GEOLOGY AND GEOCHEMISTRY OF THE
COLT MESA COPPER DEPOSIT,
CIRCLE CLIFFS AREA, UTAH

by
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A thesis submitted to the faculty of the
University of Utah in partial fulfillment of the requirements
for the degree of

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in
Geology

Department of Geology and Geophysics
University of Utah
August 1975
SUPervisory Committee Approval

of a thesis submitted by

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I have read this thesis and have found it to be of satisfactory quality for a master's degree.

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<table>
<thead>
<tr>
<th>TABLE OF CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LIST OF FIGURES</strong></td>
</tr>
<tr>
<td><strong>ABSTRACT</strong></td>
</tr>
<tr>
<td><strong>INTRODUCTION</strong></td>
</tr>
<tr>
<td><strong>GENERAL GEOLOGY</strong></td>
</tr>
<tr>
<td><strong>URANIUM MINERALIZATION</strong></td>
</tr>
<tr>
<td><strong>COLT MESA COPPER DEPOSIT</strong></td>
</tr>
<tr>
<td><strong>GEOCHEMISTRY</strong></td>
</tr>
<tr>
<td><strong>ORIGIN OF COPPER AND URANIUM</strong></td>
</tr>
<tr>
<td><strong>CONCLUSIONS</strong></td>
</tr>
<tr>
<td><strong>BIBLIOGRAPHY</strong></td>
</tr>
</tbody>
</table>
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Index map of Circle Cliffs area, Utah</td>
<td>2</td>
</tr>
<tr>
<td>2.</td>
<td>Partial stratigraphic section of the Circle Cliffs area, Utah</td>
<td>5</td>
</tr>
<tr>
<td>3.</td>
<td>Geologic map of the Circle Cliffs area, Utah (after Davison, 1967)</td>
<td>6</td>
</tr>
<tr>
<td>4.</td>
<td>Diagram of Chinle-Moenkopi contact, Circle Cliffs area, with Shinarump Member channel deposits superimposed (adapted from Davison, 1967)</td>
<td>8</td>
</tr>
<tr>
<td>5.</td>
<td>Distorted bedding in the Shinarump Member of the Chinle Formation</td>
<td>9</td>
</tr>
<tr>
<td>6.</td>
<td>The Wingate, Chinle, and Moenkopi formations, near Colt Mesa, Circle Cliffs area, Utah</td>
<td>11</td>
</tr>
<tr>
<td>7.</td>
<td>View from west of Colt Mesa mine, Circle Cliffs area, Utah</td>
<td>15</td>
</tr>
<tr>
<td>8.</td>
<td>Gallows of Moenkopi Formation in Shinarump Member channel deposits, Colt Mesa</td>
<td>16</td>
</tr>
<tr>
<td>9.</td>
<td>Diagrammatic cross-section, Colt Mesa copper deposit, Circle Cliffs area, Utah</td>
<td>17</td>
</tr>
<tr>
<td>10.</td>
<td>Map of Colt Mesa Mine with sample localities</td>
<td>18</td>
</tr>
<tr>
<td>11.</td>
<td>Atomic absorption analyses of selected samples, Colt Mesa Mine, Utah (analyses by Rocky Mountain Geochemical Corp.)</td>
<td>20</td>
</tr>
<tr>
<td>12.</td>
<td>Photomicrograph of chalcopyrite (yellow) and sphalerite (grey) surrounding the detrital quartz and feldspar grains (times 250)</td>
<td>21</td>
</tr>
</tbody>
</table>
13. Photomicrograph of chalcopyrite surrounded by digenite (blue) and covellite (red) (times 1,000, oil emersion) ........ 23

14. Copper carbonate stains on outcrop of Shinarump Member, Colt Mesa, Utah ........ 25

15. Table of characteristics shared by Colt Mesa Copper deposit and uranium deposits of the Circle Cliffs area, Utah ........ 27

16. The Cu-Fe-H$_2$O-S system, 25°C, 1 atm, total dissolved sulfur species = 10$^{-4}$, activity of ions in solution = 10$^{-6}$. Fields of solid iron compounds are omitted (adapted from Garrels and Christ, 1965) .......... 30

17. The U-H$_2$O-CO$_2$ system, 25°C, 1 atm, PCO$_2$ = 3.4, activity of ions = 10$^{-6}$ (Hostetler and Garrels, 1962) ................. 31

18. The V-H$_2$O system, 25°C, 1 atm, activity of ions = 10$^{-6}$ (Hostetler and Garrels, 1962) .............. 31

19. The Zn-H$_2$O-S-CO$_2$ system, 25°C, 1 atm, total dissolved sulfur species = 10$^{-4}$, PCO$_2$ = 10$^{-3.4}$, activity of ions in solution = 10$^{-6}$ ...................... 32

20. The Pb-H$_2$O-S-CO$_2$ system, 25°C, 1 atm, total dissolved sulfur species = 10$^{-4}$, PCO$_2$ = 10$^{-3.4}$, activity of ions in solution = 10$^{-6}$ ...................... 32

