removed rapidly. Ground water circulation was active in the Mesozoic rocks above the Paleozoic section but the Paleozoic system remained hydrologically dormant.

Hualapai Drainage in the Tapeats-Deer Area

To the west of the Tapeats-Deer area, topographic lows had been developing since the Mesozoic and the original eastward drainage on the Mesozoic cover was turned westward subsequent to the rise of the Kaibab Plateau and development of the Muav Fault. As the Hualapai drainage system developed to the west, tributaries flowing westward off the Kanab and Kaibab Plateaus rapidly stripped the Mesozoic cover from the Tapeats-Deer area. A major stream, that was to become the present Colorado River, was actively cutting its canyon in a wide northward arc that turned west immediately south of the Tapeats-Deer area. A stream flowing westward off the Kaibab Plateau, later to become Tapeats Creek, joined this major stream somewhere over the present mouth of Deer Canyon. Simultaneously these streams started to dissect the Paleozoic rocks. When the Mesozoic cover was finally breached, the upper Paleozoic section became hydrologically active. To be sure, this circulation was modest and consisted of seepage of ground water along beds and joints to the deeper canyons cut into the upper Paleozoic limestones. Due to the regional dip, ground water movement was primarily toward the west as exits formed through the overlying Mesozoic strata. The lower limestones of the Paleozoic section were not affected
and ground water lay dormant waiting for the time when the Hermit and Supai formations would be breached.

Development of the Modern Colorado River and Headward Erosion of Tapeats Creek

By the end of the Miocene, the Mesozoic cover was probably removed from the Tapeats-Deer area and by the late Pliocene the Colorado River had eroded headward through the Kaibab Plateau and captured large surface discharges from the areas to the east. With the additional water from the east, the erosive power of the Colorado River was sufficiently enhanced that it entrenched rapidly into the Paleozoic section near the Tapeats-Deer area leaving the dryer, slower cutting Tapeats Creek drainage system hanging in elevation above the Colorado River Gorge. By this time, the Tapeats drainage system was probably entrenching the lower Aubrey Group. Now that the local base level, determined by the Colorado River, was lowered rapidly below the Aubrey Group, the Tapeats system discharged into the Colorado River over high cliffs formed in the lower limestones. Consequently the lower limestone cliffs retreated headward up Tapeats Canyon east of Deer Canyon exposing first Deer Fault and then Thunder Fault. When these faults were laid open, ground water circulation at last commenced through the lower limestones. At first a very small amount of water seeped along the fracture zones but the quantity continually gained impetus as solution channels rendered the fracture zones more permeable. Ground
water discharge from these young springs aided erosion in
downstream Tapeats Canyon, helping it to carve a deep, narrow
gorge that was probably cut between the present Cogswell
Butte and the Redwall Cliffs that form the northern wall of
Surprise Valley.

Ground water circulation approached the system present
today; however, Tapeats Fault was late in being exhumed. As
Tapeats Fault was uncovered after Thunder Fault, the Thunder
system carried the larger of the discharges. This follows as
the permeability along the small Thunder fracture had a
longer time to be enhanced by solution because water circu-
lated along this fault for a longer time. However, Tapeats
Fault was a larger structure and disturbed the rocks to a
greater extent than Thunder Fault. As a result, solution
channels developed readily and through time the Tapeats Cave
system has become dominant.

Location of Caves at the Base of the Lower Paleozoic
Limestones

A pre-Supai karst system is known to have existed in
the upper levels of the Redwall Limestone in many portions of
the Grand Canyon (McKee in Preparation). Evidence of it is
found in the headward areas of a few canyons in the Tapeats-
Deer area but this system is independent of the present karst
drainage network. All caves associated with the present
system are located at the base of the Muav Limestone along
fault zones. The question is raised: why were successive
levels of caves not developed at various levels along the faults as the canyons dissected the limestones?

The answer to this question can be found by contrasting the mechanism by which the Colorado River has eroded its canyon versus the headward erosion of its tributaries. The Colorado River entrenched rapidly through the lower limestones by cutting them parallel to the bedding. Along the Colorado River caves and springs, such as those in Vasey's Paradise east of the Kaibab Plateau, do in fact occur as successive levels as the elevations of the springs attempt to keep pace with the vertical rate of erosion of the canyon (Lange 1956). In the side canyons, such as in the Tapeats and Deer area, stratification of caves is not the case. Unlike the Colorado River, the side canyons erode headward in a step-bench manner. As a group, the lower Paleozoic limestones act as a single resistant step and the underlying Bright Angel Shale as a bench. Consequently, as side canyons erode headward, the entire thickness of the limestones is attacked laterally along a vertical face.

