

## GEOLOGY AND MINERALOGY

Distribution	<u>No. of copies</u>
Division of Raw Materials, Albuquerque . . . . .	1
Division of Raw Materials, Austin. . . . .	1
Division of Raw Materials, Casper. . . . .	1
Division of Raw Materials, Denver. . . . .	1
Division of Raw Materials, Rapid City. . . . .	1
Division of Raw Materials, Salt Lake City. . . . .	1
Division of Raw Materials, Spokane . . . . .	1
Division of Raw Materials, Washington. . . . .	3
Grand Junction Operations Office . . . . .	1
Production Evaluation Division, GJ00. . . . .	6
Technical Information Service Extension, Oak Ridge . . . . .	6
U. S. Geological Survey:	
Foreign Geology Branch, Washington . . . . .	1
Fuels Branch, Washington . . . . .	1
Geochemistry and Petrology Branch, Washington. . . . .	1
Geophysics Branch, Washington. . . . .	1
Mineral Classification Branch, Washington. . . . .	1
Mineral Deposits Branch, Washington. . . . .	2
A. L. Brokaw, Grand Junction . . . . .	2
N. M. Denson, Denver . . . . .	1
R. L. Griggs, Albuquerque. . . . .	2
W. R. Keefer, Laramie. . . . .	1
E. M. MacKevett, Menlo Park, . . . . .	1
L. R. Page, Washington . . . . .	1
P. K. Sims, Denver . . . . .	2
Q. D. Singewald, Beltsville. . . . .	1
A. E. Weissenborn, Spokane . . . . .	1
P. E. Hotz, Menlo Park. . . . .	1
TEPCO, Denver. . . . .	2
TEPCO, RPS, Washington, (including master) . . . . .	2
	<u>47</u>



## CONTENTS

	Page
Abstract. . . . .	21
Introduction. . . . .	24
Purpose of work. . . . .	24
Field methods. . . . .	24
Acknowledgments. . . . .	25
Geography . . . . .	26
Location of area . . . . .	26
Roads. . . . .	28
Geology . . . . .	28
Stratigraphy . . . . .	28
General statement . . . . .	28
Permian system. . . . .	29
Cutler formation . . . . .	29
Halgaito tongue . . . . .	31
Cedar Mesa sandstone member . . . . .	34
Organ Rock tongue . . . . .	36
DeChelly sandstone member . . . . .	38
Hoskinnini tongue . . . . .	44
Triassic system . . . . .	48
Moenkopi formation . . . . .	48
Chinle formation . . . . .	54
Shinarump member. . . . .	56
Monitor Butte member. . . . .	62
Petrified Forest member . . . . .	66



## Geology--Continued

## Stratigraphy--Continued

## Triassic system--Continued

## Chinle formation--Continued

Owl Rock member . . . . .	70
Church Rock member . . . . .	74
Wingate sandstone . . . . .	79
Jurassic(?) system . . . . .	82
Kayenta formation. . . . .	82
Jurassic and Jurassic(?) system. . . . .	88
Navajo sandstone. . . . .	88
Jurassic system. . . . .	91
Carmel formation. . . . .	91
Entrada sandstone . . . . .	94
Summerville formation . . . . .	98
Bluff sandstone . . . . .	101
Morrison formation. . . . .	105
Salt Wash sandstone member . . . . .	105
Quaternary system. . . . .	106
Geologic history. . . . .	108
Eruptive rocks . . . . .	108
General statement . . . . .	108
Igneous plugs and dikes . . . . .	109
Serpentine at Garnet Ridge by Harold E. Malde and Robert E. Thaden. . . . .	115
Introduction . . . . .	115
Intrusive serpentine deposits. . . . .	116
Distribution and structural localization.	116



Geology--Continued	
Geologic history--Continued	Page
Eruptive rocks--Continued	
Serpentine at Garnet Ridge--Continued	
Intrusive serpentine deposits--Continued	
Wall-rock relations . . . . .	117
Internal relations. . . . .	117
Source of blocks and rubble . . . . .	118
Serpentine matrix . . . . .	119
Garnet. . . . .	120
Extrusive serpentine deposits. . . . .	121
Summary. . . . .	123
Mineralized exposure at Garnet Ridge . . . . .	125
Structure . . . . .	127
Folds. . . . .	127
Organ Rock anticline. . . . .	128
Oljeto syncline . . . . .	128
Agathla anticline . . . . .	129
Tse Biyi syncline . . . . .	129
Gypsum Creek dome . . . . .	130
Fractures. . . . .	130
Economic geology. . . . .	132
Ore deposits . . . . .	132
General statement . . . . .	132
Ore-bearing beds. . . . .	134
Channels . . . . .	134
Appearance. . . . .	134
Classification. . . . .	135
Trends. . . . .	139
Floors. . . . .	141
Sediments . . . . .	142



Geology--Continued	
Economic geology--Continued	
Ore deposits--Continued	
Ore-bearing beds--Continued	
Channels--Continued	
Associated swales. . . . .	144
Origin . . . . .	146
Ore bodies. . . . .	148
General statement. . . . .	148
Rods . . . . .	149
Fractures as related to rods. . . . .	159
Tabular ore bodies . . . . .	166
Corvusite-type ore bodies. . . . .	167
Rolls. . . . .	171
Age determinations. . . . .	172
Origin and localization . . . . .	176
Uranium potentialities of the area. . . . .	178
Prospecting guides. . . . .	182
Useful guides for prospecting. . . . .	183
Observable uranium minerals and abnormal	
radioactivity. . . . .	183
Channel fill. . . . .	184
Channel conglomerates containing fossil	
plant matter. . . . .	184
Guides of uncertain usefulness . . . . .	184
Limonite that impregnates channel fill. . . . .	184
Secondary copper minerals . . . . .	185
An abnormal thickness of an altered zone	
in the uppermost strata of the Moenkopi	
formation . . . . .	185
Clay boulders, cobbles, and pebbles . . . . .	185



	Page
Mines and prospects. . . . .	186
Mines in the Monument Valley area, Arizona. . . . .	186
Monument No. 2 channel . . . . .	186
Monument No. 2 mine . . . . .	187
Introduction . . . . .	187
Location and accessibility . . . . .	188
Geology. . . . .	188
Channel. . . . .	189
Uranium and vanadium deposits. . . . .	192
Basal ore zone . . . . .	193
Middle ore zone. . . . .	197
Upper ore zone . . . . .	200
Mineralogy and paragenesis of the ore deposit at the Monument No. 2 and Cato Sells mines, by Donald H. Johnson . . . . .	201
Introduction . . . . .	201
Acknowledgments. . . . .	201
Mineralogy . . . . .	202
Uranium and vanadium minerals. . . . .	203
Autunite. . . . .	203
Becquerelite. . . . .	203
Carnotite . . . . .	204
Corvusite . . . . .	204
Doloresite. . . . .	205
Fernandinite. . . . .	205
Fourmarierite . . . . .	205
Hewettite . . . . .	205



## Mines and prospects--Continued

## Mines in the Monument Valley area, Arizona--Continued

## Monument No. 2 channel--Continued

## Mineralogy--Continued

## Uranium and vanadium minerals--Continued

	Page
Metazeunerite . . . . .	206
Montroseite . . . . .	207
Navajoite . . . . .	207
Pascoite . . . . .	208
Rauvite . . . . .	208
Steigerite . . . . .	208
Tyuyamunite . . . . .	209
Uraninite . . . . .	209
Uranophane . . . . .	211
Associated minerals--nonsulfides . . . . .	211
Apatite (carbonate) . . . . .	211
Calcite . . . . .	212
Clay minerals . . . . .	212
Gypsum . . . . .	213
Ilsemannite(?) . . . . .	214
Jarosite . . . . .	215
Limonite . . . . .	215
Opal . . . . .	216
Quartz and chalcedony . . . . .	217
Wad (lithian) . . . . .	218
Associated minerals--sulfides . . . . .	218
Bornite . . . . .	218
Galena . . . . .	218
Pyrite . . . . .	219
Sphalerite . . . . .	221
Unidentified minerals . . . . .	221
Paragenesis . . . . .	222



Mines and prospects--Continued	Page
Mines in the Monument Valley area, Arizona--Continued	
Monument No. 1 channel. . . . .	228
Monument No. 1-Mitten No. 2 mine and	
Monument No. 1 Annex . . . . .	228
Introduction. . . . .	228
Location and accessibility. . . . .	229
Geology . . . . .	229
Channel . . . . .	231
Uranium-vanadium ore bodies . . . . .	237
Mineralogy. . . . .	239
Prospects in the Monument Valley area, Arizona . . . . .	241
Hunts Mesa. . . . .	242
Mitchell Mesa . . . . .	246
Koley Black area. . . . .	250
Alfred Miles channel No. 1. . . . .	254
Cecil Todechenee channel. . . . .	262
Channels at southeast edge of Hoskinnini Mesa . . . . .	263
Oil and gas possibilities . . . . .	265
Selected bibliography . . . . .	277
Unpublished reports . . . . .	287



## ILLUSTRATIONS

	Page
Figure 1. Index map of parts of Apache and Navajo Counties, Ariz. Mapped area outlined by short slanted lines . . . . .	In envelope
2. Geologic map of the Monument Valley area, Arizona .	In envelope
3. View looking northwest into Tse Biyi from crest of Hunts Mesa. Many of the buttes, monuments, and craggs are named. Monuments rise about 800 feet above valley floor. . . . .	27
4. Columnar section of consolidated sedimentary strata exposed in the Monument Valley area, Arizona. . .	In envelope
5. Photo of small cliff dwelling in a shallow alcove in the DeChelly sandstone member of the Cutler formation. Most cliff dwellings in the Monument Valley area are this shape and size. Marks on the wall above and behind the dwelling are pictographs . . . . .	40
6. Photo of Permian and Triassic formations, showing relationship of a channel to other strata. Note the symmetrical scour formed by the channel (Mitchell Mesa No. 1) in the Moenkopi formation. Channel is scoured about 75 feet into underlying strata. Rcs - Shinarump member of Chinle formation; Rm - Moenkopi formation; Pch - Hoskiinnini tongue of Cutler formation; and Pcd - DeChelly sandstone member of Cutler formation . . . . .	42



- Figure 7. Photo showing Keet Seel, the largest and best pre-  
 served cliff dwelling in the Monument Valley area.  
 The dwelling is in a large alcove in the Navajo  
 sandstone . . . . . 89
  
- 8. Photo showing sedimentary strata forming Baby Rocks  
 point. The point is capped by the Salt Wash member  
 of the Morrison formation and has part of the  
 Entrada sandstone exposed at its base. Bluff  
 sandstone is about 45 feet thick. Jms - Salt  
 Wash member of Morrison formation; Jb - Bluff  
 sandstone; Js - Summerville formation; and Je -  
 Entrada sandstone.. . . . 96
  
- 9. Photo showing unconformity between the crumpled and  
 distorted uppermost beds of the Entrada sandstone  
 and the even-bedded overlying Summerville formation  
 at Baby Rocks point. Jms - Salt Wash member of  
 the Morrison formation; Jb - Bluff sandstone; Js -  
 Summerville formation; and Je - Entrada sandstone . . . 97
  
- 10. Photo of Agathla Peak, a volcanic neck of nearly  
 black lamphrophyric rock that rises about 1,400  
 feet above the valley floor . . . . . 111
  
- 11. Geologic map of Garnet Ridge, Arizona . . . . . In envelope
  
- 12. Planetable map of pipe 2, Garnet Ridge,  
 Arizona . . . . . In envelope



- Figure 13. Geologic map and cross section of the crest of Garnet Ridge, Arizona, showing location of pipe 1 and of extrusive deposits of serpentine rubble . . . . . 122
14. Geologic map of the Monument Valley area, Arizona, on which all known channels have been plotted. Channel names and data are listed in table 3 by number . . . . . In envelope
15. Block diagrams illustrating modes of channel outcrop in the Monument Valley area, Arizona.  
 A.--Channel buried beneath overlying beds of the Shinarump member of the Chinle formation  
 B.--Resistant channel sediments standing as a ridge, erosion has removed overlying beds and adjacent shaly siltstones . . . . . 136
16. Cross sections of typical channels in the Monument Valley area, Arizona. Locations of the channels are shown on figure 14. Uppermost pair are classified as narrow channels. All the others, except the bottom one, are classified as intermediate channels. The bottom channel is classified as a broad channel. . . . . 137
17. Photo showing the symmetrical nature of Mitchell Mesa channel No. 1. The channel is about 350 feet wide and 75 feet deep. T & cs - Shinarump



Figure 17.  
(Continued)

member of Chinle formation; T<sub>m</sub> - Moenkopi formation; P<sub>ch</sub> - Hoskinnini tongue of the Cutler formation; and P<sub>cd</sub> - DeChelly sandstone member of the Cutler formation. . . . .

138

18. Channel trends, as noted in the Monument Valley area, Arizona and Utah.

A.--Monument Valley area, Arizona. A faint northwesterly orientation of the channels is suggested by the diagram.

B.--Monument Valley area, Utah. A strong northwesterly orientation of the channels is apparent in the diagram.

C.--Monument Valley area, Arizona and Utah. A dominant northwesterly orientation of channels is clearly shown. Data for Utah part of Monument Valley were furnished by R. Q. Lewis, Sr., and

D. E. Trimble, U. S. Geological Survey . . . . .

140

19. Two illustrations demonstrating the use of geophysical work as a supplement to geologic mapping in the search for channels. A.--The Koley Black area showing the many channels exposed. Channel trends based on geologic field work and interpretations. B.--The Koley Black area with extent, trend, width, and characteristics of buried channels determined as a result of geophysical investigation.

Numerals relate channels with those in A . . . . . In envelope



- Figure 20. Swales in the Monument No. 2 mine area. A broad elongate swale cut into the top of the Moenkopi formation parallels the trend of the Monument No. 2 channel . . . . . In envelope
21. Cross section of typical rod in the Monument No. 2 mine, showing position of samples . . . . . 150
22. Cross sections of simple and complex rods.  
A.--Simple rod. B.--Complex rod; tyuyamunite-limonite-gray sandstone core. C.--Complex rod; silicified wood core. . . . . 152
23. Photo of cross section of a richly mineralized rod. Light area is tyuyamunite-rich sandstone (ty) that may contain over 20 percent  $U_3O_8$ . Darker areas are weakly mineralized sediments that contain only trace amounts of  $U_3O_8$  . . . . . 153
24. Photo of cross section of complex rod containing core of silicified wood. Silicified wood (sw) forms core and is rimmed by thin band of tyuyamunite (ty) and limonite-impregnated sandstone (lt). Mass of rod is composed of gray friable sandstone (ss) with mixed limonite and tyuyamunite. Edge of rod marked by thin tyuyamunite and limonite bands . . . . . 154
25. Idealized block diagram of mine workings showing relationship of rods to one another and to mine drifts . . . . . 156



Figure 26. Photomicrographs of thin sections prepared from specimens collected in the Monument Valley area, Arizona. Photomicrographs A-C show uranium and vanadium minerals in fractures and interstices; specimens collected in Vanadium Corporation of America's Monument No. 2 mine. Photomicrograph D is of sediments of the Shinarump member distant from channel; made with crossed nicols. All enlarged 22 diameters. . . . . 160

26A. Photomicrograph showing sharp boundary between fractured and unfractured grains. Specimen from lower edge of rod. . . . . 160

26B. Photomicrograph showing parallel fractures. Specimen from lower edge of rod. . . . . 161

26C. Photomicrograph showing irregular fractures. Specimen collected about 1 foot away from edge of rod. . . . . 162

26D. Photomicrograph of thin section of sediments of the Shinarump member distant from channel. Crossed nicols. . . . . 163

27. Distribution of fractures, rods, and silicified wood in the Vanadium Corporation of America's Monument No. 2 mine. A.--Fractures. B.--Rods. C.--Silicified wood . . . . . 165

28A. Photo taken in Vanadium Corporation of America's Monument No. 2 mine showing concretionlike body in part of vanadium-rich ore body. Core is



Figure 28A. sandstone with white opal (o) filling  
Continued

interstices. Surrounding this core is a layer  
of black vanadium-impregnated sandstone (v). A  
limonite-rich (lt) rim surrounds the entire body. . . . . 169

28B. Photo showing another concretionlike mass in  
vanadium-rich ore body in basal channel sediments . . . . . 170

29. Map of the mine workings in the Vanadium Corporation  
of America's Monument No. 2 mine. Structure  
contours show the configuration of the base of  
the channel. Contours of Yazzie Mesa and South  
Ridge furnished by the U. S. Atomic Energy  
Commission. Contours on Main Ridge from drill-  
hole data and altitudes taken in the mine  
workings. . . . . In envelope

Figure 30. Geologic maps and cross sections of the Monument  
No. 2 mine area, Apache County, Ariz.

30A. Geologic map of the Monument No. 2 mine area  
showing centerline of channel.

30B. Structure contours drawn on the base of the Monument  
No. 2 channel. Contours on Yazzie Mesa and South  
Ridge furnished by the U. S. Atomic Energy  
Commission. Contours on Main Ridge prepared on  
basis of drill-hole data and altitudes determined  
in the mine workings. . . . . In envelope  
(one sheet)

30C. Cross sections of the Monument No. 2 channel showing  
general shape of the channel (B-B'), and ridge  
dividing the channel (A-A') . . . . .



- Figure 31. Trends of rods as determined in the Vanadium Corporation of America's Monument No. 2 mine, Apache County, Ariz. A.--Rods over 10 feet in length. B.--Rods less than 10 feet in length. C.--Rods of all lengths. . . . . 199
32. Geologic map and cross section of the Monument No. 1 channel. The two channel remnants of the Shinarump member form topographic highs. The channel curves to the northwest. It is uncertain if the Monument No. 1 Annex is in a part of the same channel. . . . . 230
33. Photo showing the isolated mass of the Shinarump member of the Chinle formation (Rcs) that forms the south remnant of the Monument No. 1 channel. Rm - Moenkopi formation. Mine dump marks the approximate location of the Vanadium Corporation of America's former Monument No. 1 mine . . . . . 232
34. Photo showing the three lithologic types represented in basal channel sediments: Tp - trash-pocket conglomerate; Cc - calcite-cemented sandstone; and Sc - silica-cemented sandstone. . . . . 234
35. Photo showing limonite-impregnated sediments along fractures in the Monument No. 1 channel fill. . . . . 236



- Figure 36. Geologic map of Hunts Mesa on which the centerlines of the two known channels have been drawn. It is unknown how channel no. 57 is related to channel no. 56. . . . . 242
37. Geologic map of Mitchell Mesa on which the centerlines of the known channels have been drawn. Probable relationship of channels is suggested by geophysical measurements . . . . . 247
38. Photo looking north at the Koley Black channel (no. 45). Men at the base give scale. The channel is about 270 feet wide and has been cut about 30 feet into the underlying Moenkopi formation.  $T_m$  - Moenkopi formation;  $T_{cs}$  - Shinarump member of the Chinle formation . . . . . 253
39. Geologic map of the south end of the Copper Canyon area showing distribution of channels on parts of Nakai and Hoskinnini Mesas. Data for numbered channels are given in table 3. Channels nos. 27 and 28 are known as the "channels at southeast edge of Hoskinnini Mesa." The location of the channels in Utah were determined by Richard Q. Lewis, Sr., and Donald E. Trimble, U. S. Geological Survey . . . . . 255



- Figure 40. Photo looking northeast across the West Ford of Copper Canyon showing broad deep Alfred Miles channel No. 1. Channel is about 2,150 feet wide and about 70 feet deep. Pco - Organ Rock tongue of the Cutler formation; Pcd - DeChelly sandstone member of the Cutler formation; Pch - Hoskinnini tongue of the Cutler formation; Pm - Moenkopi formation; and Pcs - Shinarump member of the Chinle formation. . . . . 258
41. Possible trend of the Alfred Miles channel No. 1 based on seismic refraction and drilling data supplied by Dart Wantlund, U. S. Bureau of Reclamation. Drill-hole data from U. S. Atomic Energy Commission drilling program on Nakai Mesa (C. Clare Gregg, written communication, 1952). Contours on the base of the Shinarump member of the Chinle formation. . . . . 260
42. Location of test wells drilled in and adjacent to the Monument Valley area, Apache and Navajo Counties, Ariz. . . . . 266
43. Generalized section of pre-Cutler rocks underlying the Monument Valley area, Apache and Navajo Counties, Ariz. . . . . In envelope



## TABLES

	Page
Table 1. Outline of geologic history of the Monument Valley area, Arizona . . . . .	.In envelope
2. X-ray identification of material in the serpentine matrix (by J. M. Axelrod). . . . .	120
3. Compilation of channel data, Monument Valley, Ariz. . .	.In envelope
4. Composition of some clay masses from the Monument Valley area, Arizona and Utah, as determined by X-ray spectrometer. Identification by Donald H. Johnson. . . . .	143
5. Calculated Pb $^{206}/U^{238}$ ages of uranium ores from the Monument No. 2 mine area, Apache County, Ariz. . .	173
6. Significant oil and gas test wells drilled in and adjacent to the Monument Valley area, Apache and Navajo Counties, Ariz. Approximate location of wells are shown on figure 42 . . . . .	.In envelope



GEOLOGY AND URANIUM-VANADIUM DEPOSITS OF THE MONUMENT VALLEY  
AREA, APACHE AND NAVAJO COUNTIES, ARIZONA

By Irving J. Witkind and Robert E. Thaden

ABSTRACT

In 1951 and 1952, the U. S. Geological Survey undertook a program of geologic mapping and uranium investigations in Apache and Navajo Counties, northeastern Arizona. The area studied encompasses the southern half of Monument Valley, and includes three 15-minute quadrangles covering about 700 square miles.

Exposed consolidated sedimentary strata range in age from the Halgaito tongue of the Cutler formation (Permian) to the Salt Wash member of the Morrison formation (Jurassic). Minettes and vogesites form volcanic plugs and dikes and are exemplified by Agathla Peak and the Porras Dikes. On Garnet Ridge are several rubble pipes filled with rounded cobbles and boulders in a matrix of serpentine.

Extensive surficial deposits, predominantly dune sand and alluvium, veneer mesa tops and valley floors.

The dominant structural element is the Monument upwarp, whose southern end is in this area. On this major feature are superimposed (1) the Organ Rock anticline, (2) the Oljeto syncline, (3) the Agathla anticline, (4) the Tse Biyi syncline, and (5) the Gypsum Creek dome. Fractures cut all strata. Faults are rare but joints are common and widespread.

Uranium-vanadium ore deposits are in the Shinarump member of the Chinle formation (Late Triassic), a light-gray crossbedded conglomeratic sandstone. Commonly, conglomerate is at the base of the Shinarump and grades upward into finer sediments, with a medium- to coarse-grained sandstone near the top. The Shinarump caps most of the isolated mesas and buttes and normally appears as a cliff about 50 feet thick. It rests unconformably on the top of the Moenkopi formation of Early and Middle(?) Triassic age. The unconformity is marked by elongate shallow depressions, termed swales, cut in the top of the Moenkopi. These swales are as much as 3 miles wide and have a relief of about 50 feet. Local relief on the unconformity does not exceed 5 feet except where symmetric and asymmetric channels are scoured as much as 75 feet into the underlying strata. These channels range from about 15 feet to as much as 2,300 feet wide.

Sixty-two channels and channel segments were noted; of these, 18 have mineralized exposures. Nine of the channels are described, including the Monument No. 1 and Monument No. 2 channels that have been and are being mined (1953). The Monument No. 2 channel, one of the richest deposits in the Monument Valley area, is a short channel that strikes N. 18° W. and is about 1-3/4 miles long. It ranges in width in its central part from 400 to 700 feet and has been cut about 50 feet into the underlying strata. The major part of the channel is occupied by the Vanadium Corporation of America's Monument No. 2 mine. During mine mapping, four types of ore bodies were noted; (1) rods, (2) tabular ore bodies, (3) corvusite-type ore bodies, and (4) rolls. The rods are cylindroidal bodies about 3 to 5 feet wide, 2 to 3 feet high, and 15 to 20 feet long. These rods are

found only in the Shinarump member of the Chinle formation. The tabular ore bodies are blanketlike masses composed of channel sediments impregnated with yellow uranium-vanadium minerals. These ore bodies are 40 to 50 feet long, range in width from 20 to 30 feet, and are 3 to 5 feet thick. The corvusite-type ore bodies are irregular-shaped masses within which the rock is thoroughly penetrated by vanadium minerals. Sediments of both the Shinarump member of the Chinle formation and the DeChelly sandstone are mineralized in this type of ore body. "Rolls," similar to those mined in the Morrison formation, are the fourth type of ore body. Not all of the channel sediments that fill the Monument No. 2 channel contain ore; weakly mineralized ground alternates at irregular intervals with richly mineralized ground, both laterally and vertically.

Swales and channels are important prospecting guides. Other useful guides are: (1) observable uranium minerals and abnormal radioactivity; (2) channel fill; and (3) channel conglomerates containing carbonaceous matter. Guides of uncertain value are: (1) limonitic impregnation of sandstone; (2) secondary copper minerals in channel fill; (3) abnormal thickness of an altered zone in the uppermost Moenkopi strata beneath channels; and (4) clay boulders, cobbles, and pebbles in channel fill.

Two tests for oil and gas have been drilled in the Monument Valley area. In 1924, the Midwest No. 1 Gypsum was completed to test the Gypsum Creek dome. It penetrated 2,083 feet to the Elbert formation of Late Devonian age. Although small shows of oil and gas were reported, the hole was abandoned. The most recent test, the Navajo A-1, was completed in 1953, on Hoskinnini Mesa, and was drilled to test the southern part of the Organ

Rock anticline. The hole was abandoned as a dry hole after being drilled 4,523 feet. No oil or gas shows were reported. It also bottomed in the Elbert formation. Other tests west and south of the Monument Valley area have been unsuccessful. However, two recent Shell Oil Company tests about 50 miles to the northeast produce both oil and gas from anticlinal structures. As favorable strata and structures underlie the Monument Valley area, the area is deemed worthy of further investigation.

### INTRODUCTION

#### PURPOSE OF WORK

In 1951 and 1952, the U. S. Geological Survey undertook, on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission, a program of uranium investigations and geologic mapping in the Monument Valley area, Apache and Navajo Counties, northeastern Arizona (fig. 1). The work had three major objectives. The first was to accumulate data basic to an understanding of the regional geology. The second was to appraise the Triassic strata as host rocks for uranium deposits, and to select areas favorable for exploration for concealed deposits. The third objective was to study the controls that influence uranium deposition and from this study to establish guides useful in prospecting for uranium deposits.

#### FIELD METHODS

The geologic mapping was done on aerial photographs at scales approximating 1:31,680 and 1:20,000. The geology was then transferred by inspection onto topographic maps at a scale of 1:48,000.

A radioactivity survey was carried on concurrently with the mapping program. Areas of abnormal radioactivity were sampled.

#### ACKNOWLEDGMENTS

Special thanks for geologic assistance during the course of this project are due to C. B. Hunt, J. D. Sears, J. F. Smith, Jr., and R. P. Fischer.

The local inhabitants advised and assisted in securing water and supplies; to all we are grateful.

It is a pleasure to acknowledge the cooperation given by geologists of the U. S. Atomic Energy Commission, in particular, Ralph H. Wilpolt, John W. Chester, and John W. Hill.

Officials of the Vanadium Corporation of America kindly permitted us to map the workings of their Monument No. 2 mine. We are indebted for assistance to Mr. D. W. Viles, Vice-President in charge of mining; Mr. Robert Anderson, former superintendent of the Monument No. 2 mine; and the late Mr. Carl Bell, mine foreman.

Among the many geologists who participated in the geologic mapping of the area were H. E. Malde, D. H. Johnson, T. L. Finnell, E. D. McKay, R. J. Claus, and C. F. Lough, all of the U. S. Geological Survey. Malde, Thaden, and Claus mapped the Garnet Ridge area (fig. 1) during a part of the summer of 1952.

Finnell spent about 6 weeks at the Monument No. 2 mine in 1951, and while there developed hypotheses (Finnell, 1957) suggesting that fractures were instrumental in the introduction and localization of the ore.

GEOGRAPHY

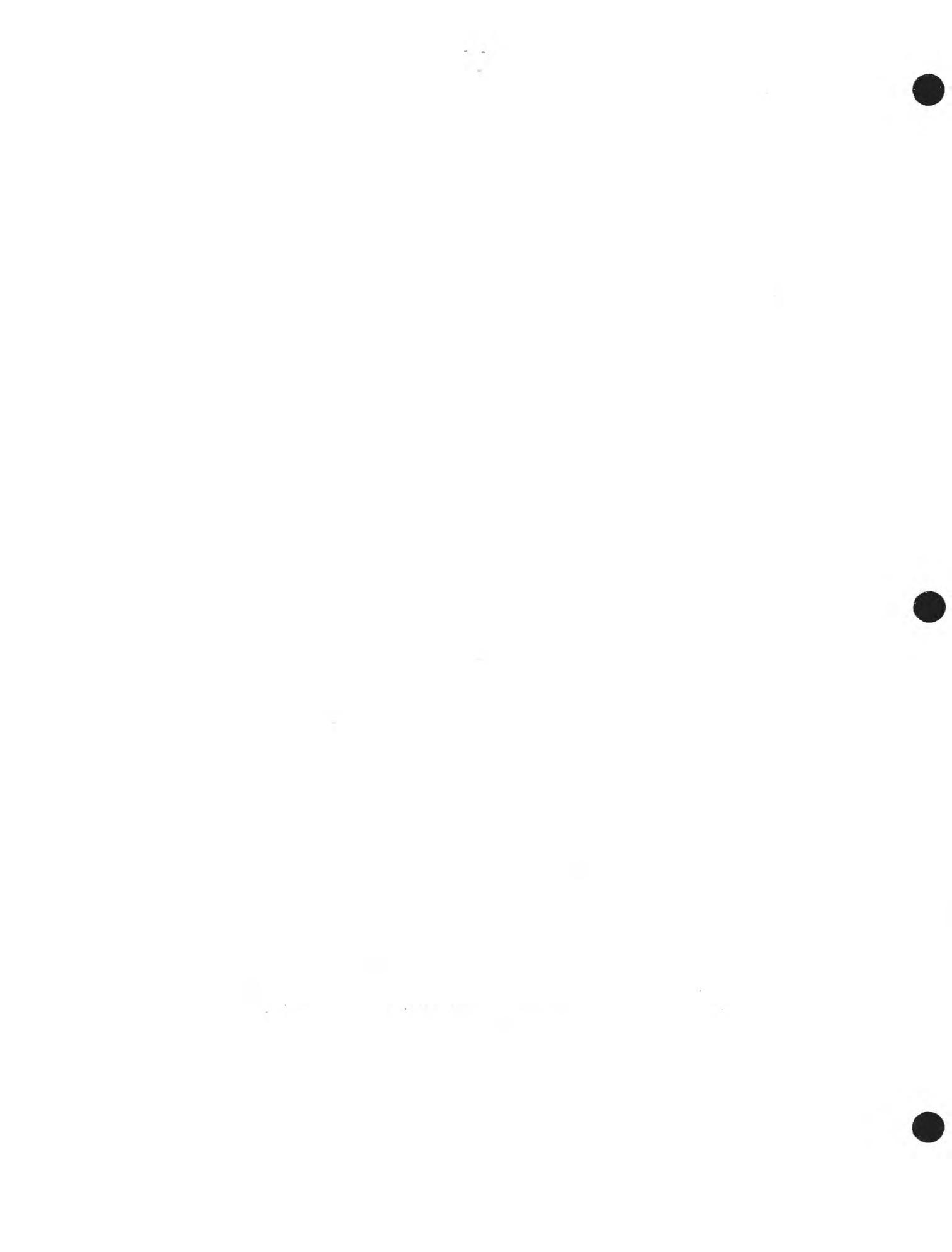
## LOCATION OF AREA

Monument Valley lacks clearly delineated geographic boundaries. In general it occupies parts of both Utah and Arizona and is near the eastern border of both states. The northern part of the valley was studied by Baker (1936); the southern part is the area described in this report. The Monument Valley area of this report extends from longitude  $109^{\circ} 45'$  W. to  $110^{\circ} 30'$  W., a distance of about 41 miles. Its northern boundary is near the  $37^{\circ} 00'$  parallel north and it extends southwards to the  $36^{\circ} 45'$  parallel north, a distance of about 17 miles. In all, the mapped area consists of three 15-minute quadrangles and covers about 700 square miles (fig. 2). The three quadrangles occupy parts of Apache and Navajo Counties, Ariz., and a small part of San Juan County, Utah. The area is wholly within the Navajo Indian Reservation.

The Monument Valley area is within the central part of the Colorado Plateau and has much of the scenery, climate, and topography typical of that section of the country. The scenic features are due to pronounced differential erosion. The valley floor is marked by isolated mesas and ridges, castellated crags, fluted columns, and monuments, which give the valley its name (fig. 3). The altitude of the area rises gradually from about 4,800 feet along the east edge to well over 7,000 feet along the west edge. The climate is arid and the region is a desert. Vegetation is sparse below 5,000 feet but becomes more abundant and varied at higher altitudes. Most of the inhabitants are Navajo Indians whose principal



Figure 3.--View looking northwest into Tse Biyi from crest of Hunts Mesa. Many of the buttes, monuments, and crags are named. Monuments rise about 800 feet above valley floor.



occupations are grazing sheep and weaving rugs. All the white inhabitants live near trading posts at Kayenta and Dinnehotso, Ariz., and Gouldings and Oljeto, Utah (fig. 1).

## ROADS

Roads are poor and travel is difficult during or following severe sandstorms or rainstorms. Most automobile traffic is restricted to four principal roads, of which the most important is the Mexican Hat-Kayenta road, known as Navajo Indian Reservation Route No. 1 (Utah Highway 47; fig. 1). It is the through route from Utah southward to Grand Canyon and Flagstaff, Ariz. Next in importance is the road that extends from the main uranium producer in this area, Vanadium Corporation of America's Monument No. 2 mine, to Mexican Water, Ariz., (fig. 1). The third road extends from the Monument No. 2 mine to Mexican Hat, Utah (fig. 1). Work during the summer of 1952 by both State and Federal highway agencies has so improved this road that the major part of it is suitable for all-weather traffic. The fourth road, passable during most of the year, extends north-eastward from Kayenta to Dinnehotso junction, and then turns southward to Chinle and Canyon DeChelly.

## GEOLOGY

### STRATIGRAPHY

#### General statement

Sedimentary strata exposed range in age from Permian to Recent. In general the older rocks crop out in the north-central part with younger rocks cropping out on the east, west, and south sides. Scattered

irregularly across all outcrops are deposits of dune sand, alluvium, and sand and gravel. Sedimentary rocks range in age from Permian to Jurassic and have an aggregate thickness of about 5,000 feet (fig. 4). Most of these strata consist of eolian and fluvial deposits which show some regularity in alternating one with another. In general, they range from light buff to deep reddish brown.

Many of the formations are light-buff or reddish-brown massive or bedded sandstones. A prominent exception is the Chinle formation. The DeChelly sandstone member of the Cutler formation resembles the Wingate sandstone as well as the Navajo sandstone. The Organ Rock and Hoskinnini tongues of the Cutler formation are so alike that north of this area, in the vicinity of Monitor Butte (fig. 1) where the intervening DeChelly sandstone pinches out, the Organ Rock and the Hoskinnini are distinguished only with difficulty (Thomas E. Mullens, written communication). Most of the units, however, are easily recognizable and the contacts are well exposed.

Wherever the massive sandstone beds are protected by a resistant cap rock they form vertical cliffs; unprotected, they form rounded, steep-sided knolls alternating with deep narrow ravines.

#### Permian system

##### Cutler formation

The Cutler formation is exposed over a large area in the northern part of the Monument Valley area, Arizona. It crops out as far west as Copper Canyon and as far east as Comb Ridge. To the south, the Cutler dips below

the surface just north of the Porras Dikes (fig. 1) due to the southward plunge of the Monument upwarp. Most of the mesas, buttes, and monuments are carved from the Cutler formation. The base of the formation is nowhere exposed in this area although to the north, Baker (1936, p. 28) reports extensive exposures of the entire formation.

The Cutler formation consists of five units; from oldest to youngest they are the Halgaito tongue, the Cedar Mesa sandstone member, the Organ Rock tongue, the DeChelly sandstone member, and the Hoskinnini tongue. The DeChelly and Cedar Mesa are buff to gray massive crossbedded sandstones. The Halgaito, Organ Rock, and Hoskinnini tongues are red fine-grained sandstones, siltstones, mudstones, and claystones. The Halgaito, Cedar Mesa, and Organ Rock maintain a uniform thickness over most of their area of exposure. The DeChelly sandstone thins northward and pinches out at Monitor Butte, but thickens both to the east and south. The Hoskinnini tongue thickens northward and thins eastward.

Diagnostic fossils were not found during the course of the present work, but Baker (1936, p. 29) reports that plant and vertebrate fossils from exposures of the Cutler formation in the Utah part of Monument Valley are of Permian age.

During most of Cutler time westward-flowing streams spread sediments across the area. The deposition of these beds was interrupted twice; once by the Cedar Mesa sandstone which had a source area to the northwest, and the second time by the DeChelly sandstone which came either from the southeast or northwest (Baker and Reeside, 1929, p. 1447). The Cutler is a thick series of red thin-bedded claystones, siltstones, and fine-grained

sandstones into which two massive sandstone units interfinger. The lower sandstone, between the Halgaito and the Organ Rock tongues, is the Cedar Mesa, and the upper sandstone, separating the Organ Rock and the Hoskinnini tongues, is the DeChelly.

#### Halgaito tongue

The Halgaito tongue, the basal member of the Cutler, is the oldest sedimentary rock exposed in the Monument Valley area, Arizona. It crops out in the core of Gypsum Creek dome (fig. 2), a small breached dome which straddles the Arizona-Utah State line just south of Mexican Hat, Utah.

The Halgaito forms a broad quaquaversally sloping plain in the central part of its outcrop area of about 8 square miles. The plain is bounded on all sides by beds of increasingly steep dip which form an annular pattern of cuestas and hogbacks, as much as 40 feet high.

The Halgaito characteristically weathers to a smooth dusty surface that is overlain by loose chips and flakes up to 3 inches in length.

In the Monument Valley area, Arizona, the Halgaito is a series of red shaly siltstones and fine-grained silty sandstones with a few small thin lenses of interbedded blue and gray limestones. Remarkably uniform in color, the rock is a moderate reddish brown with a gray cast (approximately 10 R 4.5/3).<sup>1</sup> The major constituent of the Halgaito is poorly sorted

---

<sup>1</sup> Color names used in this report after Goddard, E. N., and others, 1948, Rock-color chart, National Research Council.

---

subangular clear colorless polished quartz. Minor constituents are muscovite

and rare grains of opaque minerals. The predominant grain size is about 0.02 mm although many of the grains are as small as 0.003 mm or as large as 0.06 mm.

In any bed of the Halgaito tongue, the sequence of deposition is from coarse material at the base to fine material at the top. A shiny upper surface of clay, with glistening specks of muscovite, commonly represents the end of a sequence. Although most of the beds are from one-sixteenth to 1 inch thick, a few lenses of silt-pebble conglomerate are as thick as 8 feet. The well-rounded conglomerate pebbles are as much as 2 inches in long dimension. The conglomerates may extend several hundreds of feet, but invariably they grade laterally into typical thin-bedded Halgaito.

A thick iron oxide stain on the grains gives the rock its brilliant color, but calcite, not iron oxide, is the principal cementing agent. The formation is limy to the point that the local name for the Halgaito is the "red lime" (Gregory, 1938, p. 42).

Several lenticular limestones, not more than 8 inches thick, are in the upper part of the unit. They are blue, gray, or bluish gray and form small horizontal patches on a surface of low and gently rounded land forms. The limestone beds consist primarily of light-blue angular to rounded, rough-surfaced, concretionary limestone pellets, in a gray nearly lithographic limestone matrix. The pellets are as much as 2 inches in long dimension and give the limestone lenses a rubbly appearance.