21. The Co-H$_2$O-S-CO$_2$ system, 25°C, 1 atm, total dissolved sulfur species = 10$^{-4}$, PCO$_2$ = 10$^{-3.4}$, activity of ions in solution = 10$^{-6}$ ...................... 33

22. The Ni-H$_2$O-S-CO$_2$ system, 25°C, 1 atm, total dissolved sulfur species = 10$^{-4}$, PCO$_2$ = 10$^{-3.4}$, activity of ions in solution = 10$^{-6}$ ...................... 33

23. The Mo-H$_2$O system, 25°C, 1 atm, total dissolved sulfur species = 10$^{-4}$, activity of ions in solution = 10$^{-6}$ ...................... 34
The Ag-H$_2$O-S system, 25°C, 1 atm, total dissolved sulfur species $= 10^{-4}$, $P_{CO_2} = 10^{-3.4}$, activity of ions in solution $= 10^{-6}$. 

\[ \text{Page 34} \]
ABSTRACT

The Colt Mesa copper deposit, Circle Cliffs area, Utah, is located at the contact of a paleochannel deposit of the Shinarump Member of the Chinle Formation and the underlying Moenkopi Formation. The ore body is tabular in form and is composed of chalcopyrite, bornite, digenite covellite, and chalcocite. Minor amounts of zinc, lead, cobalt, nickel, molybdenum, uranium, vanadium and silver are associated with copper mineralization. The Colt Mesa deposit is genetically similar to uranium deposits in the Circle Cliffs area.

The ore fluid was a low temperature, dilute aqueous medium such as groundwater. All of the elements enriched in the ore zone are soluble at low concentrations in an oxidizing, neutral to slightly acid environment. Precipitation of ore elements as sulfides was caused by a decrease in the Eh of the ore solution. The greater range of solubility of uranium indicates that it can remain in solution after the precipitation of copper.
INTRODUCTION

Strata-bound copper, uranium, and vanadium deposits in sandstone are a distinctive and important class of ore deposits in Triassic and Jurassic rocks of the Colorado Plateau. The dominant elements associated in such deposits are (1) copper, (2) copper-uranium, (3) uranium, (4) uranium-vanadium, and (5) vanadium. The Colt Mesa deposit is an example of the first of these categories. This report is (1) a description of the geology of the Colt Mesa deposit, and (2) an evaluation of the geochemistry of ore solutions responsible for such deposits.

The Colt Mesa mine is located in the southwestern part of the Circle Cliffs area, Utah (Figure 1), approximately 50 miles southwest of Hanksville, Utah, and 35 miles south-east of Boulder, Utah (T. 35S., R. 7-8E.). The deposit was discovered by Mr. Butch Bullard of Hanksville, Utah, in the spring of 1968. The Colt Mesa mine was opened in 1971 and was operated intermittently until 1974. A lack of readily available water for the mill plant forced the owners to temporarily call a halt to mining.

Field work in the area was done in the summer and fall of 1974 and the spring of 1975. The author was assisted by Mr. Ronald Collings, a student at the University of Utah.
Figure 1. Index map of Circle Cliffs area, Utah.
Mr. Butch Bullard was very generous with information concerning the operation of the Colt Mesa mine. The author wishes to thank Dr. William T. Parry, William Tafuri, and Lawrence Wender of the University of Utah, and James Hindman and Eric Cather of the United States Bureau of Mines, the employees of Exxon Co., U.S.A. and Mountain Fuel Company for their advice and cooperation.
GENERAL GEOLOGY

The geology of the Circle Cliffs area has been described by Davidson (1967) in a comprehensive study conducted on behalf of the United States Atomic Energy Commission. The following brief discussion is a summary of the general geology of the area based upon field work done by the author and from Davidson (1967).

Rocks of Permian, Triassic and Jurassic age are exposed in the breached Circle Cliffs anticline. A partial stratigraphic section of the formations exposed in the area is shown in Figure 2. The oldest strata outcropping in the area is the Permian White Rim Sandstone. This formation is overlain by the Kaibab Limestone which is also Permian. These units are exposed in canyons of the Circle Cliffs area (Figure 3).