In the case of canyons that erode headward across vertical faults, the entire fault zone from the top to the bottom of the lower limestones is exposed in a relatively short time. Circulation of ground water along the permeable fault zones finds exits at the lowest possible elevation. Consequently, in headward eroding side canyons, water can escape from the base of the lower limestones as soon as the
faults are exposed, whereas along the Colorado River spring
elevations in fault zones are determined by the successive
depths of the canyon. In tributary canyons, such as Tapeats
Canyon which cut headward across vertical fault zones, water
escaped from the base of the limestones and caves formed at
these lowest levels only.

Surprise Valley Collapse

Sometime during the period when Thunder and Tapeats
Springs were developing, the north walls of old Tapeats Can-
yon collapsed in a line running from a point east of Thunder
Spring past Deer Spring and west along the Colorado River.
The amount of lubrication the developing karst springs pro-
vided for these landslides is unknown but the collapsed zone
profoundly modified the topography and location of the
springs. With Surprise Valley effectively dammed, Tapeats
Creek was apparently diverted through a topographic low to
the south and discharged into the Colorado River some 3 to 4
miles east of its old mouth. The outlet of Deer Creek was
also sealed. Having no place to discharge, Deer Creek was
forced to breach the debris and exit southward into the
Colorado River 3 miles downstream from the new outlet of
Tapeats Creek.

Not only were the canyons rearranged by the collapse,
but Thunder and Deer Springs were forced to relocate because
the original spring sites were sealed by debris in the Sur-
prise Valley Slip Planes. The Thunder water chose a series
of easterly and southerly channels along stressed joints parallel to the Surprise Valley Slip Plane and slip planes parallel to the Thunder Fault. At first, the new spring must have been dislocated slightly up dip along the Muav Limestone-Bright Angel Shale contact about 1/2 mile east of the Thunder Fault. A new set of solution tubes developed rapidly and formed most of the cave known today. As Tapeats Creek dissected the eastern part of the Surprise Valley Slump mass, the Thunder Spring water eroded a canyon headward to the west. As westward entrenchment proceeded in Thunder Canyon, joints connecting it with the eastward trending stream passage successively pirated water to the south. Because pirating continued in a westward sense, the eastern passages dried up. This explains the dry east-west passage parallel to the present cliff face and the many small, dry, southward trending solution tubes connecting this passage to the cliff face in the wall east of the present spring.

At Deer Fault, blockage of the original spring forced the water to seek outlets in Deer Canyon slightly to the west and down dip. The water flowing along Deer Fault found new exits to the present Deer and Vaughn Springs through east-west trending fracture zones parallel to the slip planes of the Surprise Valley Slump. The rate of solutional enlargement of the new outlet channels at Deer and Vaughn Springs has been slower than at Thunder Spring because the quantity of water discharging from Deer Fault through these fractures
has not been as great as the discharge through the Thunder system.

Present System

Within very recent time, the Muav Fault has been exhumed by Tapeats Canyon below the Redwall Limestone. There are no springs here at this time even though this spring has created a wide permeable zone and is undoubtedly a major hydrologic conduit north of Tapeats Canyon. The writer feels that springs do not exist along the Muav Fault in Tapeats Canyon because the fault was uncovered very late after the Thunder and Tapeats systems had developed. Consequently, the present hydraulic gradients north of the Tapeats Amphitheater favor flow toward the pipe-like karst drainage system already emplaced along the Thunder and Tapeats fracture zones.

Future Evolution of the System

It is interesting to speculate on the evolution of the karst flow system as canyon erosion progresses. Deer and Tapeats Canyons have permanently defined their downstream courses through the slump zones. It can be assumed that these canyons will persist as long as another land collapse does not occur.

Vaughn Spring is already losing its influence as a water discharge point to Deer Spring which is pirating water from a point further upstream along Deer Fault. Since Deer Spring lies in a more favorable down gradient location and it
flows continuously versus the ephemeral flow of Vaughn Spring, it will eventually dissolve caves large enough to carry the entire flow of water in Deer Fault and Vaughn Spring will be left as a dry remnant.