The complete thickness of the Halgaito is not exposed in the Monument Valley area, Arizona. However, more than 300 feet of its upper part crop out and its base can be seen in Utah just north of

the State line. It is reasonably certain that the Halgaito in the Monument Valley area is about the same thickness as the Halgaito section measured by Gregory (1938, p. 68) on the east flank of the Raplee anticline a few miles to the north. At that locality it is 402 feet thick.

The lower contact of the Halgaito, along the road near Mexican Hat, Utah, appears sharp and conformable with the underlying Rico formation of Permian age. Here the basal beds of the Halgaito are reddish-brown thin-bedded silty claystone or are gray to dark-brown lenticular rubbly limestone beds up to 3 feet thick interbedded with the silty claystones. At none of the localities visited was a limestone in contact with the Rico.

The upper contact also appears conformable, although other workers (Prommel and Crum, 1927, p. 384; Gregory, 1938, p. 42) have noted local unconformities between the Halgaito and the overlying Cedar Mesa sandstone member in other areas. Typical Halgaito is terminated at the upper contact by light-green, light-blue, and nearly white limy siltstone beds of the basal Cedar Mesa which carry abundant nodules of brilliant red and white chalcedony. Except for this obvious lithologic change, nothing along the rather limited extent of exposed Halgaito-Cedar Mesa contact suggests unconformity between the two.

No fossils were discovered anywhere in the unit. Baker (1936, p. 30), however, reports vertebrate remains tentatively identified as either Ephiacodon or Sphenacodon from Halgaito exposures in the

Utah part of Monument Valley, and Gregory (1938, p. 42) remarks that bone fragments found in the limestone lenses are diagnostic of a Permian age for the Halgaito.

The Halgaito represents the first sediments deposited by the westward-flowing streams (p. 31). East of the Monument Valley area, Cutler sediments are largely arkoses. As these sediments are traced westward they become finer grained and pass into nonred beds west of the mapped area (Baker and Reeside, 1929, p. 1446). In the Monument Valley area the bedding and predominant silt size of the sediments imply deposition distant from the source area and by relatively slow-moving streams. The thin interbedded blue and gray limestones and the silt-pebble conglomerates suggest the presence of intermittent playa lakes. Dried chips and flakes formed when these playa lakes dried. These fragments were broken, rounded, and then incorporated into the next laid beds when the waters readvanced, forming conglomerate pebbles.

#### Cedar Mesa sandstone member

The Cedar Mesa sandstone member of the Cutler formation crops out only north of Meridian Butte (fig. 2), and flanks the Gypsum Creek dome on the east as a series of low parallel hogbacks, and on the west and southwest as low mesas and cliffs.

In the Monument Valley area, Arizona, the Cedar Mesa is predominantly a series of variegated sandstone, sandy siltstone, siltstone, limy siltstone, and limestone beds; a few beds are as thick as 30 feet. Lateral gradation of the strata of the Cedar Mesa with an accompanying change in color is well displayed.

Much of the Cedar Mesa is a moderate orangish-brown (5 YR 5/5) well-sorted silty very fine grained quartz sandstone. The quartz grains are subrounded, covered by a faint iron oxide stain, and average about 0.06 mm in diameter. The grains range from 0.03 mm to 0.09 mm. The only significant minor constituents are calcite and green grains of a chlorite-like mineral. Calcite cement is abundant.

Another prominent lithic type in the Cedar Mesa is a light-brownish-gray (5 YR 7/1) poorly cemented sandstone that has a pink cast. The quartz grains are subangular and average about 0.07 mm in diameter. The grains are clear, colorless and are not stained. Sorting is only fair. Again, the only minor constituent of note is a green mineral of the chlorite group.

No good sites for measuring sections of the Cedar Mesa are available in the Monument Valley area, Arizona. However, several approximate measurements suggest an average thickness of about 315 feet. This thickness is much less than the 610 feet noted by Gregory (1938, p. 68) on the east flank of the Raplee anticline a few miles north of the mapped area.

The contact of the Cedar Mesa with the overlying Organ Rock member of the Cutler formation is poorly exposed. Where the contact is not covered by sand, it is concealed by a thick mantle of decomposed and disaggregated material. At the base of Meridian Butte (fig. 2), the contact is marked by an abrupt transition in color. The lower bed of the Organ Rock is a dark-reddish-brown micaceous siltstone with few sand grains. No evidence exists of an angular relationship between the units nor is there any indication of an erosional surface. A disconformable surface with relief exceeding 15 feet is known in some areas north of the Arizona-Utah State line, but in the Monument Valley area the contact between the members is marked primarily by the color change.

The southward thinning of the Cedar Mesa and a change from sandstone in the north to thin-bedded interfingering sandstone and red shaly siltstone beds mark the first break in the deposition of Cutler red beds (p. 30). The source of the Cedar Mesa is (Baker and Reeside, 1929, p. 1447) northwest of the area mapped. Near its southern limit of deposition, (south of the Monument Valley area) it loses its entity as a sandstone and becomes a transitional unit, with sandstone beds (i.e., Cedar Mesa) grading into typical Cutler red beds.

#### Organ Rock tongue

The Organ Rock tongue of the Cutler formation is exposed throughout the northern half of the Monument Valley area, Arizona. It forms the floor of Copper Canyon (fig. 2) and comprises the pedestals upon which are perched the monuments for which Monument Valley is named.

Where the Organ Rock has no overlying protective rocks, it forms badlands characterized by steep concave slopes, shallow nearly vertical-walled gullies, flat-topped knobs, and sharp-ridged divides. Where capped by the DeChelly sandstone member, the Organ Rock stands as a gently concave slope that steepens near the top of the unit and is nearly vertical at the contact.

The Organ Rock is predominantly a reddish-brown (10 R 4/3), poorly sorted siltstone. Here and there, especially near the base of the unit, are a few white to buff very fine grained silty sandstone lenses a few inches thick. The grain size changes gradually in the upper 25 to 50 feet, becoming coarser near the contact. At the upper contact the Organ Rock is a fine-grained sandstone indistinguishable from basal DeChelly.

The silt grains are mostly angular to subangular clear colorless quartz with a pronounced iron oxide stain. The average grain size is about 0.05 mm, but sorting is poor. Enough very small grains are included to make the member a clayey siltstone.

The cement appears to be a mixture of calcite and iron oxide. Splotches of clear calcite, up to several millimeters in diameter, are scattered through the member. This calcite has etched the quartz where they are in contact. Calcite also forms small bundles of subhedral crystals; each crystal is about the same size as the quartz grains. Other minor constituents include magnetite, gypsum, zircon, biotite, and muscovite.

The Organ Rock is dominantly even bedded and the bedding is remarkably parallel throughout the unit, whether it be siltstone in beds 2 inches thick, or sandstone in beds 20 feet thick. Some of the siltstone and many of the sandstone beds show crossbedding gently inclined to the horizontal.

The Organ Rock is about 670 feet thick near the Monument No. 2 mine area (fig. 1). Baker (1936, p. 34) cites a thickness of 696 feet for the Organ Rock on the east side of Monument Pass, Utah. Gregory's measurements (Gregory, 1938, p. 46) in San Juan County, Utah, and measurements by Miser (1925, p. 130-131) along the San Juan River demonstrate a southward thickening of the Organ Rock toward the Monument Valley area.

From a distance the contact between the Organ Rock and the overlying DeChelly appears sharp; the color changes from dark reddish brown to light brown, the slope changes from a steep angle to vertical, and bedding

planes disappear. On the outcrop, however, these criteria are invalid. Upon close inspection it can be seen that the upper 25 to 50 feet of the Organ Rock grade in color and in grain size to material that is megascopically identical to the DeChelly. The slope gradually steepens and approaches the vertical in the vicinity of, but not necessarily at, the contact. Nor can the lack of bedding planes be used to pick the contact, for the bedding planes, although closely spaced in the lower Organ Rock, are less closely spaced near the top of the member and persist into basal strata of the DeChelly tens of feet. For mapping purposes we selected a zone about 20 feet thick in which the bedding planes of the Organ Rock disappear, the steep slope of the Organ Rock gives way to the vertical cliff of the DeChelly, and the color changes from the dark reddish brown of the Organ Rock to the light tan of the DeChelly.

No fossils were found in the Organ Rock. Baker (1936, p. 35) reports the presence of two fossil plants of Permian age, as well as fragmental vertebrate remains that have also been identified as Permian in age.

At the close of Cedar Mesa deposition, westerly flowing streams began depositing another sequence of red beds which form the Organ Rock tongue. The even bedding and the fine grain of the red bed sediments suggest that the streams were relatively sluggish. Near the close of Organ Rock deposition, light-colored sands, either from the southeast or northwest, (Baker and Reeside, 1929, p. 1447) gradually mingled with the red fluvial sediments and eventually displaced them.

#### DeChelly sandstone member

One of the most distinctive stratigraphic units in the Monument Valley area is the grayish-yellow to tan (5 Y 8/4) massive crossbedded fine-grained DeChelly sandstone member of the Cutler formation. Commonly it is stained

by wash from overlying units. The DeChelly sandstone forms the main part of the monuments and larger mesas.

Wherever the DeChelly sandstone is protected by overlying formations, it forms unscalable vertical walls. The unit, however, is not extremely resistant and where unprotected weathers to round hummocky knolls. In places a great variety of alcoves, recesses, and tunnels have been formed at its base. These range in size from very small ones to great arched alcoves that are of a size sufficient to accomodate whole villages of cliff dwellings (fig. 5).

The DeChelly is a poorly sorted fine-grained sandstone with the grains ranging in size from 0.06 mm to 0.50 mm although a bimodal grain-size distribution exists. One grain size ranges from 0.25 mm to 0.50 mm (the average is about 0.30 mm) in diameter; the other ranges from about 0.06 mm to 0.12 mm (the average is about 0.10 mm). The grains range in shape from subround to round, but a few of the larger grains are overgrown by authigenic quartz and are angular. Most of the grains are of colorless quartz. However, small amounts of microcline, plagioclase feldspar, chalcedony, muscovite, biotite, and zircon are scattered at random throughout the sandstone. A thin brown film of iron oxide coats each grain, and it is this film that imparts color to the unit.

The sandstone is weakly cemented by chalcedony, calcium carbonate, and iron oxide, so the unit is friable.

The DeChelly sandstone ranges in thickness from 300 feet to 550 feet, and it thins and disappears to the north in the vicinity of Monitor Butte, about 15 miles north of the Utah-Arizona State line. In the western part



Figure 5.--Photo of small cliff dwelling in a shallow alcove in the DeChelly sandstone member of the Cutler formation. Most cliff dwellings in the Monument Valley area are this shape and size. Marks on the wall above and behind the dwelling are pictographs.



of the Monument Valley area the DeChelly is about 300 feet thick and decreases rapidly in thickness northward to its pinchout. The DeChelly thickens in an easterly and southerly direction. In the center of Monument Valley, near Tse Biyi, it is about 450 feet thick. Farther east, near the Monument No. 2 mine (fig. 2), it is as much as 550 feet thick; and, to the south near Canyon DeChelly, beyond the limits of the mapped area, the DeChelly sandstone is well over 800 feet thick (McKee, 1934, p. 224).

A prominent and distinct disconformity unusually free of relief is at the top of the DeChelly sandstone (fig. 6). This disconformity is marked by the abrupt change from the light-tan massive crossbedded DeChelly sandstone to the dark-red even-bedded sandstone beds of the basal part of the Hoskinnini tongue of the Cutler formation. We consider these basal Hoskinnini beds to be a "reworked zone" composed partly of DeChelly sediments.

The top of the DeChelly sandstone, as here selected, differs from that chosen by Baker (1936). Baker recognized the disconformity but chose to include it and the "reworked zone" within the DeChelly sandstone. He indicates the boundary between the DeChelly and the overlying Hoskinnini as a gradational one marked by a series of beds 20 feet or more thick that show a gradual lithologic change from massive crossbedded sandstone to even-bedded red beds.

The disconformity, however, is so widespread and so persistent that we consider it significant. We suggest tentatively, therefore, that the disconformity marks the boundary between two major stratigraphic units. The complete absence of fossils in the Hoskinnini prevents any conclusive





Figure 6.--Photo of Permian and Triassic formations, showing relationship of a channel to other strata. Note the symmetrical scour formed by the channel (Mitchell Mesa No. 1) in the Moenkopi formation. Channel is scoured about 75 feet into underlying strata. Tcs - Shinarump member of Chinle formation; Tm - Moenkopi formation; Pch - Hoskinnini tongue of Cutler formation; and Pcd - DeChelly sandstone member of Cutler formation.



determination as to the relative ages of the units involved, and the base of the Hoskinnini may mark the rock system break between the Permian and the Triassic. Lacking paleontologic evidence, the point of view expressed above is not followed on the map (fig. 2).

Fossils were not found in the DeChelly sandstone although vertebrate and invertebrate footprints were noted in several localities. The best track locality that has been discovered is along the east edge of Todicheenie bench near the upper end of Adahchijiyahi Canyon (fig. 2). Baker (1936, p. 37) reports a lack of fossils in the DeChelly sandstone although he found specimens of Walchia piniformis and Yakia hetophylla of known Permian age in the transitional beds that mark the change from the Organ Rock tongue to the DeChelly sandstone member.

The DeChelly is the uppermost of two sandstone beds that interfinger with typical Cutler red beds (p. 30). The broad sweeping cross-laminae so typical of the DeChelly imply an eolian origin. The source of the sands that formed the DeChelly is unknown; however, the DeChelly interfingers with the Cutler red beds from the southeast and thickens in that direction. If the source area is considered to be near the greater thickness, it would appear that the DeChelly came from the southeast. Baker and Reeside (1929, p. 1447) note that the dominant dip of the crossbedding planes and the direction of thinning suggest a southeasterly source. They conclude, however, "It seems to the writers highly probable that all the light-colored sandstones came from the north or northwest."

Hoskinnini tongue

The Hoskinnini tongue of the Cutler formation is widespread in the Monument Valley area. Commonly, it crops out as a steep face, but near the tops of many mesas and monuments, it weathers to a steep slope below the more gentle slopes formed by the shaly siltstone beds of the overlying Moenkopi formation. The extent of outcrop of the Hoskinnini is nearly coincident with that of the DeChelly. The type locality of the Hoskinnini is given by Baker and Reeside (1929, p. 1443) as the north face of Hoskinnini Mesa several miles west of Oljeto Trading Post on Moonlight Wash (i.e., Oljeto Wash). The unit is so consistent in its makeup over such great distances that stratigraphic sections similar to the exposures at Hoskinnini Mesa can be found almost everywhere in the western part of the area.

The Hoskinnini tongue consists of a series of dark-red even-bedded nodular-weathering siltstone and fine-grained sandstone beds. In appearance the beds are similar to those of the Organ Rock tongue. In the Monitor Butte area, for instance, where the intervening DeChelly sandstone is absent, Baker (1936, p. 39) reports that the Hoskinnini is inseparable from the Organ Rock tongue of the Cutler formation. However, recent work by Thomas E. Mullens (written communication) of the U. S. Geological Survey in the Clay Hills area of Utah has suggested that the Hoskinnini can be differentiated from the Organ Rock tongue. Mullens has found that the Hoskinnini is a very fine grained sandstone containing abundant well-rounded medium-sized grains. This lithology, plus the smooth surface weathering characteristic of the Hoskinnini in the Clay Hills area, Mullens contends, is adequate to separate the Hoskinnini

from the underlying Organ Rock. J. H. Stewart and his associates / using

---

/ Stewart, J. H., Williams, G. A., Albee, H. F., and Raup, O. B., in preparation, Stratigraphy of Triassic and associated formations in part of the Colorado Plateau region, with a section on Sedimentary petrology by R. A. Cadigan: U. S. Geol. Survey Bull.

---

criteria established by Mullens have traced the Hoskinnini northward from the Clay Hills area, where it is as much as 100 feet thick, to a pinchout in the middle of the White Canyon area, Utah.

In the Monument Valley area, Arizona, the Hoskinnini tongue can be divided into two units. Because of their thinness, however, these divisions have been combined and mapped as one unit (Pch). The lower unit consists of an orange to dark-red massive sandstone (p. 41), which lies disconformably on the DeChelly. The upper unit is the dark-red even-bedded sandstone of the type Hoskinnini. Locally small discrete blocks of DeChelly sandstone are embedded in the lower Hoskinnini sandstone. Elsewhere, small tan whorls can be traced from the DeChelly into the basal few feet of this same sandstone. We consider this lower sandstone to be a reworked zone consisting in part of DeChelly, and in part of Hoskinnini sediments (p. 41). In many places the reworked zone is missing, and in these localities the dark-red even-bedded strata of the upper unit of the Hoskinnini tongue lie directly on the DeChelly sandstone.

Grains of two sizes are in the lower sandstone; some are distinctly coarse and average about 0.40 mm in diameter, although a few ellipsoidal grains are as much as 1.30 mm long. Smaller grains are dominant, and

average about 0.06 mm in diameter. Much of the coarse material is within the small tan whorls that can be traced into the underlying DeChelly sandstone. The upper unit of the Hoskinnini consists of even-bedded fine-grained sandstone. In this unit, local lenses of siltstone and grit persist for lateral distances of 10 to 20 yards. Most of the grains range in shape from subangular to round with the coarser sediments slightly more angular, possibly as a result of authigenic quartz overgrowths.

The major constituent of the Hoskinnini is quartz; plagioclase feldspar and chalcedony are accessory minerals. Coating all grains is a thin film of iron oxide. Calcium carbonate is the principal cement.

The Hoskinnini thins eastward. Thomas E. Mullens (written communication) reports the Hoskinnini to be about 100 feet thick in the Red House Cliffs area. North of the Red House Cliffs it pinches out in the middle of the White Canyon area (Stewart and others<sup>1</sup>). Baker (1936, p. 39)

---

<sup>1</sup> Stewart, J. H., Williams, G. A., Albee, H. F., and Raup, O. B., in preparation, Stratigraphy of Triassic and associated formations in part of the Colorado Plateau region, with a section on Sedimentary petrology by R. A. Cadigan: U. S. Geol. Survey Bull.

---

cites a thickness of 55 feet in the Canyon of the San Juan River at the mouth of Nakai Creek, and about 50 feet near the northeast corner of Hoskinnini Mesa. In the Monument Valley area, Arizona, the Hoskinnini is about 45 feet thick along the flanks of Hoskinnini Mesa, but near the Monument No. 2 mine (fig. 2) it is only about 15 feet thick. It is missing

from several of the monuments in the Utah part of Monument Valley (Baker, 1936, p. 39). However, at no place examined in the Arizona part of the Monument Valley area was the Hoskinnini absent.

The following section of the Hoskinnini tongue of the Cutler formation measured at the southeast end of Hoskinnini Mesa, about 12 miles northwest of Agathla Peak (fig. 2), is characteristic.

	<u>Feet</u>	<u>Inches</u>
Moenkopi formation		
Hoskinnini tongue of Cutler formation		
Limestone, crinkly, contains mixture of calcite and pink quartz. . . . .		0.25
Sandstone, even-bedded, dark-red . . . . .	3	
Limestone, crinkly, contains mixture of calcite and pink quartz. . . . .		0.75
Siltstone, shaly, dark-red, thin-bedded, nodular weathering . . . . .	10	
Sandstone, massive, dark-red, fine-grained, thin- bedded; weathers as rounded ledges . . . . .	6	
Sandstone, dark-red, massive, fine-grained . . .	$\frac{19}{38}$	
Unconformity		
DeChelly sandstone member of Cutler formation		

Although the Moenkopi is reported (Longwell, and others, 1923, p. 9), as unconformably overlying the Cutler formation, Baker (1936, p. 40-43) could find no evidence of the unconformity in the Utah part of Monument Valley. However, he cites several localities in the Arizona part of the Monument Valley area where this unconformity could be observed. We found no localities where the Moenkopi unconformably overlay the Hoskinnini.

The upper contact of the Hoskinnini is gradational. Baker (1936, p. 40) selects the upper contact at a horizon 8 to 11 feet above two crinkly limestones. Both limestones are unusually persistent in the western part of the Monument Valley area. They were not found, however, in the eastern part, possibly being replaced in that area by a persistent bed of white to gray fine-grained sandstone about 4 feet thick.

In most localities examined the strata 8 to 11 feet above the crinkly limestones change from arenaceous even-bedded red beds to chocolate-colored beds composed of shaly siltstone. This change is expressed topographically by the transition from a steep slope formed by the Hoskinnini red beds to moderate slopes composed of the shaly siltstones of the Moenkopi formation.

Paleontologic evidence for the age of the Hoskinnini is lacking. Baker (1936, p. 40) suggests, (on the basis of lithologic similarity to the sediments forming the Organ Rock tongue), that the Hoskinnini is Permian in age and represents the highest of the three red bed tongues of the Cutler formation.

#### Triassic system

##### Moenkopi formation

Conformably overlying the Hoskinnini tongue of the Cutler formation are the chocolate-brown to dark reddish-brown (10 R 3/4) easily eroded shaly siltstone and sandstone beds of the Moenkopi formation of Early and Middle(?) Triassic age. Where it is protected by a cap of the Shinarump member of the Chinle formation, the Moenkopi forms gentle to moderately steep talus-covered slopes; where unprotected, it is intricately dissected into a maze of canyons, ridges, low cliffs, benches, and isolated tables.

On weathered surfaces the Moenkopi is dark reddish-brown (10 R 5/4) with local areas of chocolate brown (10 R 3/3). Its coloration is diagnostic and contrasts markedly with the light gray of the overlying Shinarump member of the Chinle formation and the light tan of the DeChelly. Fresh surfaces of the Moenkopi formation are light-brown to pinkish-brown. In places Moenkopi beds are a light yellowish-gray (5 Y 7/2) to a light olive-gray (5 Y 5/2). These have no great extent and laterally grade imperceptibly into the dark siltstone and sandstone beds of typical Moenkopi.

Distinctive features of the Moenkopi are many minor structures such as ripple marks, rain pits, and shrinkage cracks. Three main types of ripple marks were observed. The dominant type, confined principally to shaly siltstone, consists of even, asymmetrical, parallel crests and troughs, averaging about 1 inch from crest to crest. These current-type ripples have been called parallel ripple marks by McKee (1954, p. 57). The second type are cusplike and commonly appear as small basins about 3 inches in diameter. McKee (1954, p. 60) considers these characteristic of stream deposits. In the Monument Valley area they are common in the sandstones. Interference ripples ("tadpole nests") are the third type and are relatively scarce. They resemble a honeycomb and appear as a series of small deep cells each about 1 inch in diameter, surrounded by sharp crested walls. Raindrop pits and shrinkage cracks are found locally and are best preserved in the fine-grained sediments. In many places these shrinkage cracks (mud-cracks") are filled with a fine-grained sand. Scattered through the

siltstones are a few rounded quartz grains larger than silt size. The sandstone beds are fine grained with most of the grains ranging in size from about 0.10 mm to a maximum of about 0.30 mm. Most of the grains are angular to subangular. Colorless quartz is the major constituent, and accessory minerals are microcline, plagioclase feldspar, and mica. Zircon and garnet grains have been noted. All of the grains are coated with a film of brown iron oxide. Calcium carbonate is the main binding agent, with both chalcedony and iron cementing the grains.

Along the east and west flanks of Skeleton Mesa (fig. 2) lenticular beds of satin spar gypsum up to 14 inches thick are intercalated in the shaly siltstone beds. Although gypsum in the Moenkopi is widespread in western Utah (McKee, 1954, p. 47), it is uncommon in the Monument Valley area.

Measured sections of the Moenkopi formation indicate a persistent and gradual thinning to the east. This conforms well to the regional pattern of the Moenkopi. McKee (1954, p. 76) reports that the Moenkopi is as much as 2,000 feet thick in western Utah and that it gradually thins eastward. In the Zion Park region the Moenkopi is more than 1,600 feet thick (Gregory, 1950, p. 59). Eastward the formation thins to about 900 feet in the Capitol Reef area (Smith, Hinrichs, and Luedke, 1952), and near the western edge of the Monument Valley area it is only about 275 feet thick. As one traces the formation eastward in Monument Valley, it continues to thin and is only about 65 feet thick near the eastern edge.

The following section is considered characteristic of the Moenkopi formation as developed in the western part of the Monument Valley area, Arizona.

Section of Moenkopi formation measured at southeast end of Hoskinnini Mesa, about 12 miles northwest of Agathla Peak

	<u>Feet</u>
Shinarump member of Chinle formation	
Unconformity	
Moenkopi formation	
Siltstone, shaly, dark-reddish-brown with light-grayish-green zone 2 feet thick near top; thin-bedded, interleaved lenticular sandstone beds each about 2 feet thick through entire sequence . . . . .	171
Sandstone, dark-reddish-brown massive fine-grained. . . . .	3
Siltstone, shaly, reddish-brown, forms gentle slope . . . . .	4
Sandstone, dark-red, even-bedded, forms cliff . . . . .	27
Siltstone, shaly, dark-red, interbedded with platy ripple-marked sandstone. . . . .	13
Sandstone, dark-reddish-brown crossbedded, fine- to medium-grained; locally alters to a light-gray . . . . .	5
Siltstone, shaly, dark-red to brown, ripple-marked . . . . .	23
	246
Hoskinnini tongue of Cutler formation	

In several localities broad elongate shallow depressions, termed swales, are cut in the top of the Moenkopi (p. 144). These swales range in width from half a mile to as much as 3 miles and extend in length for 3 to 4 miles. They have about 50 feet of relief.

The contact with the Hoskinnini tongue is gradational wherever observed in this area. In mapping, the contact used was the change from the massive nodular weathering ledge-forming siltstones and fine-grained sandstones of the Hoskinnini to the thin-bedded shaly siltstones of the Moenkopi. This contact was emphasized in the western part of the area by the crinkly limestones, and in the eastern part by a bed of white to gray fine-grained sandstone (p. 48). Commonly this contact is marked by a topographic break between the clifflike escarpments of the Hoskinnini and the receding slopes formed by the Moenkopi. As selected, this contact is about 8 to 11 feet below the contact selected by Baker (1936, p. 40).

The upper contact is distinctly unconformable, for an undulatory erosional surface of wide extent bevels the top of the Moenkopi formation. No evidence of angular discordance was noted. This disconformity shows but slight relief when viewed in gross aspect although the swales referred to above cause it to be undulatory and deep channel scours (p.135) interrupt its smooth undulations. In general, relief along the disconformity, if one excepts the deep channel scours and the broad swales, does not exceed 3 to 5 feet.

McKee (1954, p. 37) reports as a common phenomenon hills or mounds of Moenkopi sediments that stick up into the Shinarump member of the Chinle formation. Features of a similar nature were not noted in the Monument Valley area.

In the Monument Valley area a discoloration or bleaching of Moenkopi sediments is nearly everywhere present below the disconformity. Generally this discoloration occurs as a 6 inch uninterrupted grayish-green zone

which contrasts markedly with the reddish brown of underlying normal Moenkopi sediments. Locally, however, especially below channels (p. 185), this light-grayish-green zone may increase in thickness to as much as 7 feet. The grayish-green discoloration is strongest in those sediments directly below the disconformity. A few inches below the Shinarump member, the intensity of the grayish-green color diminishes through a transitional zone about 6 inches thick that consists of alternating bands of grayish green and reddish brown. Below this transition zone is the normal reddish-brown color of the Moenkopi.

Fossils were not found in the Moenkopi in the Monument Valley area of Arizona. An Early Triassic and possibly Middle(?) Triassic vertebrate fauna has been found in the general area of Meteor Crater, Ariz. (Welles, 1947).

The Moenkopi in the mapped area seems to have been deposited in a marginal marine area which was exposed to subaerial erosion at intermittent periods during its formation. Ripple marks imply a relatively shallow water origin for some of the sediments. Raindrop impressions and shrinkage cracks suggest that Moenkopi sediments were exposed to the atmosphere. The presence of gypsum beds suggests local lagoons and playas. Many of the sandstones in the Monument Valley area are interpreted by McKee (1954, p. 78) to represent stream-laid deposits built along delta fronts.

Moenkopi sediments in the Monument Valley area probably can best be considered as near shore mud flats on a broad plain sloping gently westward to the sea from higher lands in western Colorado (Baker, 1933, p. 36). On these mud flats, lagoons and playas formed, and locally delta-like deposits were built onto this sloping plain by westward-flowing rivers (McKee, 1954, p. 79).

As the seas that deposited the silts and sands of the Moenkopi withdrew, a surface of low relief was exposed. McKee (1951a, p. 88) considers that this surface was dissected for a considerable period of time. In view of the complete absence of any deposits that can be definitely related to such an extensive period of dissection, we believe that the period of exposure was relatively short and that the deposition of the Shinarump member of the Chinle formation began shortly after the surface of the Moenkopi was exposed. We suggest that most of the channels, swales, and other features that mark the contact of the Moenkopi and Shinarump were formed by the streams that deposited sands and gravels of the Shinarump member. These clastics were deposited by northerly flowing streams from a newly raised highland mass in central and southern Arizona (McKee, 1951b, p. 493).

#### Chinle formation

The Chinle formation consists of conglomeratic sandstone, variegated siltstone, mudstone, and claystone beds in which light gray, gray, green, lavender, violet, black, and yellow are outstanding colors. In the Monument Valley area the predominant cast of the formation is a light greenish gray with the uppermost unit, the Church Rock member, a contrasting reddish brown.

Badland topography is characteristic, due primarily to the easily eroded claystones and mudstones. A cliff about 50 feet high, formed by the Shinarump member, commonly marks the basal part of the unit. Locally, large masses of red sandstone and siltstone talus derived from the overlying strata form a protective cap over the Chinle claystones and mudstones.

As the Chinle weathers back, these areas are dissected and preserved as demoiselles. Wherever exposed, the Chinle formation is marked by large landslide blocks. Blocks as much as a quarter of a mile on a side flank Skeleton Mesa and attest to the lack of internal strength of the Chinle.

In dry weather the claystone and siltstone beds are firm, compact, and well indurated, and their surfaces are marked by a spongy "popcorn" appearance. In wet weather, however, the strata become slick, sticky, and almost impassable.

Gregory, (1917, p. 42), divided the Chinle formation into four divisions. Each division was given a letter of the alphabet with Division A representing the youngest and Division D the oldest. In order to conform to common stratigraphic practice we have designated each of the members of Gregory's Chinle by a geographic name and propose that the following nomenclature be used in the Monument Valley area, Arizona, for those four members of the Chinle formation delineated by Gregory. In 1956, the Geologic Names Committee of the U. S. Geological Survey approved the inclusion of the Shinarump conglomerate as the basal member of the Chinle formation. As used in this report, therefore, the Chinle in the Monument Valley area consists of five members.

<u>Gregory</u>	<u>Proposed usage</u>
Division A of the Chinle formation	Church Rock member of Chinle formation (new)
Division B of Chinle formation	Owl Rock member of Chinle formation (new)
Division C of Chinle formation	Petrified Forest member of Chinle formation (Gregory, 1950, p. 67)
Division D of Chinle formation	Monitor Butte member of Chinle forma- tion (new)
Shinarump conglomerate	Shinarump member of Chinle formation (Stewart, 1957)

In many places contacts between the several members are gradational. Those contacts originally established by Gregory (1917, p. 42) have been used in the course of this work.

and northern Arizona, state that "The pebbles in the Shinarump are composed almost entirely of quartz, quartzite, and chert."

Some pebbles are as much as 5 inches in diameter although most are considerably smaller, their average size being about three-fourths to 1 inch. The pebbles are predominantly quartz with smaller amounts of quartzite and chert. Less inert materials are present in extremely small quantities; in a few localities fragments of volcanic ash, limestone, schist, and granite are found.

Most of the formation is medium- to coarse-grained sandstone with the coarse-grained size predominating. Fine-grained sandstone beds are rare. The grains are subangular to subround, with considerable authigenic quartz overgrowth responsible for their angularity. The major constituent of the sandstone matrix is colorless vitreous quartz; minor constituents include small amounts of microcline, plagioclase feldspar, mica, zircon, and chalcedony. The main binding agent is silica; calcite and iron oxide are subordinate cements. In a few small areas argillaceous material acts as a cement.

The Shinarump member maintains a relatively uniform thickness over large areas. Although it thickens in places, this seems to be more of a local phenomenon than a regional trend. In the Utah part of Monument Valley it is as much as 210 feet thick although it averages between 100 and 140 feet in thickness (Baker, 1936, p. 45-46). In the Monument Valley area, Arizona, the Shinarump maintains a thickness of 50 to 75 feet that is constant for miles. Locally the Shinarump thins laterally, and in a distance of as little as a fourth of a mile may pinch out. The maximum thickness measured was about 150 feet. Variations in thickness that have

been observed can be attributed in part to the erosional unconformity at the base and in part to the gradational character of its contact with the overlying Monitor Butte member of the Chinle.

The following section, about 2-1/2 miles due east of Agathla Peak, is characteristic:

Section of Shinarump member of Chinle formation about 2-1/2 miles east of Agathla Peak

	<u>Feet</u>
Chinle formation	
Shinarump member	
Conglomerate, light-gray to yellowish-brown; rounded pebbles of quartz, quartzite, and chert, all vari-colored, and with maximum diameter of about 2 inches; matrix of medium- to coarse-grained sand grains; locally grades laterally into conglomeratic sandstone; forms cliff. . . . .	15
Sandstone, light-gray, massive, crossbedded, platy, medium- to coarse-grained; friable; small rounded pebbles of quartz, quartzite, and chert scattered at random through mass . . . . .	41
	56
Disconformity	
Moenkopi formation	

In most places, the contact of the Shinarump member with the overlying Monitor Butte member of the Chinle is ill-defined. Gregory (1913, p. 433) and Woodruff (1910, p. 87) both suggest that an

unconformity may be at the top of the Shinarump in this region, but we have found no evidence to substantiate this. On the contrary, the Shinarump and the Monitor Butte members intertongue. Richard Q. Lewis, Sr., and Donald E. Trimble (written communication) studying the Utah part of Monument Valley, report an absence of unconformity and state unequivocally that intertonguing exists between the Shinarump and the overlying member of the Chinle. Baker (1936, p. 46) reports the same and concludes that the Shinarump can be regarded as the basal conglomerate of the Chinle formation.

Wherever examined in the Monument Valley area, Arizona, the contact between the Shinarump member and the overlying sediments is gradational. The sandstone of the Shinarump grades into a series of alternating sandstones and claystones of the Monitor Butte member. At some places the upper contact of the Shinarump is arbitrarily selected at a zone that is marked by a concentration of black concretions each about one-thirty-second of an inch in diameter. Almost directly above this zone are the crossbedded sandstones and dark-colored clays of the Monitor Butte member of the Chinle formation.

Vertebrate and invertebrate fossils are practically nonexistent in the Shinarump member, probably because they were destroyed by the coarse clastic sediments. McKee (1936, p. 261) collected some pebbles from the Shinarump that contained an invertebrate fauna typical of the

marine facies of the Kaibab limestone of Permian age. These pebbles suggest to McKee a source for the Shinarump to the south and east of the Monument Valley area.

Large quantities of wood were buried during Shinarump time and are of value in dating the formation. Existing opinion is that these trees grew on the uplands and along the banks of the streams that deposited the Shinarump sediments. Their age, therefore, is the age of the enclosing sediments. All of the logs that have been examined in the Shinarump have undergone some transportation. Daugherty (1941, p. 29) reports that although the majority of the logs he examined in the Shinarump had been rafted into their present location, some of the logs found in the Chinle strata exposed in the Petrified Forest National Monument were buried in place. In the Monument Valley area the fossil wood ranges from large silicified logs as much as 60 feet long and 3 to 5 feet in diameter to tiny pieces of carbonized wood associated with uraniferous deposits. Species have not been identified. The form Araucarioxylon arizonicum has been identified to the south in the Petrified Forest National Monument as well as in other localities (Daugherty, 1941, p. 8). It has a widespread distribution, and it seems likely that it may also be among the silicified logs exposed in the Monument Valley area.

Daugherty (1941) interprets the age of these fossil logs in the Chinle as Late Triassic. He believes that all of the fossil plants in the Shinarump are identical with species found in the other members of the Chinle and that the area probably consisted of broad open-forest grass-covered uplands dissected by the tree-lined streams. He suggests that present-day savannahlike areas are the closest approach to conditions that existed during early Chinle (Shinarump) time. Daugherty contends that the climatic range was from tropical to subtropical. Normally, rainfall was ample, but these periods of adequate moisture were interrupted by short periods of aridity.

#### Monitor Butte member

In the Monument Valley area, Arizona, the somber-colored claystone, siltstone, sandstone, and conglomeratic sandstone beds of the Monitor Butte member commonly intertongue with the underlying Shinarump member.

The Monitor Butte member is well exposed along the northeast flank of Monitor Butte, its type locality. The butte is about 14 miles northwest of Oljeto, Utah.

In the Monument Valley area, Arizona, the Monitor Butte member is best exposed near the volcanic neck, Agathla Peak, and along the flanks and around the southern nose of the Agathla anticline (fig. 2). In these areas it consists predominantly of crossbedded conglomeratic sandstone beds interleaved with dark-gray claystones. It forms buttes, mesas, and badlands. In places dissection has developed narrow deep gullies which alternate at irregular intervals with steep-ridged

interfluves. The Monitor Butte member also crops out along the flanks of Skeleton Mesa; in this locality it consists predominantly of dark-purple claystone and siltstone beds.

In places, the attitude of the beds forming the Monitor Butte member are extremely irregular and do not conform to the regional strike and dip. Folding, faulting, intraformational unconformities, and other evidence of penecontemporaneous deformation are at most exposures. These phenomena, however, are not repeated in either the overlying or underlying strata.

Many features common in the Shinarump member are duplicated in the Monitor Butte member. Crossbedding is extensive in both units, as is interfingering of the several beds. However, the Monitor Butte is marked by several distinctive features. Among these are perfectly formed and extensive foreset beds. Locally these simulate bedding planes and the normal bedding is difficult to discern. Peculiar imbricating cusplike ripple marks are characteristic of the Monitor Butte member. Distinctive also are lenses of a brown conglomerate composed largely of angular to well-rounded dark-brown pebbles of calcareous siltstone. The pebbles are as large as 80.0 mm. Included with these are quartz, quartzite, and chert pebbles similar in shape, size, and color to those of the Shinarump.

Much of the Monitor Butte member is dark-gray to grayish-orange crossbedded medium- to coarse-grained sandstone lenses. In these lenses the individual grains are angular to subround quartz with minor amounts of microcline, muscovite, chalcedony, and zircon. Much

of the angularity of the quartz grains is attributable to authigenic quartz. Calcite is the dominant cement, with silica, iron oxide, and argillaceous matter important locally.

Because the upper and lower contacts of the Monitor Butte member are gradational, and because of the large amount of intraformational disturbance, thickness figures cannot be precise. In general, it is about 100 feet thick in the Monument Valley area of Arizona. At its type locality the Monitor Butte member is about 107 feet thick (p. 66).

The position of the upper contact is arbitrary and differs from place to place. In those areas where the Monitor Butte member consists predominantly of sandstone and conglomeratic sandstone, (e.g., near Agathla Peak), the upper contact is selected as the last sandstone above which is an uninterrupted sequence of variegated siltstone and claystone beds. Elsewhere, as along the flanks of Skeleton Mesa, where the Monitor Butte member consists predominantly of dark-purple claystone and siltstone beds, the upper contact is selected as that horizon at which the sediments change in color from dark purple to light gray green.

The following is presented as the type section of the Monitor Butte member of the Chinle formation:

Section of Monitor Butte member of the Chinle formation  
measured at north end of Monitor Butte in SE 1/4, sec. 3,  
T. 41 S., R. 13 E., Utah, about a quarter of a mile  
southwest of the Whirlwind mine.