The Moenkopi Formation of Early Triassic age outcrops in the floor of the breached anticline. The Moenkopi is a dark red-brown to yellow-tan siltstone and mudstone with minor beds of sandstone. It contains dolomitic beds and nodules and stringers of dolomite. The Moenkopi Formation in many places is altered to a yellow-gray or pale green five to ten feet below the contact with the overlying Chinle Formation.
<table>
<thead>
<tr>
<th>System</th>
<th>Series</th>
<th>Group, formation and member</th>
<th>Thickness (ft)</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jur. - Triassic</td>
<td>Glen Canyon Gp.</td>
<td>Navajo Sandstone</td>
<td>950-1400</td>
<td>sandstone; white to tan, crossbeds</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kayenta Formation</td>
<td>250-400</td>
<td>siltstone and sandstone; red-brown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wingate Sandstone</td>
<td>230-350</td>
<td>sandstone; tan to light orange, cliff-forming</td>
</tr>
<tr>
<td>Upper Triassic</td>
<td>Church Rock Member</td>
<td></td>
<td>0-25</td>
<td>sandstone; orange-brown</td>
</tr>
<tr>
<td></td>
<td>Owl Rock Member</td>
<td></td>
<td>150-250</td>
<td>sandstone and mudstone; red-brown</td>
</tr>
<tr>
<td></td>
<td>Petrified Forest Member</td>
<td></td>
<td>150-350</td>
<td>mudstone and siltstone; variegated, bentonitic</td>
</tr>
<tr>
<td></td>
<td>Monitor Butte Member</td>
<td></td>
<td>100-200</td>
<td>siltstone, mudstone and sandstone; gray-green to tan, fine-grained, micaceous</td>
</tr>
<tr>
<td></td>
<td>Shinarump Member</td>
<td></td>
<td>0-250</td>
<td>sandstone, siltstone, and conglomerate; gray-green to tan, crossbeds, carbonaceous material, uranium deposits</td>
</tr>
<tr>
<td></td>
<td>Unconformity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle and Lower Triassic</td>
<td>Moenkopi Formation</td>
<td></td>
<td>200-600</td>
<td>siltstone, sandstone, and mudstone; red-brown to yellow-gray, thin-bedded, locally petrolierous</td>
</tr>
</tbody>
</table>

Figure 2. Partial stratigraphic section of the Circle Cliffs area, Utah.
Figure 3. Geologic map of the Circle Cliffs area, Utah (after Davison, 1967).

Explanation

- **GCGp** Glen Canyon Group
- **TrC** Chinle Formation
- **TrM** Moenkopi Formation
- **Pf** Permian Formations
- **Fault**

Scale: 1:250,000

5 miles
The Late Triassic Chinle Formation is subdivided into, in ascending order, the Shinarump, Monitor Butte, Petrified Forest, Church Rock and Owl Rock members. The Shinarump Member of the Chinle is a white to tan, medium-grained, poorly sorted, feldspathic and micaceous sandstone, conglomerate and siltstone. The majority of matrix present in the Shinarump is kaolinite (Schultz, 1963). The sandstone is generally massive or contains trough crossbedding. The unit contains sparse to abundant organic material in the form of logs, twigs, and disseminated organic debris.

The Shinarump is a fluvial deposit partly composed of channel sandstones and conglomerate deposited in scours cut into the underlying Moenkopi Formation. Because of these channel deposits the Shinarump is highly variable in thickness. The geometry of the Shinarump trunk channel sands in the Circle Cliffs area is shown in Figure 4. Paleocurrent directions recorded in the Shinarump channel sandstones are overlain and flanked by thin bedded siltstones and sandstones that are probably the result of floodplain or overbank deposition. The Shinarump and the overlying Monitor Butte locally display deformed bedding in thin bedded silts and sands (Figure 5). These structures resemble "slump" bedding present in the Monitor Butte Member in the San Rafael Swell area, Utah.

The Monitor Butte Member is a siltstone, claystone and sandstone which contains a large amount of weathered
Figure 4. Diagram of Chinle-Moenkopi contact, Circle Cliffs area, with Shinarump Member channel deposits superimposed (adapted from Davidson, 1967).
Figure 5. Distorted bedding in the Shinarump Member of the Chinle Formation.
volcanic debris. Volcanic material is a major constituent of the overlying petrified Forest Member. The Church Rock and Owl Rock members of the Chinle Formation are lacustrine and fluvial siltstones and sandstones.

The Glen Canyon Group is composed of the Wingate, Kayenta and Navajo formations. The resistant aeolian Navajo and Wingate sandstones form a ring of cliffs around the floor of the Circle Cliffs Anticline (Figure 6).

During the deposition of the Moenkopi and Chinle formations, the Circle Cliffs area participated in regional northwestward tilting. The first major recognizable structural deformation of the area began in the Late Cretaceous and continued until the Paleocene Epoch. The area was folded to form the Circle Cliffs Anticline. The anticline trends north-northwest and is doubly plunging. The eastern flank of the anticline dips at a steeper angle than the western flank.

Faults are a minor feature in the Circle Cliffs area. Most of the faults are high angle normal faults which have, on the average, 10 to 30 feet of displacement. The majority of the faults occur in the central part of the anticline and are probably due to foundering of the anticline after deformation.
Figure 6. The Wingate, Chinle, and Moenkopi formations, near Colt Mesa, Circle Cliffs area, Utah.
URANIUM MINERALIZATION

Uranium deposits in the Circle Cliffs area are usually relatively small. Mines and prospects of the area are shown in Figure 4. The economic uranium deposits of the Circle Cliffs area occur at the base of channel sandstones at the contact of the Shinarump Member of the Chinle Formation with the Moenkopi Formation. The deposits are tabular and elongate parallel to the long dimensions of the channel sandstones. The mineralized Shinarump Member generally contains at least some organic debris and moderate amounts of clay galls and lenses.

The mineralogy of the deposits is relatively simple. Uraninite is a major constituent and the deposits also contain chalcopyrite, sphalerite, and galena. Spectrographic analyses reported in Davidson (1959) indicate enrichment of nickel, cobalt, silver, molybdenum, yttrium and ytterbium in ore zones. The deposits are not associated with anomalous vanadium or selenium (Davidson, 1959).