Thunder Spring is actively cutting its canyon headward to the west along the flank of the Surprise Valley Slip Plane. As the canyon cuts westward, water finds exits to the south further down dip through joints that connect the east-west trending passages to the cliff face. In time, Thunder Spring will make its way back to Thunder Fault and will aid headward erosion northeastward into the lower Paleozoic limestones along the Thunder Fault Zone.

Tapeats Spring is already helping to cut a north trending canyon along Tapeats Fault. As the exact hydrologic relationship between Thunder and Tapeats Springs is not well defined where they pirate water from the Muav Fault, nothing can be said regarding dominance of one spring over the other, should this occur.

Headward erosion of Crazy Jug Canyon has begun along the shattered zone created by the Muav Fault. Also, the eastward dip of the flank of the Crazy Jug Monocline in the area insures the continued presence of canyons along the fault. If the youthful Crazy Jug Canyon can become a major topographic feature, it may be able to erode far enough north past Big Saddle to recapture the ground water presently flowing southward along the fault but pirated to the southwest
by Tapeats and Thunder Springs. If this ever occurs, Crazy Jug Canyon will develop large karst springs and will eventually capture all of the Thunder and Tapeats water that it rightfully claims, leaving Thunder and Tapeats Caves as passed-by suitors of the Muav Fault waters.
LIST OF REFERENCES


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123


KARSTIC GROUND WATER CIRCULATION AND POTENTIAL POLLUTION PROBLEMS IN THE PALEOZOIC CARBONATE ROCKS OF THE TETON RANGE, GRAND TETON NATIONAL PARK, WYOMING

A Proposal Submitted to the Yellowstone Environmental Council

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Project Duration

May 20, 1975 through May 31, 1976

Objective

The objective of the proposed study is to acquire sufficient geologic and hydrologic data to permit construction of a complete description of ground water circulation through the karstified Paleozoic limestones that lie within and along the western and south-western boundaries of the Grand Teton National Park. These data will be used to determine the directions and rates of ground water flow through the limestones so that the impacts on the National Park resulting from possible ground water pollution arising from recreational and commercial development in the vicinity can be accurately predicted.

Location

Figure 1 shows the proposed study area, which includes 110 square miles of the Teton Range between Rendezvous Peak on the south and Teton Canyon on the north. The proposed area encompasses the southwest quarter of the Grand Teton National Park and adjacent portions of the Bridger-Teton and Targhee National Forests.

The project will be administered through the Department of Geology at the University of Wyoming. The Wyoming Water Resources Research Institute has agreed to provide the project with office space, secretarial support, and essential field and laboratory facilities. Field camps, established in the study area, will be consistent with standard National Park and National Forest policies.
Introduction

The study area lies entirely within the Middle Rocky Mountain physiographic province (Fenneman, 1931) and is characterized by mountainous uplifts with intervening intermontane downwarps. The Teton Range lies between the Jackson Hole downwarp to the east and the Teton Basin to the west. The Teton Mountains are a Basin and Range type structure that consist of an asymmetric fault block uplifted along the eastern margin. The range has a crystalline Pre-Cambrian core and is flanked on the west by low dipping Paleozoic and younger strata (Horberg and Fryxell, 1942; Edmund, 1951; Bradley, 1956). In addition, isolated exposures of faulted sedimentary rocks crop out along the eastern flank of the range.

Stratigraphy

Over 10,000 feet of Paleozoic, Mesozoic, and Tertiary sediments are present in the study area. The carbonate rocks of interest to this study occur only in the Paleozoic sequence which is summarized in Table 1.

Structural Geology

Structural deformation in the Teton Range is dominated by major north-trending normal and reverse faults, and a few minor thrust faults. Large scale folds occur in the northern and southern parts of the range; however, stratigraphic dips are toward the west throughout most of the area.