	<u>Feet</u>
petrified Forest member of Chinle formation	
Monitor Butte member of Chinle formation	
Siltstone and claystone, grayish-orange to moderate-yellowish-brown, containing beds of crossbedded conglomeratic sandstone, and fine- to coarse-grained sandstone lenses; weathers to form gentle scree-covered slopes. . . . .	8
Sandstone, yellowish-gray, fine- to medium-grained, thin-bedded, platy, cusplike ripple marks; grades laterally into dark-gray to light-gray siltstone. . . .	1
Claystone, grayish-yellow-green, fissile; weathers to form gentle scree-covered slope. . . . .	9
Sandstone, dark-gray to pale-yellowish-brown, fine-grained, massive, dense, well-indurated, cemented by calcite. . . . .	2
Sandstone, dusky-yellow, poorly consolidated, grades laterally into a siltstone facies, small fragments of silicified wood included. . . . .	7

Sandstone, locally conglomeratic, grayish-orange to light-brown, fine-to coarse-grained though predominantly medium-grained, massive, crossbedded, cusplike ripple marks, forms cliff. . . . .	25
Claystone, siltstone, and sandstone sequence alternating with one another at irregular intervals, predominantly light-gray to dark-gray. Thin-bedded in upper part, crossbedded, platy, forms broad gentle scree-covered slope . . . . .	<u>55</u> 107

#### Shinarump member of Chinle formation

No recognizable vertebrate or invertebrate fossils were found although rare bone fragments are in the conglomerate beds. Fossilized wood resembles that in the Shinarump member and most likely represents the conifers Araucarioxylon and Woodworthia.

The northward-flowing streams that deposited the Shinarump continued uninterrupted during the beginning of Monitor Butte deposition. This is indicated by the similarity in materials and bedding, and by the extensive intertonguing between the two units. Near the end of Monitor Butte deposition the flow dwindled and the size of the material deposited decreased.

#### Petrified Forest member

Overlying the dark sandstone and mudstone beds of the Monitor Butte member are a series of irregularly bedded variegated siltstone and claystone beds that form the Petrified Forest member of the Chinle

formation. This unit was named by Gregory (1950, p. 67) for exposures in Zion Park, Utah. The thick uninterrupted sequence of fine-grained sediments and the vivid hues distinguish this unit from the remainder of the Chinle.

This member of the Chinle is extremely weak and forms "badland" topography characterized by low round hillocks, immature mesas, deep intricately sculptured steep-walled ravines, and narrow ridges.

Because the Petrified Forest member is weak, landsliding is common, and normally involves not only the Petrified Forest member itself but also the overlying strata.

A large part of the Petrified Forest member is a massive uniform-textured well-indurated siltstone and mudstone in various tints and shades of pink, red, blue, gray, violet, and green. Locally small discontinuous lenses of mud pebbles form conglomerates which interrupt this sequence. In the massive facies the dominant grains are angular quartz about 0.006 mm long. Dispersed through these small grains are individual quartz grains as much as 0.24 mm in size. Calcite is the principal cement with silica and clay as minor binding agents.

Dispersed throughout this member are light-gray claystones which swell notably when wet. In these, the dominant mineral has been identified as montmorillonite (Allen, 1930, p. 284). Other evidence of volcanic activity during Chinle time has been reported by Waters and Granger (1953) who noted fragments of altered volcanic glass and bits of microlite-filled lava in thin sections of sediments of the Chinle. Allen (1930, p. 286), commenting on the mottling in the Chinle,

suggests that this peculiar type of coloration developed in bentonitic sediments after deposition in response to environmental conditions under which the sediments accumulated.

The Petrified Forest member is about 620 feet thick at Tyende Mesa near Agathla Park, and about 510 feet along the east flank of Skeleton Mesa. Stewart and others— report the unit as about 500 to 700 feet

---

— Stewart, J. H., Williams, G. A., Albee, H. F., and Raup, O. B., in preparation, Stratigraphy of Triassic and associated formations in part of the Colorado Plateau region, with a section on Sedimentary petrology by R. A. Cadigan: U. S. Geol. Survey Bull.

---

thick in the Monument Valley area.

The section measured on the east flank of Tyende Mesa below Owl Rock (fig. 2) is characteristic.

Section of Petrified Forest member of Chinle formation measured at Owl Rock, about 7-1/2 miles north of Kayenta, Ariz.

Feet

Owl Rock member of Chinle formation

Petrified Forest member of Chinle formation

Claystone, mudstone, and siltstone, grayish-brown to

red, mottled; interbedded platy lenses of well-

rounded mud pebbles in a siltstone matrix; elsewhere

nodules form conglomerate lenses containing

pelecypod remains. . . . .

472

Feet

Claystone, mudstone, and siltstone, variegated,  
 generally light-greenish-gray to pale-red,  
 spongy "popcornlike" surface weathers to form  
 angular to rounded fragments; locally mudstone  
 gives way laterally to siltstone with inter-  
 calated medium-grained sandstone lenses about  
 2 feet thick. . . . .

148  
 620

Monitor Butte member of Chinle formation

The upper contact is selected as the first limestone ledge below which is an unbroken series of variegated claystone, mudstone, and siltstone beds, and above which is a series of cherty limestone beds alternating with claystone, mudstone, and siltstone beds. In several localities, the Petrified Forest member intertongues with the overlying Owl Rock member.

Petrified wood is sparsely distributed through the claystone and siltstone beds of this member, but elsewhere in northern Arizona the amount of fossil wood found in this member is in such quantities as to form fossil forests. Daugherty (1941, p. 9) reports such forests at Round Rock, Adamana, and Beautiful Valley, Ariz. Most of the logs (probably conifers) found in this member appear to have been rafted into place. Identifiable fossils were not found in the Monument Valley area, Arizona, but elsewhere in northern Arizona, (Camp, and others, 1947, p. 8) invertebrates such as molluscs are present, as well as vertebrates such as fish, (Pyctodonts, Semionotids), amphibians, (Metoposaurus), and reptiles (Coelophysis).

With the continued slackening of stream flow first apparent during the later stages of Monitor Butte deposition (p. 66), siltstones and claystones began to be deposited by relatively quiet waters. This depositional environment continued during the formation of the Petrified Forest member. Probably the climate was arid and the landscape even and monotonous. Some volcanic activity is suggested by the presence of volcanic shards.

#### Owl Rock member

The Owl Rock member of the Chinle formation is a series of cherty limestone and limestone conglomerate beds alternating with claystone, mudstone, and siltstone beds. Wherever this member crops out the resistant limestone beds form a series of jutting ledges that serve partly to protect the underlying strata.

In the Monument Valley area, Arizona, the Owl Rock member is best exposed at its type locality near the base of Owl Rock.

Limestone conglomerate beds give way along the strike to massive cherty limestone beds which have subangular to angular nodules of black chert scattered irregularly throughout the beds. A light-bluish-gray (5 B 7/1) color predominates although locally greater concentrations of chert tend to darken the limestone beds to gray blue. The ledges formed by these limestones normally range from about 2 to 20 feet in thickness and are separated one from another by siltstone and mudstone masses as much as 30 feet thick. The cherty limestone beds weather to form

nodular, blocky, well-jointed ledges. As many as six of these limestone ledges were noted in the Monument Valley area. Of these only five were persistent and could be traced with any degree of confidence.

The Owl Rock member ranges in thickness from about 120 to 166 feet. At Owl Rock the member is 166 feet thick; farther south along Comb Ridge near Chaistla Butte it is about 134 feet thick; to the west along the east flank of Skeleton Mesa it is about 128 feet in thickness. A comparable thickness for this unit is reported by Gregory (1917, p. 44-45) who cites a thickness of 152 feet for this member of the Chinle at the mouth of Tseyi-hatsosi Canyon near Boot Mesa (fig. 2).

The following is presented as the type section of the Owl Rock member of the Chinle formation:

Section of Owl Rock member of Chinle formation measured at  
Owl Rock about 7-1/2 miles north of Kayenta, Ariz.

	<u>Feet</u>
Church Rock member of Chinle formation	
Owl Rock member of Chinle formation	
Limestone, pale-grayish-green, cherty, persistent cliff-former; weathers to form blocky masses. . . . .	7
Mudstone, pale-reddish-brown, some intercalated siltstone lenses; forms gentle slopes . . . . .	11
Limestone, pale-grayish-green; includes black angular chert nodules; persistent cliff-former. . . . .	2
Mudstone, pale-reddish-brown, forms gentle slopes . . . . .	2
Limestone, grayish-green; includes black angular chert nodules; cliff-former . . . . .	2
Siltstone, brown, massive, very slightly fissile; locally stands as vertical face . . . . .	11
Mudstone, pale-reddish-brown to mottled appearance resulting from scattered small green specks; forms gentle slopes . . . . .	26
Limestone, pale-gray; includes black angular chert nodules; persistent cliff-former. . . . .	10
Mudstone, pale-reddish-brown; locally grades into siltstone; forms gentle slopes. . . . .	16

Limestone, light-gray, massive; includes black angular chert nodules; persistent cliff-former. . . . .	<u>Feet</u> 10
Mudstone, pale-red; locally altered to conglomeratic siltstone near top; lower part forms slopes, upper part stands as vertical face. . . . .	33
Claystone, gray to purple, discontinuous; locally forms ledges. . . . .	1
Mudstone, reddish-brown; forms gentle slopes. . . . .	16
Limestone, light-gray; includes black angular chert nodules; weathers to form blocky masses . . . . .	19
	<hr/> 166

Petrified Forest member of Chinle formation

In most places the upper contact is the uppermost limestone ledge in the mudstone and limestone sequence. Directly overlying the limestone bed is a sequence of reddish-brown parallel and crossbedded siltstone and sandstone beds (i.e., Church Rock member) that contrast markedly with the underlying grayish-green mudstone, siltstone, and cherty limestone beds. In places the sediments of the Owl Rock member intertongue with the overlying Church Rock member. Along Comb Ridge in the area near the Monument No. 2 mine the mottled grayish-green siltstone beds of the Owl Rock member are replaced laterally by the reddish-brown siltstone and sandstone beds of the Church Rock member. Here, therefore, the distinctive limestone ledge selected as the top of the Owl Rock member is underlain by typical Church Rock sediments. Similar intertonguing between these two units has been noted elsewhere in the Monument Valley area.

Invertebrates collected from a limestone conglomerate in the Owl Rock member have been identified by John B. Reeside, Jr. (written communication) as "Unio n. sp." He states, "Only one species appears to be present, but it does not match any of the dozen or so of described upper Triassic species."

Although fossil wood has been found, it is in much smaller amounts than in the underlying Petrified Forest member. Fossil wood collected from this member elsewhere in Arizona has been assigned a Late Triassic age (Daugherty, 1941).

The Owl Rock member represents an episode marked by alternating lacustrine and fluviatile deposition. The fluviatile conditions that had continued uninterrupted since the beginning of deposition of the Shinarump member had slackened sufficiently by the close of Petrified Forest time to permit the formation of ephemeral fresh-water playa lakes. In these, dense massive light-gray limestones of limited extent were deposited. These limestone beds in turn were soon buried by siltstones and claystones brought in by sporadic revivals of stream flow.

#### Church Rock member

Overlying the grayish-green limestone and claystone beds of the Owl Rock member are the reddish-brown (10 R 4/3) parallel and crossbedded siltstone and sandstone beds of the Church Rock member of the Chinle formation.

In detail the Church Rock member of the Chinle formation is marked by medium-scale trough-type cross-stratification (Stewart and others-<sup>✓</sup>).

---

<sup>✓</sup> Stewart, J. H., Williams, G. A., Albee, H. F., and Raup, O. B., in preparation, Stratigraphy of Triassic and associated formations in part of the Colorado Plateau region with a section on Sedimentary petrology by R. A. Cadigan: U. S. Geol. Survey Bull.

---

The sorting is consistent and uniform. Most of the material is silt size although local lenses of sandstone are present. Grains are subangular and only a few show any rounding. The major mineral is colorless quartz with the grains coated by a thin film of brown iron oxide.

The Church Rock is remarkably uniform along most of its outcrop. The following section measured along Comb Ridge near Kayenta, Ariz., is considered typical:

Section of Church Rock member of Chinle formation measured  
on Comb Ridge about 6-1/2 miles northeast of Kayenta, Ariz.

	<u>Feet</u>
Wingate sandstone	
Church Rock member of Chinle formation	
Siltstone, reddish-brown, fissile, even-bedded; weathers to form nodular ledges. . . . .	12
Siltstone, reddish-brown, crossbedded; locally inter- bedded lenses of fissile shaly siltstone . . . . .	11
Sandstone, grayish-brown, crossbedded, coarse-grained; includes granules as much as one-quarter of an inch in diameter; thin discontinuous seams of chocolate- brown siltstone along bedding planes . . . . .	4
Siltstone, reddish-orange altering locally to light- gray; interbedded lenses of coarse-grained sandstone .	20
Siltstone, reddish-orange, massive; weathers to form blocks about 2 feet on a side. . . . .	3
Siltstone, reddish-orange, to reddish-brown, even- bedded, slightly fissile, mottled surface covered with light-gray spots about 2 inches in diameter . . .	75
Siltstone, reddish-brown, even-bedded; locally discontinuous; gray spots irregularly distributed over surface . . . . .	5

	<u>Feet</u>
Siltstone, reddish-orange, even-bedded, extremely fissile; locally interbedded with massive crossbedded siltstone beds. . . . .	52
Siltstone, reddish-orange, fissile; locally discontinuous . . . . .	6
Siltstone, reddish-brown, even-bedded although locally crossbedded; weathers as blocky ledges. . .	52
Sandstone, light-tan to light-brown, thin-bedded, platy; faintly ripple-marked. . . . .	6
	246

#### Owl Rock member of Chinle formation

The Church Rock member differs in thickness at various localities. An average thickness for this member in the area west and south of Agathla Peak is about 150 feet.

In most places in the Monument Valley area a recognizable contact exists between the Church Rock member and the Wingate sandstone. In gross aspect the change is from a parallel and crossbedded deposit with depositional features typical of fluvial deposits, to a massive deposit marked by large sweeping cross-laminae commonly attributed to eolian deposits. In detail the contact is marked in many localities by distinctive well-rounded coarse quartz grains in the basal sediments of the Wingate sandstone.

We interpret the intertonguing between the Owl Rock and Church Rock members (p. 73) as confirming the concept that the Church Rock is an integral part of the Chinle formation. This viewpoint is not held by J. W. Harshbarger and C. A. Repenning of the U. S. Geological Survey,

who have studied the Chinle-Wingate relations south of the Monument Valley area. In several localities on the Navajo Indian Reservation they have noted an irregular erosional surface overlain by a thin granule pebble conglomerate between divisions A and B (Church Rock and Owl Rock members) of the Chinle (Harshbarger, Repenning, and Jackson, 1951, p. 96). Further, they cite intertonguing relationships in the Lukachukai Mountains, Ariz., between the Church Rock (Division A) and the overlying Wingate sandstone as evidence that the Church Rock (Division A) has closer affinities to the overlying Wingate than to the underlying Owl Rock member. On the basis of this intertonguing plus the erosional surface and the overlying granule pebble conglomerate, Harshbarger and Repenning contend that the Chinle-Wingate contact is below the Church Rock (Division A). This interpretation would remove the Church Rock (Division A) from the Chinle and assign it as the basal member of the Wingate sandstone.

We are unable to agree with this interpretation. Although Callahan (1951, p. 51) reports a pebble conglomerate between the Chinle formation and the Glen Canyon group in the vicinity of Kayenta, Ariz., we were unable to find such a horizon. In the mapped area, we have not found a pebble-granule conglomerate at the base of the Church Rock member, nor have we found an erosional surface. Moreover, we have not perceived any intertonguing relations between the Church Rock and the Wingate in the area we studied. Similar lack of intertonguing between Division A of the Chinle (Church Rock) and the Wingate sandstone was reported by Alfred F. Trites, Jr., for the White Canyon district, Utah; J. D. Sears for the San Juan River area, Utah; and Richard Q. Lewis, Sr., for the Monument Valley area, Utah, and the Elk Ridge area, Utah (all oral communications).

Unfortunately, what fossil evidence is available affords little assistance in the solution of this controversy. Faced with this problem and pending further stratigraphic work the Geologic Names Committee of the U. S. Geological Survey has ruled that north of Laguna Creek (fig. 2) Division A (of the Chinle) is to be known as the Church Rock member of the Chinle formation. South of Laguna Creek the same sequence of strata is to be known as the Rock Point member of the Wingate sandstone.

We are indebted to C. A. Repenning for the following information concerning the fossil content of strata (i.e., Rock Point) stratigraphically equivalent to the Church Rock member of the Chinle formation. Only a few fossils have been found; these consist mainly of unidentifiable plant remains, petrified wood fragments, and a few fragmentary reptilian remains. The reptilian remains were identified as the phytosaur Machaeroprosoopus by David H. Dunkle of the U. S. National Museum. Camp (1930) assigns Machaeroprosoopus to the Letten Kohle and Lower Keuper of the German Triassic. Hence, on what fossil evidence exists, the age of the Rock Point (i.e., Church Rock) is Triassic.

#### Wingate sandstone

Overlying the Church Rock member of the Chinle formation is the reddish-brown (10 R 5/4) crossbedded massive fine-grained Wingate sandstone, the basal member of the Glen Canyon group. The unit forms cliffs and commonly crops out in its full thickness. A close-spaced

nearly vertical fracture system has been imposed on the Wingate and dissection along these vertical planes has resulted in perpendicular smooth-faced walls which in places are as much as 350 feet high. The imposing walls are an effective barrier for long distances, and generally the only way across the cliff is by means of built trails.

On weathered surfaces the Wingate is a deep reddish brown, and dark surface stains give the formation a somber hue. On fresh surfaces the rock is lighter, ranging in color from pale pink to very light buff. Large-scale crossbedding is typical of the Wingate and can be observed wherever the formation crops out. Many of the beds show the broad curving tangential laminae typical of eolian deposits. The texture is unusually uniform. The Wingate is composed predominantly of subround to round fine-grained quartz sand with small amounts of well-rounded coarse quartz grains in the lower few feet. Authigenic quartz overgrowths give some grains an angular surface. Minor constituents include microcline, plagioclase feldspar, tourmaline, and chert. Among the heavy minerals are small quantities of zircon, magnetite(?), and garnet. The grains are cemented dominantly by calcium carbonate and to a lesser extent by secondary silica and iron oxide. Coating all of the grains is a thin film of brown iron oxide.

The Wingate sandstone thins to the east and to the southeast from the Monument Valley area (Harshbarger, Repenning, and Jackson, 1951, p. 96). This progressive thinning, however, is interrupted by local erratic changes. Thus, the Wingate is between 310 and 320 feet thick along the west flank of Skeleton Mesa (fig. 2). At the northeast tip of Skeleton

Mesa, however, we have measured a thickness of 360 feet. At Boot Mesa the Wingate is about 350 feet thick, and Harshbarger, Repenning, and Jackson, (1951, p. 96) give the thickness of the Wingate as 305 feet near Kayenta, Ariz. To the east, the progressive thinning is apparent along Comb Ridge north of Dinnehotso, Ariz., where the Wingate has thinned to 210 feet.

The contact with the underlying Church Rock member is conformable within the Monument Valley area of Arizona and no evidence of inter-tonguing between the Church Rock (Division A of the Chinle formation) and Wingate was observed (p. 78). Farther south, in the Lukachukai area, Harshbarger and his colleagues (1951, p. 96) report such inter-tonguing relationships and Baker (1936, p. 49) reports that in the Utah part of Monument Valley "irregularly bedded sandstones at the top of the Chinle formation grade into the Wingate sandstone."

The contact with the Kayenta formation is gradational and transitional. No break is apparent and, as far as is known, the contact is conformable.

No fossils were collected from the Wingate sandstone, and hence no evidence exists as to the age of this formation in the Monument Valley area, Arizona. Previous reports have tentatively classified the Wingate as Jurassic(?). However, in the Lukachukai area fossils of Triassic age (p. 79) have been found in sediments (i.e., Rock Point) that inter-tongue with the Wingate. On this basis, J. W. Harshbarger and C. A. Repenning have proposed, and the Geologic Names Committee of the U. S. Geological Survey have accepted, a Triassic age for the Wingate sandstone.

The tangential crossbedding that marks the Wingate sandstone of the Monument Valley area indicates that the unit was deposited by winds under terrestrial conditions of extreme aridity. Stewart and others—

---

— Stewart, J. H., Williams, G. A., Albee, H. F., and Raup, O. B., in preparation, Stratigraphy of Triassic and associated formations in part of the Colorado Plateau region, with a section on Sedimentary petrology by R. A. Cadigan: U. S. Geol. Survey Bull.

---

suggest that most of the sediments came from the northwest. The Monument Valley area seems to be near the center of the Wingate's gross depositional area, which is in the form of a large shallow basin with one elongate protuberance to the east into New Mexico (Baker, Dane, and Reeside, 1936, p. 52). Near the margins of the basin Baker, Dane, and Reeside (1936, p. 53) consider the Wingate to have been deposited by a commingling of water-worked and wind-worked material. They consider the sediments in the center of the basin, however, to be composed of eolian material.

#### Jurassic(?) system

##### Kayenta formation

The middle member of the Glen Canyon group is the Kayenta formation, probably of Jurassic(?) age. The Kayenta is pale-reddish-brown (10 R 5/5) to grayish-red (5 R 5/2) irregularly bedded calcareous sandstone with intercalated layers of shale, arenaceous limestone, and conglomerate. Its type locality is along Comb Ridge about 1 mile northeast of the town of Kayenta, Ariz. (fig. 1).

Commonly, the basal part of the Kayenta forms a resistant ledge that protects the underlying Wingate sandstone. The upper part is less durable and weathers to a steep slope below the escarpment formed by the overlying Navajo sandstone. In detail, this steep slope is marked by a series of ledges and narrow platforms that are separated by short slopes.

Irregular bedding, which is characteristic of the Kayenta, is conspicuous, and was used in the course of mapping as a guide in delineating this formation from both the underlying and overlying massive crossbedded sandstones.

In detail, individual sandstone beds and lenses in the Kayenta formation cannot be differentiated either in color or lithology from similar appearing beds in either the Wingate or Navajo sandstones. Many of these sandstone lenses in the Kayenta are as much as 20 feet thick, are massive, and show good large-scale crossbedding. Lenticularity is typical of all the beds comprising the Kayenta whether they are of shale, sandstone, limestone, or conglomerate. Intertonguing between these units is common and results in rapid changes in lithology along the strike.

In gross aspect the Kayenta is reddish brown, and locally grayish red. The strata range in color from dark orangish-brown to dark greenish-gray with individual beds colored buff, orange, pink, lavender, and purplish red.

In the sandstone beds the grains range in size from very fine grained (0.06 mm - 0.15 mm) to fine grained (0.20 mm). Most of the grains range in shape from subangular to round, but some grains are

angular. Lime pebbles are common in the conglomerates as are angular nodules of black chert. Locally, a limestone conglomerate with included irregularly distributed red and gray shale fragments is present. The pebbles of the conglomerate range in shape and lithology from well-rounded quartz, quartzite, and chert pebbles to angular fragments of limestone and chert.

The major mineral in the sandstone units is colorless quartz, with microcline, plagioclase feldspar, chert, and tourmaline present in sparse amounts. Other accessory minerals are magnetite, zircon, and garnet. Most of the grains are coated with a thin film of brown iron oxide. The major cementing material is calcite although secondary silica and iron oxide are important locally.

In general, the formation thins eastward although this thinning is not uniform. The erratic thickening and thinning is well displayed in a series of measured sections which extend from Skeleton Mesa on the west to Garnet Ridge on the east (fig. 2). At Skeleton Mesa the Kayenta maintains a thickness of about 165 feet. About 12 miles to the southeast, at its type locality near Kayenta, Ariz., the Kayenta is about 144 feet thick (Baker, Dane, and Reeside, 1936, p. 5). Still farther east along Comb Ridge, about 4 miles from its type locality, the formation has increased in thickness to 162 feet. Eastward, near the Porras Dikes, in a distance as short as 2 miles, the formation has dwindled to 146 feet again. Along Comb Ridge, west of Garnet Ridge, the Kayenta is about 68 feet thick, and near the very east edge of the mapped area the Kayenta is only about 45 feet thick.

The following section is characteristic of the Kayenta formation as developed on Tyende Mesa, Navajo County, Ariz.:

Section of Kayenta formation measured at west end of Adahchijiyahi  
Canyon about 9-1/4 miles west of Agathla Peak

	<u>Feet</u>
Navajo sandstone	
Kayenta formation	
Sandstone, reddish-brown, fine-grained, even-bedded, locally thin-bedded to platy. . . . .	40
Conglomerate, light-gray, lenticular; composed of angular to rounded pebbles of fine-grained sandstone, limestone, quartz, quartzite, and chert . . . . .	3
Sandstone, reddish-brown, massive, even-bedded. . . . .	3
Conglomerate, light-gray, lenticular; composed of angular to rounded pebbles of fine-grained sandstone, limestone, quartz, quartzite, and chert. . . . .	6
Sandstone, reddish-brown, crossbedded, grain size ranges from fine- to medium-grained . . . . .	5
Sandstone, light-gray to buff, platy, crossbedded, fine-grained, ledge-former . . . . .	5
Sandstone, reddish-brown, even-bedded, fine-grained; locally interbedded lenses of coarse-grained sandstone. . .	10
Sandstone, dark-gray, crossbedded, fine-grained, dense and very well indurated . . . . .	1
Sandstone, reddish-brown, massive, crossbedded, fine- grained; separated into layers about 6 feet thick by local lenses of pebbles . . . . .	29
	102
Wingate sandstone	

The upper and lower contacts are arbitrary. We have included within the Kayenta all those units that show distinct irregular bedding planes. In many localities throughout the area we have selected a thin light-gray sandstone at the base of the Kayenta as marking the basal contact with the underlying Wingate. The upper contact was selected primarily on the presence or absence of bedding planes, for near its upper boundary the sandstone beds thicken and the bedding planes become less distinct. In several places the bedding planes at the top of the formation fade and disappear laterally and the sandstone beds grade smoothly and imperceptibly into the overlying Navajo sandstone. Many of these bedding planes reappear some 200 yards distant at about the same horizon at which they disappeared.

The Kayenta is classified tentatively as Jurassic(?). No fossils were collected from the formation although previous workers (Baker, Dane, and Reeside, 1936, p. 5) report the presence of dinosaur tracks, unnamed species of Unio pelecypods, and other fossils that are unidentified.

In 1953, vertebrate remains were discovered in the upper part of the Kayenta formation near Kayenta, Ariz., by B. C. Hoy of the U. S. Department of the Interior, Bureau of Indian Affairs. G. E. Lewis of the U. S. Geological Survey quarried the remains and studied them. His report (written communication, 1955) reads as follows:

"The preliminary, incomplete identification and pertinent stratigraphic information are:

Class REPTILIA

Subclass SYNAPSIDA

Order ICTIDOSAURIA

Superfamily Tritylodontoidea near Bienotherium Young

"The newly discovered skulls represent the first new-world discovery of tritylodontoids. They seem to be close morphologically to Tritylodon of the Stormberg series of South Africa, and even closer to Bienotherium of the Lufeng series of Yunnan, China. These old-world vertebrates occur in rocks generally placed in Upper Triassic.

"Most modern paleontologic opinion somewhat arbitrarily places the tritylodontoids in the Reptilia, but they are on the transitional morphologic boundary between reptiles and mammals."

The conglomerates, irregular bedding, channeling, and general coarseness of the sediments all indicate that the Kayenta is a stream deposit. Conditions of aridity prevailed and the shale lenses were probably deposited in pools of quiet water. Likely most of the sediments came from the north and northeast (Stewart and others<sup>1</sup>). The Monument Valley area seems to

---

<sup>1</sup> Stewart, J. H., Williams, G. A., Albee, H. F., and Raup, O. B., in preparation, Stratigraphy of Triassic and associated formations in part of the Colorado Plateau region, with a section on Sedimentary petrology by R. A. Cadigan: U. S. Geol. Survey Bull.

---

be near the southern edge of the Kayenta basin of deposition (Baker, Dane, and Reeside, 1936, p. 46).

Jurassic and Jurassic(?) system

## Navajo sandstone

The Navajo sandstone, the uppermost formation of the Glen Canyon group is a light-buff to pink (10 YR 8/2) massive crossbedded sandstone. Where it is protected by a resistant cap rock it forms high cliffs. Unprotected, the formation weathers to rounded steep-sided mammillary forms. Wherever it is exposed, its color, uniformity of grain size, and typical crossbedding easily identify it.

In the western part of the area, alcoves of all sizes are at the base of many of the steep cliffs formed by the Navajo sandstone. Most of the large cliff dwellings such as Betatakin, Keet Seel (fig. 7), and Inscription House are in the larger of these alcoves.

Although most of the Navajo consists of massive and crossbedded sandstone, lenticular sandy limestone beds are scattered irregularly throughout the upper part of the formation. These beds are extremely resistant and are composed of disseminated grains of quartz scattered through a limestone matrix. In the eastern part of the area these beds cap mesas.

The Navajo is light buff to pink, although in places it ranges in color from light gray to brownish tan. Most of the grains range in shape from subround to round, and only a very few are angular. In grain size, the sandstone ranges from very fine grained to fine grained with the majority of the grains ranging from 0.10 mm to 0.26 mm in diameter. The Navajo is predominantly a quartz sandstone with small amounts of microcline, plagioclase feldspar, chalcedony, magnetite, zircon, tourmaline,

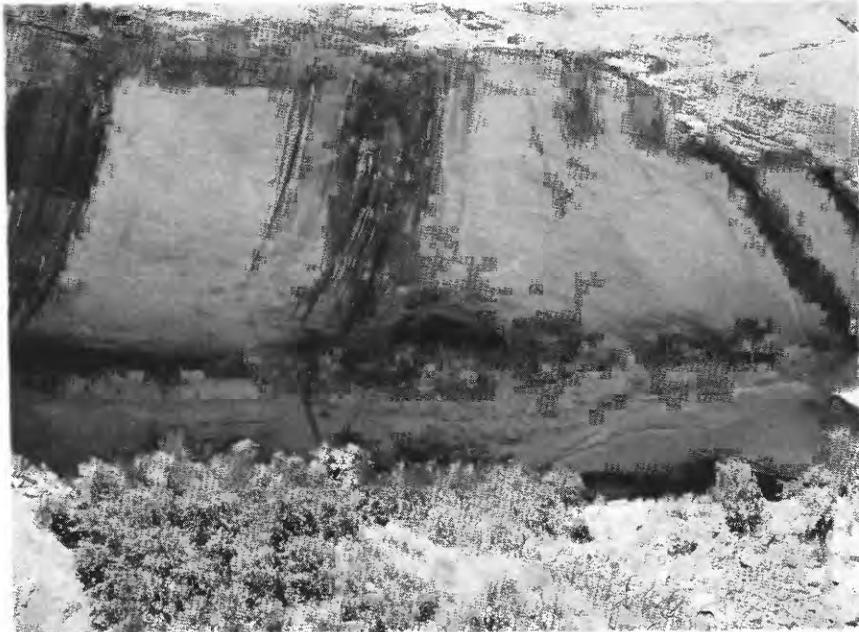


Figure 7.--Photo showing Keet Seel, the largest and best preserved cliff dwelling in the Monument Valley area. The dwelling is in a large alcove in the Navajo sandstone.



and garnet. The Navajo is weakly to firmly cemented by calcite, silica, and iron oxide. The cementation, however, is poor in most places and the Navajo is, in general, an extremely friable rock. A thin film of brown iron oxide coats each grain.

The top of the Navajo is exposed in only two places in the mapped area. Along Comb Ridge near Chaistla Butte, the Navajo is about 524 feet thick; farther to the east, also, on Comb Ridge, north of Garnet Ridge (fig. 2), the Navajo is about 665 feet thick.

The contact between the light-buff crossbedded sandstone beds of the Navajo and the overlying dark-red even-bedded siltstone beds of the Carmel formation is marked by an unconformity of practically no relief. Angularity between the formations, if any, is too slight to measure within the limited area of contact exposed in the Monument Valley area.

No fossils were found in the Navajo sandstone during the course of the present work. However, a member of the Navajo Mountain-Monument Valley expedition of 1933, discovered a small "dinosaur about the size of a turkey" in the Navajo sandstone (Camp and Vanderhoof, 1935, p. 385). The discovery site was about 1 mile north of the Keet Seel ruin on the west side of Keet Seel Canyon (fig. 2). The fossil was the first vertebrate skeleton to be recorded from the Navajo sandstone. It was about 500 feet above the top of the Wingate sandstone and lay parallel to the crossbedded sandstone in which it was found. The specimen was studied by Camp (1936) who named it Segisaurus halli, n. gen. and sp. and deduced that it probably had a "bipedal ostrichlike mode of locomotion." Camp (1936) stated, regarding the age of the form, "It represents a single member of an unknown upland fauna and despite its primitive characters it could be placed in either the Triassic or Jurassic."

The Navajo represents an accumulation of wind-worked and wind-deposited sand that probably came from the west or northwest (Stewart and others<sup>1</sup>). The local members of dark-gray dense un-

---

<sup>1</sup> Stewart, J. H., Williams, G. A., Albee, H. F., and Raup, O. B., in preparation, Stratigraphy of Triassic and associated formations in part of the Colorado Plateau region, with a section on Sedimentary petrology by R. A. Cadigan: U. S. Geol. Survey Bull.

---

fossiliferous limestone in the upper part of the Navajo represent ephemeral playa lakes in what must have been a large desert. The Monument Valley area is near the eastern margin of a large northeast-trending wedge-shaped mass of eolian sand (Baker, Dane, and Reeside, 1936, p. 44) that constitutes the Navajo sandstone.

#### Jurassic system

##### Carmel formation

The Carmel formation, basal member of the San Rafael group, is exposed only in the southeastern and eastern parts of the Monument Valley area, Arizona (fig. 2). It is composed of alternating siltstone and sandstone beds with fissile siltstone beds predominating in the lower half and crossbedded sandstone beds in the upper half. Generally the siltstone beds form gentle slopes between the benches and ledges formed by the more resistant sandstone beds. From a distance the Carmel is dark reddish brown; (10 R 4/4), but in detail it ranges in color from light gray to orange

brown to reddish brown. Commonly, the siltstone beds are reddish brown; the sandstone beds, however, are gray near the base of the formation and are gray, orangish gray, and brownish red near the top.

The siltstone beds are remarkably alike. They are reddish brown, fissile, and composed of poorly sorted clear colorless polished angular quartz heavily stained with iron oxide. Magnetite, feldspar, mica, and a chlorite-like mineral are accessory minerals. The average grain size is about 0.06 mm, but many of the grains are small as 0.04 mm or as large as 0.11 mm.

The sandstone beds are poorly sorted and are composed of clear colorless quartz with magnetite as an accessory mineral. The grains range in shape from subround to round, and the larger grains are frosted and nearly spherical. Most of the grains range in size from 0.10 mm to 0.30 mm.

Both iron oxide and calcite are binding agents. The siltstone beds are held together by iron oxide, and the sandstone beds are cemented by calcite. A few of the grains have authigenic quartz overgrowths, but quartz apparently is not a major cement.

Ripple marks and small patches of polygonal networks are exposed on the surface of the sandstone beds. These polygons are as much as 8 inches across and are bounded by low rounded walls of sandstone up to 8 inches high and 6 inches thick. The walls may represent mud cracks that were filled with sand and subsequently cemented. The walls now are more resistant to erosion than the surrounding rock.

The Carmel is about 118 feet thick at Garnet Ridge (fig. 2). It varies a few feet in thickness from place to place probably because of variation in the thickness of the siltstone beds in the upper part of the formation.

The contact of the Carmel with the overlying Entrada sandstone member of the San Rafael group is marked in most places by a color and grain size change from the dark reddish-brown siltstone of the Carmel to the brilliant orangish-brown fine-grained sandstone of the Entrada.

No fossils were collected from the Carmel formation in the Monument Valley area, Arizona, although the formation is fossiliferous in other parts of the Colorado Plateau. Imlay (1948) reports an invertebrate fauna of Middle and Late Jurassic age from the San Rafael Swell.

The presence of exceptionally large frosted sand grains in the sandstone beds, the alternating beds of siltstone and sandstone, the polygonal networks, and current-type crossbedding and ripple marks all imply that the Carmel was deposited during changing environmental conditions. These conditions probably ranged from periods of marginal marine inundation to periods of subaerial erosion.

According to Baker, Dane, and Reeside (1936, p. 54) the San Rafael group represents two invasions of a marine sea (i.e., the Carmel sea) from the northwest, separated by a large eolian deposit. Deposits of the first advance of the sea are represented by the Carmel formation, and the Monument Valley area, Arizona, probably was at or near the southern margin of this sea. With the withdrawal of the sea, wind-worked material represented by the Entrada sandstone was deposited over the area. A readvance

of the Carmel sea resulted in deposition of silts and sands that now form the Summerville formation. During this second advance, the area again was probably near or at the fluctuating southern margin of the sea.

#### Entrada sandstone

The Entrada sandstone is part of the San Rafael group. It is an orangish to reddish-brown massive even to crossbedded fine-grained sandstone with intercalated thick siltstone beds in its upper part. Commonly the lower third to two-thirds of the formation crops out as a steep slope below a vertical wall that is formed by the upper part of the formation. On Garnet Ridge (fig. 2), the lower part is an extensive knobby tableland that encircles the ridge and which breaks away to form steep slopes at the edges. The upper part of the formation nearly everywhere weathers to hoodoos for which Baby Rocks Point is named. These hoodoos develop, however, only where the formation is nearly horizontal and where the Entrada is protected by a resistant cap.

The lower part of the Entrada is a brilliant orangish-red and reddish-brown massive tangentially crossbedded very fine grained quartz sandstone which is about 30 feet thick on the north side of Garnet Ridge and nearly twice that thick at the southwest end. Crossbedding in this basal unit is much like that of the Navajo except that it is more intricate and is on a smaller scale. The sand grains in the lower part of the Entrada are polished and well sorted, averaging about 0.10 mm in diameter. The orangish-red and reddish-brown color is imparted by iron oxide stain on the quartz grains, and the iron oxide also is the bulk of the cementing material. Magnetite is the major accessory mineral.

The upper part of the Entrada is a dull reddish-brown predominantly massive even-bedded very fine grained sandstone that is interbedded with several thick siltstone beds. The lithology of the whole formation changes rapidly from place to place. Consequently, the massive even-bedded sandstone and siltstone beds of the upper part of the formation make up fully two-thirds of the thickness of the Entrada on the north side of Garnet Ridge, but less than one-third at the southwest end. Sorting is poor in the siltstone beds and angular polished grains of quartz average about 0.06 mm in size. All grains are stained with iron oxide. Iron oxide is the principal cementing agent although calcite and authigenic silica are important locally. The siltstone beds range in thickness from one-tenth of an inch to several inches, but they weather as a unit to form hoodoos.

The upper 20 feet of the Entrada are very fine grained dark reddish-brown sandstone beds (fig. 8). The sandstone is even bedded and weathers as hoodoos. The upper part of this unit is contorted into open folds that are broken by high-angle faults of small throw. These structures may have developed as a result of disturbances prior to consolidation, or they may represent a collapse in beds from which soluble material was removed soon after deposition. It is certain that the disturbance of these beds was completed prior to deposition of the overlying Summerville formation, as the undeformed basal sandstone of the Summerville rests on the truncated edges of the folded upper Entrada beds (fig. 9).

The thickness of the Entrada, as measured on Garnet Ridge, is about 100 feet. The thickness differs only a foot or so from place to place even though the ratio of siltstone to sandstone becomes smaller from the northeast to southwest end of the ridge.