The alteration associated with the uranium deposits of the Circle Cliffs is very minor. Alteration of the host rock is confined to replacement of matrix and detrital grains by the ore minerals.

The uranium deposits show no correlation with structural features in the area such as faults and deformation.
The faulted rocks of the Circle Cliffs area have been drilled and sampled by the A.E.C. Minor alteration was associated with faulting, but no significant uranium mineralization was discovered in the fault zones (Davidson, 1967).
COLT MESA COPPER DEPOSIT

The Colt Mesa copper deposit occurs at the base of a channel sandstone of the Shinarump Member which forms a cap on Colt Mesa (Figure 7). The main Colt Mesa channel sandstone is approximately 1,700 feet wide and 100 to 150 feet thick. Paleocurrent data taken from measurements of crossbed orientation indicate a westward direction of sediment transport. In the northern part of the Mesa a smaller west-northwest trending channel transects the main channel (Figure 4). Both channel deposits are present in the cliffs to the west of Colt Mesa. The base of the channel deposits contains rip-ups and galls of Moenkopi clay (Figure 8).

The geometry and location of the deposit show no relation to faults or other structural features. The ore body lies at the contact of the main Shinarump channel and the Moenkopi Formation, and is elongate parallel to the long dimension of the channel. The mineralized zone is approximately 1,000 feet long, 50 feet wide and is 0-8 feet in thickness (Figure 9). Colt Mesa was drilled extensively by the Colt Mesa Mining Company in an effort to determine the size of the ore body. Present mine workings are diagrammed in Figure 10.
Figure 7. View from west of Colt Mesa mine, Circle Cliffs area, Utah.
Figure 8. Galls of Moenkopi Formation in Shinarump Member channel deposits, Colt Mesa.
Figure 9. Diagrammatic cross-section, Colt Mesa copper deposit, Circle Cliffs area, Utah.
Figure 10. Map of Colt Mesa Mine with sample localities.
The primary ore mineral is chalcopyrite which is intimately associated with minor amounts of sphalerite. Chalcocite, bornite, covellite and digenite are common in the ore zone. The Colt Mesa deposit is also enriched in U, V, Ag, Mo, Ni, Co, and Pb (Figure 11). The ore minerals fill pore spaces and replace the kaolinite matrix of the host rock. Detrital feldspar and quartz grains show slight corrosion in the most intensely mineralized zone.

Chalcopyrite in the Colt Mesa deposit does not show exsolution textures or twinning. It usually occurs with minor amounts of sphalerite. In the southern part of the mine area chalcopyrite cores are surrounded by rims of digenite, covellite, and chalcocite. Microprobe analyses of chalcopyrite show relatively low metal/sulfur ratios (approximately 0.98:1). Metal/sulfur ratios of high temperature chalcopyrite are slightly metal-rich (Barton, 1973).

Chalcocite, covellite, digenite and bornite appear to be secondary products of chalcopyrite. Much of the altered chalcopyrite appears as worm-like remnants in a bornite matrix which is in turn surrounded by digenite, then chalcocite and covellite. Also present are anomalous low-iron bornite and blaublueibender covellite. This alteration represents a progressive loss of iron:

\[
\text{CuFeS}_2 \rightarrow \text{Cu}_5\text{FeS}_4 \rightarrow (\text{Cu},\text{Fe})_9\text{S}_5 \rightarrow \text{CuS}
\]

The relative change of composition of these sulfides is shown in Figure 12.
<table>
<thead>
<tr>
<th>Sample #</th>
<th>Description</th>
<th>%Cu</th>
<th>%Zn</th>
<th>%Pb</th>
<th>%Fe</th>
<th>%U$_3$O$_8$</th>
<th>%V$_2$O$_5$</th>
<th>Ag ppm</th>
<th>Mo ppm</th>
<th>Co ppm</th>
<th>Ni ppm</th>
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<td>4</td>
<td>siltst. (cp, sph, cv)</td>
<td>12.0</td>
<td>.83</td>
<td>.10</td>
<td>10.7</td>
<td>-</td>
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<td>-</td>
<td>.083%</td>
<td>.23%</td>
<td>.16%</td>
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<td>.03</td>
<td>16.3</td>
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<td>.018</td>
<td>-</td>
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<td>615</td>
<td>400</td>
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<td>5.3</td>
<td>-</td>
<td>.008</td>
<td>6</td>
<td>4</td>
<td>145</td>
<td>75</td>
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<tr>
<td></td>
<td>barren sandst.</td>
<td>165</td>
<td>20</td>
<td>20</td>
<td>2.8</td>
<td>-</td>
<td>.002</td>
<td>-</td>
<td>-</td>
<td>25</td>
<td>15</td>
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Figure 11. Atomic absorption analyses of selected samples, Colt Mesa Mine, Utah (analyses by Rocky Mountain Geochemical Corp.).
Figure 12. Photomicrograph of chalcopyrite (yellow) and sphalerite (grey) surrounding the detrital quartz and feldspar grains (times 250).
The alteration of chalcopyrite and removal of iron is most pronounced in the more porous parts of the ore body and in the vicinity of a perched water table in the southern part of Colt Mesa. This alteration is also associated with malachite and azurite. For these reasons it appears that the bornite, digenite, chalcocite and covellite are secondary alteration products of chalcopyrite. It is also significant to note that the Shinarump Member of Colt Mesa contains finely disseminated limonite, while at depth to the west of Colt Mesa iron present in the Shinarump is in the form of pyrite. Therefore the Shinarump sandstone of Colt Mesa has probably been invaded by shallow groundwaters with the ability to dissolve and redistribute pyrite and redeposit it as limonite (or copper-iron sulfide).