The dominant structure in the region is the Teton Fault, an arcuate, high-angle normal fault that bounds the Teton Range to the east. This fault has been traced over 40 miles and has as much as
<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
<th>Thickness (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphoria Formation</td>
<td>non-resistant series of silty sandstones, phosphatic shales, cherty limestone at top (Sheldon, 1956).</td>
<td>200</td>
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<tr>
<td>(Permian)</td>
<td></td>
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<tr>
<td>Tensleep Formation</td>
<td>calcareous, fine-grained massive quartzitic sandstone, with interbedded arenaceous limestone and dolomites. Forms massive cliffs. (Branson 1939, Williams, 1948, Bachrach, 1956).</td>
<td>800</td>
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<tr>
<td>(Pennsylvanian)</td>
<td></td>
<td></td>
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<tr>
<td>Amsden Formation</td>
<td>interbedded calcareous shales, crystalline dolomitic limestones, and sparse, thin calcareous sandstones, underlain by basal quartzitic, cross bedded sandstone, generally covered (Branson, 1939; Williams, 1948; Bachrach, 1956).</td>
<td>350</td>
</tr>
<tr>
<td>(Pennsylvanian)</td>
<td></td>
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<tr>
<td>Madison Formation</td>
<td>thin-bedded limestone with sparsely intercalated thin shales, forms massive cliffs, cavernous limestone exhibiting numerous filled channels and solution features (Peale, 1893; Sloss and Hamblin, 1942; Richards, 1955; Roberts, 1966; Sando, 1974).</td>
<td>1110</td>
</tr>
<tr>
<td>(Mississippian)</td>
<td></td>
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<tr>
<td>Darby Formation</td>
<td>thin-bedded dolomite and limestone with intercalated calcareous shales, forms slopes (Wanless, Belknap, and Foster, 1955; Andrichuk, 1956).</td>
<td>350</td>
</tr>
<tr>
<td>(Devonian)</td>
<td></td>
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<tr>
<td>Bighorn Formation</td>
<td>highly jointed massive to thin-bedded fine-grained siliceous dolomite, dense, brittle, with pitted surface, cavernous, forms prominent cliffs (Blackwelder, 1913; Miller, 1930).</td>
<td>450</td>
</tr>
<tr>
<td>(Ordovician)</td>
<td></td>
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<tr>
<td>Gallatin Formation</td>
<td>massive limestone at base grading upward into thin-bedded limestone, intercalated thin-bedded, soft shales (Miller, 1936).</td>
<td>180</td>
</tr>
<tr>
<td>(Cambrian)</td>
<td></td>
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<tr>
<td>Gros Ventre Formation</td>
<td>at top, soft shales with beds of pebbly limestone and intraformational breccia, largely covered, in middle, two massively-bedded, cliff-forming cavernous limestone (Death Canyon limestone) separated by 15 ft. of shales, lower units are soft arenaceous shales with thin beds of argillaceous sandstone (Miller, 1936).</td>
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<tr>
<td>(Cambrian)</td>
<td></td>
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<tr>
<td>Flathead Formation</td>
<td>sandstone with thin beds of arenaceous shales, intercalated thin beds of quartzite (Miller, 1936).</td>
<td>175</td>
</tr>
<tr>
<td>(Cambrian)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
30,000 feet of displacement (St. John, 1879; Blackwelder, 1915; Fryxell, 1930; Horberg, 1938; Edmund, 1951; Love, 1956; Love and others, 1972). Activity on the structure reached a maximum in Pliocene or early Plistocene time; however, small scarps along the fault displace Pinedale glacial deposits and demonstrate continuing tectonic activity (Fryxell, 1938; Love and Montagne, 1956).

Numerous major and minor faults exist in the study area in addition to the Teton Fault and are described in Weed and Iddings (1899), Blackwelder (1915), Horberg (1938), Edmund (1951, 1956), Love (1954, 1972), and Love and Montagne (1956). Faulting subsidiary to the major north-trending structures is particularly pronounced in the northern and southern parts of the range. However, Figure 2 illustrates that lesser structures occur throughout the region and even the stable central part of the range has experienced deformation.

Because the interstitial permeabilities of the Paleozoic rocks in the study area are generally small, tectonic structure is extremely important in delineating zones of large permeability. This results because the fractures provide zones of large permeability that facilitate ground water circulation. Consequently, comparison of figures 2 and 3 illustrates a close correlation between the known karst features and local structural elements.

Ground Water Circulation

An extensive and very active karst topography occurs on all the major exposed carbonates in the Teton Range. The karst is especially pronounced in the outcrops of the Madison and Death Canyon limestones,
Figure 2. Major structural elements taken from ERTS imagery in the proposed study area and adjacent parts of the Teton Range.
EXPLANATION

- **Sinking Stream, symbol points in direction of subsurface flow**
- **Flow path verified from dye trace**
- **Mapped cave**
- **Karst spring**
- **Structurally controlled subsurface drainage systems**

**Figure 3.** Location of known karst features in the study area.
and the Bighorn Dolomite. Terrane underlain by these rocks in the study area is characterized by sinking streams, dolines, karren, caverns containing underground streams, and numerous limestone springs. Preliminary examination of the cavern systems in the area by the co-investigator indicates that karst systems of different geologic ages exist in the region and range from Mississippian to Holocene in age.