Figure 8.--Photo showing sedimentary strata forming Baby Rocks point. The point is capped by the Salt Wash member of the Morrison formation and has part of the Entrada sandstone exposed at its base. Bluff sandstone is about 45 feet thick. Jms - Salt Wash member of Morrison formation; Jb - Bluff sandstone; Js - Summerville formation; and Je - Entrada sandstone.



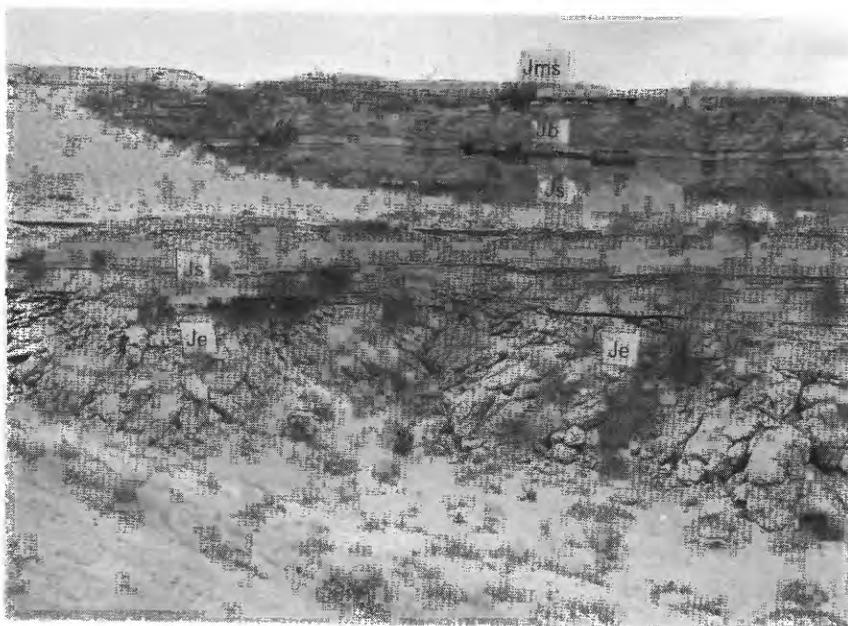


Figure 9. Photo showing unconformity between the crumpled and distorted uppermost beds of the Entrada sandstone and the even-bedded overlying Summerville formation at Baby Rocks point.  
Jms - Salt Wash member of the Morrison formation;  
Jb - Bluff sandstone; Js - Summerville formation;  
and Je - Entrada sandstone.



The contact between the Entrada and the overlying Summerville is sharp. The crests on the folds in the uppermost Entrada sandstone beds have been planed smooth and are overlain directly by about 5 feet of massive Summerville sandstone.

On the withdrawal of the Carmel sea following deposition of the Carmel formation (p. ) a surface of low relief was exposed. On this surface wind-worked material was deposited, most of it derived principally from the northwest (Baker, Dane, and Reeside, 1936, p. 46). Some of the material, however, probably came from the south, as a result of a renewed uplift of the Navajo highland (Smith, 1951, p. 100).

#### Summerville formation

The Summerville formation, part of the San Rafael group, is well exposed at Baby Rocks Point, Red Point, and Garnet Ridge (fig. 2). Because of lithologic changes, outcrop characteristics at these localities differ. At Baby Rocks Point and at Red Point the Summerville forms slopes, except for 5 feet of sandstone at the base which forms a bench.

Lithologies of the Summerville at Baby Rocks Point and Red Point are similar. In these localities it consists of quartz sandstone that is reddish brown, thin bedded, and fine grained, and which contains in its upper part, some sandstone beds that are white and silty. At Baby Rocks Point the Summerville is about 35 feet thick (fig. 8). A section measured on the west flank of Baby Rocks Point is considered characteristic of the Summerville at that locality.

Section of Summerville formation measured at Baby Rocks Point  
about 10 miles southwest of Dinnehotso, Ariz.

	<u>Feet</u>
Bluff sandstone	
Summerville formation	
Siltstone, brown to reddish-brown, even-bedded; weathers into rounded ledges, although unit as a whole forms a cliff. . . . .	32
Sandstone, white, fine-grained; grades imperceptibly into siltstone above. . . . .	<u>1</u>
Total thickness of Summerville	33

Entrada sandstone

Measurements of the thickness of the Summerville formation at Garnet Ridge range from 39 to 47 feet. A section measured on the northwest side of Garnet Ridge is selected as characteristic.

Section of Summerville formation measured on the northwest side  
of Garnet Ridge

Bluff sandstone

Summerville formation

Siltstone, alternating white and moderate-red or white and pale-reddish-brown; thoroughly contorted. . . . .	36
Sandstone, bright-orangish-brown, very well sorted, fine-grained, crossbedded; lower 18 inches bleached white or very pale green; the bleaching locally extends downward about an inch into the Entrada sandstone . . . . .	<u>5</u>
Total thickness of Summerville	<u>41</u>

Entrada sandstone

The basal sandstone of the Summerville at Garnet Ridge consists of quartz grains that are well rounded, frosted, and exceptionally well sorted, averaging in diameter 0.13 mm. The grains are cemented by calcite and by some iron oxide. In most places the sandstone appears structureless, but differential weathering locally reveals gently inclined crossbedding. The bleached zone in the bottom of the sandstone is a conspicuous marker.

Overlying the sandstone is thin-bedded pale-red and white siltstone intricately contorted and faulted. Bedding is distinguishable by alternating colors and by minor variations in grain size. A few beds are fine-grained sandstone, but these cannot be traced far owing to the contorted bedding. The siltstone in the uppermost 12 inches is less deformed and is nearly flat lying at the top of the formation.

The contact of the Summerville formation with the overlying Bluff sandstone is marked by a change from contorted red and white siltstone to evenly bedded pale-green and grayish-red siltstone. The change occurs gradually in a zone a few inches to a foot thick and is encountered from 36 to 42 feet above the basal sandstone of the Summerville formation. Lack of definiteness of a contact plane suggests that the Bluff sandstone and the Summerville formation are conformable.

The uniformity and sorting of sand in the basal sandstone of the Summerville were perhaps caused by eolian or beach processes. The upper silty beds suggest nearshore marine deposition. A cause for the convoluted beds remains elusive, but they were perhaps deformed by collapse after removal of chemical precipitates.

The Summerville represents the second southward advance of the Carmel sea into this part of northeastern Arizona. Probably the Monument Valley area was at or near the fluctuating southern margin of the sea and was exposed intermittently to subaerial erosion.

#### Bluff sandstone

The Bluff sandstone is the uppermost unit of the San Rafael group in the Monument Valley area, Arizona. At Baby Rocks Point, the Bluff stands as a reddish-brown banded vertical cliff below the capping Salt Wash sandstone member of the Morrison formation (fig. 9). At Garnet Ridge the lower half is a slope which becomes steep in the upper half where sandstone beds form ledges.

At Baby Rocks Point and Red Point, the Bluff is a series of reddish-brown to chocolate-brown shale and sandstone beds. In general, the shale beds are even bedded, fissile, and intercalated with siltstone and sandstone beds. The sandstone beds are massive, even bedded, and range from fine to coarse grained. In these localities the Bluff is about 45 feet thick. The following section is characteristic of the Bluff at Baby Rocks Point.

Section of Bluff sandstone measured at Baby Rocks Point  
about 10 miles southwest of Dinnehotso, Ariz.

	<u>Feet</u>
Salt Wash member of Morrison formation	
Bluff sandstone	
Sandstone, light-brown, massive, even-bedded, fine-grained, friable, weakly cemented; inter- bedded lenses of coarse-grained sandstone locally. . . . .	27
Shale, chocolate-brown; bounded by one-quarter of an inch thick white siltstone . . . . .	1
Sandstone, reddish-brown, massive, even-bedded, fine-grained . . . . .	6
Shale, chocolate-brown; bounded by one-quarter of an inch thick white sandstone . . . . .	1
Sandstone, reddish-brown, even-bedded fine-grained . . . . .	4
Shale, reddish-brown, even-bedded, fissile; intercalated white sandstone lenses. . . . .	6
Total thickness of Bluff	<u>45</u>

Summerville formation

At Garnet Ridge the upper half of the Bluff sandstone resembles the beds exposed at Baby Rocks Point and Red Point, but the lower half consists of fissile siltstone that is variegated pale green and grayish red. Where the siltstone merges with the upper beds, it becomes sandy and less green. The following section is representative:

Section of Bluff sandstone on the northwest side of Garnet Ridge

	<u>Feet</u>
Salt Wash member of Morrison formation	
Bluff sandstone	
Sandstone, friable, white to very light gray; grades upward into fissile, dusky-red siltstone; with immediately underlying unit, weathers as hoodoos at southwest part of Garnet Ridge . . . . .	4
Sandstone, silty, friable, light-brown to white, gradational with bed above. . . . .	18
Sandstone, moderate-brown, massive to irregularly bedded; forms ledge . . . . .	3
Siltstone, fissile, dusky-red; sandy at the top; gradational with bed above. . . . .	4
Sandstone, fine-grained, white to very light gray, irregularly bedded; forms ledge . . . . .	3
Siltstone, fissile, dusky-red, and sandstone, friable, light-brown, in alternating beds. . . . .	18
Sandstone, fine-grained, friable, white to very light gray; forms ledge . . . . .	2
Siltstone, fissile, variegated pale-green and grayish-red; more sandy near the top. . . . .	48
Total thickness of Bluff	<u>99</u>
Summerville formation	

Bedding in the lower siltstone of the Bluff at Garnet Ridge is even and flat lying at most places, but locally is tilted, folded, and cut by high-angle faults. The angles of dip of the deformed beds do not exceed 10° to bedding, and the deformed zones, 20 to 30 feet above the base, are never more than 10 feet thick.

The upper half of the Bluff at Garnet Ridge is marked by three light-colored sandstone beds which form ledges. Although commonly massive, these sandstones are locally crossbedded. The grains are frosted, cemented by calcite, and range in size from 0.06 to 0.28 mm. Polygonal networks similar to those in sandstone beds in the Carmel formation (p. 92), but of smaller size, are common. Dusky-red siltstone between the sandstone beds forms slopes horizontally streaked with light-colored layers that contain sand. Ripple marks are common.

At the type locality at Bluff, Utah, the Bluff sandstone is essentially one massive bed of white crossbedded medium- to coarse-grained sandstone 200 to 350 feet thick. In the Monument Valley area, Arizona, however, it is thinner and finer grained. It thins southwestward to about 100 feet at Garnet Ridge and to 45 feet at Baby Rocks Point.

The contact of the Bluff sandstone with the Salt Wash member of the Morrison formation is marked by an abrupt change to massive, crossbedded coarse sandstone. An unconformity cannot be demonstrated because of the limited extent of the outcrop, but Stokes (1944, p. 974) suggests that the contact is unconformable.

Duplication in the Bluff of many of the sedimentary features of the Carmel, including ripple marks, crossbedding, and polygonal networks resembling mudcracks, suggests that the Bluff was deposited in a nearshore environment similar to that of the Carmel. Farther northeast, the massive crossbedded character of the Bluff suggests a more landward environment.

As the Carmel sea withdrew for the last time, the silts and sands of the Summerville were exposed as a surface of low relief. (p. 93). On this surface eolian sands, represented by the Bluff sandstone, were deposited.

The sand probably was derived from the northwest. This deposit of sand forms a southeastward-trending wedge of wind-worked material that reaches its maximum thickness near Bluff, Utah, and is almost pinched out near the Monument Valley area, Arizona.

### Morrison formation

#### Salt Wash sandstone member

Only the basal part of the Salt Wash sandstone member of the Morrison formation is preserved in the Monument Valley area, Arizona. On Baby Rocks Point and Red Point (fig. 2) the basal 30 to 50 feet of the Salt Wash form a more or less flat-topped cap rock (fig. 8). On Garnet Ridge only 32 feet of the Salt Wash are preserved.

The Salt Wash remnant on Garnet Ridge is predominantly yellowish-orange (10 YR 7/2) massive crossbedded medium- to coarse-grained sandstone which contains some pebbles. The single exception is a 2-foot lens of maroon and bluish-gray shale about 2 feet below the crest of the ridge at the north end of the outcrop. Sorting is good in most sandstone beds, but some layers contain grains of coarse sand and even pebbles up to an inch in diameter. Most of the grains average about 0.25 mm and very few are less than 0.15 mm in diameter. The grains are subround to round and consist primarily of quartz, and minor amounts of chert.

The Salt Wash is very weakly cemented by authigenic quartz, and contains minor amounts of calcite, dark mineral grains, and iron oxide. A little iron stain streaks the coarse-grained layers, both in the flat-lying and inclined beds.

The principal source for the coarse clastics that form the Salt Wash member of the Morrison seems to have been a highland in west-central Arizona (Craig, and others, 1955, p. 150). Streams spread northeastward from this highland mass and deposited the Salt Wash sediments on a surface of low relief.

#### Quaternary system

Surficial deposits in the Monument Valley area, Arizona, include dune sand, alluvium, colluvium, talus breccia, and landslide blocks, which mantle and veneer large areas of bedrock. Scattered across and buried in these deposits are archeological sites. Open sites are common, and evidence of the former inhabitants is represented by a profusion of potsherds, arrowheads, spear points, remnants of one-room dwellings and foundations of ovens and cists. Hunt (1955) has made some attempts at dating the archeological sites in Cane Wash (fig. 2) through a study of the surficial deposits.

Two ages of dune sand are in Cane Valley. These have been identified tentatively as "old dunes" (preoccupation) and "new dunes" (postoccupation). No attempt was made to separate these in the field, however, and they are shown on figure 2 as dune sand (Qd). The new dunes are postoccupation, unconsolidated, and subject to transport by the wind; they have not been stabilized. The older dunes are preoccupation, stabilized, dark brown in color and contain fossil plant matter, principally as tree stumps of cottonwood, juniper, and pine (Hunt, 1955, p. 584).

Throughout the area alluvium, more or less mantled by dune sand, fills most of the stream washes. Data are not available as to the thickness of this alluvial fill, but resistivity investigations in Oljeto Wash have suggested a combined dune sand and alluvial thickness of between 80 and 100 feet. Three ages of alluvial fill exist. The oldest is a Late Wisconsin alluvium, possibly correlative with the Jeddito formation of Hack (1942, p. 60). A second alluvium, known as the Tsegi formation (Hack, 1942, p. 62), rests upon the Jeddito(?) fill and contains most of the artifacts of the ancient prepottery inhabitants (A. P. Hunt, 1953, p. 21). The third alluvial fill is the most recent and is referred to as the Naha formation (Hack, 1942, p. 62, 67). It represents postoccupation alluviation.

A study by Hunt (1955) of the interrelationships between the alluvial fills, the two ages of dune sand, and the archeological sites in Cane Wash (i.e., also known as Cane Valley or Little Capitan Valley) suggests the following sequence of events:

- (1) Deposition at the close of Pleistocene time of an extensive alluvial deposit (the Jeddito formation(?)) containing mammoth remains.
- (2) A period of great aridity (the Thermal maximum) when the "old dunes" formed.
- (3) A moist period when alluvial fill (i.e., the Tsegi formation) and lake beds developed. The area was inhabited by a prepottery people at this time.

- (4) A gradual diminution of water supply coupled with several severe drouths resulted in a gradual exodus of the inhabitants (the Anasazi people) from the Navajo country. The exodus occurred in the period 1275-1300 A.D.
- (5) A third alluvial fill (the Naha formation) was formed in the period 1300-1700 A.D.
- (6) Dune sand, postoccupation, began covering the alluvial fills.
- (7) The present arroyo cutting began in the last two decades of the 19th century.

#### GEOLOGIC HISTORY

The pertinent details of the geologic history of the Monument Valley area, Ariz., are summarized in table 1.

##### Eruptive rocks

##### General statement

The sedimentary rocks of the Monument Valley area, Arizona, are disturbed in many places by materials that have been injected from below. Dikes, volcanic plugs, and other manifestations of eruptive activity are scattered irregularly through the area. They generally stand as topographic highs and their dark-grayish-green to bright-green color contrasts markedly with the buff to reddish brown of the sedimentary rocks through which they protrude.

Three types of eruptive structures can be distinguished; these are: (1) volcanic plugs composed of lamprophyric intrusive breccia; (2) igneous dikes, also composed of lamprophyric rocks; and (3) rubble pipes composed of ultrabasic material with a heterogenous mixture of sedimentary and crystalline inclusions.

The plugs and dikes are more or less widely scattered throughout the eastern half of the mapped area. Structures of similar form, also of lamprophyric composition, are common elsewhere on the Navajo Indian Reservation (Williams, 1936). The rubble pipes, on the other hand, are rare. In this part of Arizona, they are in a narrow zone along Comb Ridge that extends from Garnet Ridge on the south to the San Juan River on the north (fig. 1). Many structures on the Colorado Plateau that have been mapped as diatremes (Williams, 1936) bear a superficial resemblance to the rubble pipes but differ from them in chemical composition and structure. The rubble pipes appear to be chemically and structurally similar to the diamond pipes of South Africa and to the kimberlite tuff plugs described by Balk (1954, p. 381) at Buell Park and vicinity, northeastern Arizona.

#### Igneous plugs and dikes

The denuded volcanic plugs are the most spectacular of the eruptive bodies. They are concentrated near the middle of the Monument Valley area in a rude line that trends somewhat west of north along the crest of the major structural feature of the region, the Monument upwarp. The most conspicuous plugs are Church Rock, (just south of the area),

Chaistla Butte, and Agathla Peak (figs. 2 and 10), the latter a tremendous monolith which rises over 1,400 feet above the surrounding plain and is visible for many miles.

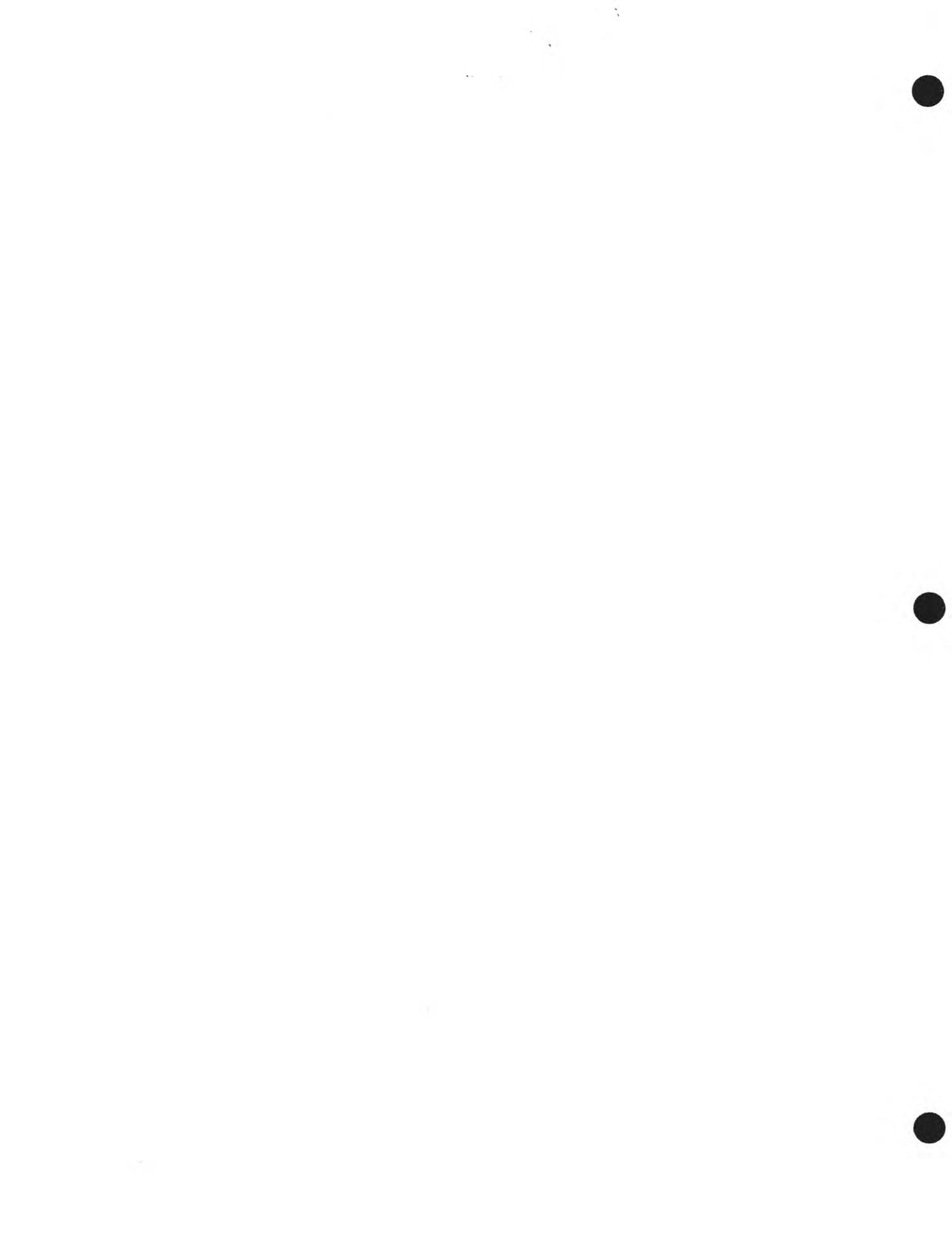
All the volcanic plugs are a dark grayish green, all stand as cones surrounded by a flaring apron of sedimentary rocks, and all are nearly circular. Each is a chaotic mass of large, angular to rounded fragments of lamprophyric volcanic rock and small amounts of sedimentary and crystalline xenoliths incorporated in a younger lamprophyric matrix. In some places the matrix is sheared, broken, and ground into fine particles. In other places the matrix is platy, foliate, and wrapped around the blocks by flowage. In still other places it is dense. The included blocks of lamprophyre range in size from pebbles and cobbles to huge boulders 20 to 30 feet on a side. Most of the foreign inclusions are not larger than cobbles. Pulverized sedimentary rock forms an appreciable part of the matrix at some places. Calcite has thoroughly cemented all of the material in the plugs, and it is largely this cement that gives them strength to stand as topographic highs. Williams (1936, p. 130) refers to the plugs as coarse tuff breccias, but we consider the term intrusive breccia more descriptive.

Alteration of the foreign inclusions in the breccia is rare. A few of the fragments of sedimentary rocks have weakly bleached surfaces. Most of the crystalline inclusions are acidic rocks of the granite family, and most appear unaltered. A few, principally those that contain much feldspar, have had their exposed surfaces, including fracture planes, altered to light-pink porous "rinds" of clayey material as much as one-quarter of an inch thick.





Figure 10.--Photo of Agatha Peak, a volcanic neck of nearly black lamprophyric rock that rises about 1,400 feet above the valley floor.



Much of the material in the volcanic plugs is unsorted. A prominent exception to this lack of sorting is in the upper part of Agathla Peak where there is some sorting, partial alinement of the long axes of the inclusions, and a rudimentary layering.

All the volcanic plugs are cut by black dense dikes that trace irregular courses through the breccia. Most of the dikes are less than 12 feet wide, but several exceed 50 feet. Others pinch and swell as they branch and anastomose, or thin abruptly, as they pass around large sedimentary inclusions in the breccia. On Agathla Peak, a few of the dikes appear to have followed parting planes in the breccia blocks.

Mineralogically the matrix and cognate breccia blocks in the plugs, the dense black dikes in the plugs, and the dikes found elsewhere in the Monument Valley area are nearly alike, and differ mainly in color, grain size, structure, and texture. In general, the igneous intrusives are alkaline rocks characterized by a high potash content (Williams, 1936, p. 148). The plugs and dikes are largely biotite vogesite, but where biotite is abundant in zones, cavities, and pods, the rock is diopside minette.

The dikes, other than the late dikes that cut the plugs, are in elongate swarms that are confined principally to the eastern part of the area mapped. One extensive dike swarm occupies fractures along the crest of the Gypsum Creek dome (fig. 2) and trends parallel to the long axis of the dome. On the flank of Comb Ridge, dikes fill fractures that are radial to the Monument upwarp. Many of the dikes are less than 10 feet in width and less than half a mile long, although one is 1-1/4 miles

in length. Some dikes merge to form plugs, such as at the Porras Dikes (fig. 2), for example, where the plugs stand as towers 400 feet high. Commonly the dikes form low irregular ridges 2 to 30 feet high that protrude above the enclosing sedimentary rocks.

All the dikes contain inclusions, almost all of which are crystalline. Only a few sedimentary inclusions have been found, and these are but a few inches in long dimension. A few of the inclusions are slightly altered on exposed surfaces. (p. 110).

Most of the dikes are much more foliate near their walls owing, primarily, to the parallel arrangement of biotite crystals. The platy structure is conformable to the contacts.

Other than the pronounced foliation near the contacts, the igneous intrusions are only slightly affected by the country rock. Poorly developed chilled zones are found locally, but the mineralogic composition of the igneous material apparently is not changed. The intruding masses have torn off and included small pieces of the country rock, many of which have bleached surfaces. Bleaching along fractures and for an inch or two into the wall rock also can be seen locally. At the Porras Dikes the wall rock has been silicified locally and the silicification extends laterally several inches from the dike contacts.

The intrusives, except for the late aphanitic dikes that cut the plugs, are sugary textured, medium purplish or greenish gray to black, and are spotted with clusters of biotite and diopside phenocrysts. The biotite phenocrysts occur as thin books and are distinctly of two generations: the older ones are as much as 4 mm in size and the younger ones range up to about 2 mm. The largest diopside phenocrysts are about 1 by 3 mm. Small second generation crystals are disseminated throughout the groundmass.

The groundmass of the rocks forming the plugs and dikes is mostly laths of subhedral orthoclase feldspar interspersed with small crystals of second generation biotite and diopside. No plagioclase was identified, but it is possible that small quantities are present. Minerals in the rocks forming both the intrusive breccias and the dikes are practically unaltered. A few biotite flakes show patches or rims of the green color that is characteristic of chlorite alteration, but the other constituents of the rocks are fresh.

Listed below are the results of Rosiwal counts that were made on lamprophyric rocks from four widely separated places in Monument Valley:

	Rock	Rock	Rock	Rock
	<u>no. 1</u>	<u>no. 2</u>	<u>no. 3</u>	<u>no. 4</u>
Groundmass (principally orthoclase)	58.1	75.9	72.6	67.1
Biotite	16.1	13.7	14.8	13.5
Diopside	21.5	8.4	12.6	19.4
Calcite	2.3	2.0		
Quartz	2.0			

The age of the volcanic disturbances in Monument Valley is unknown. Williams (1936, p. 148) suggests that the Navajo volcanoes were active during Middle and Late Pliocene although he states that fossil evidence is lacking. We found fossils in several xenoliths of Mancos shale (Late Cretaceous), thus establishing a maximum age for the intrusions.

## Serpentine at Garnet Ridge

By Harold E. Malde and Robert E. Thaden

Introduction

Garnet Ridge was named from pyrope garnet that is in serpentine deposits which intrude rocks of Jurassic age about 35 miles northeast of Kayenta, Ariz. (fig. 1). The serpentine deposits are mainly in pipes choked with rock debris derived from a section more than 5,000 feet thick, ranging in age from Precambrian(?) to Cretaceous.

Garnets have been known from the Navajo country since the Ives expedition (Newberry, 1861, p. 93) but were not seen by geologists until 1908 when D. B. Sterrett visited several localities, among them Garnet Ridge. Sterrett (1909, p. 824-825) described garnet-bearing unconsolidated deposits at Garnet Ridge which had the "general appearance . . . of a glacial deposit." A glacial origin was adopted, with doubt, by Woodruff (1910) for a similar deposit near Mule Ear, 18 miles north of Garnet Ridge. Gregory (1915; 1916; 1917, p. 102, 146-147), after examining the garnet-bearing deposits at Garnet Ridge and nearby Mule Ear and Moses Rock, decided that the conclusion of glacial origin is untenable because the deposits cut across bedding and are clearly intrusive. Later, Miser (1925, pl. 15) mapped the Mule Ear deposit as a volcanic neck. Disrupted sandstones at Mule Ear were explained by Williams (1936, p. 134) as "the result of the upward-punching action of an igneous plug," and he endorsed an igneous cause for the disruption of beds and injection of garnet-bearing deposits at Garnet Ridge.

The general relations previously described are confirmed by the present work, but we find that volcanism is not conclusively demonstrated. The greenish matrix of the garnet-bearing deposits, previously assumed to

be a finely comminuted minette--a prominent variety of basalt in the region--is largely serpentine. To attribute the serpentine to volcanism ignores consideration of nonmagmatic source rocks, although it is unquestionably intrusive. Some of the serpentine occurs in extrusive deposits, but these are so lithologically similar to the intrusive deposits that they can be distinguished only by their physiographic relations.

#### Intrusive serpentine deposits

Distribution and structural localization.--The intrusive serpentine deposits occur as pipe fillings and, rarely, as dikes and sills. The pipes are aligned northeast, parallel to the regional strike, but the dikes are parallel to joints which trend northwest (fig. 11). Pipe 1 (fig. 11), at the ridge crest, measures about 1,000 feet across; three others (pipes 2, 3, and 4) about 2 miles northeast form a cluster 1,500 by 4,000 feet which trends northwest.

Garnet Ridge lies east of an upwarp which produces a bend in Comb Ridge (fig. 2). Where the rocks of Comb Ridge curve around the upwarp, they dip more steeply than elsewhere, coincidentally with the anomalous occurrence of serpentine. A clearer suggestion of structural control is expressed by the line of pipes--Garnet Ridge, Moses Rock, and Mule Ear--which pierce Comb Ridge where the beds rise steeply in a monocline.

The pipes are steep walled and irregularly shaped. The southern wall of pipe 1 (fig. 11) is exposed in profile for a depth of more than 100 feet and is nearly a vertical plane, apparently corresponding to a joint face. Pipe 2 is bounded in part by nearly vertical walls that parallel northwest-trending joints (fig. 12). A syncline with 180 feet of closure, deepest at this cluster of pipes, may have developed after the pipes were formed. Eruption of material would account for subsidence.

Wall-rock relations.--Wall rocks of the serpentine pipes are commonly fresh country rock with large-scale fractures. On the other hand, wall rocks of the few dikes commonly contain secondary minerals.

Pipe walls are deformed or altered in two places: (1) beds of the Carmel formation on the north side of pipe 2 are deformed by small-scale folds and broken by reverse faults along which serpentine has been injected; (2) Entrada sandstone at the southeast corner of pipe 2 is laced with fractures and bleached in a zone 20 feet wide.

Dike walls are altered in two places; (1) walls of a vertical dike, which crosses the crest of Garnet Ridge, are cemented by silica in a zone a foot or two wide; (2) a dike northwest of pipe 2 is cemented by limonite which extends outward as an aureole from 3 to 50 feet wide in the enclosing Navajo sandstone (p. 126).

Internal relations.--Two kinds of material fill the pipes: (1) breccia blocks which subsided as much as 1,200 feet into the pipes, and (2) serpentine-bearing rubble, squeezed between the breccia blocks, containing crystalline rocks from more than 4,000 feet below.

The breccia blocks fill about two-thirds of the pipe and comprise a chaos of rock types originally far apart stratigraphically, now juxtaposed. Many are several hundred feet long. Most of them are angular, but faces, edges, and corners in contact with the serpentine rubble are smoothed, striated, and polished. Tabular blocks usually dip toward the center (fig. 12).

The serpentine-bearing rubble is no less chaotically mixed than the breccia blocks. Rocks from the crystalline basement and from strata of Paleozoic age are held in a fine-grained matrix rich in serpentine.

The inclusions range in size from sand size to large boulders, most of them are of pebble size. The large inclusions are well rounded, but the smaller ones are angular; all are smoothed and polished. Fabric is expressed locally by oriented inclusions and schistosity of the serpentine matrix but is not common.

Chemical alteration within the pipes is hard to find. Pieces of fossiliferous limestone show no recrystallization and lack thermal metamorphic minerals. Few inclusions of black shale and red sandstone are bleached. A few of the crystalline basement rocks have porous light-colored rinds as much as half an inch thick.

Source of blocks and rubble.--Nearly all the breccia blocks are from the Salt Wash member of the Morrison formation and the San Rafael group. Blocks from older beds are lacking. Pipe 2 includes a few blocks of dark-gray shale that contain species of pelagic foraminifera— such as are found

---

Steven K. Fox, U. S. Geological Survey, identified Gümbelina globulosa (Ehrenberg) and Globigerina cretacea d Orbigny.

---

in the Mancos shale, stratigraphically about 1,200 feet higher.

Inclusions in the serpentine rubble apparently were all derived from considerable depth. About half are biotite granite gneiss and epidotiferous granulite, in equal amounts. One-fourth are sedimentary rocks among which carbonate types containing fossils of Paleozoic age predominate. The remaining fourth is comprised of schistose garnetiferous amphibolite (tremolite), foliated hornblendite, pyroxenic (enstatite)

amphibolite (cummingtonite), and antigorite-tremolite-actinolite-calcite aggregates. Rare types include granite and fine-grained basic igneous rocks. The crystalline rocks were presumably brought up from a Precambrian terrane. Inclusions of limestone were derived from depths as shallow as 2,000 feet. Brachiopod molds in an xenolith of red quartzite are of early Paleozoic age and indicate a deeply buried sedimentary terrane nowhere

---

✓ Ruben J. Ross, U. S. Geological Survey, identified one mold as an Orthid brachiopod known to range from Lower Cambrian into Ordovician.

---

exposed in the region.

Serpentine matrix.--The matrix of the serpentine rubble is pale grayish green, very fine-grained, firm, and compact. It breaks apart into lumps and clods that remain coherent when wet. Pebbles break out leaving smooth, polished molds. When soaked with acid it effervesces freely but fails to disintegrate. In a few places, limonite is a cement or forms streaks which follow wavy partings. Associated with the limonite are carbonate veins faced with zeolites.

The serpentine matrix is mineralogically more or less uniform. In approximate order of decreasing abundance, the predominant minerals are: antigorite (altered from olivine), calcite, chlorite, white mica, melilite, clay, fresh biotite (perhaps exotic), chrome diopside, opaque oxides (probably ilmenite and chromite), and zeolites. Accessories (some of which may be exotic) include: actinolite, hornblende, microcline, quartz, gypsum, crysotile, and pyrope. No unaltered olivine is present in the

samples examined, although ghosts of former crystals, from 0.5 to 1.5 mm in diameter, are common. X-ray analyses made by J. M. Axelrod, U. S. Geological Survey, are listed in table 2.

Table 2.--X-ray identification of material in the serpentine matrix  
(by J. M. Axelrod).

<u>Film no.</u>	<u>Description</u>	<u>Identification</u>
6989	Light-green groundmass	Montmorillonite group ( $b_0 = 9.21$ ), antigorite, and some other minerals not identified
6990	Reddish clay	Montmorillonite group ( $b_0 = 9.20$ )
6991	Lavender, micaceous	Chlorite
6992	Talc	Antigorite

Mineralogically, the serpentine matrix resembles the kimberlitic tuff plugs at Buell Park, Ariz., 100 miles southeast (Balk, 1954, Allen and Balk, 1954, p. 100-118). Charles Milton, U. S. Geological Survey, studied samples from Garnet Ridge and suggested that they are allied mineralogically with the chloritized-calcitized-serpentinized periodite bodies of Kansas, Illinois, New York, and Virginia (oral communication).

Garnet.--The garnet that is not reworked and winnowed from the serpentine deposits is mostly in epidotiferous granulite. The granulite is medium to coarse grained and ranges from a massive type containing little garnet to a banded type rich in garnet (15 percent). Hornblende, extensively replaced by chlorite and less so by iron oxide and quartz, makes up from 25 to 50 percent of the granulite. The remainder consists of epidote laths

enclosed in plagioclase crystals several times larger. The epidote laths are smaller and more tightly packed near hornblende than elsewhere.

Distribution of garnet is irregular. Some garnet is in foliated amphibolite.

All the garnets are pyrope containing from 25 to 45 percent almandite ( $n = 1.74-1.76$ ; sp. gr.  $- 3.67-3.89$ ). Spectrographic analyses by G. W. Boyes, U. S. Geological Survey, show rather constant amounts of silicon, aluminum, iron, manganese, calcium, and magnesium, but variable amounts of chromium. The chromium content ranges from more than 1 percent to as little as a few hundredths of a percent.

#### Extrusive serpentine deposits

The extrusive serpentine deposits are lithologically like the intrusive deposits. Physiographic relations show that their source was at the pipelike intrusive deposits. They form rounded mounds of surficial debris at two places: (1) on a row of bedrock knobs leading from pipe 1; and (2) on wall rock adjacent to pipe 2.

The mounds of serpentine rubble that cap knobs leading from pipe 1 define a curving line 2,000 feet long, descending 80 feet in altitude, and lying about 60 feet above the surrounding land (fig. 13). The rubble mounds decrease in thickness from 15 to 5 feet. Most rest on siltstone occurring low in the Bluff sandstone, but two are 20 or 30 feet lower on siltstone of the Summerville formation. The rubble mound farthest from the pipe is on a block of Bluff sandstone, 100 by 200 feet, displaced 50 feet or more below its normal stratigraphic position, but rests on undeformed

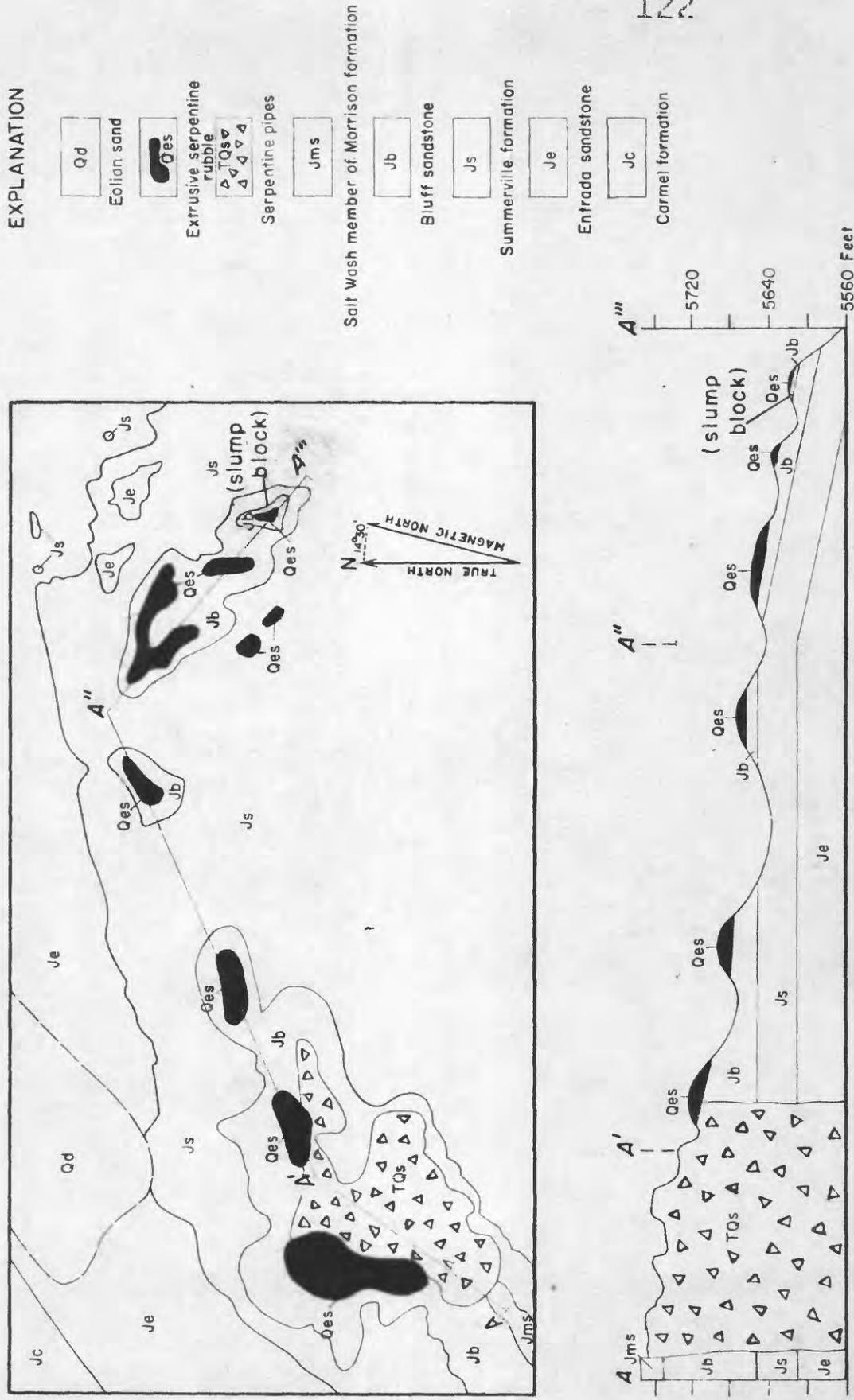


Figure 13.--GEOLOGIC MAP AND CROSS SECTION OF THE CREST OF GARNET RIDGE, ARIZONA, SHOWING LOCATION OF PIPE 1 AND OF EXTRUSIVE DEPOSITS OF SERPENTINE RUBBLE



beds. Mounds of serpentine rubble which overlap wall rock at the pipe are regarded as extrusive but are believed connected downward in the pipe with an intrusive source. Those on the knobs have no present connection with their only available source--the intrusive serpentine at pipe 1.