Sphalerite in the Colt Mesa deposit is resinous and pale gray in color. Although it is not as plentiful as chalcopyrite, sphalerite is ubiquitous in the ore zone. Like chalcopyrite, the sphalerite replaces the host rock matrix. Chalcopyrite locally appears to replace sphalerite. Microprobe analyses of sphalerite indicate that it contains approximately .01 mole percent FeS. The low iron content of the sphalerite is consistent with a low temperature of formation (Figure 13).

Alteration associated with the Colt Mesa deposit is very minor. Samples of Shinarump and Moenkopi adjacent to ore and distant from ore show no gross differences in com-
Figure 13. Photomicrograph of chalcopyrite surrounded by digenite (blue) and covellite (red) (times 1,000, oil emersion).
position or appearance. Detrital feldspar grains are not altered except in the most intensely mineralized rocks. Alteration at this deposit is limited to the replacement of the ore host by sulfides and enrichment in Co, Ni, Mo, U, V, and Ag within the ore zone. The Moenkopi Formation is altered from red-brown to yellow-tan immediately below the Shinarump Member. However, this alteration is not continuous or extensive, and is a common feature in the Circle Cliffs area.

Oxidized copper and cobalt minerals such as malachite, azurite and erythrite stain the Shinarump outcrop and mine workings at Colt Mesa. The bright green and blue copper carbonate stains on the outcrop led to the discovery of the copper deposit (Figure 14).

Examples of Triassic copper or copper-uranium deposits include the Sierra Nacimiento and Coyote deposits of New Mexico and the White Canyon deposits of Utah. These deposits are located in basal units of the Chinle Formation or Chinle Formation equivalents. The ore bodies generally occupy the lower parts of fluvial channel sandstones. Copper minerals found in these deposits include chalcopyrite, bornite, chalcocite, digenite, malachite and azurite.

Deposits of copper in Permian rocks of Texas, Oklahoma and New Mexico bear a gross resemblance to the Triassic copper deposits of the Colorado Plateau. The Permian deposits have been discussed by Smith (1974) and are
Figure 14. Copper carbonate stains on outcrop of Shinarump Member, Colt Mesa, Utah.
thought to be caused by concentration of copper in a subsurface sabka environment. They differ from the Colorado Plateau deposits in that (1) the host rock is a transitional deltaic deposit and (2) they are associated with evaporite sequences.

Similarities between the Colt Mesa copper deposit and uranium deposits of the Circle Cliffs area include: (1) location at the Shinarump-Moenkopi contact, (2) position at the base of Shinarump channel sandstone, (3) tabular geometry, elongate parallel to the long dimension of the channel deposit, (4) lack of significant alteration, (5) ore mineralogy and enrichment of Mo, Co, Ni, and Ag in the ore zone, (6) lack of association with igneous activity (Figure 15). From these similarities it is possible to conclude that the Colt Mesa copper deposit and uranium deposits of the Circle Cliffs area are the same type of phenomena. The only major difference between the deposits is that the dominant ore mineral of Colt Mesa is chalcopyrite and in the uranium deposits is uraninite.
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Colt Mesa Deposit</th>
<th>Uranium Deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location at Shinarump-Moenkopi contact</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Location at base of Shinarump channel sandstone deposits</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Tabular geometry</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Scant alteration of host rock</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Accessory enrichment of Mo, Pb, Zn, Ni, Co, U, Cu</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Lack of association with faults or igneous features</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Figure 15. Table of characteristics shared by Colt Mesa Copper deposit and uranium deposits of the Circle Cliffs area, Utah.
GEOCHEMISTRY

The geochemistry of the Colt Mesa deposit can be divided into two major sections. The first area of concern is the solubility and transport of the ore elements. The second section deals with the chemical changes causing deposition.

The nature of the ore solution responsible for the copper and uranium deposits of the Circle Cliffs area is a major influence on the position and character of the deposits. Any postulated ore solution must be consistent with the localization of these deposits in porous channel sands, the lack of correlation with igneous activity or faulting, the lack of alteration associated with the deposits, and the low temperature character of the deposits. The most likely candidate for the ore fluid which is compatible with these features is ordinary groundwater.