The morphology of the karst in the study area was examined by the co-investigator during the summer field seasons of 1972, 1973, and 1974. Several dye tracings using Rodamine-B and Flourescein dyes were conducted and lead to the identification of 4 principal types of subsurface karstic circulation systems: (1) flow concordant with the stratigraphic dip, areas A and B of figure 3, (2) flow across the stratigraphic dip, area C, (3) flow along the strike of regional structures, area E, and (4) fault or fracture controlled circulation, areas D and F. Travel times observed during the tracings were as rapid as free flowing surface streams.

The significance of the tracings conducted to date is that the ground water flow through the karst systems is usually independent of surface topography and drainage patterns and the response times observed demonstrate open channel flow within the ground water system (see figure 3). Both of these factors are of prime concern with regard to the movement of pollutants in the region. It is obvious that if man-made or natural waste is generated in a given drainage basin, it will more than likely reappear miles away in a totally different drainage basin. Because the travel times are small, the pollutant will be transmitted intact through the karst systems in a
very short period of time. Much of the water in these systems originates on National Forest lands but discharges through springs into Grand Teton National Park.

Methodology

The proposed study is a field research project that will involve the collection of geologic and hydrologic data. Data that will be collected will include but not be limited to:

A. Geologic data:

1. aerial inventory of the location and lithology of the carbonate rocks that crop out in the study area,
2. location of all principal tectonic structures in the study area including faults and folds,
3. stratigraphic thicknesses, and
4. geologic data that can be used to differentiate relative ages of specific karst systems inventoried.

B. Hydrologic data:

1. location of the principal karst features including sinking creeks, extensive cavern systems, and major limestone springs,
2. tracings of subterranean streams using dye tests to verify interconnection between karstic elements and determine response rates,
3. spot measurements of stream losses and spring discharges,
4. selected chemical sampling where appropriate,
5. inventory of contributing areas to specific karst features, and
6. inventory of the geologic controls that influence the development of the karst systems observed.

These data will be collected simultaneously, region by region as the field season proceeds. Preliminary aerial reconnaissance using aircraft
and satellite imagery will be used to identify fruitful areas of field research. Once promising field sites are selected, ground inventories will be conducted that will utilize existing published data and interpretations.

An effort is being made to secure thermal infra-red imagery for the study area either through the National Park Service or the National Forest Service. Such coverage has been proved invaluable for identifying and differentiating karstic features due to the contrast between rock and subsurface water temperatures. The utility of thermal infra-red photography to this study are obvious. However, such coverage is not absolutely essential for the execution of this proposal and consequently the ultimate success of the study is not contingent upon obtaining it.

Data Presentation

The primary product of this study will be a Master's thesis prepared by the co-investigator that is designed to fulfill the thesis requirements for a Master of Science degree with an emphasis on ground water for the Department of Geology, University of Wyoming. The results of the study will also be sufficiently significant to warrant publication in a national level geologic or hydrologic journal.

Because much of the data that will be generated is planimetric in nature, all maps prepared for this study will be compatible with the U. S. Geological Survey 7.5 minute base maps available for the area. This base may be enlarged to a suitable scale if required for accurate presentation of the data.
Justification

Information gained through this study will benefit the National Park Service because directions, rates, and flow characteristics of ground water circulation will be documented. These data can be used to evaluate directly the potential environmental impacts arising from recreational or commercial facilities developed on the limestone terranes either in or adjacent to the Park.

When this study is completed, the National Park Service and National Forest Service will have sufficient information on the ground water hydrology in the study area that these data can be incorporated directly into both planning and management operations. For example, this project will provide significant information on potential safe water supplies that may be needed as the park grows.

At the present time very little information is available on the ground water hydrology within the Grand Teton National Park and little is published on the spectacular cavern systems that exist in the Teton Range. Substantial information on both of these topics will accrue directly from this study and can be synthesized by the interpretive staff of the Park Service for presentation to the public. Because the Teton carbonates contain one of the most extensive alpine karst systems in the continental United States, many speleological depth and distance records remain to be broken as exploration of the Teton karst systems proceed.
SELECTED REFERENCES