The mounds near pipe 1 appear to be remnants of a more extensive deposit spread either on an erosion surface about 60 feet above the surrounding land, or confined to a valley at that altitude; the topography was subsequently inverted. Movement of the rubble mass on the low gradient was probably aided by the structural weakness of serpentine and was imperceptibly slow. (Movement comparable to that observed in surface serpentine flows in California is assumed.)

A mound of serpentine rubble overlaps the northwest wall of pipe 2 and lies from 20 to 30 feet above the level of erosion reached in surrounding country rock. The mound is about 100 feet above eroded debris in the pipe. Another mound of serpentine rubble northwest of the pipe is elongate parallel to the trend of a dike that lies farther northwest. A prospect trench 8-1/2 feet deep in the mound failed to reach the base, but an extension of the dike possibly underlies it.

#### Summary

Large areas of rubble, in places several thousand feet from the pipes, are interpreted by us as surficial flows that were derived from the intrusive rubble and that were extruded on a surface only 60 feet or so above the present level of erosion. The required evolution of the pipes, then, that satisfies our structural interpretations, is an

initial period of gaseous explosion, collapse, and rubble injection during Tertiary time under a sedimentary cover that included the Mancos shale, and reactivation of pressure from below in late Quaternary time, at which time the surface rubble was extruded.

It is unknown whether the rubble pipes are related to the volcanic plugs. Williams (1936, p. 131) classified all of the eruptive features in Monument Valley as volcanoes and notes their resemblance to the diatremes of the Schwabian Alb. Shoemaker (1956, written communication) similarly considers them diatremes and attributes their structural differences to differing stages of development and levels of exposure. We cannot agree and in general believe that two distinct and different types of eruptive bodies are in the Monument Valley area. Most common are diatremelike features such as the volcanic plugs. These are represented by Agathla Peak, Chaistla Butte, Church Rock, Alhambra Rock, and many others. Less common are rubble pipes such as are exposed on Garnet Ridge. Two prime factors influence us: first, the totally different mineralogic composition that exists between the rubble pipes and the volcanic plugs. The rubble pipes consist principally of serpentine (antigorite altered from olivine), whereas the plugs are composed primarily of alkalic feldspar (orthoclase), biotite, and diopside, and olivine is present only as a very minor constituent. Second is the totally different shape. All of the plugs are distinct topographic highs, commonly standing well above the surrounding surface. The rubble pipes, on the other hand, have little relief and normally blend with the adjacent ground surface.

It seems likely that other rubble pipes may form much of Buell Park, Ariz., for the description given by Balk (1954, p. 381) closely resembles the Garnet Ridge rubble pipes. In discussing the rocks that crop out at Buell Park, Balk states in part: "...flatlying Paleozoic and Mesozoic sediments of the Colorado Plateau are pierced by at least three vertical plugs of kimberlite tuff.... Undisturbed vertical contacts are locally exposed, lacking any contact effects upon the sandstone wall rocks. Layers of tuff and xenoliths, vertical along contacts, flatten inward and lie nearly horizontal in several places. Pale green and amber olivine, enstatite, pyrope garnet, chrome diopside, emerald-green actinolite, magnetite, titanoclinohumite, black spinel, ilmenite, and other mafics are the most important minerals, listed in order of decreasing abundance. Antigorite extensively replaces olivine and constitutes a large volume of the tuff...."

In this connection Williams (1936, p. 143) notes the great dissimilarity between the rocks at Buell Park and those found elsewhere in the Navajo country.

#### Mineralized exposure at Garnet Ridge

A rubble dike at the northeast end of the ridge has been stained with iron oxide to a brownish-green color. The dike also contains veinlets of ankerite. The country rock adjacent to the dike is more friable than normal and contains small quantities of copper and uranium minerals. Three mineralized zones are roughly parallel to the dike walls and extend short distances along fractures in the country rock that intersect the dike. The zone closest to the dike is 1 to 3 inches wide and is bleached to a light buff. The middle zone, which is up to 2 inches

wide and is absent in places, contains bluish-green copper minerals. The outer zone is 1 to 2 feet wide and is stained with limonite. This zone grades into normal Navajo sandstone away from the dike. Yellow uranium-bearing minerals are sparsely disseminated in all three zones but are most abundant in the copper-bearing zone. Tyuyamunite is the only uranium-bearing mineral that has been identified. The uranium and copper appear to be in specimen quantities only.

During the winter of 1951-52, the U. S. Atomic Energy Commission completed a drilling program at the Keith Francis claim, which includes this dike. Four inclined holes were drilled, all of which intersected the dike. Weakly mineralized ground was penetrated, but the grade was considered inadequate to justify additional work.

## STRUCTURE

Folds

In this part of northeastern Arizona the main structural element is the Monument upwarp, a broad flattened anticline whose crest is wrinkled by corrugations that are the structural elements within the Monument Valley area. The upwarp, which has a north-south axis, begins in the southern part of the Green River Desert--Cataract Canyon region (Baker, 1946, p. 94), and extends southward to terminate as a gently plunging nose in the southern part of Monument Valley. The east flank of the upwarp in this area is marked by Comb Ridge, a continuous escarpment of reddish-brown strata extending from Kayenta, Ariz., more than 90 miles northeastward into Utah. The west flank is less apparent and is probably marked by the folds which cross the plateaus far to the west of the Monument Valley area. Most of the strata dip gently away from the anticlinal crest, although locally, dips exceed  $35^{\circ}$ . Commonly, the steeply dipping strata flatten rapidly.

Structure contours of the Monument Valley area, Arizona, delineate five subordinate structural elements near the crest of the Monument upwarp (fig. 2). These are: (1) the Organ Rock anticline, (2) the Oljeto syncline, (3) the Agathla anticline, (4) the Tse Biyi syncline, and (5) the Gypsum Creek dome. Two of these, the Organ Rock anticline and the Oljeto syncline, have been described by Baker (1936) in his report on the Utah part of Monument Valley. In general, they are asymmetrical, with their axial planes dipping west. In addition to these previously described structural elements, three others have been noted and are here named. The first, and most prominent, is the Agathla anticline, a broad, asymmetrical

fold plunging to the southwest. The second is the Tse Biyi syncline, a north-trending shallow basin. The third is the Gypsum Creek dome, an asymmetrical structure with steeper dips on the east flank than on the west.

#### Organ Rock anticline

Baker (1936, p. 67) has traced the Organ Rock anticline southward from the San Juan River to the Utah-Arizona State line. From this point the well-developed anticline can be traced to the south along the east sides of Hoskinnini and Skeleton Mesas until it finally passes out of this area to end near Marsh Pass. Locally, small flexures and minor undulations are superimposed on the crest and flanks of the anticline. One of these is a small dome along the east edge of Hoskinnini Mesa.

The anticline is asymmetrical. It has a sinuous axial plane that dips west. On the east flank dips of  $10^{\circ}$  to  $15^{\circ}$  to the east have been measured near the Oljeto Trading Post (Baker, 1936, p. 67) and these steepen to a maximum of  $35^{\circ}$  in the Arizona part of the Monument Valley area. Dips on the west flank do not exceed  $5^{\circ}$  to the west and are marked by minor undulations. The west flank extends westward about 10 miles to the trough of the Nakai syncline (beyond the limits of the mapped area).

#### Oljeto syncline

Baker (1936, p. 67) traced the sinuous axis of the Oljeto syncline from the San Juan River south to the Utah-Arizona State line. In both Utah and Arizona the axis of the syncline approximately follows the

course of Oljeto Wash (fig. 2). South beyond the southern reaches of Oljeto Wash the synclinal axis is within the swale which marks the west edge of Tyende Mesa (fig. 2). The syncline is asymmetric. The steeply dipping east flank of the Organ Rock anticline forms the west flank of the Oljeto syncline, but dips along the east flank of the syncline are low and generally average  $3^{\circ}$  to the west.

#### Agathla anticline

Of the structures not previously described, the Agathla anticline is the most prominent. It is named for the volcanic neck, Agathla Peak, which protrudes through the northwest flank of the anticlinal nose (fig. 2). The anticline is a broad asymmetrical southwest-plunging feature whose southeast flank is Comb Ridge and whose northwest flank merges at its western end, with the east flank of the Oljeto syncline.

The anticlinal axis trends northeast, although it gradually curves to the north and aligns with the north-trending synclinal axis that marks the Tse Biyi syncline (fig. 2). The axis of the Agathla anticline can be traced for about 16 miles. Dips are steepest on the northwest, where dips as high as  $14^{\circ}$  have been measured. Along the southwest nose and on the southeast flank the dips average  $4^{\circ}$ . The closure is about 400 feet.

#### Tse Biyi syncline

Within Tse Biyi, the rocks are flexed downward into a north-trending elongate irregular-shaped basin (fig. 2), here named the Tse Biyi syncline. Near the south end of the basin the synclinal axis, which is

continuous with the Agathla anticlinal axis, trends slightly east of north. Northward, the axis curves and strikes north for the greater length of the basin. The extent of the syncline is unknown; in the Monument Valley area, however, it is about 7 miles long. On the south flank of the syncline the dips are between  $9^{\circ}$  and  $10^{\circ}$ . The dips along the west flank average  $4^{\circ}$  although locally dips of  $6^{\circ}$  have been noted. Dips along the northeast flank of the basin do not exceed  $1^{\circ}$ .

#### Gypsum Creek dome

The third structural element not previously described is named the Gypsum Creek dome (fig. 2). The axis of the dome forms a broad arc concave to the west. The 8 mile long axis trends northeast along the south edge of the dome, near the crest the trend is almost north, and at the north edge the axis strikes northwest. The dome is asymmetrical with dips averaging  $7^{\circ}$  on the east flank, and  $3^{\circ}$  on the west flank. It plunges about  $1^{\circ}$  to both the north and south. Closure on the dome is about 400 feet. Dikes occupy a series of fractures along the crest of the Gypsum Creek dome and are parallel to the axial trend (p. 112).

#### Fractures

Both faults and joints are exposed in the Monument Valley area, Arizona. In general the faults appear as small-scale normal and reverse faults involving displacements of only a few inches or feet. Intra-formational faults are common in the Monitor Butte member of the Chinle (p. 63) and are present but not as extensive in the Moenkopi and Summerville formations.

Joints are common and prominent and normally form a reticulate pattern of the surface. They include hairline breaks that can be traced only a few feet as well as extensive cracks that extend for miles. All formations exposed are cut by joints, and these affect the mode of weathering of the unit.

At depth, in those mines where the workings permit examination of the joints they commonly are clustered in zones 2 to 6 feet wide. Most are nearly vertical and are healed with fibrous quartz, calcium carbonate, and gypsum.

In the sandstone aquifers, the joints serve as channelways. Many of the springs that issue from the base of the Navajo are along vertical joints that extend from the base of the sandstone to its top. Alteration of the strata along joints is common with the normal reddish-brown color of the strata altered to a light greenish-gray.

The joints are expressed in the topography by sheer cliffs that are formed in many of the massive eolian sandstone beds. In many places the joints extend parallel with the cliff face, and the great blocks that form the talus slopes have resulted from disintegration of rock slabs detached from the main rock mass along joint surfaces.

Several sets of joints have been observed. The dominant set ranges from N. 25° W. to N. 65° W.; a second set from north to N. 15° E.; and a third set strikes about due east. All sets are vertical or nearly vertical.

Ore deposits

General statement

Economic deposits in the Monument Valley area, Arizona, include uranium, vanadium, and oil. Elsewhere in the same general region small shows of gold, silver, and copper have excited interest, but no sizeable deposits of commercial grade have been found. The great interest displayed since 1948, in uranium-vanadium deposits has furnished, in part, some basis for this report. In general, this part of the report discusses the history of the Monument Valley area, Arizona, in terms of uranium-vanadium production, and attempts to furnish some geologic concepts and prospecting guides that might assist prospectors in their search for commercially profitable deposits of uranium and vanadium.

Uranium-vanadium minerals have been reported from the Monument Valley area for many years. Gregory (1917, p. 149) mentions "carnotite" among pebbles of the Shinarump conglomerate, and Baker (1936) in his unpublished notes, compiled during his work in the Utah part of Monument Valley, also notes the presence of "carnotite" associated with fossilized wood in the Shinarump conglomerate.

The history of uranium and vanadium ore production from the Monument Valley area, Arizona, is essentially the history of two deposits: the Monument No. 1 and No. 2 mines (fig. 1). Both are in scour channels filled with Shinarump sediments. In both places the Vanadium Corporation of America has been the major producer of uranium and vanadium ore. Relatively little is known concerning their early

history. Both appear to have been active in the period 1942 to 1944, and the Monument No. 2 mine assumed considerable importance as a producer of uranium and vanadium ore on the Colorado Plateau after 1948.

The Monument No. 1 mine began producing ore in 1942, and continued intermittently until 1950, at which time the Vanadium Corporation of America abandoned their mine. Production at no time was large. Since then prospectors have examined the remnant of the Monument No. 1 channel and have made a few attempts at mining. In 1952, the Foutz Mining Company (now the Industrial Uranium Co.) of Farmington, N. Mex., opened a small adit in the flank of the channel and began producing low-grade uranium and vanadium ore. They named their mine the Mitten No. 2 and produced small amounts of ore. No ore was produced from the Monument No. 1 mine in 1953. In 1954, the Foutz Mining Company drilled an unexplored part of the Monument No. 1 channel, discovered and began to mine a sizeable ore body.

In 1942, Luke Yazzie, a Navajo, staked a mineralized outcrop southeast of Yazzie Mesa and then told one of the traders in the vicinity, Mr. Harry Goulding, of this mineralized exposure. Goulding contacted Mr. Denny W. Viles, an official of the Vanadium Corporation of America, and guided Viles to the area. As the news of the mineralized exposure spread, officials of other organizations examined the area. In 1942, the Vanadium Corporation of America leased the claim (Monument No. 2 mine) from the Navajo Tribal Council.

Mining in the Monument No. 2 mine was carried on during the period 1942-45, but production was small. In 1948, production began on a large scale after a bulldozer uncovered rich vanadium ore at the surface.

At first, the ore was mined by stripping methods. By 1949, production had greatly increased, and the Vanadium Corporation of America began underground mining operations. In 1950, underground mining was started at the West Red Oxide workings and at the South workings (fig. 30A). Since then the underground workings have been extended the entire length and width of the channel. In 1952, the company began to alter the operations gradually from underground to stripping methods. In June 1953, both types of operations were being conducted concurrently in different parts of the mine.

Other companies and independent operators have mined from this channel adjacent to the Vanadium Corporation of America lease. The Climax Uranium Company has mined along both flanks of the channel and at the southern end. The northern end of the channel has been mined by John M. Yazzie, a Navajo, and his associate Thomas Clani. Two Navajo Indians, Black and Blackwater, have also mined ore from the east flank of the channel. Their workings were leased in 1953 to W. E. Pollock and B. N. Byler.

#### Ore-bearing beds

#### Channels

Appearance. --The work in the Monument Valley area, Arizona and Utah, has repeatedly confirmed the fact that all of the uranium ore deposits are in symmetric and asymmetric troughs cut into the Moenkopi formation and DeChelly sandstone member of the Cutler formation and filled with sediments of the Shinarump member of the Chinle formation (fig. 14).

These troughs are known as channels, and they accentuate the unconformity between the Shinarump member of the Chinle formation and the Moenkopi formation. Most channels are exposed along mesa edges and in valley walls as U-shaped depressions cut into the Moenkopi formation and filled with conglomeratic sandstone (fig. 15A). In this mode of outcrop the channels are buried beneath overlying beds of the Shinarump member. Where these upper beds of the Shinarump member have been removed, the channel sediments appear as narrow elongate exposures of gray conglomeratic sandstone bounded by the red shaly siltstones of the Moenkopi formation or as ridges (fig. 15B) standing above the general level of the dissected Moenkopi surface. Cross sections of some typical channels of the Monument Valley area, Arizona, are shown in figures 16 and 17.

Classification.--Commonly, the channels are difficult to trace, many because they are not well exposed, others because they vary greatly in length. A channel may crop out along a mesa rim, yet a projection of its trend fails to disclose it on the opposite rim or, for that matter, anywhere else along the rim. Other channels, however, are more continuous, and aligned exposures of a channel can be projected across a mesa top. One channel was traced for 4 miles; others end within a mile or two.

A distance of 2 miles has been established arbitrarily as the division between the basinlike "short channels" and "long channels."

A drilling program completed by the U. S. Atomic Energy Commission (Chester and Donnerstag, 1953) in the Monument No. 2 channel established that these shorter channels terminate in curves, gently concave upward (fig. 30B). There has been no extensive drilling in long channels; therefore, how they terminate is unknown.



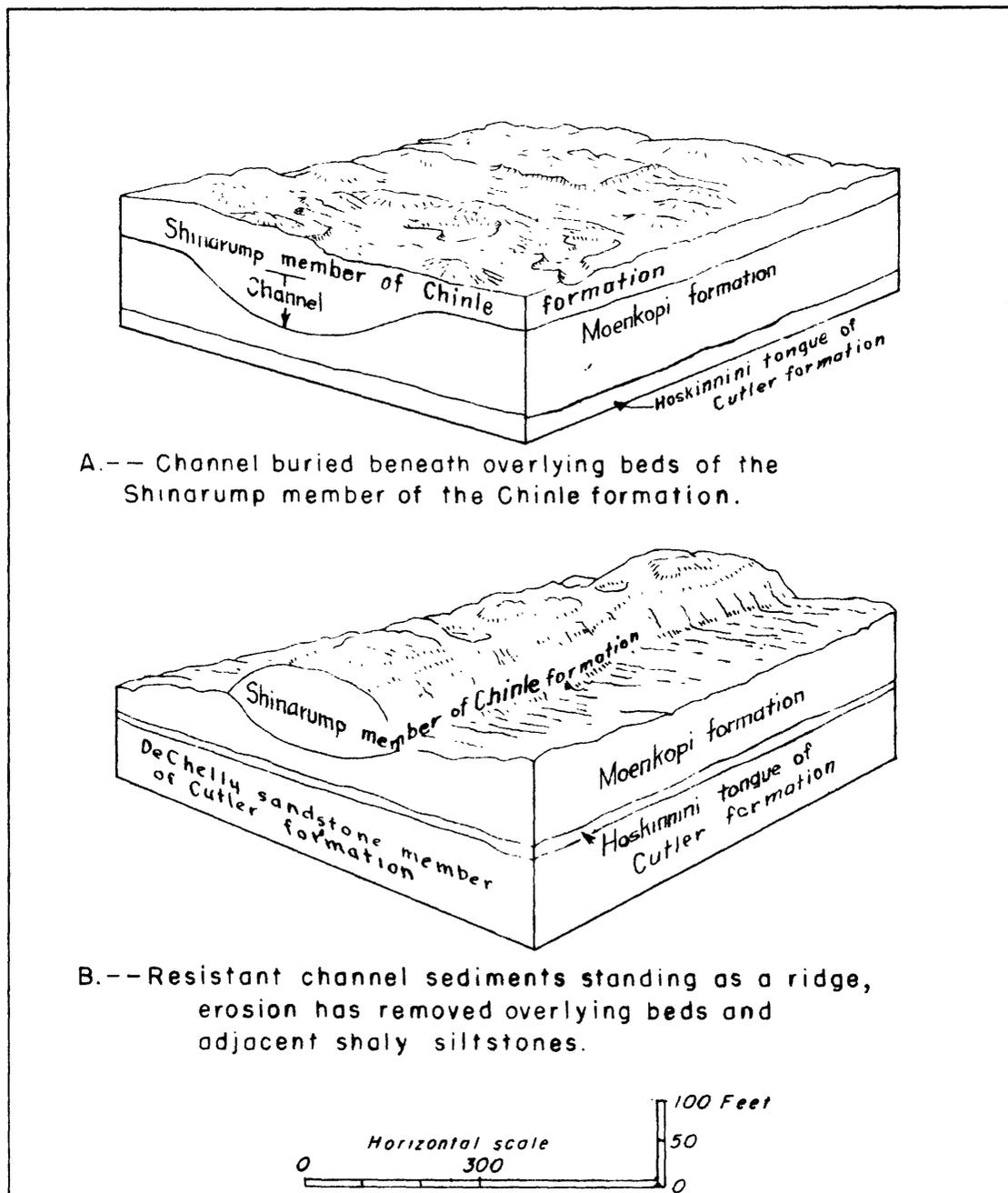


FIGURE 15.--BLOCK DIAGRAMS ILLUSTRATING MODES OF CHANNEL OUTCROP IN THE MONUMENT VALLEY AREA, ARIZONA.



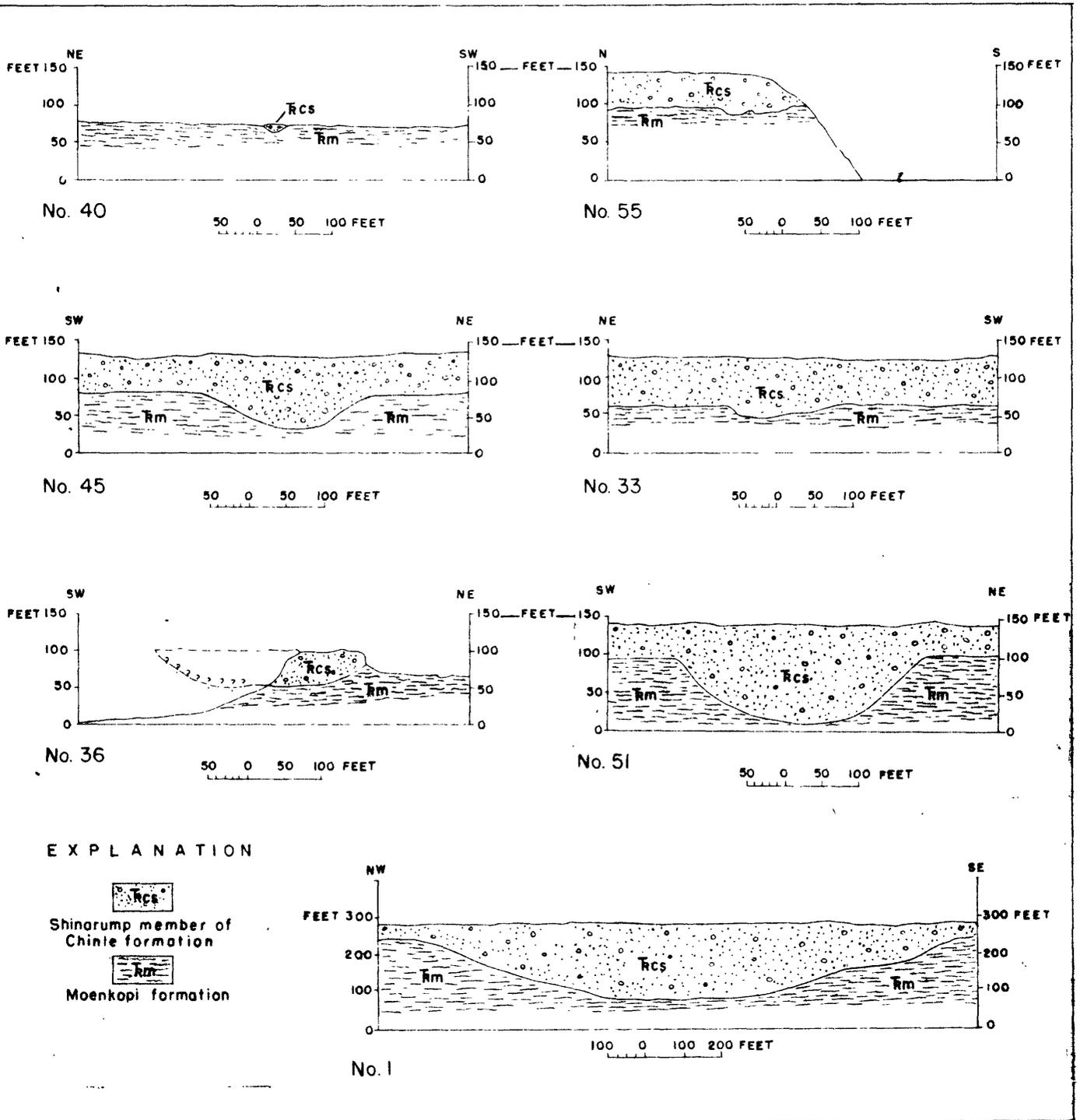


Figure 18.--CROSS SECTIONS OF TYPICAL CHANNELS IN THE MONUMENT VALLEY AREA, ARIZONA. LOCATIONS OF THE CHANNELS ARE SHOWN ON FIGURE 14. UPPERMOST PAIR ARE CLASSIFIED AS NARROW CHANNELS. ALL THE OTHERS, EXCEPT THE BOTTOM ONE, ARE CLASSIFIED AS INTERMEDIATE CHANNELS. THE BOTTOM CHANNEL IS CLASSIFIED AS A BROAD CHANNEL.





Figure 17.--Photo showing the symmetrical nature of Mitchell Mesa channel No. 1. The channel is about 350 feet wide and 75 feet deep. Fcs - Shinarump member of Chinle formation; Fm - Moenkopi formation; Pch - Hoskinnini tongue of the Cutler formation; and Pcd - DeChelly sandstone member of the Cutler formation.



The channels have been divided into three classes based upon width (table 3). The first class includes channels up to 50 feet in width. The second class comprises channels ranging from 50 feet to 350 feet in width. The third class includes channels over 350 feet wide. Channel sediments, sorting, and bedding seem identical in all three classes.

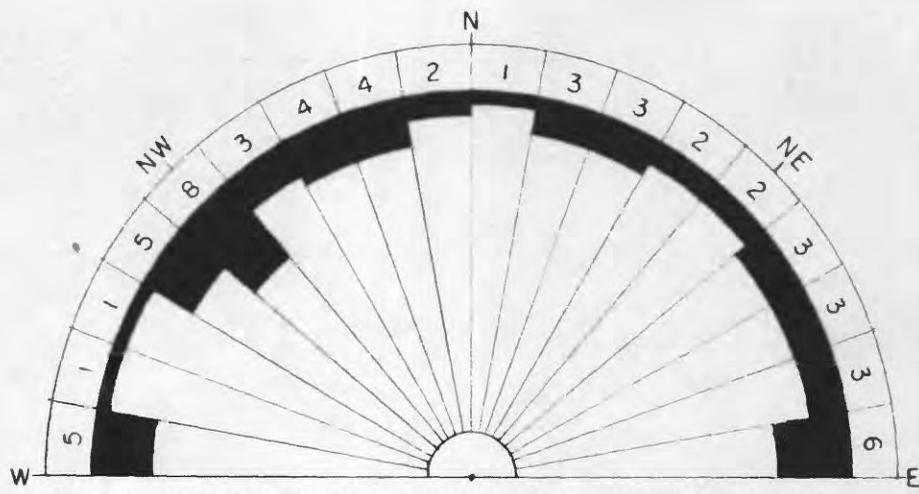
During the course of the field work, 62 channels were noted. Of this number 16 were included in the first class, 34 in the second class, and 12 in the third.

Trends.--Many channels in the Monument Valley area trend northwest although this is not universal as figure 18 illustrates. It does seem however, that a northwest trend is the preferred orientation. In an area as small as the Monument Valley area, Arizona, this northwest orientation is merely suggested by a diagram of the channel trends (fig. 18A). However, when a diagram (fig. 18C) is prepared of all channels noted in a much larger area (the Utah and Arizona parts of Monument Valley), it indicates clearly the dominant northwest orientation.

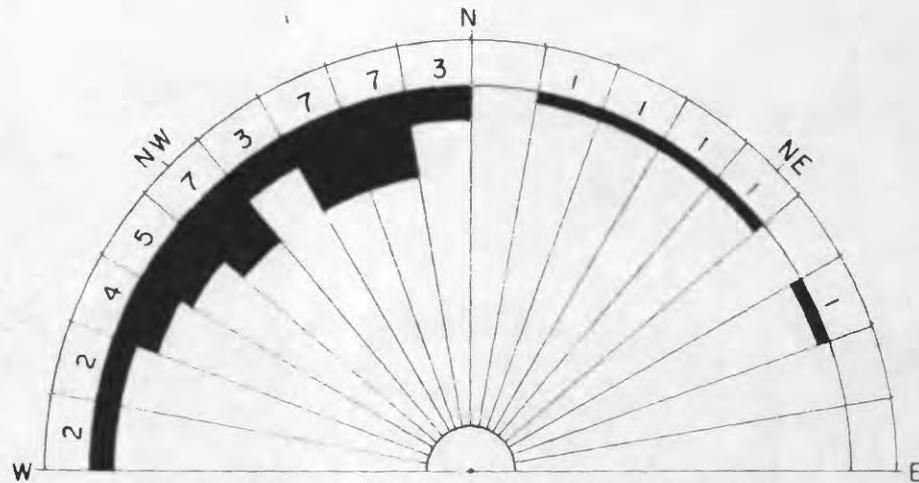
Geologic field data indicate that most channels are relatively straight. A few channels, however, such as the Monument No. 1 channel, (fig. 32) apparently describe wide curves.

Confirmation of both the relative straightness and the short character of some channels stems from a geophysical investigation in the Koley Black area (fig. 19) by Black and Jackson (1954) of the U. S. Geological Survey. The fact that channel no. 45 (fig. 19) ends within 350 feet of the outcrop could not be foreseen from surface exposures.

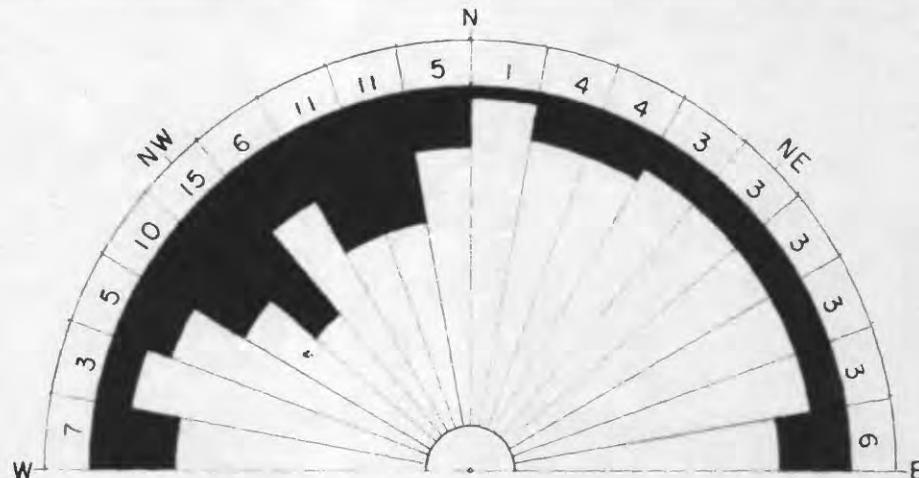




A. -- Monument Valley area, Arizona. A faint northwesterly orientation of the channels is suggested by the diagram.



B. -- Monument Valley area, Utah. A strong northwesterly orientation of the channels is apparent in the diagram.



C. -- Monument Valley area, Arizona and Utah. A dominant northwesterly orientation of channels is clearly shown. Data for Utah part of Monument Valley were furnished by R.Q. Lewis, Sr., and D.E. Trimble, U.S. Geological Survey.

FIGURE 18.--CHANNEL TRENDS, AS NOTED IN THE MONUMENT VALLEY AREA, ARIZONA AND UTAH.



Single channels are most common, but several bifurcate, and of these, at least one appears to divide into a series of subparallel smaller channels. This seems to be the case in the Koley Black area, where a single large channel branches to form several minor channels (fig. 19). The Monument No. 2 channel also bifurcates; the two parts join after several hundred feet to form again one large channel (fig. 30B).

Floors.--Little is known about the configuration of channel floors. From mine workings in the Monument No. 2 and Monument No. 1 channels, the floors are known to be undulatory and locally extremely irregular, both in longitudinal extent and in cross section (fig. 30C). Geophysical work in the Koley Black area (fig. 19) and along the Alfred Miles No. 1 channel (fig. 41) has also indicated that broad shallow scours are in channel floors. The floors of the Monument No. 2 and the Monument No. 1 channels have similar scours. It has been suggested by some geologists of the U. S. Atomic Energy Commission (Chester and Donnerstag, 1953) that these basal scours are important in localizing ore. They state "In the majority of deposits the mineralized material is confined to the bottom or lower sides of the channel and most often in scours or potholes in the channel."

The mapping of the Vanadium Corporation of America's Monument No. 2 mine suggests that although these scours may be favorable localities for ore deposition, by no means are they the only ones. In general, the major deposits of uranium ore are in the basal sediments. However, ore is found along the flanks, in the center, and in the uppermost channel sediments (p. 193).

Sediments.--Sediments filling the channels range from fine- and coarse-grained sandstones to conglomerates. Parts of channels are filled completely with a massive well-sorted uniform-textured medium-grained sandstone, totally devoid of pebbles or conglomerate lenses. Other parts contain conglomerate with minor amounts of interstitial coarse-grained sand.

Our impression is that the channels contain more fossil wood than the formation as a whole. Some of this wood is replaced by silica, some by copper carbonates and sulfides, some by uraninite, and some has been altered to carbon. Flattened logs of black carbonaceous material (vitrain?) are associated with several ore deposits. Some of the rich ore bodies at the Monument No. 2 mine may represent deposition of uranium minerals around logs (p.157). Pieces of wood partly replaced by secondary copper minerals (azurite, malachite) have been found in basal sediments of the Alfred Miles channels Nos. 1 and 2 and in Double channel (table 3).

At least two types of clay are included in sediments of the Shinarump member of the Chinle formation. By far the most abundant are altered and unaltered clay fragments derived from the Moenkopi formation. Lesser amounts of clay are represented by altered volcanic ash which was included during deposition of the Shinarump member.

Whether either type of clay fragment is instrumental in the localization of uranium ore is unknown. Conflicting evidence has been noted at several mineralized localities. In the Monument No. 2 mine it is thought that clay has no significance in such localization, but at both the Monument No. 1 Annex and the Skyline mine clay pebbles appear to have acted as localizing agents for the accumulation of uranium minerals.

In the Skyline channel, San Juan County, Utah, clay masses of unknown origin, as much as 4 feet on a side, are distributed profusely throughout the channel sediments. Similar clay masses are found in other channels. Preliminary X-ray work by Donald H. Johnson, has indicated that most of these clay masses are composed of quartz, hydromica, and possibly a little montmorillonite (table 4).

Table 4.--Composition of some clay masses from the Monument Valley area, Arizona and Utah, as determined by X-ray spectrometer. Identification by Donald H. Johnson.

<u>Sample number</u>	<u>Location</u>	<u>Composition</u>
W-175A	Monument No. 1 mine, Navajo County, Ariz.	Quartz, hydromica, and a little kaolinite.
W-175B	Monument No. 1 mine, Navajo County, Ariz.	Quartz, hydromica, and carbonate apatite(?)
W-176A	Base of channel, Monument No. 1 mine, Navajo County, Ariz.	Quartz, hydromica, and a little carbonate apatite(?).
W-176B	Base of channel, Monument No. 1 mine, Navajo County, Ariz.	Quartz, hydromica, and a little carbonate apatite(?) and kaolinite or chlorite
W-180	Monument No. 1 mine, Navajo County, Ariz.	Quartz, hydromica, a little kaolinite, and possibly a little montmorillonite.
W-182	Monument No. 1 Annex, Navajo County, Ariz.	Quartz, hydromica, and probably a little mont- morillonite.

Table 4.--Composition of some clay masses from the Monument Valley area, Arizona and Utah, as determined by X-ray spectrometer--  
Continued. Identification by Donald H. Johnson.

<u>Sample number</u>	<u>Location</u>	<u>Composition</u>
W-186	Skyline mine, San Juan County, Utah.	Quartz and hydromica.
W-187	Skyline mine, San Juan County, Utah.	Quartz and hydromica.
W-188	Skyline mine, San Juan County, Utah.	Quartz, hydromica, and perhaps a little mont- morillonite.

Associated swales.--Several channels are along the axes of broad shallow swales cut in the top of the Moenkopi formation. Whether all channels are so associated with swales is unknown; it seems likely that they are, for this channel-swale relationship has been noted repeatedly at several widely separated localities in the Monument Valley area (Witkind, 1956a). The swales parallel the channel, range in width from 2 to 3 miles and have about 40 feet of relief. A few have been traced for distances as much as 4 miles. Because the swales are so wide in comparison to their depth, they are difficult to perceive visually. Commonly they are easily apparent on maps of the base of the Shinarump member of the Chinle formation. Experience has indicated that such maps are compiled most easily and accurately in the Monument Valley area by isopaching the combined Hoskinnini tongue of the Cutler formation and Moenkopi

formation (fig. 4). This interval is used because of the ease of recognizing the disconformity at the base of the Hoskinnini tongue both on the ground and on aerial photographs. The disconformity is an excellent datum for isopachous work as it is remarkably free of relief.

This channel-swale relationship is best illustrated in the Monument No. 2 mine area (fig. 20). Isopachous maps of the combined Hoskinnini tongue and Moenkopi formation in the Monument Valley area indicate a gradual thinning in an easterly direction (p. 50). In the Monument No. 2 mine area the regional thickness of the combined Hoskinnini tongue and Moenkopi has decreased to 80 feet. As the channel is approached laterally, the combined thickness dwindles to about 30 feet at the channel flank. Inasmuch as the datum used (disconformity between the Hoskinnini and DeChelly members of the Cutler formation) is nearly plane, this thinning reflects a swale in the top of the Moenkopi. The swale is about 3 miles wide and its axis is marked by the Monument No. 2 channel. The channel has been scoured about 50 feet into the underlying strata. Thus about 30 feet of the Hoskinnini member and Moenkopi are removed as well as the top 20 feet of the DeChelly sandstone member.

Swales similar to this one are associated with channels along both edges of Hoskinnini Mesa.

If each channel is associated with a swale, then a device may exist for the discovery of those channels which are buried beneath younger strata. Isopachous maps of the combined thickness of the Hoskinnini tongue and Moenkopi formation could be prepared on the basis of surface exposures. Such maps would indicate the presence of the swales. Once

parts of the swales are found, it may be possible to follow them beneath younger strata by geophysical techniques. If, as we believe, the channels do occupy a position near the axis of the swale, "fences" of holes drilled normal to the trend of the swale might help locate the channel more exactly.