A dilute aqueous system, at 25 degrees C and 1 atm pressure is a reasonable theoretical approximation of the ore fluid. In this environment, the physical solubility of various elements can best be evaluated and compared with the use of redox potential (Eh) - pH diagrams. The construction of these diagrams illustrating mineral equilibria is discussed comprehensively by Pourbaix (1949) and Garrels and Christ (1965).
Diagrams 16 through 24 for elements encountered in the Colt Mesa deposit, are drawn for the following conditions; temperature = 25 degrees C, pressure = 1 atm, boundaries of ions and solids at activities of $10^{-6}$ of metallic ions, $P_{CO_2} = 10^{-3.4}$, and total dissolved sulfur = $10^{-4}$. The $P_{CO_2}$ value is the partial pressure of CO$_2$ in equilibrium with the atmosphere. The total dissolved sulfur species is an average concentration of dissolved sulfur in natural waters (Garrels & Christ, 1965). Superimposed upon each Eh-pH diagram is a dashed line which indicates the Eh-pH limits of natural groundwater. This information is taken from the work of Baas Becking et al. (1960). An arrow within this field illustrates, in a general fashion, the change in the chemical environment of the fluid which initiates ore deposition. Each diagram in Figures 16 through 24 includes those minerals which occur in nature under the specified conditions.

Figure 16 has been altered and simplified from a diagram in Garrels and Christ (1965). In the system Cu-Fe-H$_2$O-S, divalent copper ion at an activity of $10^{-6}$ is stable under oxidizing and neutral to acid conditions. If the Eh of the solution gradually decreases the first solid to appear along line A-A' as a stable phase is chalcocite. As the Eh is lowered, iron-copper sulfides become stable solid phases:

$$2H^+ + 5Cu_2S + 2FeS_2 = 2Cu_5FeS_4 + H_2S$$
$$4H^+ + Cu_5FeS_4 + 4FeS_2 = 5CuFeS_2 + 2H_2S$$
Figure 16. The Cu-Fe-H₂O-S system, 25°C, 1 atm, total dissolved sulfur species = 10⁻⁴, activity of ions in solution = 10⁻⁶. Fields of solid iron compounds are omitted (adapted from Garrels and Christ, 1965).
Figure 17. The U-H$_2$O-CO$_2$ system, 25°C, 1 atm, P$_{CO_2}$ = 3.4, activity of ions = 10$^{-6}$ (Hostetler and Garrels, 1962).

Figure 18. The V-H$_2$O- system, 25°C, 1 atm, activity of ions = 10$^{-6}$ (Hostetler and Garrels, 1962).
Figure 19. The Zn-H$_2$O-S-CO$_2$ system, 25°C, 1 atm, total dissolved sulfur species = $10^{-4}$, $P_{CO_2} = 10^{-3.4}$, activity of ions in solution = $10^{-6}$.

Figure 20. The Pb-H$_2$O-S-CO$_2$ system, 25°C, 1 atm, total dissolved sulfur species = $10^{-4}$, $P_{CO_2} = 10^{-3.4}$, activity of ions in solution = $10^{-6}$.
Figure 21. The Co-H$_2$O-S-CO$_2$ system, 25°C, 1 atm, total dissolved sulfur species = $10^{-4}$, $P_{CO_2} = 10^{-3.4}$, activity of ions in solution = $10^{-6}$.

Figure 22. The Ni-H$_2$O-S-CO$_2$ system, 25°C, 1 atm, total dissolved sulfur species = $10^{-4}$, $P_{CO_2} = 10^{-3.4}$, activity of ions in solution = $3\times 10^{-6}$. 
Figure 23. The Mo-H\textsubscript{2}O system, 25°C, 1 atm, total dissolved sulfur species = 10^{-4}, activity of ions in solution = 10^{-6}.

Figure 24. The Ag-H\textsubscript{2}O-S system, 25°C, 1 atm, total dissolved sulfur species = 10^{-4}, P\textsubscript{CO}\textsubscript{2} = 10^{-3.4}, activity of ions in solution = 10^{-6}.
Although the stability relations of copper and iron sulfides are extremely complex (as is demonstrated in Figure 16), it may be stated in a general fashion that the combination of simple sulfides of iron and copper under reducing conditions will result in the formation of bornite and chalcopyrite. Experiments conducted by Roberts (1963) indicate that this transformation can occur at room temperatures. The transformation is independent of pH (Roberts, 1963). In addition, chalcopyrite is apparently far more stable than the simple sulfides of iron and copper. It is not known what causes this extraordinary degree of stability of chalcopyrite, although it could be due to its higher lattice energy.

At point A' on Figure 16 the only compound of copper and iron present is chalcopyrite. Iron in excess of that required for chalcopyrite is present as the divalent iron ion. The decrease in Eh from point A to point A' in a solution containing copper and iron would result in an ore deposit consisting only of chalcopyrite with no pyrite.

The solubility of uranium and vanadium (Figures 17 and 18) in natural groundwater is considerable. From Figures 17 and 18 it can be noted that vanadium is slightly more soluble than uranium under these conditions. The soluble fields of ionic species of these elements correspond in part to that of copper ion, with two major exceptions. First, copper is not soluble in alkaline environments,
while uranium and vanadium are. Secondly, with decreasing Eh, copper is precipitated as sulfide at a slightly higher Eh than uranium or vanadium is precipitated as low valent oxides. These differences explain why copper sulfides (1) are not often found in large quantity with economic uranium deposits, and (2) are never found in large quantity with economic vanadium deposits.

Figure 19 shows that zinc is similar in chemical behavior to copper in dilute aqueous systems. Lead (Figure 20) is not as soluble as zinc or copper in low temperature aqueous systems. At higher concentrations of lead ion or sulfur, anglesite, PbSO\(_4\), occupies a large portion of the lead ion field in Figure 20.

Figures 21 through 24 illustrate the fields of solubility of molybdenum, silver, nickel and cobalt. Cobalt and nickel (Figures 21 and 22) are soluble under the same conditions as zinc and copper. Molybdenum is very soluble except in very acid solutions or in solutions of very low redox potential. The marked solubility of molybdenum (Figure 23) explains its presence as a 'halo' around many strata-bound deposits, including the Colt Mesa copper deposit.

Silver (Figure 24) has a limited field of stability in dilute aqueous systems. However, under positive redox potential conditions, it is present as a soluble species. The apparent solubility of silver under oxidizing condi-
tions explains its presence at Colt Mesa and also could account for the presence of large strata-bound silver deposits such as Silver Reef, Utah.

The preceding Eh-pH diagrams illustrate that copper, uranium and other associated metals are soluble (at a concentration of approximately .2 ppm) in groundwater that is neutral to acid in pH and has a relatively high redox potential (+.2). These concentrations of metallic ions can be augmented by the presence of (1) soluble metallo-organic complexes, and (2) metals adsorbed on detrital particles that may be transported in groundwater.

Ong, Swanson and Busque (1970) have shown that humic acids have the capacity to form complex, soluble metal ions. Baker (1973) has discovered that 'metal humates' are readily mobilized in the presence of humic acids. Also, Collins (1973) has suggested that copper and other metals may be adsorbed on suspended particles. Unfortunately, the amount of copper in solution that these processes contribute is not known quantitatively.

Copper and other metals in groundwater at concentration of .2 ppm can be precipitated as sulfides by a reduction in Eh of the environment as indicated by the reaction paths drawn on Figures 16 through 24. Two processes can be called upon to lower the redox potential of an aqueous environment; (1) decomposition of organic debris by sulfate-reducing bacteria, and (2) increasing isolation
from an oxygen-rich environment. The decay of organic material is the most significant of these two processes.

Alteration associated with ore deposition in the Circle Cliffs area is limited to (1) replacement of kaolinite matrix by ore sulfides, and (2) slight corrosion of feldspar and quartz grains. In a neutral to acid solution the dissociation of kaolinite proceeds according to this reaction:

\[ H_4Al_2Si_2O_9 + 6H^+aq = 2Al^{3+} + 2H_4SiO_4aq + H_2O \]

The destruction and replacement of kaolinite is directly related to the deposition of ore sulfides and is not evident in barren sandstone adjacent to ore. Therefore it is likely that the chemical process of sulfide precipitation is the major control on the dissociation of kaolinite. For example, the formation of chalcocite releases hydrogen ions and increases the acidity of the solution:

\[ 2Cu^{++} + H_2S = Cu_2S + 2H^+ \]

This process could cause the dissociation of kaolinite. Also, the kaolinite matrix is extremely fine grained, which increases its susceptibility to dissociation.

The slight corrosion of quartz grains associated with ore is more difficult to explain. Quartz, in general, is very insoluble except under highly alkaline conditions. A possible answer to this problem involves the pressure solution of quartz grains by intervening water-saturated material. This mechanism, discussed by Weyl (1959), involves
the slight dissolution of quartz at grain boundaries surrounded by an aqueous film. If a material (such as a sulfide) is very fine grained and is water saturated, it will provide a greater number of water films which cause diffusion of silica from the quartz grains. This process would operate during compaction of the sandstone host. If this is the case, it seems reasonable that the ore was deposited prior to deep burial of the host rock.

The preceding discussion has outlined a theoretical model for the transportation and deposition of copper and other metals in a low temperature dilute aqueous system. A neutral to acid, slightly oxidizing solution is consistent with the Eh and pH limits of natural groundwater. It is now important to see if this type of groundwater is consistent with conditions present in the Shinarump Member of the Chinle Formation.

The Shinarump Member and the Petrified Forest Member of the Chinle Formation represent indirect evidence as to the conditions that prevailed during their deposition. Both of these units contain moderate to abundant remains of organic life. The Shinarump contains moderate to abundant amounts of carbonaceous debris. The type and amounts of fossils preserved in these units indicates a humid, temperate environment with much vegetable life (Stewart, Poole and Wilson, 1972).