Origin.--At least two hypotheses have been proposed to explain the origin of channels. The first suggests that the channels were formed during an episode of erosion subsequent to the deposition of the Moenkopi formation but prior to the deposition of the Shinarump member of the Chinle. This viewpoint is exemplified by Gregory and Moore (1931, p. 52) who wrote:

"After Moenkopi time there was widespread erosion which partly beveled the soft Moenkopi strata and in places carved distinct erosion channels in them. The subsequently deposited Shinarump conglomerate constitutes a very widespread thin veneer which covers this erosion surface and fills its depressions."

Adherents of this viewpoint regard the unconformity and the channels as having formed probably during Middle Triassic, with the Shinarump member deposited much later in a second independent episode, most likely in Late Triassic time.

The second hypothesis suggests that the channels were cut by the streams that deposited the Shinarump member; and, therefore, are contemporaneous in age with basal sediments of the Shinarump.

There appears to be general agreement that the Shinarump member was deposited on a widespread surface of low relief, but no agreement exists as to when this surface was formed. Stokes (1950, p. 97) considers

it to have formed synchronously with the deposition of the Shinarump, which represents a pediment deposit. McKee (1951a, p. 91), however, considers it to have been an already formed flood plain, upon which the Shinarump was later deposited.

Apparently streams transported sands and gravels from a raised area to the south and gradually spread them northward as a thin blanket (p. 66). When one considers the coarse-grained and resistant materials that compose the Shinarump member, it seems unlikely that the formation could have been deposited without scouring the soft siltstones and shales of the underlying Moenkopi formation. It is suggested, therefore, that most of the scouring of channel occurred during deposition of the Shinarump member and not, to any large extent at least, in any period of erosion prior to this deposition.

Why one channel is continuous and another not is unknown. The short channels may represent scour depressions within broad shallow stream valleys (i.e., swales). If these basinlike short channels do represent deep scours along the course of a former stream, it may be possible to project the trends and locate other short channels now concealed beneath overlying beds of the Shinarump member. As yet, such alinement of channels has not been found.

Bryan, (1920, p. 191) in discussing present-day streams, suggests that scour depressions are most likely to form near the outside bends of streams where the erosive force of the stream is at a maximum. If this concept is applied to the Shinarump member, it may be that a former

meandering stream carrying sediments of the Shinarump member cut these deep scours wherever it swung about. Monument No. 1 (p. 231), a gently curving short channel, might have formed in this manner.

Another possibility is that local variations in the hardness of the Moenkopi formation that once formed the banks of the former streams may have caused the formation of narrows. The subsequent increase in stream velocity, together with an increase in gradient due to ponding upstream from the constriction, may have increased downward erosion at the expense of lateral planation, resulting in the formation of short channels. Mathews (1917), referring to elongate scour depressions as much as 2,000 to 7,200 feet long, 200 to 300 feet wide, and 40 to 60 feet deep in the floor of the Susquehanna River, suggests that these "deeps," as he calls them, are the result of such constrictions.

### Ore bodies

#### General statement

Four types of ore bodies can be differentiated in channel sediments of the Shinarump member of the Chinle formation in the Monument Valley area, Arizona and Utah. Of these the most striking are cylindrical, loglike masses of very rich tyuyamunite ore that have been called "rods" (Witkind, 1956b). Bodies similar to these have been noted in the Morrison formation and have been referred to as "cylindrical masses" (Coffin, 1921, p. 163). The second type of ore body consists of blanketlike deposits of uranium ore that are generally in the basal part of a channel and are elongated parallel to the channel trend. These are known as tabular ore

bodies. These first two types comprise the major uranium ore bodies. The third type of ore body has so far been found only in the Monument No. 2 mine and consists of irregular masses of sediments that are thoroughly impregnated with vanadium minerals. This type, referred to as a corvusite-type ore body, has a highly irregular shape. It varies in thickness and length and locally includes sediments of both the Shinarump member of the Chinle formation and the underlying DeChelly sandstone member of the Cutler formation. Rolls are the fourth type of ore body, and they can be divided into two categories based on exposures in the Monument No. 2 mine. The first category includes rolls formed only in sediments of the Shinarump member. These consist of channel sediments impregnated with yellow uranium minerals that form curved bands which cut across bedding planes. The second type of roll is found only in sediments of the DeChelly sandstone member and consists of curving laminae of concentrations of vanadium minerals that cross the bedding. These rolls seem to be related to the intersection of fractures and bedding planes.

#### Rods

The rods are exposed in the Monument No. 2 mine where they appear in profusion and form richly mineralized bodies (fig. 21) apparently scattered at random through the channel sediments. The channel sediments surrounding these rods commonly contain only trace amounts of uranium. The uranium content about 1 foot away from the edge of a rod may be as low as 0.002 percent; whereas a sample from the edge of the rod will be up to 14 percent or more uranium. Although present practice is to



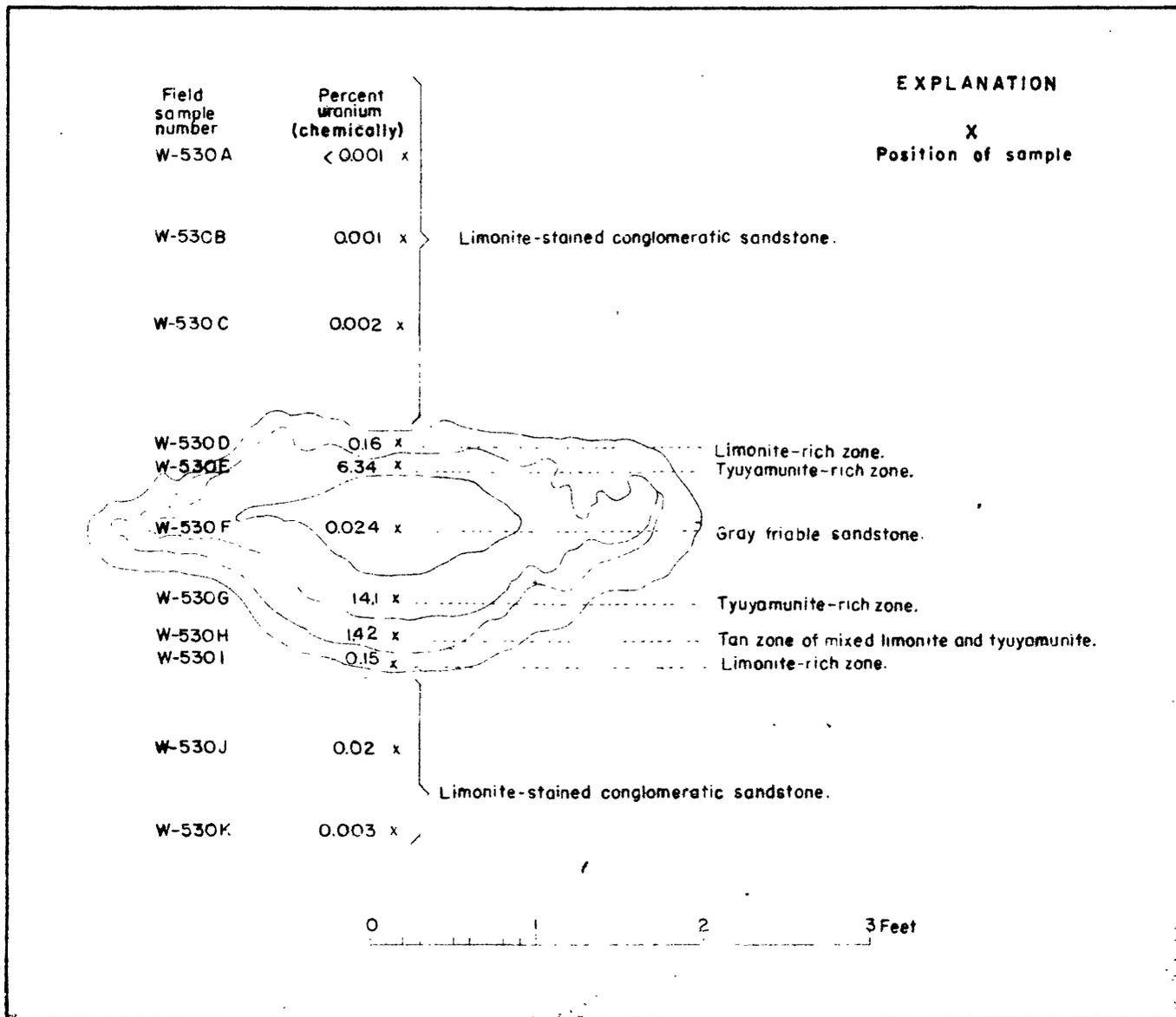


Figure 21.--CROSS SECTION OF TYPICAL ROD IN THE MONUMENT NO. 2 MINE, SHOWING POSITION OF SAMPLES.



mine and ship the entire face, it is apparent that the bulk of the rock, even that 1 foot or less from the rod, is essentially barren. The friable sandstone centers of the rods also are weakly mineralized. This discrepancy in grade between rods and confining sediments is repeated throughout the mine.

The origin of these rods is obscure. Some may result from chemical changes induced in the mineralizing solutions by organic matter; others may result from unusual conditions of permeability and porosity in the host rock.

The rods in the Shinarump member of the Chinle formation can be classified roughly into two categories: simple and complex. The simple rod is illustrated in figure 22A. It consists of an outer rim of sandstone impregnated with limonite within which is a rim of tyuyamunite-impregnated sandstone. The tyuyamunite in turn surrounds a core of extremely friable light-gray sandstone.

The complex rod is bounded similarly by an outer rim of limonite-impregnated sandstone within which is a rim of tyuyamunite-impregnated sandstone (fig. 22B and C). These rims, however, are much more irregular than in the simple rod. A further subdivision of the complex rod has two subtypes. One type contains irregular masses of mixed limonite and tyuyamunite randomly distributed throughout the gray sandstone center (fig. 22B, and fig. 23). The second type may have these irregular masses of limonite and tyuyamunite in the sandstone center, but in addition, it has a central core of silicified wood (fig. 22C and fig. 24).



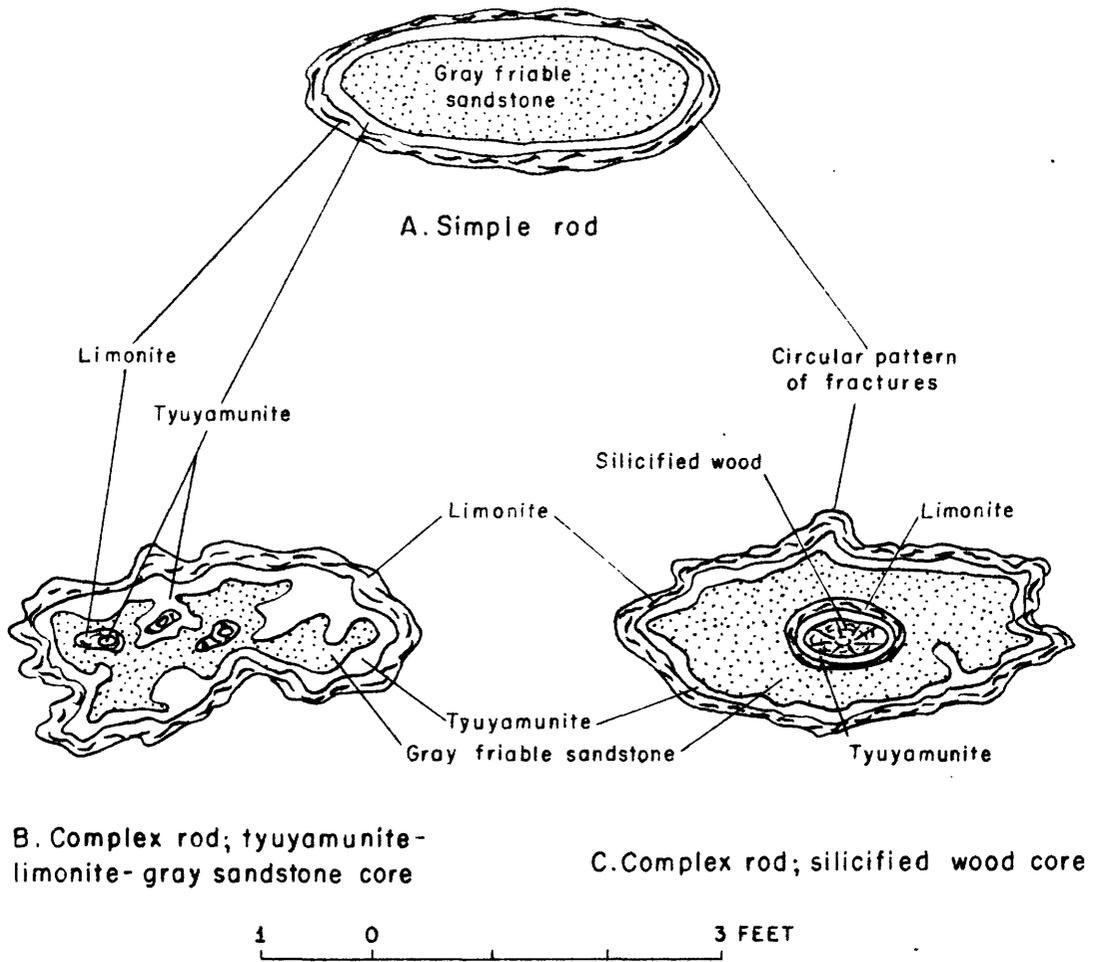


Figure 22.-- CROSS SECTIONS OF SIMPLE AND COMPLEX RODS.



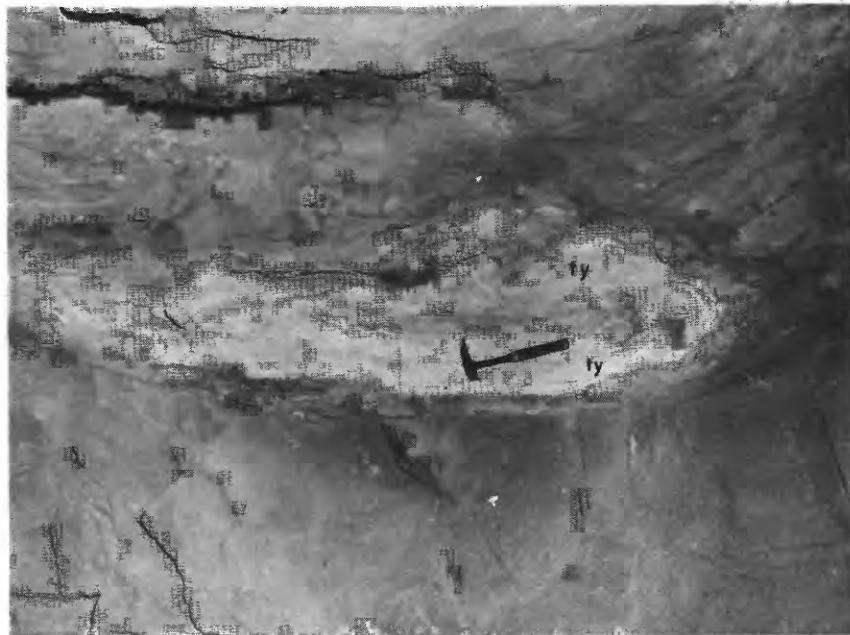
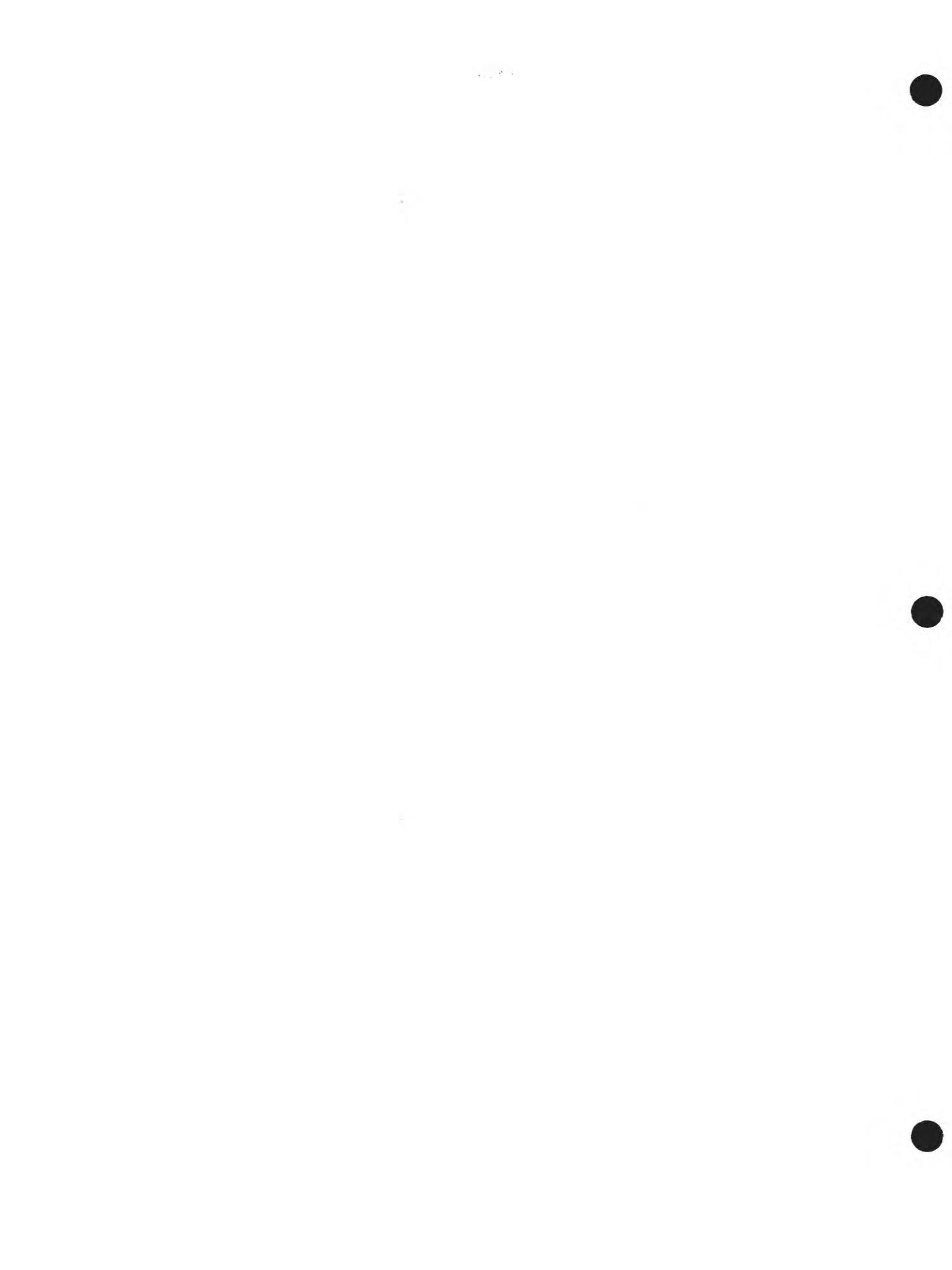


Figure 23.--Photo of cross section of a richly mineralized rod. Light area is tyuyamunite-rich sandstone (ty) that may contain over 20 percent  $U_3O_8$ . Darker areas are weakly mineralized sediments that contain only trace amounts of  $U_3O_8$ .





Figure 24.--Photo of cross section of complex rod containing core of silicified wood. Silicified wood (sw) forms core and is rimmed by thin band of tyuyamunite (ty) and limonite-impregnated sandstone (lt). Mass of rod is composed of gray friable sandstone (ss) with mixed limonite and tyuyamunite. Edge of rod marked by thin tyuyamunite and limonite bands.



Near some of the rods the bedding of the confining strata is interrupted at the rims; elsewhere the bedding arches over the rods. Grain size changes abruptly at the edges of some rods. Most rods are remarkably straight but a few taper and bifurcate. Many rods of the complex type are associated with silicified wood; and, invariably, where longitudinal exposures are available, the silicified wood is seen to be collinear with rods (fig. 25). Exposures of several rods are large enough to afford longitudinal examination of the gray sandstone core filling the center. In these the direction of crossbedding is totally different from the direction of crossbedding of those sediments outside the rods.

Many of the rods were interpreted by the senior author to represent supplantation of coalified logs by sand, silt, and clay as well as by those primary minerals which upon oxidation would alter to limonite and tyuyamunite. To test this concept six samples were sent to James M. Schopf of the U. S. Geological Survey. Five of the samples were collected from the rims of the rods, and the sixth was collected from silicified wood in the core of a rod. Of the 6 samples submitted, Schopf identified only 1 as fossil wood, and that was the one collected from the silicified wood core of the rod; the others contained no trace of organic matter. It seems, therefore, that although parts of some rods may represent replacement of some form of former plant matter, the mineralized rims of the rods do not. The distribution of the rods (figs, 27 and 29), however, and the collinearity apparent between many rods and silicified remnants of logs (p. 151) suggest that some relationship does exist



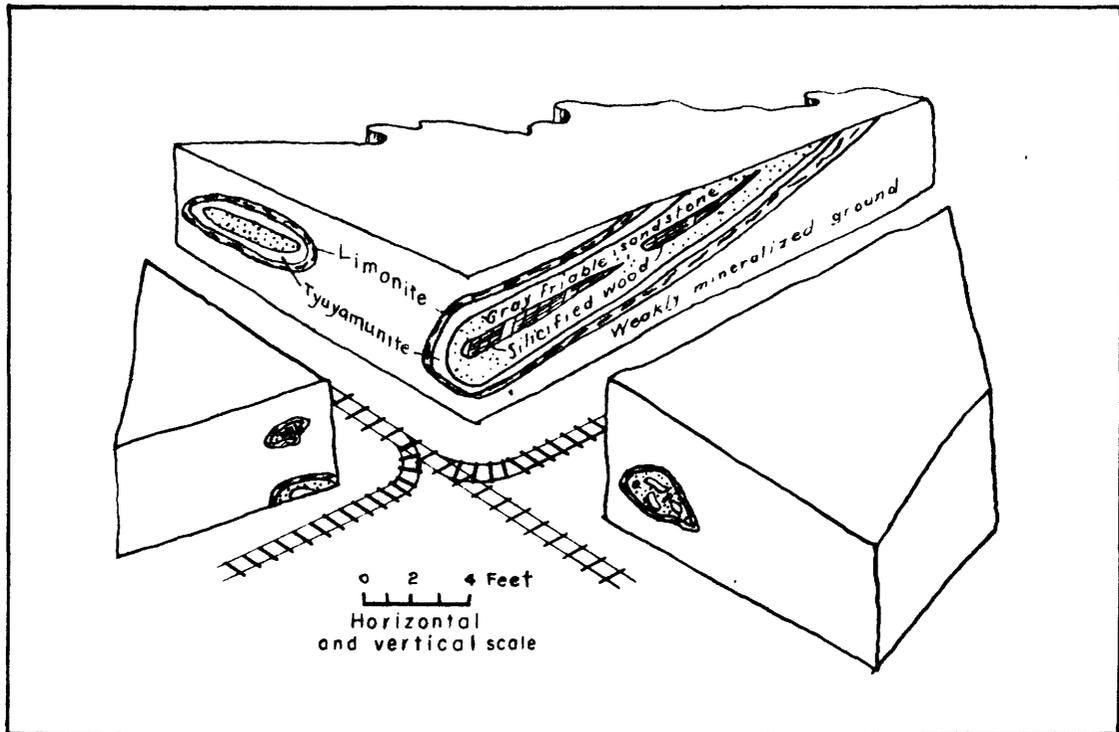


FIGURE 25.—IDEALIZED BLOCK DIAGRAM OF MINE WORKINGS SHOWING RELATIONSHIP OF RODS TO ONE ANOTHER AND TO MINE DRIFTS.



between buried former logs and the rods. Possibly, the shape, size, and distribution of the rods were determined by the buried logs. During or shortly after burial the original organic matter of the buried logs may have been removed, and other, more stable materials, such as sand, silt, and clay, deposited in the voids so formed. The removal of the organic matter and its subsequent supplantation was probably a gradual process and affected only part of any log at any one time. It may have been during this episode that porosity and permeability changed sufficiently to localize the ore-bearing solutions. Thus, those rods over which the bedding arches, as well as those that show abrupt changes in grain size between the confining strata and the rod boundaries, may represent merely the former presence of buried logs which have since been supplanted by sand, silt, and clay.

Other rods may have been formed by mineralizing solutions in response to halos of decomposition products such as humic colloids, organic resins, and various other hydrocarbons spreading outward from buried logs. Possible examples of this type are those rods that contain silicified wood at their centers.

Still another possibility is that these rods may have formed completely independent of plant matter and may merely reflect fracture patterns formed during processes of compaction and authigenic crystal growth. It may be that no single concept alone will explain how rods formed. Perhaps combinations of the concepts mentioned above are involved. For instance, the shape, size, and distribution of the rods may have been determined by the presence of buried logs. After the logs were buried, their rims may have been partly

replaced by more stable materials. If, at this time, compaction and authigenic crystal growth began, fracturing involving slight movement may have occurred along the zones represented by the former edges of the log. In the voids formed as a result of this movement and fracturing the ore solutions may have deposited their minerals.

Fischer (1947, p. 455), in discussing the vanadium deposits of the Colorado Plateau, implies that an affinity may exist between vanadium deposits, channel sediments, and organic matter in the Morrison formation of Jurassic age. Still referring to the Morrison formation, Fischer and Hilpert (1952, p. 12) indicate that although fossil plants are erratically distributed, most of the carnotite deposits are in parts of the sandstone that contain fairly abundant plant remains. From our observations in the Monument Valley area on the habits of uranium ores in the Shinarump member of the Chinle formation, we concur with the concept expressed by Fischer and Hilpert and believe that a close spatial relationship exists between pockets of uranium ore, channel sediments, and former plant matter.

The channels apparently were places where plant matter was concentrated. Trees growing along the flanks of these ancient streams may have fallen into them and then have been buried by the channel sediments. Other plant material may have been rafted into the channels and buried. Subsequently, when mineralizing solutions moved through the Shinarump member, favorable physical and chemical conditions, resulting primarily from the former presence of buried logs, may have been responsible for the formation of rods.

Fractures as related to rods

Small fractures cut the sand grains that form the rims of the rods (fig. 26). In consequence a crudely circular pattern of fractures delineates each rod (fig. 22). These fractures, restricted to the rims of the rods, invariably follow the crenulations that form the edges of the complex rods and persist for the entire length of the rods. These fractures are not apparent in those grains that fill the cores of the rods, nor in the grains beyond the boundaries of the rods (fig. 26D). The fracturing is restricted to (1) the limonite-impregnated sandstone zone and (2) the tyuyamunite-impregnated sandstone zone, both of which form the rims of the rods. Moreover, the fracturing stops along very definite boundaries (fig. 26A); the separation between fractured and unfractured grains may be a zone not more than 1 mm wide.

Two systems of fractures were noted in thin sections; one consists of a set of parallel fractures (fig. 26B) with a subsidiary set trending more or less at right angles; the other in a plexus of fractures that lacks orientation (fig. 26C). Each fracture of the parallel set is about 0.20 mm away from adjacent fractures, and each fracture can be traced for as much as 5 to 10 mm in a relatively straight line as it continues uninterrupted through sand grains. In places this parallel set of fractures is cut by a subsidiary set that is at right angles to the main set. The subsidiary set offsets the main fractures slightly. Those fractures that have no determinable pattern are less common. The fractures are jagged and end at the grain boundaries. The gross appearance of this fracture system is that of an interlacing network.



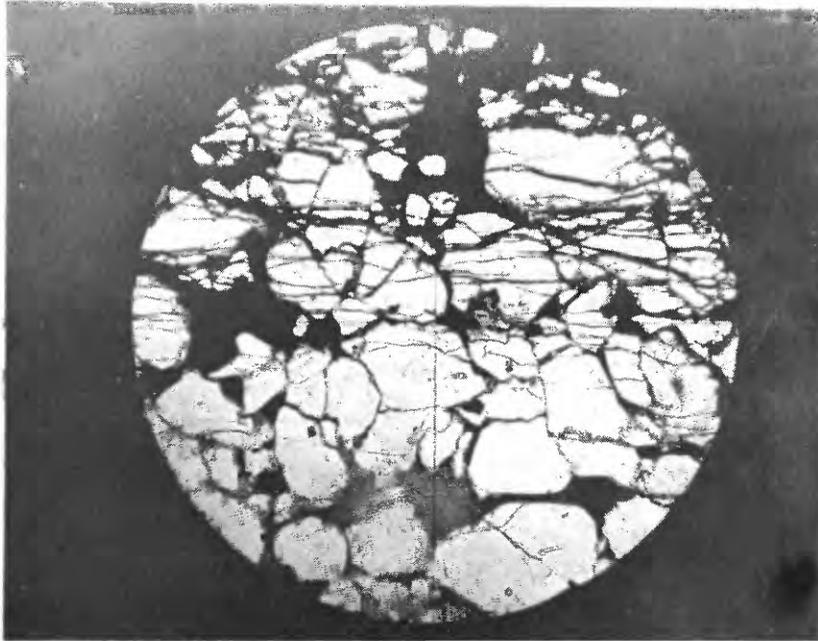


Figure 26.--Photomicrographs of thin sections prepared from specimens collected in the Monument Valley area, Arizona. Photomicrographs A-C show uranium and vanadium minerals in fractures and interstices; specimens collected in Vanadium Corporation of America's Monument No. 2 mine. Photomicrograph D is of sediments of the Shinarump member distant from channel; made with crossed nicols. All enlarged 22 diameters. A.--Photomicrograph showing sharp boundary between fractured and unfractured grains. Specimen from upper edge of rod.



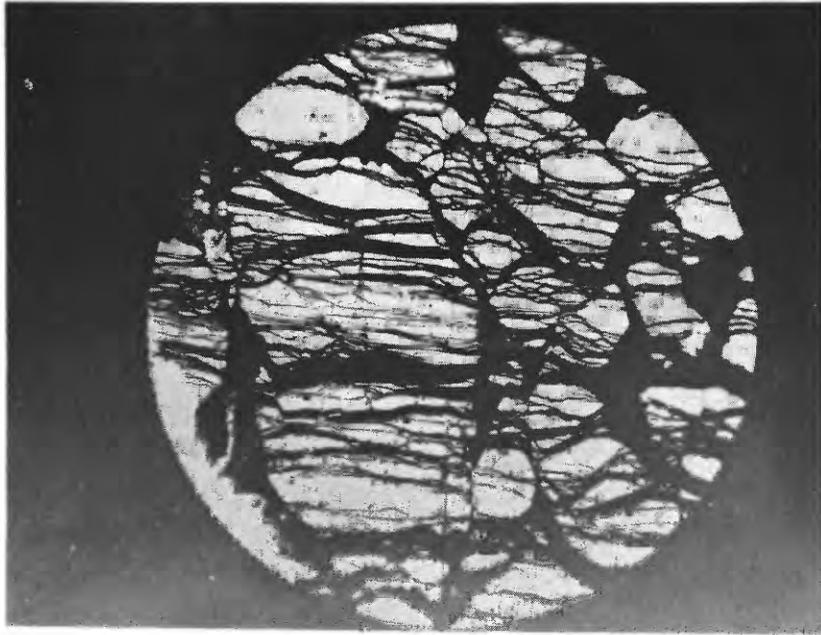


Figure 26B.--Photomicrograph showing parallel fractures.  
Specimen from lower edge of rod.





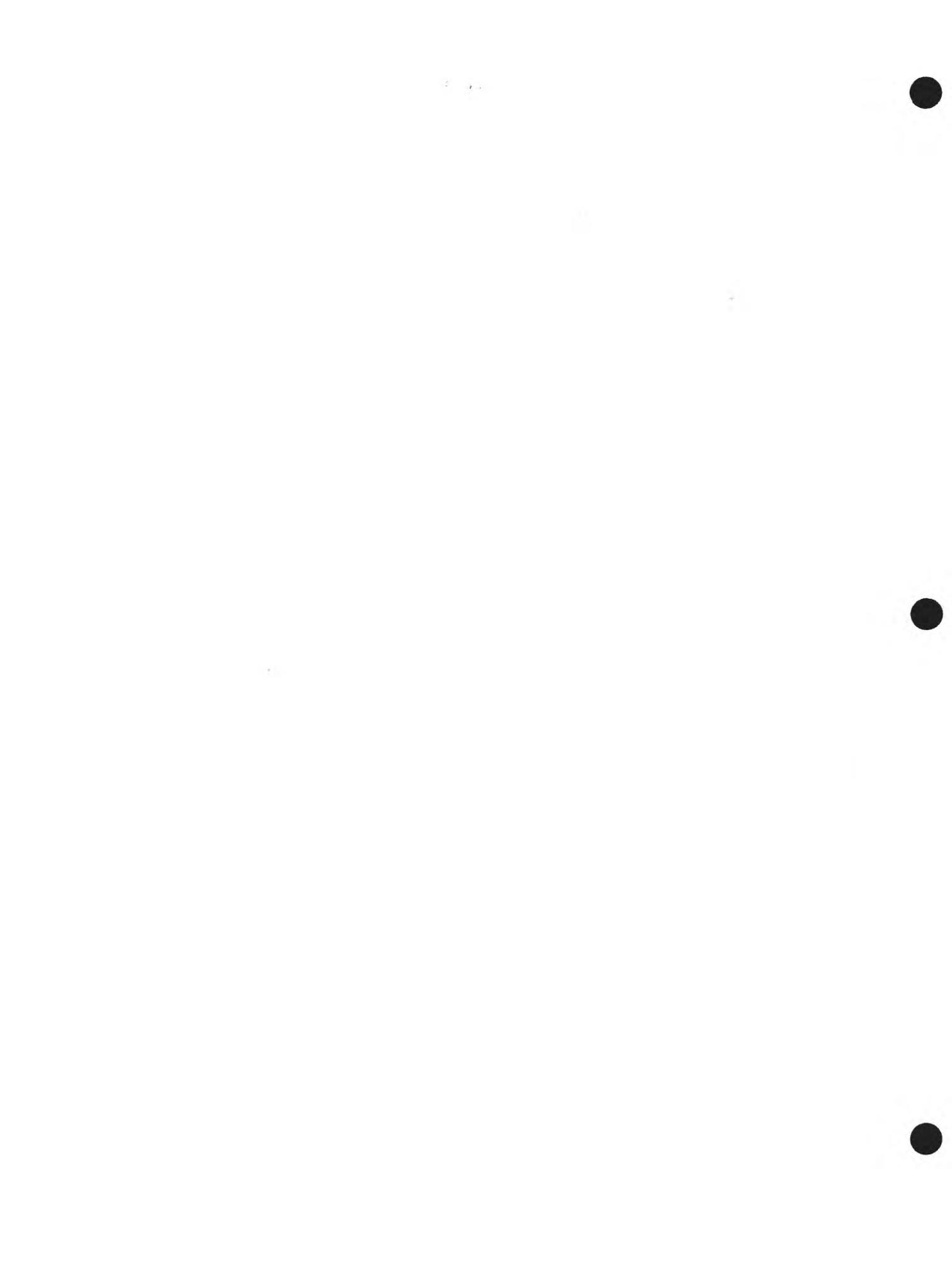
Figure 26C.--Photomicrograph showing irregular fractures.  
Specimen collected about 1 foot away from edge of rod.

11





Figure 26D.--Photomicrograph of thin section of sediments of the Shinarump member distant from channel. Crossed nicols.



Filling the fractures, interstices, and other voids are secondary uranium and vanadium minerals, calcite, and authigenic quartz. The depositional sequence seems to be authigenic quartz first; secondary uranium and vanadium minerals, second; and emplacement of calcite, last.

The annular pattern formed by the fractures that outline the rods is distinctive and has been found only in the Monument No. 2 mine. How these circular fracture patterns developed is unknown. One answer may involve factors of selective cementation. Perhaps those grains in the fractured zones were once tightly cemented. When stress was applied, the cemented grains may have fractured, but the uncemented grains may have merely rolled and readjusted themselves to the forces applied.

The effect of fractures in localizing the uranium deposits is unknown. In an attempt to resolve this question three diagrams were prepared. The first is of the fractures mapped in the Monument No. 2 mine (fig. 27A). Most of the fractures trend northwest. The second diagram (fig. 27B) includes all the rods on which strikes were taken. A random trend is apparent. The third diagram indicates the trend of silicified logs noted in the mine workings (fig. 27C). Again a random orientation is apparent. If fractures were a controlling influence, one would expect a northwest orientation of the major ore bodies (i.e., rods) comparable to that shown by the fractures. As the diagram of the rod lacks this orientation, there seems to be some evidence against fracture control. Contrary evidence is suggested by the resemblance between the diagrams of the silicified logs and of the rods. The similarity between the random orientation apparent in the diagrams of



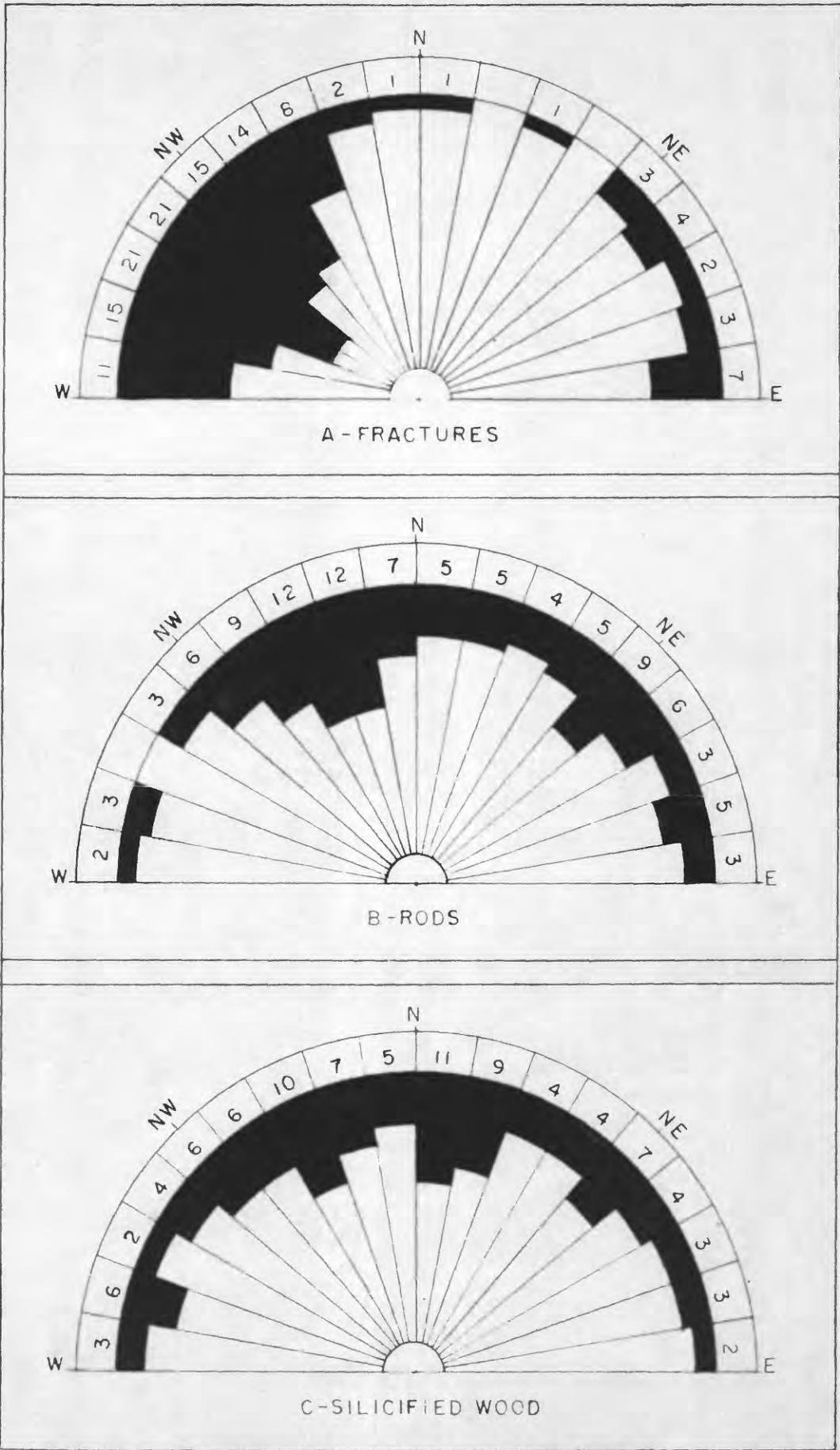


FIGURE 27.--DISTRIBUTION OF FRACTURES, RODS, AND SILICIFIED WOOD IN THE VANADIUM CORPORATION OF AMERICAS MONUMENT NO. 2 MINE.



the rods and the silicified wood suggests that some relationship, as yet unestablished, exists between the rods and silicified wood.