The decay of organic material present in such an environment would result in a gradual lowering of Eh. This
would be augmented by burial of Shinarump sediments and the loss of access to free oxygen. A subsidiary effect of the decomposition of organic matter is an increase in the acidity of the environment. The pH of groundwater in contact with decaying organic matter is usually less than 7 and may be as low as 3 or 4 (Krauskopf, 1967). This type of environment is consistent with the theoretical model of a neutral to slightly acid dilute ore solution.
ORIGIN OF COPPER AND URANIUM

There are three hypotheses of origin of copper and uranium in the ore solution which may be considered: (1) hydrothermal fluids, (2) copper- and uranium-rich granite rocks, and (3) volcanic debris. Any theory pertaining to the origin of the metals which occur in the Circle Cliffs area must account for: (1) widespread distribution of low-grade deposits, (2) localization of these deposits in the Shinarump sandstone, (3) low temperatures of formation, and (4) lack of correlation of the deposits with igneous or structural features.

A distant hydrothermal source for the ore metals is perhaps the most convenient theory available for evaluation. Uranium and copper have been found in vein or pipe deposits in igneous laccolithic intrusives on the Colorado Plateau (Finch, 1967). Presumably, hydrothermal fluids enriched in copper and uranium could have contaminated groundwater systems. However, several difficulties are encountered in this theory. First, the fluids would have had to undergo a very gradual cooling and dilution, or precipitation of ore metals would have been immediate. On the other hand, a hydrothermal fluid would have had to undergo a very gradual cooling and dilution, or precipitation of ore metals would have been immediate. On the other
hand, a hydrothermal fluid would have had to contribute metals in solution over the entire area of the Circle Cliffs, which is approximately 1,600 square miles. For a point source such as an hydrothermal conduit, this would require a fairly large volume of solution to contaminate natural waters. This would be unusual in light of the fact that vein deposits of uranium and copper in the Colorado Plateau are generally small and rare, and contribute to only 4% of all uranium found in the Colorado Plateau (Finch, 1967).

The weathering of granitic rocks in an ancestral highland such as the Mogollon area of Arizona could result in copper and uranium enrichment in groundwaters. Granitic rocks contain, on the average, about 3.5 to 4.8 ppm uranium and 10 ppm copper. It is conceivable that the weathering of such rocks could produce natural waters enriched in copper and uranium. However, it is significant to note that much of the copper and uranium derived from these rocks would be lost to surface drainage systems and only a fraction of these metals would enter the groundwater system. This theory does not account for the fact that major strata-bound ores are not found in orderly areal distribution about granitic source areas. It seems unlikely that a groundwater solution in the Shinarump sandstone would deposit large amounts of copper and uranium in the Monument Valley area of Utah and Arizona and continue northward to
deposit similar ore bodies in the Circle Cliffs and the
San Rafael Swell areas of Utah.

The Shinarump Member of the Chinle Formation in the
Circle Cliffs area is overlain by the Monitor Butte and
Petrified Forest members of the Chinle Formation, both of
which are largely composed of volcanic debris. Volcanic
material contains relatively large amounts of copper
(30 - 10 ppm) and uranium (30 - 10 ppm) (Rosholt, Prijana
& Noble, 1961) which is usually concentrated in the glass
or pumice fraction of the debris. If the glass in volca­
ic debris is devitrified, the metals in the glass are mo­
obilized. This theory would account for: (1) widespread
distribution of economic and uneconomic mineralization
over a large area, (2) location of deposits in the Shina­
rump sandstone, (3) low temperatures of formation of the
deposits, (4) lack of correlation of deposits with igneous
or structural features. Volcanic debris is almost always
associated with strata-bound copper and uranium deposits
and is regarded as a guide to ore in Wyoming, the Colorado
Plateau, and Texas.

The major difficulty in proposing volcanic debris as
a source of metals is the process of clay formation which
accompanies devitrification. The clays formed, notably
montmorillonite, should readily fix metal ions and remove
them from solution. This process may not be immediate and
does not appear to fix metal ions efficiently. For exam­
ple, studies of vitric and devitrified tuffs in Tertiary
basins of Wyoming have shown that devitrified samples have lost up to 60% of their original uranium content (Ros­

The direction of groundwater movement during Triassic time was probably to the northwest. This supposition is based on the tendency of subsurface waters to flow in the same general direction as the surface drainage systems. If the groundwater present in the Shinarump Member shortly after its deposition was carrying metals in solution, deposition of these metals would occur when the redox po­
tential of the solution was sufficiently low. Under con­
ditions of gradually decreasing Eh, copper precipitates from solution before uranium. At a minimum concentration of .2ppm of copper and associated metals, a period of 10,000 to 100,000 years would be necessary to deposit the ores of the Circle Cliffs area. These figures are based on the average rate of groundwater flow of 1 ft./day and constant metal content of the solution of .2ppm and are only approximate.
Several inferences can be drawn from a study of the Colt Mesa copper deposit:

1. The Colt Mesa copper deposit is a low temperature deposit related genetically to the uranium deposits of the Circle Cliffs area.

2. Copper, uranium and other elements common in the Circle Cliffs deposits are soluble in oxidizing, neutral to acid solutions. Uranium is, however, soluble in slightly more reducing and significantly more alkaline solutions than copper.

3. Copper and uranium deposits may be segregated spatially because of their chemical differences. The presence of strata-bound copper sulfide deposits can be a general indicator of uranium mineralization.

4. Mo, Co, Ni, and possibly other elements not evaluated may be used as local indicators of ore deposition.
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