Parallelism between rolls of ore and fossil logs is reported by Fischer and Hilpert (1952, p. 5) in discussing the Ureavan mineral belt.

#### Tabular ore bodies

As of June 1953, tabular ore bodies had been found in the Monument No. 2 mine and in the Monument No. 1-Mitten No. 2 mine (fig. 2). The tabular ore bodies in the Monument No. 2 mine consist of conglomeratic sandstone containing scattered fragments of fossil plant matter and large amounts of yellow uranium minerals. The bodies are irregular in shape and outline but commonly are elongate parallel to the channel's trend. They are biconvex in both longitudinal and transverse section and range in width from 20 to 40 feet, areas much as 6 feet thick, and are about 60 feet long. They thicken downward into small depressions in the channel floor; the richest ore seems to be concentrated in these depressions. The tabular ore body is best exemplified in the Monument No. 1-Mitten No. 2 mine (fig. 2). However, it is much larger and is probably representative of those ore bodies found in the Mitten No. 1 and Skyline mines on Oljeto Mesa, Utah, and in the Whirlwind mine on Monitor Butte, Utah. Drilling by the U. S. Atomic Energy Commission on Holiday Mesa, Utah, has disclosed a similar type of ore body there. Two sedimentary units form the Monument No. 1-Mitten No. 2 ore body. A trash-pocket conglomerate composed of angular claystone fragments, rounded pebbles of quartz, chert, and quartzite, and fossil plant matter, all in a matrix of coarse-grained sandstone, generally forms the upper

part of the ore body. The lower part is composed of a coarse-grained silica-cemented sandstone. Intercalated between these units are lenses of barren hard calcite-cemented sandstone. The ore body is biconvex or planoconvex, about 675 feet long, extends in width from one channel flank to the other (50 to 120 feet), and ranges in thickness from 1 to 18 feet, although it averages 7 feet thick.

#### Corvusite-type ore bodies

Irregular-shaped sandstone masses, filled with blue-black vanadium minerals, principally "corvusite," are scattered along the length of the Monument No. 2 channel. These have been called corvusite-type ore bodies. Some of these bodies are near the base of the channel, whereas, others are near the surface, about 40 feet above the channel floor. In the corvusite-type ore bodies that are along the channel base the vanadium minerals fill interstices in both the Shinarump member of the Chinle formation, and locally in the DeChelly sandstone member of the Cutler formation, which in this area underlies the channel. The shapes and margins of these corvusite-type bodies are so irregular that specific dimensions are difficult to determine. In general, the bodies range in length from 100 to 600 feet, are about 100 feet wide, and are as much as 40 feet thick.

In corvusite-type ore bodies the concentration of vanadium minerals differs from place to place. Locally the vanadium minerals have so thoroughly impregnated the strata that they appear a deep blue black. Near the margins of these vanadium-rich areas, small dark-brown

irregular-shaped limonite-rich and vanadium-poor splotches appear. The margins commonly are gradational and consist of limonite-rich sediments weakly impregnated with vanadium minerals.

As far as can be perceived, these corvusite-type ore bodies near the base of the channel have no specific trend, lack recognizable margins, and impregnate sediments of both the Shinarump member and the DeChelly sandstone.

Within the corvusite-type ore bodies are small concretionlike masses of sediment which show a rudimentary zoning. Generally these are crudely ellipsoid, irregular in outline (fig. 28) and commonly lie in a nearly horizontal position. They are about 10 feet long, about 8 feet wide, and about 4 feet high. The outer shell consists of limonite-impregnated sandstone about 6 inches thick. Within this limonite-rich shell is an irregular zone ranging from 1 to 8 feet thick formed of sediments impregnated with blue-black vanadium minerals. The core ranges in thickness from 2 to as much as 5 feet and consists of white opal which fills interstices in the sandstone. In a few localities the white material encloses fragments of an extremely friable coaly substance (vitrain?).

The corvusite-type ore bodies are most abundant near the base of the channel although a few crop out. The near-surface bodies have been oxidized to deep red hewettite. In those bodies that

---

✓ The color is so prevalent that the workings in the mine are referred to as the West Red Oxide, East Red Oxide, and South Red Oxide workings.

---



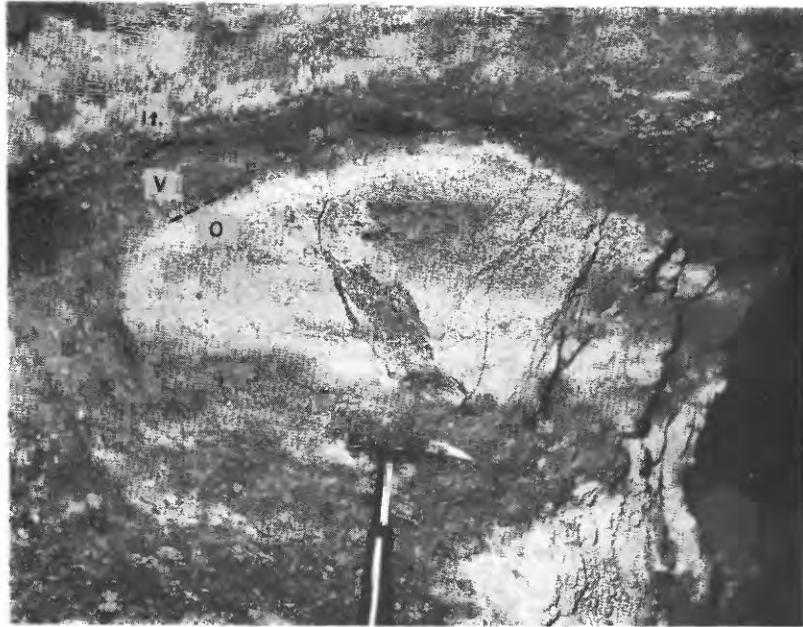


Figure 28A.--Photo taken in Vanadium Corporation of America's Monument No. 2 mine showing concretionlike body in part of vanadium-rich ore body. Core is sandstone with white opal (o) filling interstices. Surrounding this core is a layer of black vanadium-impregnated sandstone (v). A limonite-rich (lt) rim surrounds the entire body.





Figure 28B.--Photo showing another concretionlike mass in vanadium-rich ore body in basal channel sediments.

2



are near the base of the channel, the principal vanadium mineral is corvusite, although hewettite is also present. Other minerals collected are navajoite and steigerite (Weeks and Thompson, 1954), as well as specimens of uraninite, becquerelite, and uranophane. Tyuyamunite and carnotite are abundant near the margins of these ore bodies, commonly in rods, although in places they appear as yellow disseminated specks contrasting markedly with the blue-black color of the corvusite- and hewettite-rich areas.

### Rolls

The fourth type of ore body, known as a roll, is prevalent in ore deposits in the Morrison formation on the Colorado Plateau. Rolls, however, are very minor features in the ore deposits of the Monument Valley area. They are best displayed in the Monument No. 2 mine where two types are found.

Those in the Shinarump member of the Chinle formation consist of bands of yellow uranium minerals filling interstices in the sandstone. These bands range in size from some that are about 2 inches thick, which can be traced for 6 to 8 feet, to others as much as 1 foot wide and 12 to 15 feet long. Each band is separated from its neighbor by weakly mineralized or barren rock 1 to 2 feet thick.

The rolls in the DeChelly sandstone member of the Cutler formation are found only in those parts of the mine that underlie corvusite-type ore bodies. They consist of curved bands of vanadium minerals, principally corvusite, alternating with barren rock. These mineralized

bands resemble diffusion bands, and each ranges in thickness from half an inch to 3 inches. Each mineralized band is separated from its neighbor by barren sediments which are about 4 inches thick. These rolls seem to be related to the intersection of crossbedding planes and fractures, for the size of the rolls is determined by the spacing between the joints. The rolls are small features and form ellipsoids, each about 3 feet wide and about 2 feet high. Their length is unknown. In places the vanadium-rich bands follow crossbedding planes. Where fractures intersect the crossbedding planes, the vanadium minerals have followed the fracture and impregnate the sediments adjacent to the fracture. Several localities were noted where vanadium minerals were profuse near the upper end of a vertical fracture but lessened as the fracture closed with depth. The minerals seem to have moved in waves of concentration both laterally and vertically from the crossbedding planes and joints into that part of the rock free of vanadium minerals. The resulting effect has been to create a series of curving vanadium-rich bands that parallel the bedding in places and elsewhere cross it. As the rolls are controlled to some extent by the crossbedding planes, the attitude of the rolls depends upon the strike and dip of the crossbeds.

#### Age determinations

Since 1949, L. R. Stieff and T. W. Stern of the U. S. Geological Survey have been studying the age of the Colorado Plateau uranium deposits. This work has developed data that are convincing in answering the basic questions as to the time of formation of the deposits.

As an inherent part of this program 12 samples of ore from the Monument No. 2 mine area were studied (table 5). Of these, nine were discrete specimens of uraninite, becquerelite, uranophane, or carnotite which were collected from the mines in the area. The remaining three were mill pulp samples.

Table 5.--Calculated  $Pb^{206}/U^{238}$  ages of uranium ores from the Monument

No. 2 mine area, Apache County, Ariz. Determinations made by L. R. Stieff and T. W. Stern, U. S. Geological Survey.

<u>Mine</u>	<u>Sample description</u>	<u><math>Pb^{206}/U^{238}</math> age to the nearest 5 million years</u>
Vanadium Corporation of America's		
Monument No. 2	Uraninite	70
Do.	do.	85
Do	do.	100
Climax Uranium Cato Sells Tract No. 1	do.	60
Average age of uraninite specimens		78
Vanadium Corporation of America's		
Monument No. 2	Uranophane	175
Do.	do.	130
Do.	Becquerelite	15
Do.	Carnotite	75
Climax-Uranium Cato Sells Tract No. 1	Becquerelite	5
Average age of altered specimens		80

Table 5.--Calculated  $Pb^{206}/U^{238}$  ages of uranium ores from the Monument No. 2 mine area, Apache County, Ariz.--Continued. Determinations made by L. R. Stieff and T. W. Stern, U. S. Geological Survey.

<u>Mine</u>	<u>Sample description</u>	<u><math>Pb^{206}/U^{238}</math> age to the nearest 5 million years</u>
Vanadium Corporation of America's		
Monument No. 2	Mill pulp	170
Do.	do.	250
Do.	do.	330
Average age of mill-pulp sample		250

The work completed by Stieff and Stern (1952a, 1952b), and Stieff, Stern, and Milkey (1953) has indicated that completely reliable age determinations can be made only on ore samples which have not been altered in any way since their deposition. Unfortunately, none of the twelve samples can be described as unaltered. Indeed, the range is extreme, extending from samples of uraninite that are but slightly altered to mill-pulp samples. This degree of alteration is reflected in the uncorrected age determinations. The  $Pb^{206}/U^{238}$  age determinations completed on relatively unaltered uraninite specimens give an average (unweighted arithmetic mean) computed age of about 78 million years (table 5). The range in computed age of these specimens is from a minimum of 60 million years to a maximum of 100 million years. Determinations completed on secondary uranium minerals (uranophane, becquerelite, and carnotite) give an average computed age of about 80 million years;

here, however, the range is from a minimum of 5 million years to a maximum of 175 million years. The mill-pulp samples give computed ages that average 250 million years and range from 170 million years to 330 million years.

The ages calculated for the specimens of relatively unaltered uraninite would appear to be the most reliable (p. 174). However, Stieff, Stern, and Milkey (1953, p. 8) report that if no direct consideration is given to the quality of the samples in determining their arithmetic averages, the computed average ages "are probably higher than the actual age of the ore." This type of error is included in the averages shown on table 5. It would seem, therefore, that the computed average age of 78 million years determined for uraninite specimens from the Monument No. 2 mine area may be high. How much higher it is than the true age is uncertain. Stieff, Stern, and Milkey, (1953, p. 13) note that the most reliable age determinations made (on uraninite specimens from the Happy Jack and Shinarump No. 1 mines in Utah) give apparent ages of 65 and 75 million years. These ages are considered to be within 10 million years of the true age of the samples. It would seem, therefore, that the true age of the ore in the Monument No. 2 mine probably is between 65 and 75 million years old.

The age for the Late Triassic (i.e., the age of the Shinarump member of the Chinle formation) is given by the Committee on the Measurement of Geologic Time (Marble, 1950) as about 160 million years. In comparison to the 78 million year apparent age determined for the ores in the Monument No. 2 mine, this means that the age of the sediments

that contain the ore is twice the age of the contained ore. In contrast, the beginning of the Tertiary is dated as 60 million years (Marble, 1950). It would seem, therefore, that the uraniferous ores in the deposit at the Monument No. 2 mine were emplaced during Late Cretaceous or early Tertiary time.

#### Origin and localization

Two basic related questions face most geologists studying the uranium-vanadium ore deposits on the Colorado Plateau. The first involves the source of the ore metals and the method by which they were introduced into the host rock. The second major question is the mode of localization of the uranium-vanadium ore bodies. Both of these questions have been studied in the Monument Valley area, Arizona, by the writers as well as by others. Conclusive answers have not been reached although progress has been made on these problems and hypotheses have been proposed that may lead eventually to the final answer.

During the Tertiary much of the Colorado Plateau was subjected to vigorous structural deformation and widespread igneous activity. The Henry, La Sal, Abajo, Ute, and Carrizo Mountains may have been formed at that time and probably represent surface manifestations of a deep-seated buried magma. Mineralizing fluids, possibly derived from this crystallizing buried magma, may have been carried to the host rock along fractures and faults resulting from the structural deformation. Possibly these solutions mingled with ground water in the Shinarump member, and the ensuing mixture then moved through the host rock.

Another source for the uranium and vanadium may be the devitrification of the volcanic ash contained in the Chinle formation (Waters and Granger, 1953). It may be that some of the uranium and vanadium came from the magmatic waters and some from the devitrification of the volcanic ash.

Possibly the mineralizing solutions moved laterally through the host rock until they encountered favorable traps in the form of channels. Within these channels uranium minerals may have been deposited in response to two factors; one of these being chemical; the other, physical. Localization of the uranium ore seems to be related in some manner to carbonaceous matter, or to the decomposition products therefrom. If the chemical role was dominant, the organic matter may have acted as a precipitant. Conversely, if the physical factors were more important, the change in porosity and permeability at the edge of the rods resulting from the fractured quartz grains may have been instrumental in localizing the uranium minerals.

Probably the rods were originally composed partly of uraninite, pyrite, and associated primary vanadium minerals. In time, most of the uraninite altered to becquerelite and with the addition of some vanadium to tyuyamunite; the pyrite was oxidized to limonite; and those areas rich in vanadium (montroseite) were altered to corvusite, which is being altered to hewettite.

Following the emplacement of the primary minerals, ground water assumed a role of prime importance as a leaching agent. The ground-water leached soluble uranium-vanadium minerals from the rods and then moved them both laterally and vertically, depositing them finally to form large volumes of weakly mineralized channel sediments.

We tend to favor the hypothesis that the spacing of the rich ore bodies (i.e., rods) is attributable to the original distribution of logs buried in the confining sediments of the Shinarump member. Further, we suggest that favorable conditions of permeability and porosity in the rods may have been contributing factors in the deposition and localization of the uranium ore. We also attribute the tabular ore bodies found in some channels (p. 166) to conditions of reduced permeability and porosity. These conditions may stem from poor sorting or the presence of large amounts of calcite, and interstitial clay, rather than fracturing.

Finnell (1957), as a result of his work at the Monument No. 2 mine, has suggested the possibility that structure controlled ore deposition. Finnell states, "During the Laramide orogeny, movement along the bedding planes brecciated the channel-filling sediments. Resistance of the thicker channel sediments to the bedding plane slippage set up stresses that formed a zone of en echelon strike-slip vertical faults along the channel length. The ore-bearing solutions may have risen along the vertical faults from a deep source, and spread out to deposit ore in the highly permeable brecciated sandstone and conglomerate."

#### Uranium potentialities of the area

As of June 1953, only two areas produced uranium ore in the Monument Valley area, Arizona, the Monument No. 1 mine area in Navajo County, and the Monument No. 2 mine area in Apache County. As of July 1953, 6 mines were operating in the Monument No. 2 mine area, and of these, 5 were

closing down. Despite this bleak showing, prospecting continues. This is attributable to the richness of the deposit at the Monument No. 2 mine which will always act as a major stimulant to the search for new deposits of uranium ore in the Monument Valley area. Moreover, drilling programs by the U. S. Atomic Energy Commission as well as by private industry in channels within the Utah part of Monument Valley has indicated that uraniferous deposits are in many channels that are barren on the outcrop. This is well shown in the Monument No. 1 channel. Originally a uraniferous deposit was worked at the east edge of the channel. The deposit thinned; and, in 1950, the mine was abandoned. Subsequently, drilling in another part of the same channel resulted in the discovery of a new uraniferous deposit.

Because the ore deposits in channel sediments alternate at irregular intervals with barren strata, and because no method exists at present for differentiating between ore-bearing and barren channels, all channels are suspect. This has stimulated an intensive search for the channels.

Finch (1953, p. 32) reports that an arcuate belt of favorable ground extends through the northern part of the Monument Valley area, Arizona. The southern edge of the belt, according to him, is well defined and extends from the Monument No. 2 mine on the east to the Whirlwind mine near the San Juan River, Utah, on the north. The northern edge of the belt parallels the southern edge and is about 4 miles distant from it. Channels within this belt presumably are more likely to contain ore than those outside the belt. Warren I. Finch (written communication) has also suggested that those channels nearest a pinchout of the Shinarump member are most favorable. He postulates such a pinchout just north of the Monument Valley area, Arizona.

We do not agree with Finch on either of these concepts. In the course of our work, we were unable to distinguish any belt of favorable ground through the Monument Valley area. Rather than a specific sector of the Monument Valley area being favorable, we believe that all channels constitute favorable ground, and that ore deposits are as likely to be found in channels away from a pinchout of the Shinarump member, or belt of presumably favorable ground, as in those channels near the pinchout or in the so-called favorable belt. In general the drilling programs have been concentrated in those areas near the known ore deposits. Consequently, little is known about those channels that are exposed in other areas. This creates a misleading impression that certain parts of the Monument Valley area are more favorable than others, when, in fact, all that is expressed is the degree of knowledge available regarding those parts.

Intensive geologic investigations in the Monument Valley area, Arizona, by both the U. S. Geological Survey and the U. S. Atomic Energy Commission, began in the spring of 1951. Since that time all of the known mineralized exposures have been examined and most have been sampled by geologists of one or the other organization. As of 1954, the U. S. Geological Survey had not drilled in the Monument Valley area of either Arizona or Utah. The U. S. Atomic Energy Commission, however, has completed 4 drilling programs in the Arizona part of Monument Valley and 3 in the Utah part. The four areas in the Arizona part of the Monument Valley area investigated by the U. S. Atomic Energy Commission are the Monument No. 2 mine area, Hunts Mesa, Nakai and Hoskinnini Mesas, and the Koley Black area (Cold Mesa).

As it was soon realized that the uranium deposits are localized in channels, all of the drilling programs attempted to delineate the channels as well as to test them for ore. The results have been inconclusive. Although some mineralized ground was found by the drilling programs, the grades and quantities were low.

As of June 1953, a thorough test of any single channel in the Monument Valley area, Arizona, had not been made. The geologic work in this area as well as the drilling completed in the Utah part of Monument Valley suggest that rich deposits of uranium are not continuous along a channel's length (p. 228); barren or very weakly mineralized zones alternate at irregular intervals with richly mineralized ground. Because the drilling programs in the Monument Valley area, Arizona, have been confined to that part of the channel directly behind the mineralized outcrop and have not tested the entire channel, these tests are inconclusive, and their results do not present a valid picture of the amount of mineralized rock in the entire channel.

In our present state of knowledge we are unable to say conclusively that any one channel either contains economic deposits of uranium minerals or is barren. All should be tested. If the trend, extent, width, and depth of scour into underlying strata of a channel can be determined (and this, in our opinion, can be done most easily and cheaply by geophysical methods), drilling programs entirely within the confines of the channels can test these favorable areas. The drilling would have to extend the entire length of a channel to assure conclusive results, either positive or negative.

It is unknown how many channels are in the Monument Valley area. Of the total 700 square miles included, about 300 square miles of the Shinarump member have been removed by erosion. The Shinarump member underlies, then, about 400 square miles. Only 40 square miles of the Shinarump member are exposed, however, and the remaining 360 square miles are buried, more or less deeply, beneath surficial deposits and younger consolidated strata. Sixty-two channels were found in the 40 square miles of the exposed Shinarump member. If the channels are distributed at random, then another 540 channels may be concealed beneath the 360 square miles of the buried Shinarump member. How many channels contain mineralized sediments is unknown; but, if a fraction of the postulated 540 channels do, then the Monument Valley area must be considered a potential major uranium-producing area.

#### Prospecting guides

The following prospecting guides have been revised and enlarged from the list of guides proposed in 1951 (I. J. Witkind and others, unpublished report, 1951). These guides must still be considered tentative. They are of greatest value only in the area covered by this report.

The guides are in two categories, those thought to be useful in prospecting for uranium ore deposits throughout the Monument Valley area, Arizona, and those of uncertain use. These last exhibit anomalous relationships; in places they are associated with mineralized outcrops, elsewhere they are distant from such exposures.

## Useful guides for prospecting

Guides considered useful in prospecting for uranium ore deposits in the Monument Valley area, Arizona, are: 1) observable uranium minerals and abnormal radioactivity, 2) channel fill, and 3) channel conglomerates containing fossil plant matter.

Guides of uncertain use are: 1) limonite that impregnates channel fill; 2) secondary copper minerals; 3) an abnormal thickness of an altered zone in uppermost Moenkopi strata; and 4) clay boulders, cobbles, and pebbles.

Observable uranium minerals and abnormal radioactivity

The brilliant yellow minerals, tyuyamunite, metatyuyamunite, and carnotite, are the most common uranium minerals exposed at mineralized outcrops. Torbernite and autunite, generally apple green in color, are less common, and these normally are in the shaly siltstone beds forming the bleached zone of the uppermost strata of the Moenkopi formation (p. 52). In several localities abnormal radioactivity was noted on outcrops without any visible uranium minerals. Generally, analyses of samples from these localities indicated that the source of radioactivity was either small fragments of bony material or podlike lenses of black coaly material (vitrain?). Bony material and pods of vitrain were found, however, that were not radioactive.

### Channel fill

All known uranium ore deposits in the Monument Valley area are in and near sediments of the Shinarump member that fill channels (p. 56 ). Consequently, channel fills are considered to be one of the best guides to deposits of uranium ore. Not all channels are mineralized at the outcrop. Of the 62 channels noted, only 17 were mineralized at the outcrop. Of these, only seven contained uranium minerals (table 3). The absence of uranium minerals on outcrops of channel sediments does not, in our opinion, make a channel fill unfavorable. This conclusion is based on the known spotty distribution of mineralized areas in those channels that contain ore (p. 228).

### Channel conglomerates containing fossil plant matter

In the Monument No. 2 mine many of the rods are associated with silicified wood (p. 151), elsewhere in the Monument Valley area uranium minerals replace carbonaceous matter (p. 191). Generally, these associations are in conglomerate or conglomeratic sandstone lenses in channel fill (p. 191). We suggest, therefore, that the presence of fossil wood, either carbonized or silicified, in channel conglomerate or conglomeratic sandstone lenses, is a favorable guide to the discovery of deposits of uranium ore.

### Guides of uncertain usefulness

#### Limonite that impregnates channel fill

In the Monument Valley area limonite both stains the surface of sediments in the Shinarump member and in places impregnates them thoroughly (p. 192). The light-brown color of limonite stain is on the

surface everywhere. However, the widespread limonite effect has been found only in the Monument No. 2 channel (p. 192). Along many channels the surface of the channel fill is stained a light brown, however, fresh exposures of the same channel fill are light gray.

#### Secondary copper minerals

Secondary copper minerals, principally azurite and malachite, are associated with many of the more promising uranium localities (fig. 14 and table 3). These minerals fill fractures and interstices, and coat sand grains. In several localities they replace wood (p. 259). However, only minute amounts of copper are at the Monument No. 2 mine. Secondary copper minerals have also been noted distant from channel sediments.

#### An abnormal thickness of an altered zone in the uppermost strata of the Moenkopi formation

The thickening of an altered zone in the uppermost strata of the Moenkopi formation directly below channel sediments was noted at some of the more favorable uranium prospects (fig. 14). The zone also thickens below the Monument No. 1 channel and is present in those wedges of Moenkopi that are preserved below the Monument No. 2 channel. However, the thickening of the altered zone below channels is not consistent, for the zone remains unchanged or thins below several channels.

#### Clay boulders, cobbles, and pebbles

In several mines in the Monument Valley area of Utah and Arizona, clay boulders, cobbles, and pebbles are associated with ore (p. 237). In the Monument No. 2 mine, however, ore is lacking in some places where there are concentrations of clay detritus.

MINES AND PROSPECTS

The uranium-vanadium deposits of the Monument Valley area, Arizona, have been divided arbitrarily into two categories for purposes of description. The first category includes the present operating mines in the area. Descriptions of mines in the Monument No. 2 and Monument No. 1 channels form this section. The second category consists of several promising prospects.

As of 1952-53, only the group of mines in the Monument No. 2 channel were producing uranium-vanadium ore in sizeable quantities. Small amounts of ore were produced in 1952 from the Mitten No. 2 mine (Monument No. 1 channel), but production was so small as to be negligible. In 1954, as a result of a drilling program (p. 228) a new deposit of ore was found in the sediments of the Monument No. 1 channel.

MINES IN THE MONUMENT VALLEY AREA, ARIZONAMonument No. 2 channel

There are six mines in the Monument No. 2 channel (fig. 14, channel no. 58); they are: 1) the Vanadium Corporation of America's Monument No. 2 mine; 2) the Climax-Uranium Company's Cato Sells Tract No. 1 (also called Cato Sells Monument mine); 3) the Climax-Uranium Company's Cato Sells Tract No. 2; 4) the Climax-Uranium Company's Cato Sells Tract No. 1 South; 5) the Black and Blackwater mine (leased in 1953 to W. E. Pollock and B. N. Byler); and 6) the John M. Yazzie mine (operated jointly by John M. Yazzie and Thomas Clani).

Of these, the largest is the Vanadium Corporation of America's Monument No. 2 mine; it exceeds the others not only in extent and complexity of workings, but also in amount of ore produced. In an attempt to answer the various problems inherent in the origin and localization of uranium ore, the workings of the Monument No. 2 mine were mapped and studied during parts of the summers of 1951 and 1952 (fig. 29). In general the features characteristic of the mine are duplicated in all of the other mines in this channel.

#### Monument No. 2 mine

##### Introduction

By far the most prolific producer of uranium ore in the Monument Valley area, Arizona, is the Monument No. 2 mine, owned by the Vanadium Corporation of America, and operated under a lease from the Navajo Tribal Council. The mine has been in operation since 1942.

No other mine in the area has even closely approached it in the production of uranium and vanadium ores. Yet, in general, nothing about the geologic or geographic setting seems distinctive. Channel sediments are similar to those cropping out elsewhere in the valley. The size and shape of the channel do not seem unusual; it is not as large as some, nor as small as others. It is worthy of note that the original exposures gave but slight indication of the large amounts of ore contained in the channel sediments.

During 1951 and 1952, the U. S. Atomic Energy Commission (John W. Chester and Philip H. Donnerstag, written communication, 1953) completed drilling programs on Yazzie Mesa and on South Ridge (fig. 30).

### Location and accessibility

The Monument No. 2 mine is in the northern part of Apache County, Ariz. It is at latitude  $36^{\circ} 55' 42''$  N. and longitude  $109^{\circ} 55' 6''$  W., about 4-1/2 miles south of the Utah-Arizona State line and about 1 mile west of Comb Ridge (fig. 2).

In 1953, mining operations involved both stripping (open pit) and underground methods. The underground workings were reached either by inclined shaft or through adits along the base of the channel. As of June 1953, most of the workings were underground; the only strip mining was in the North workings and near the Red Oxide workings.

All ore produced was trucked to company-owned mills at Durango and Naturita, Colo.

### Geology

In the Monument No. 2 mine area consolidated sedimentary strata range in age from the Halgaito beds of Permian age to the Navajo sandstone of Jurassic age (fig. 4). However, in the immediate vicinity of the mine the strata range only from the DeChelly sandstone member of the Cutler formation of Permian age to the Shinarump member of the Chinle formation of Late Triassic age. The Shinarump member is about 35 feet thick, except where, as a result of channeling, it thickens to 85 feet or slightly more.

These strata form a cuesta that dips to the east about  $5^{\circ}$  and is part of the east limb of the Monument upwarp. Dissection of this eastward-dipping cuesta has been severe.

Three sets of fractures noted in and near the mine are probably related to the regional structure. They trend about: (1) N.  $65^{\circ}$  W., (2) N.  $30^{\circ}$  W., and (3) N.  $40^{\circ}$  E. to east-west. Most of the fractures trend northwest (fig. 27A). Strike-slip movement has been noted on some fractures; commonly the west wall has moved south, although the movement on any single fracture surface does not seem to exceed half an inch. The fractures cut ore.

### Channel

The Monument No. 2 mine is in a broad short channel (p. 135) that strikes N.  $18^{\circ}$  W., ranges in width in its central part from 400 to 700 feet, and has been cut about 50 feet into the underlying strata. Because the beds of the Hoskinnini member of the Cutler formation and the Moenkopi formation are thin at this locality, the scour has cut through them with the result that channel sediments of the Shinarump member of the Chinle formation rest disconformably on the DeChelly sandstone member of the Cutler formation.

Although regionally both the Hoskinnini member and Moenkopi thin eastward, abrupt thinning of these strata near the channel may be significant. Isopachous maps of the combined thickness of the Hoskinnini member and Moenkopi in the immediate vicinity of the Monument No. 2 channel indicate that an elongate broad swale parallels the channel (fig. 20, p. 144). Inasmuch as the base of the Hoskinnini member is even and devoid of relief (fig. 6), this thinning must reflect an undulation in the top of the Moenkopi. This swale is about 3 miles wide and can be

traced for a distance of about 3-1/2 to 4 miles before it disappears below the alluvial fill of Cane Wash. We interpret it to be a shallow swale in whose center a channel (Monument No. 2 channel) was scoured.

The cross-sectional shape of the Monument No. 2 channel varies from place to place along the length of the channel. In the North workings (fig. 29), the channel appears as a symmetrical scour; this is also true at South Ridge. However, in the South and Bobcat workings, the floor of the channel is divided by a low ridge of sandstone that separates the channel into two unequal parts (fig. 30C). The ridge of sandstone may be equivalent to the Hoskinnini member. It is composed of a light-buff even-bedded medium-grained sandstone that truncates the crossbedded fine-grained DeChelly sandstone member. This even-bedded sandstone layer is in turn truncated on both sides by the sediments of the Shinarump that fill the two parts of the divided channel.

The length of the channel has been determined (John W. Chester and Philip H. Donnerstag, written communication, 1953). It extends in a relatively straight line for 1-1/2 to 2 miles and is divided into three segments of unequal length by two deep valleys (fig. 30A). The north end of the channel (about 1,000 feet long) is on Yazzie Mesa. The middle part of the channel (about 2,800 feet long) and, incidentally, the part that contains the major amounts of ore, is on the Monument No. 2 cuesta and has been called Main Ridge. The south part of the channel (2,000 feet long) is on South Ridge.

Data obtained during the drilling and mapping programs were used to contour the base of the channel (figs. 29 and 30B). Those lines delineating the ends of the channel on Yazzie Mesa and on South Ridge are

based on illustrations supplied by the U. S. Atomic Energy Commission prepared from the drill data. These contour lines indicate that both ends of the channel terminate as gently concave upward curves. The contours suggest that locally the floor of the channel is gently undulatory both in cross and longitudinal sections and is marked in places by scour pits 200 to 250 feet long, about 100 feet wide, and from 5 to 10 feet deep.

Channel sediments seem identical to other sediments in the Shinarump member of the Chinle formation and consist principally of medium- to coarse-grained conglomeratic sandstone beds containing as predominant constituents durable materials such as quartz, quartzite, and chert. Clay and siltstone as boulders, cobbles, and pebbles, are distributed profusely throughout the channel sediments. In several places the uppermost channel sediments are interrupted by lenticular beds of clay as much as 8 feet thick that can be traced longitudinally and laterally for as much as 300 feet. Fossil plant matter is scattered through the channel sediments. Much of it appears as silicified logs and as elongate pod-shaped masses of a coaly substance (vitrain?). In other places the cellular woody structure of former logs has been retained where the logs have been replaced by uraninite and pyrite. Near the portal of incline no. 3 (fig. 29) a fossil log, partly replaced by vanadium minerals, uraninite, and pyrite, affords excellent specimens of replaced woody texture. Examples of uraninite replacing wood have been found also in the Cato Sells mine (Alice D. Weeks, written communication, 1952). The possibility exists that during deposition of the sediments that filled the channel, many more logs were included in channel fill than can be identified as such under present conditions.

Oxidized minerals are everywhere in the mine workings. Limonite impregnates and stains the channel sediments but is not as profuse in sediments of the Shinarump member adjacent to the channel. On the valley sides this is emphasized by the contrast in color between the brown of the channel sediments and the light buff of the adjacent sediments. Throughout the mine workings the limonite is distributed so profusely that those few areas in the mine free of limonite are considered unusual. The limonite-free areas contain only small amounts of uranium-vanadium ore.

#### Uranium and vanadium deposits

All four types of ore bodies (p. 148) are in the Monument No. 2 mine. These are in such profusion that it is difficult to delineate specific ore zones. In general, however, three ill-defined ore zones can be discerned. Ore bodies in each of these zones seem to alternate at irregular intervals with one another and with barren or very poorly mineralized sediments. Thus, channel sediments containing concentrations of rods may be close to, or distant from corvusite-type areas; however, no pattern is apparent. The relation of the richly mineralized parts of the channel to the weakly mineralized parts seem independent of channel shape, channel sediments, position in channel sediments, or any other discernable feature.

The principal production of both uranium and vanadium is from a basal ore zone that ranges in thickness from a pinchout to as much as 40 feet, and seems to be continuous along the entire base of the channel. Locally it includes about 20 feet of the underlying DeChelly sandstone member of the Cutler formation. The top of the zone is undulatory. Ten

to 20 feet above the top of the basal zone is a middle ore zone that contains many rods. This zone ranges in thickness from 5 to 15 feet and is characterized by clusters of rods. It is not continuous for the length of the channel. The third and uppermost zone is near the surface and is about 15 feet above the top of the middle ore zone and as much as 10 feet thick; here, the principal ore seems to be vanadium. This upper ore zone is discontinuous also.

#### Basal ore zone

Ore is mined from the basal ore zone along the entire length of the channel. This zone includes the most productive part of the channel sediments. All types of ore bodies are in this zone, although in general, corvusite-type and tabular ore bodies seem to predominate.

At the south end of the channel (South Ridge, fig 29), the workings are in a corvusite-type ore body. This ore body is about 250 feet long, 100 feet wide, and about 35 feet thick. Only sediments of the Shinarump member of the Chinle are mineralized. Rods and tabular ore bodies are rare.

At the south edge of Main Ridge (fig. 29) the channel bifurcates. The east fork of the channel includes the South workings; the west fork includes the Bobcat workings. Both sets of workings are in the basal ore zone. The west edge of the Bobcat workings rise slightly and grade imperceptibly into the middle ore zone which contains the upper Bobcat workings. A clear demarcation between the zones in this part of the channel is impossible. Rods are common in both Bobcat and upper Bobcat workings.

The west edge of the South workings consists of a large corvusite-type ore body which grades eastward into an area of channel sediments marked by many rods and a few tabular ore bodies. Although these irregular-shaped corvusite-type ore bodies are found throughout the mine, there seems to be a greater concentration of vanadium in this part of the South workings. Here, sediments of the Shinarump member show the deep blue-black color of vanadium minerals for a length of about 200 feet and a width of about 50 feet. The mineralized ground is about 20 feet thick and includes some of the underlying sediments of the DeChelly sandstone member of the Cutler formation to a depth of 10 to 15 feet. Corvusite is so profuse in these workings that the brown limonite coloration typical of sediments in the Monument No. 2 channel is almost obliterated. Locally the blue-black color is broken by irregular streaks of the brilliant scarlet hewettite, or by large irregular masses of a white material (opal?) in the interstices of the sandstone. All of the basal sediments in this part of the channel have been impregnated, and the ore produced is always a deep blue black.

The east part of the South workings has many rods in a conglomeratic sandstone that is colored deep brown by limonite. Most of these limonite-colored sediments are in a scour pit along the thalweg of this side of the channel (fig. 29). The scour pit is elongate, parallel to the trend of the channel, about 250 feet long, 100 feet wide, and about 10 feet deep. The corvusite-type ore body seems to be along a slight rise that marks the west edge of the scour pit. There is a marked contrast between the two parts of the South workings. On the west the sediments are deep blue black and contain only small amounts of yellow uranium minerals.

Locally small patches of the scarlet color of hewettite as well as splotches of white material (opal?) interrupt the blue-black color. The east side contains conglomeratic sandstone of similar lithology, but here the sediments are a deep brown as a result of the limonite impregnation. Scattered irregularly through these relatively barren sediments are the richly mineralized yellow-colored rods.

All three ore zones are being mined in the central part of Main Ridge and are more clearly delineated there than elsewhere. The basal zone is mined through inclines nos. 2 and 3 (fig. 29), and the underground workings have extended toward each other along the channel axis since figure 29 was completed. Near incline no. 2, a corvusite-type ore body is on the west flank of a depression in the channel floor. The scour is elongate, parallel to the trend of the channel, about 200 feet long, 50 feet wide, and about 5 feet deep. Part of the ore body is in the scour although its margins extend laterally beyond the limits of the scour. In general, the ore body is about 350 feet long, about 50 feet wide, and about 40 feet thick. Of this thickness, 20 feet involve sediments of the DeChelly sandstone member; the remaining strata form the basal channel sediments.

In several places in this part of the mine extensive fractures pass through the Shinarump member of the Chinle formation into the underlying DeChelly sandstone member of the Cutler formation (fig. 29). Locally vanadium minerals have moved through the fractures and permeated the adjacent sediments. The vanadium minerals decrease in quantity with distance away from the contact of the Shinarump member and the DeChelly

sandstone member. Distinct rolls, which are so typical of the ore deposits in the Morrison formation of Jurassic age, are in that part of the DeChelly sandstone member which in this area immediately underlies the Shinarump member (p. 189). Here the rolls seem to be related to a combination of bedding planes and fractures (p. 172).

Both high-grade uranium and vanadium ore have been mined from this part of the basal ore zone. The vanadium impregnates the sediments thoroughly and all strata, the DeChelly as well as the Shinarump member, are a deep blue black. Uranium commonly is present as disseminated fragments of relatively unoxidized uraninite. Most of the specimens of uraninite used in the age determination studies by Stieff and Stern (1952b) were secured from this part of the basal ore zone. Rods and tabular ore bodies are present locally but not in such profusion as in other parts of the mine.

The basal ore zone is also being mined through incline no. 3. Here the zone consists of limonite-impregnated sediments which contain many rods. Several of the rods have cores of uraninite, that are surrounded by a rim of becquerelite, which in turn are rimmed by uranophane. Most of the rods, however, are similar to those found elsewhere in the mine.

As of 1953, the main part of the basal ore zone along the north edge of Main Ridge had not been mined (fig. 29). The North workings, which are along the east flank of the channel, probably are in an edge of the basal ore zone. Rods are plentiful and, in addition, tabular ore bodies that range in thickness from 2 to 4 feet and form a crude oblong about 60 to 80 feet are exposed in the North workings.

Yellow uranium minerals associated with much fossil plant matter make up the greatest part of these tabular ore bodies. These bodies are interpreted to be former "trash" pockets--original basins along the flank of the channel in which plant matter accumulated. Secondary vanadium minerals, principally hewettite, impregnate many of the sediments in the North workings.

The north end of the channel has been mined on Yazzie Mesa by John M. Yazzie and Thomas Clani. It seems likely that the ore produced came from the basal ore zone. Rods were the principal source of the ore.

#### Middle ore zone

In 1953, the middle ore zone was being mined in three places, the upper Bobcat workings, the South workings incline, and the incline no. 1 workings (fig. 29). Along the south edge of Main Ridge the upper Bobcat workings are in channel sediments that contain many rods. In the South workings incline (fig. 29) a similar situation exists. The rods in both these localities seem to be scattered erratically through the sediments and, in general, are not as plentiful as in other parts of the mine. By far the greatest concentration of rods is exposed in that part of the middle ore zone reached by the incline no. 1 workings. Here, a crudely circular mass of sediments of the Shinarump member of the Chinle formation, about 300 feet in diameter and about 15 feet thick, contains rods of all sizes and shapes. As plotted, this circular area is in about the center of the channel with its base about 30 feet above the channel floor. Upper and lower margins are irregular, and its base seems to be about

20 feet above the top of the basal ore zone which directly underlies it. About 20 feet of barren sediments of the Shinarump member overlies this part of the middle ore zone.

Rods are best displayed in this area, and most seem to be confined to undulatory conglomerate beds that are elongate parallel to the channel's trend. The rods studied in this area repeated what had been found to be true of other rods in the channel--namely, the larger rods are aligned in a northwesterly direction parallel to the channel trend (fig. 31A). Whereas a similar alignment is not discernable in the smaller rods; these seem to trend in all directions (fig. 31B). The greatest concentration of the rods seems to be in the center of this circular mass of sediments, although some of the largest rods are along the southwest edge. In this locality, rods as much as 100 feet long and 3 to 6 feet in diameter are common.

Although the rods comprise the richer concentrations of ore, secondary yellow uranium minerals are found elsewhere in the middle ore zone. Between many rods disseminated yellow uranium minerals fill interstices in the sandstone and result in weakly mineralized ground between the rods. Commonly this dissemination is very slight, as is illustrated by figure 21. This relationship between the rods and surrounding sediments, although best illustrated in the middle ore zone, is found elsewhere in the mine. Thus, channel sediments in the basal ore zone also have weakly mineralized ground between the rods. Further, sparse amounts of yellow uranium minerals fill some fractures and coat crossbedding planes in that part of the DeChelly sandstone member of the Cutler formation which directly underlies the Shinarump member of the Chinle formation.

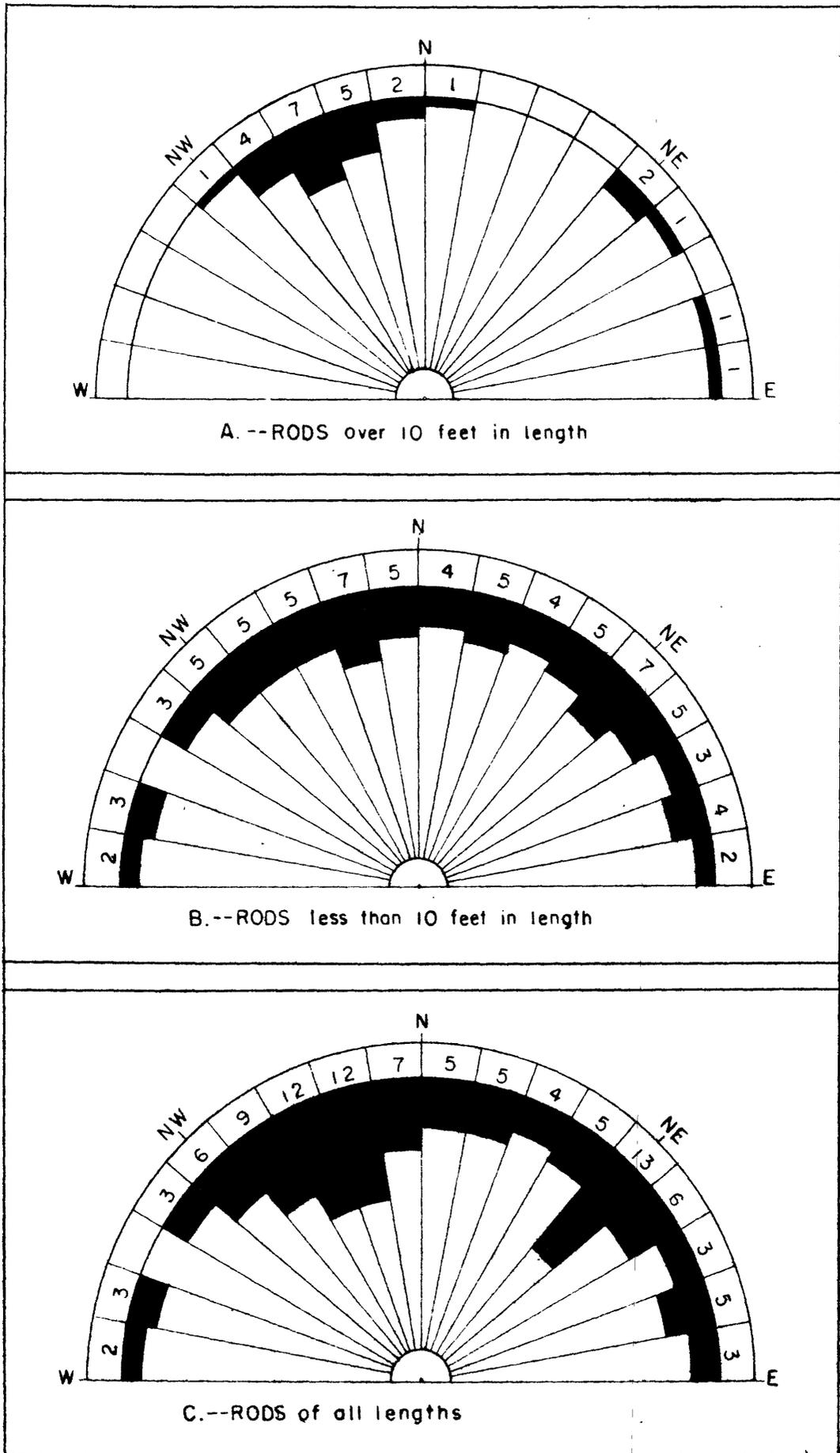


FIGURE 31. --TRENDS OF RODS AS DETERMINED IN THE VANADIUM CORPORATION OF AMERICA'S MONUMENT NO. 2 MINE, APACHE COUNTY, ARIZ.



Upper ore zone

The upper ore zone is the most restricted of the three zones. It is best exposed near the north edge of Main Ridge in the East Red Oxide, South Red Oxide, and West/<sup>Red</sup>Oxide workings and in the Central workings. Although rods are in these workings, the principal ore produced has been vanadium and the Red Oxide workings derive their names from the large amounts of hewettite and meta-hewettite present. Oxidation has been so complete in this area that most of the sediments contain large amounts of these secondary vanadium minerals; primary vanadium minerals are rare. It may be that each of these workings represent corvusite-type ore bodies that have been oxidized.

Mineralogy and paragenesis of the ore deposit at the  
Monument No. 2 and Cato Sells mines

By Donald H. Johnson

Introduction

As part of a U. S. Geological Survey program in the Monument Valley area, Arizona, the writer spent about 3 weeks in the summer of 1951, 2 months in the summer of 1952, and 6 weeks in the summer of 1953, at the Monument No. 2 mine. In 1951 the writer was associated with Tommy L. Finnell, and in 1952 and 1953 with D. J. Milton.

Field work consisted of reconnaissance mapping in the vicinity of the mines, detailed mapping of parts of the mines, and detailed mineralogical sampling of all the accessible mine workings. Laboratory work during parts of 1953 and 1954, was devoted to mineral identification and study of specimens.

Acknowledgments

The writer is indebted to Denny W. Viles, vice-president, Robert Anderson, superintendent, and Carl Bell, mine foreman, of the Vanadium Corporation of America for permission to examine and collect specimens in the Monument No. 2 mine, and to Clarence Cox, mine foreman, of the Climax Uranium Company to examine and collect specimens in the Cato Sells mines.

Alice D. Weeks, Mary E. Thompson, Leonard B. Riley, and Thomas W. Stern of the U. S. Geological Survey visited the mines with me and gave me information and advice.

Personnel of the Survey's laboratories performed much of the analytical work. Particular mention should be made of A. T. Myers and J. N. Stich, spectroscopy, A. J. Gude and E. A. Cisney X-ray identifications, and L. F. Rader and his staff, chemistry.

### Mineralogy

Each mineral from the ore deposit at the Monument No. 2 and Cato Sells mines that has been noted and studied is listed below, and their description follows:

#### Uranium and vanadium minerals

Autunite	(p. 203)	Montroseite	(p. 207)
Becquerelite	(p. 203)	Navajoite	(p. 207)
Carnotite	(p. 204)	Pascoite	(p. 208)
Corvusite	(p. 204)	Rauvite	(p. 208)
Doloresite	(p. 205)	Steigerite	(p. 208)
Fernandinite	(p. 205)	Tyuyamunite and	
Fourmarierite	(p. 205)	metatyuyamunite	(p. 209)
Hewettite	(p. 205)	Uraninite	(p. 209)
Metazeunerite	(p. 206)	Uranophane	(p. 211)

## Associated minerals

<u>Nonsulfides</u>		<u>Sulfides</u>	
Apatite (carbonate)	(p. 211)	Bornite	(p. 218)
Calcite	(p. 212)	Galena	(p. 218)
Clay minerals	(p. 212)	Pyrite	(p. 219)
Gypsum	(p. 213)	Sphalerite and	
Ilsemannite (?)	(p. 214)	sulfur	(p. 221)
Jarosite	(p. 215)	<u>Unidentified</u>	
Limonite	(p. 215)	<u>minerals</u>	(p. 221)
Opal	(p. 216)		
Quartz and chalcedony	(p. 217)		
Wad (lithian)	(p. 218)		

Uranium and vanadium minerals

Autunite -  $\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 10-12\text{H}_2\text{O}$ .--Some scattered crystals of autunite were found in the North workings of the Monument No. 2 mine (fig. 29) only a few feet from the cliff face. They appeared as tiny yellow micaceous crystals partly filling the interstices of the conglomerate in which they were found. Locally they partially coated a few pebbles. The crystals fluoresced a brilliant yellow green under short wave ultra-violet light.

Becquerelite -  $2\text{UO}_3 \cdot 3\text{H}_2\text{O}$ .--Becquerelite is found in many places in the deposit, although it forms no great part of the ore. The becquerelite is firm, dense, and ranges in color from dark orange to a bright yellow. It is generally massive, but a few thin sections show wood-cell structure.

Most of the becquerelite forms compact halos surrounding ellipsoidal nodules of uraninite. Nodules range from nearly solid uraninite with a paper-thin shell of becquerelite to massive becquerelite with only a tiny relict of unaltered uraninite in the center. A few nodules of becquerelite have been found without the uraninite. Veinlets of becquerelite cut most of the uraninite.

Carnotite -  $K_2(UO_2)_2(VO_4)_2 \cdot 1-3H_2O$ .--Apparently carnotite is uncommon in this deposit; only a few specimens have been identified. It appears as a loosely coherent yellow powder mixed with and concealed by tyuyamunite, for spectrographic analyses of some samples of yellow ore indicate small amounts of potassium. Carnotite stains and coats pebbles in the conglomerate and forms small patchy impregnations in sandstone. The ratio of carnotite to tyuyamunite appears to be very small.

Corvusite -  $V_2O_4 \cdot 6V_2O_5 \cdot nH_2O(?)$ .--Corvusite is the most abundant nonuranium-bearing ore mineral in the mine. It is most plentiful in the workings on South Ridge and in the South workings and small amounts have been found in all but the northern parts of the workings on Main Ridge (fig. 29).

The corvusite ranges in color from typical blue black through blackish brown to a medium dark brown, and in clayey pellets to orangish brown. Locally it is associated with small quantities of rauvite, hewettite, navajoite, and probably uraninite and other uranium minerals, and limonite. It fills interstices in the sandstone and conglomerate. A small number of pellets and small lenses of corvusite mixed with silt were found. The corvusite does not seem to have replaced detrital grains in the sandstone as have tyuyamunite and its associated minerals.

Doloresite -  $3V_2O_4 \cdot 4H_2O$ . --A small vuggy seam of doloresite

✓ Data furnished by Alice D. Weeks, U. S. Geological Survey.

crystals was collected from the fossil log that is cut by incline no. 3 (p. 189). The mineral is nearly black, has a submetallic luster and a greenish-black streak (Stern, and others, in press).

Fernandinite -  $CaO \cdot V_2O_4 \cdot 5V_2O_5 \cdot 14H_2O$ . --Small amounts of

✓ Data furnished by Alice D. Weeks, U. S. Geological Survey.

fernandinite have been found near the fossil log cut by incline no. 3 (p. 189). The fernandinite is greenish black, has a high luster and is soft with a greasy smear comparable to graphite.

Fourmarierite -  $PbU_4O_{13} \cdot 7H_2O$ . --A little fourmarierite has been found in specimens of ore from this deposit by Thomas W. Stern and others (oral communication). It is in the form of small reddish grains in specimens of uraninite and becquerelite. The fourmarierite appears to be one of the earliest secondary minerals forming from the uraninite.

Hewettite -  $CaV_6O_{16} \cdot 9H_2O$ . --Hewettite is moderately abundant in this ore deposit. Several varieties have been found. The most abundant is a deep red earthy variety that coats fractures and fills seams up to 10 cm thick. These seam fillings are principally in or adjacent to corvusite or tyuyamunite ore, but some small fillings have been found in relatively barren rock several feet from ore. Less abundant are bright-red cross-fibrous seam fillings 1 to 20 mm thick that are in the workings in the

north and the south-central part of Main Ridge (fig. 29). Some of these seam fillings resemble the occurrence of navajoite, and look as if they might grade laterally into navajoite, but no such transition has actually been traced.

Several radiating clusters of acicular crystals of hewettite were found in the North workings. The crystals were attached to pebbles and projected into small cavities in the conglomerate. Individual crystals were about half a millimeter thick and up to 15 mm long. A few feet from the above occurrence were found bladed crystals, 1 by 2 by 10 mm, of brownish-red hewettite. The crystals occurred as divergent to sub-parallel groups coating pebbles in conglomerate.

As found in the mine, hewettite is a deep red; but, when it is removed from the mine, it soon becomes a dull chocolate brown. Possibly the change is due to loss of water, but specimens that were sealed in glass jars containing wet paper before removal from the mine also became brown after a period of time although the air in the jars was still water saturated. Specimens removed from the mine in light tight containers, not sealed against moisture, changed color to a lesser degree. The writer believes, therefore, that light may cause or hasten the discoloration of hewettite.

Metazeunerite -  $\text{Cu}(\text{UO}_2)_2(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$  -- In the South workings of the Monument No. 2 mine, a small pocket, about a foot in diameter and 2 to 3 feet long is impregnated with metazeunerite. The metazeunerite forms powdery green coatings on pebbles and silicified wood in the conglomerate. Tiny tetragonal crystals of metazeunerite about 0.1 mm on a side, are scattered through the interstices of the conglomerate along with white powdery gypsum.

Montroseite -  $(V,Fe)O(OH)$  or  $VO(OH)$ .--No montroseite has been positively identified from the workings on Main Ridge (fig. 29); but on South Ridge, where oxidation has been less extensive, montroseite has been found in the workings.

It occurs with pyrite as shiny dark crystals up to half a millimeter long and as black masses. The ore is black where montroseite is abundant but more commonly has the blue-black cast of corvusite ore with only scattered crystals and patches of montroseite. Probably small amounts of montroseite are in the blue-black ore exposed in the Main Ridge workings.

In some specimens the montroseite occurs as tiny black crystals growing upon quartz sand grains that have been markedly corroded and etched. Many of the montroseite crystals, along with their sand grain bases, are partly or completely enclosed by colorless authigenic quartz.

Much of the montroseitic ore contains little uranium; a Geiger-Muller counter indicates no significant radioactivity in some specimens. Other specimens contain some uraninite, but secondary uranium minerals are nowhere apparent.

Navajoite -  $V_2O_5 \cdot 3H_2O$ .--Navajoite is a new mineral collected from the South workings of the Monument No. 2 mine and described by Weeks, Thompson, and Sherwood (1954). Although it has not been found elsewhere, it occurs in a number of places in the Monument No. 2 mine, particularly in the southwestern part of the Main Ridge workings. It forms dark-brown fibrous coatings on pebbles in conglomerate and fills fractures in sandstone and siltstone as cross fibers, 1 to 5 mm long. It has been found with hewettite and in blue-black to dark-brown corvusite-type ore with other vanadium minerals, and sometimes pyrite, gypsum, and ilsemannite.

Pascoite -  $\text{Ca}_3\text{V}_{10}\text{O}_{28} \cdot 16\text{H}_2\text{O}$  --Pascoite appears as an orange

✓ Data furnished by Alice D. Weeks, U. S. Geological Survey.

water soluble mineral that forms coatings on the mine walls.

Rauvite -  $\text{CaO} \cdot 2\text{UO}_3 \cdot 5\text{V}_2\text{O}_5 \cdot 16\text{H}_2\text{O} (?)$  --Rauvite is found in many parts of the Monument No. 2 mine and commonly is confused with other minerals. Much of the rauvite forms resinous, very dark brown, brownish-purple, or reddish-black masses, up to an inch across, which fill crevices in silicified wood or occupy cavities in the conglomerate. Other forms of rauvite that have been recognized are as blackish, brownish, or orange pellets that resemble claystone in appearance, and as powdery brownish to orange claylike material dispersed through conglomerate and conglomeratic sandstone. The rauvite is invariably associated with corvusite, hewettite, and other vanadium minerals, and in many places with tyuyamunite.

Steigerite -  $\text{Al}_2(\text{VO}_4)_2 \cdot 6-1/2\text{H}_2\text{O}$  --Steigerite is always found as powdery yellow coatings on fracture surfaces near high-grade ore. The total amount of steigerite in the mine is very small.

Steigerite was first identified from the Monument No. 2 mine in 1952, by Alice D. Weeks and Mary E. Thompson of the U. S. Geological Survey who found it coating a fracture surface in the southern part of the Main Ridge workings. Since then steigerite has been found in several other places in these workings and in the Monument No. 2 mine workings on South Ridge (fig. 29).

Tyuyamunite -  $\text{Ca}(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 7-10-1/2\text{H}_2\text{O}$  and Metatyuyamunite -  $\text{Ca}(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 5-7\text{H}_2\text{O}$ .--By far the most abundant ore mineral in the Monument No. 2 mine is tyuyamunite (metatyuyamunite is considered with tyuyamunite here, as the two cannot be distinguished in the field, and as they may well change from one to the other with changing moisture conditions). The tyuyamunite occurs as tiny (0.0 to 0.5 mm) flaky yellow crystals coating pebbles, silicified wood, and fracture surfaces, and as bright-yellow powdery to compact earthy material which fills the interstices of the rock. In places where the sand grains have been completely replaced, the tyuyamunite forms solid masses up to 6 inches across.

Most of the tyuyamunite is in rods and tabular ore bodies (p. 151).

Uraninite -  $\text{UO}_2$ .--Although it is not abundant enough to make an important contribution to the ore, uraninite has been found in many places in the Monument No. 2 mine and is important mineralogically.

Three varieties of uraninite have been distinguished in the mine. One variety is hard and massive, with a dull to greasy luster, and a specific gravity of 6 to 7. It appears similar to vein pitchblende. The second variety is moderately hard, with a bright resinous to nearly vitreous luster and a specific gravity of 4 to 5, and probably this variety contains admixed coal. Most of these specimens show fossil wood textures. The third variety is softer, with a dull luster and a specific gravity of 5 to 6. Much of it has a sooty appearance, but it will not rub off on the fingers.

Most of the uraninite occurs as ellipsoidal nodules, surrounded by orange to yellow halos of becquerelite and uranophane, all enclosed in coarse-grained to conglomeratic sandstone. The enclosing sandstone is

impregnated with yellow tyuyamunite, but most commonly the sandstone is profusely impregnated with a reddish limonite that commonly decreases in amount and becomes browner away from the nodule.

Many uraninite nodules show woody structures or textures, ranging from gross forms of twigs and limbs to actual cell structure. Much of the uraninite that does not replace wood contains relict quartz grains.

On the western edge of the channel, in the South workings, (fig. 29) a pillar contained a very compact mass of ore composed of uraninite, becquerelite, tyuyamunite, navajoite, corvusite, pyrite, and other minerals. Most of the uraninite appeared as flat-lying irregular laths, about a quarter of an inch thick, 2 to 5 inches wide and 1 to 3 feet long. Separating the laths and filling cracks in them were orange and yellow secondary uranium-vanadium minerals and pyrite. Some of the uraninite laths contained zones of pyrite as thick as the laths, and in these zones replacement of wood cells by uraninite and pyrite was striking. In some, the cells appear to have walls of pyrite and centers of uraninite, whereas in other fragments the reverse was true.

Pyrite is enclosed in many of the uraninite nodules as tiny irregular grains and as ellipsoidal masses up to a quarter of an inch in long dimension. Most of these pyrite grains are embayed and veined by uraninite.

A cross section of a fossil log is exposed near the portal of incline no. 3 (fig. 29). This log, about 10 by 15 inches, is composed of carbonaceous matter that has been largely replaced by uraninite, black and blue-black vanadium minerals, pyrite, and other minerals. The uraninite and vanadium minerals seem to replace the carbonaceous matter and locally preserve the cell structure. The pyrite occurs mostly as

granular nodules and veinlets, but in a few places pyrite has replaced some carbonaceous matter and has preserved the cell structure. Small amounts of secondary yellow uranium-vanadium minerals are scattered through the log as films and veinlets. A few tiny yellow crystals of native sulfur were found in a cavity in the log, and several tiny black sphalerite crystals have been identified by Thomas W. Stern. A mineralized halo is in the medium-grained sandstone which surrounds the log. The inner zone of the halo contains blue-black vanadium minerals, a little uraninite, considerable pyrite, and some yellow tyuyamunite. The outer zone contains some tyuyamunite along with orange and brown secondary vanadium minerals and limonite. The halo grades out into barren-looking sandstone.

Two similar, but smaller, logs were found in an open cut north of incline no. 3.

Uranophane -  $\text{Ca}(\text{UO}_2)_2\text{Si}_2\text{O}_7 \cdot 6\text{H}_2\text{O}$  -- Many of the orange to yellow shells surrounding uraninite nodules contain uranophane. Some of the uranophane has a bladed or fibrous texture in hand specimens, but much of it is indistinguishable from becquerelite. In thin section, the uranophane is generally lighter yellow and much more transparent than becquerelite and is bladed to fibrous. The long axes of the bladed and fibrous crystals are roughly parallel to the radii of the nodules.

Associated minerals (nonsulfides)

Apatite (carbonate) -  $\text{Ca}_{10}(\text{PO}_4)_6(\text{CO}_3)\cdot\text{H}_2\text{O}$  -- A small pebble of carbonate-apatite was found in the conglomerate of the North workings (fig. 29). The pebble was very light gray and had a claystone texture. The carbonate-apatite probably represents former bone material and is not related to the ore.

Calcite - CaCO<sub>3</sub>.--Only small amounts of calcite are found in the Monument No. 2 mine, for silica and clay appear to be the dominant cements, particularly in the ore, where calcite is almost totally lacking.

A few small patches and small cavity fillings of calcite in the form of dog-tooth spar are in the South workings (fig. 29). Some of the patches have a concretionary aspect. One in particular has a nearly spherical core of sandstone, impregnated with tyuyamunite and fine-grained calcite. This core is surrounded by half an inch to a 1-inch rim of calcite crystals which contains a few scattered sand grains. This body is enclosed in sandstone. The calcite patches or concretions generally are in weakly mineralized conglomerate or conglomeric sandstone above lenses of high-grade brownish or yellow ore.

Clay minerals.--Mineral grains of clay size (less than 1/256 mm) are abundant throughout this ore deposit, but actual clay minerals constitute only a small fraction of this material. Although no absolute abundances were estimated from maximum peak heights on X-ray diffractometer graphs for a number of samples, without exception, these samples contained abundant quartz. Whether this quartz is allogenic or authigenic is not known; the frequent occurrence of authigenic quartz rims on quartz grains in the sandstones suggests that much of the quartz in the clay size fractions may also be authigenic. All the samples examined contained hydromica, which, except in a few specimens, was the most abundant constituent. Spectrographic analyses of a number of specimens showed very little vanadium, and it appears that the vanadium hydromica found abundantly in some of the mines elsewhere on the Colorado Plateau is rare or absent in the ore deposit in the Monument No. 2 channel.

Kaolinite was found in more than half the samples, commonly in small amounts, but a few samples contained more kaolinite than hydromica.

Montmorillonite was found in about half the samples. In most of these samples the amount of montmorillonite was about equal to or slightly less than the amount of kaolinite. A few samples contained considerably more montmorillonite than kaolinite, but no sample contained as much montmorillonite as hydromica.

A little apatite, probably carbonate apatite, showed in a few samples.

For comparison, a number of samples of mudstone from the Shinarump member of the Chinle formation away from the ore deposit in the Monument No. 2 channel were examined. These samples showed the same mineralogy and relative mineral abundances as those collected in the ore deposit at the Monument No. 2 channel. It would appear, therefore, that the clays of the Shinarump member in the mine are the same as those away from the mine and show no changes which can be related to ore-bearing solutions.

Gypsum -  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ .--Gypsum has been found throughout the mine, although it is nowhere abundant. It occurs as soft powdery fillings of fractures. These fillings commonly are about a millimeter thick but range from paper thin up to 1 cm thick. Many of the tiny faults that are found throughout the mine have thin coatings of gypsum or calcite on their surface; and, in some places, the faults would be indiscernable but for this coating.

Locally, a few thin plates of selenite, up to 0.2 mm thick and 1 to 2 mm long, are dispersed among the interstices of conglomerate and conglomeratic sandstone, but in one place a pocket in conglomerate was found where gypsum formed as much as 25 percent of the rock. The pocket

was about 18 inches across and 3 feet long, and the gypsum was most abundant in the center, decreasing moderately toward the edges of the pocket. At the borders of the pocket, the abundance of gypsum decreased markedly, so that only scattered selenite flakes were found a few inches away. Associated with the gypsum were abundant silicified wood and a little metazeunerite.

On South Ridge a single crystal of selenite, half an inch by half an inch by 1 inch, of optical quality was found enclosed in relatively unaltered, conglomeratic, montroseite-uraninite ore. Its occurrence was such as to suggest that it may have been deposited with the primary ore. Only small scattered flakes of gypsum were found in the nearby ore.

Ilsemannite(?) -  $\text{Mo}_3\text{O}_8 \cdot n\text{H}_2\text{O}$ ---Powdery blue ilsemannite(?) both coats and impregnates friable conglomerate in a wall along the west edge of the channel in the South workings (fig. 29). It is in a zone 6 inches to 2 feet thick and about 8 feet long.

The ilsemannite(?) is associated with corvusite, navajoite, hewettite, and some uraninite, as well as gypsum, partly altered pyrite, and a little unidentified iron sulfate.

The ilsemannite(?) was so powdery fine grained, and so dispersed that little data could be obtained from it. Identification was on the basis of its blue to grayish-blue color, a chemical test for molybdenum, and solubility in water with the formation of a blue solution. No X-ray comparison data were available.

Although the ilsemannite(?) seems to be secondary, no primary molybdenum mineral from which it could be derived has yet been found.

Jarosite -  $KFe_3(SO_4)_2(OH)_6$ .--Jarosite has been identified in specimens from the North workings of the Monument No. 2 mine (fig. 29). It is a light-yellowish-brown earthy material which fills interstices in medium- to coarse-grained sediments of the Shinarump member. Identification was by means of its X-ray powder pattern.

The abundance of jarosite in the ore deposit of the Monument No. 2 channel was not estimated. Its brownish color renders it indistinguishable from iron oxides when mixed with these minerals in the form of limonite. The jarosite presumably represents an intermediate stage in the oxidation of pyrite to iron oxides. Inasmuch as it generally cannot be distinguished in the field from the other minerals of the limonite, the limonite mentioned below may or may not contain appreciable quantities of jarosite.

Limonite.--Limonite appears throughout the Shinarump member of the Chinle formation in the Monument Valley area, Arizona, as stains and permeations, but it is nowhere as abundant as in the ore deposit in the Monument No. 2 channel. Sediments of the Shinarump member filling the channel are colored dark brown by the limonite, and the channel course can be traced on the basis of color alone.

Within the ore deposit most of the lenses and beds of siltstone, sandstone, and conglomerate are stained and permeated with limonite. The limonite seems to be related to the uranium and vanadium ore; those lenses and beds with very little or no limonite are nearly devoid of uranium or vanadium minerals, whereas, the rocks strongly impregnated with limonite commonly contain large amounts of uranium and vanadium minerals. This relationship of limonite with ore is not rigid, for much of the rock that is lightly to moderately stained and impregnated with limonite is of marginal grade and some of it is barren.

The limonite is mostly soft and powdery and shows no boxwork or other relict structures. No complete mineralogical breakdown of the limonite has been attempted, but most samples appear to contain goethite, hematite, and a little jarosite. The limonite associated with the rods appears to be somewhat redder than the rest, perhaps due to a higher proportion of hematite.

The origin of the excess limonite within the ore deposit is not definitely known, although the oxidation of pyrite might account for it. Concretions of fine-grained interstitial pyrite are found in sandstones throughout most of the unoxidized or slightly oxidized parts of the mines, and a few such concretions, partly oxidized to limonite, have been found in highly oxidized areas. A series of nodular concretions showing all stages of oxidation from pyrite to limonite, was found in the East Red Oxide workings (fig. 29).

The formation of such large quantities of limonite by the oxidation of pyrite would be accompanied by the formation of great quantities of sulfate. Except for a small amount of gypsum and a little jarosite, no sulfates have been found in the mines. Their absence may be explained by their solubility in ground water; even now the ground water in Cane Valley just below the mines contains relatively large amounts of sulfate in solution.

Opal -  $\text{SiO}_2 \cdot n\text{H}_2\text{O}$  --A small amount of opal forms thin coatings on fracture surfaces and on pebbles in conglomerate near the surface or near rim outcrops in the North workings (fig. 29). The coatings range in thickness from minute films to botryoidal incrustations 5 mm thick.

Most of the opal is the variety hyalite, but some translucent white, pale green, and gray opal is found. The opal fluoresces a moderate to brilliant green under short wave ultraviolet light.

The opal is apparently the product of surface weathering, as it is found confined to relatively open fractures and loose conglomerate near outcrops.

Quartz and chalcedony - SiO<sub>2</sub>.--Quartz is by far the most abundant mineral in the ore deposit in the Monument No. 2 channel. The quartz in the Shinarump member of the Chinle formation of the ore deposit at the Monument No. 2 channel occurs as subround to round, fine to coarse sand grains and as pebbles ranging up to 5 inches and averaging about an inch in diameter. The sand grains are transparent to translucent colorless, to dark gray smoky quartz.

In many places the quartz appears to have been corroded and etched rather severely. Etched quartz grains are found within uraninite and other uranium minerals.

Authigenic quartz has been deposited on the older quartz grains in many places, with optical continuity. A large proportion of the sediments of the Shinarump member in the mines shows this authigenic quartz, which in places is so well developed as to form moderately to well-cemented quartz crystal sandstones. Several specimens of the Shinarump member collected from outside the Monument No. 2 channel lacked authigenic quartz overgrowths. Authigenic quartz has been added to the DeChelly sandstone member of the Cutler formation in most places where ore minerals extend down to or into the top of the DeChelly sandstone member.

Chalcedonic quartz occurs as silicified wood. Silification of the wood appears to be earlier than the ore and may have taken place shortly after deposition of the Shinarump member.

Wad (lithian).--Throughout the mine, wad is found as sooty black to brownish-black coatings and fracture fillings. The coatings are soft, often powdery, and without form. The composition of the wad is variable; all specimens contain much manganese, and some specimens contain significant amounts of one or more of the following elements: barium, cobalt, iron and lithium. The name lithiophorite has been applied by some persons to the lithian wad from the Monument No. 2 mine, but inasmuch as the wad shows none of the scaly or botryoidal structure of typical lithiophorite, it would seem better to term the material from the Monument No. 2 mine lithian wad.

#### Associated minerals (sulfides)

Bornite -  $Cu_5FeS_4$ .--Minute amounts of bornite have been recognized in a specimen from the incline no. 3 workings (fig. 29). The bornite coats sand grains in films of microscopic thickness, so thin that attempts to secure a sample for X-ray powder patterns was unsuccessful. Identification was made on the basis of its "peacock ore" appearance under the binocular microscope and microchemical tests for copper and iron.

With the exception of metazeunerite, this is the only copper mineral found in the Monument No. 2 mine.

Galena -  $PbS$ .--Small grains of galena have been found associated with uraninite nodules in the incline no. 2 workings (fig. 29). The galena was in the form of small crystals and irregular grains inclosed in the uraninite.

The galena (nonradiogenic lead) was used by Stieff, Stern, and Milkey (1953) for correction of isotopic ratios in their determinations of the age of uraninite from the Monument No. 2 mine (p. 173).

Pyrite - FeS<sub>2</sub>.--At least four forms of pyrite have been found in the Monument No. 2 mine. Probably the most important type from the standpoint of paragenetic implications is one that occurs with uraninite. Specimens of fossil wood, replaced by pyrite and uraninite, were found in a pillar in the South workings (fig. 29). The wood was replaced so completely that it was not possible to determine its state at the time of replacement. The striking feature was the inverted replacement relationships shown in two specimens collected only 2 feet apart. In one, the cell walls were pyrite and the cell contents were uraninite; in the other, the cell walls were uraninite and the cell contents, pyrite. Replacement by the two minerals must have been essentially simultaneous, with some subtle influence causing the inverted relationships.

The second form of pyrite was collected from a small greenish-gray claystone lens in the workings on South Ridge (fig. 29). About 20 cubes, 2 to 5 mm on edge, were found singly and in small groups. The crystals were sharp and bright with no sign of alteration, although the uranium and vanadium ore in the vicinity had begun to show appreciable oxidation.

The third type of pyrite occurs as concretionary masses of tiny euhedral crystals interstitial to quartz grains in sandstone and conglomeratic sandstone. The concretions have been found scattered throughout the length and breadth of the mine but are most abundant in the workings on South Ridge, incline no. 1 and the upper levels of the

incline no. 2 workings. Stratigraphically they range through the Shinarump member of the Chinle formation and into the upper few inches of the DeChelly sandstone member of the Cutler formation. Individual concretions are ellipsoidal to lenticular and range in size from the size of buckshot up to flat lenses a few inches thick and several feet in length and width. The concretions lie roughly parallel to bedding. They may occur singly or in groups; members of groups may be arrayed along bedding, in a narrow stratigraphic zone, or be irregularly scattered. The sand grains in the concretions look the same as in the surrounding sandstone, but the interstices in the concretions are filled with myriad bright euhedral pyrite crystals. Most of the crystals are so small that their form cannot be recognized, but a few of the larger crystals appear as cubes, octahedrons, and pyritohedrons. Many of the concretions appear relatively fresh, with bright pyrite crystals inside and only a thin shell, one-sixteenth to half an inch thick, of limonitic sandstone. Others are in more advanced stages of oxidation, and some have been completely limonitized. In some groups all stages of oxidation were seen. Most of the concretions had a sharp boundary with the enclosing sandstone, much of which contained little or no limonite. This suggests that the limonite that accompanies much of the ore was not derived from these pyritic concretions. Most of the concretions are in relatively barren sandstone or low grade ore; none has been found in high-grade yellow ore, although several have been found in lower grade ore adjacent to the high grade.

A fourth type appears as small rosettes of marcasite-like crystals filling a small fault in the incline no. 2 workings. The crystals are irregular and poorly formed and are about 1 by 5 mm in size. They were identified as pyrite by X-ray.

Sphalerite - ZnS, and sulfur - S.--Incline no. 3 cut through a fossil log and exposed a cross section of it in each wall of the incline (p. 191). The log, composed of carbonaceous matter, had been impregnated and partly replaced by uraninite, pyrite, and other minerals. From the core of the log two 1 mm, black isometric crystals were collected. These crystals were identified as sphalerite by Thomas W. Stern (written communication).

A tiny cavity in the core of the log yielded several 1 mm transparent yellow crystals of native sulfur.

#### Unidentified minerals

In addition to the minerals described above, several minerals have been found that are as yet unidentified because of small quantity, low purity, or nonagreement with data on known minerals and lack of sufficient data to establish them as new species.

Small, thin incrustations of a bright-orange mineral were collected on the walls of a damp drift in the incline no. 3 workings. The drift was in the otherwise barren DeChelly sandstone member underlying tyuyamunite-bearing sandstone and conglomerate of the Shinarump member. The mineral is a hydrous vanadate, but the X-ray pattern does not match the patterns of pascoite or hummerite, or any other mineral in the film library of the U. S. Geological Survey. The orange mineral had apparently leached from the overlying ore.

In the upper part of the incline no. 3 workings, tiny irregular green flakes coat fracture surfaces in siltstone pebbles. These pebbles are in a conglomerate lens 6 inches thick and about 15 to 20 feet in horizontal extent that contains small amounts of a viscous oily material. No matching X-ray pattern was found for this green mineral. A micro-chemical test with potassium mercuric thiocyanate suggests that this mineral might contain nickel.

One or more very impure iron sulfate minerals were found in a drift wall on the western edge of the channel in the incline no. 2 workings. The iron sulfate was associated with ilsemaninite, partly altered pyrite, and gypsum. Attempts to separate the iron sulfate from the other minerals for identification have been unsuccessful.

Gruner and Gardner (1952) report having found roscoelite, fernaldinite, and alunite in the Monument No. 2 mine. The writer did not find any of these minerals.

#### Paragenesis

The following account of the paragenetic relationships in the ore deposit in the Monument No. 2 channel is based largely on the study of mineral occurrences, hand specimens collected in the mines, along with microscopic examination of thin and polished sections of the ore and country rock. It is realized that for so large an ore deposit and with such varied mineralogy this study is not exhaustive.

No vanadium mineral with the vanadium in a lower oxidation state than  $V^{3+}$ , as in montroseite, has been found on the Colorado Plateau. It is, therefore, inferred that the original vanadium mineral in the ore deposit in the Monument No. 2 channel was montroseite.

Uraninite, in which uranium has a valence of four, is the least oxidized uranium mineral known to occur in nature. It is, therefore, concluded from the mineralogy that the ore forming solutions yielded  $U^{4+}$  and  $V^{3+}$  ions, along with smaller amounts of  $Fe^{2+}$ ,  $Pb^{2+}$ ,  $Zn^{2+}$ ,  $Cu^{2+}$ ,  $Mo^{4+}$ ,  $Co^{2+}$ , and  $S^{2-}$ . Some silica and carbonate may have been added also, though these materials may have been derived from the host rock.

The fact that montroseite ore is found without uranium and that no vanadium is found in the uraninite implies separate loci of deposition or independent episodes of mineralization. No direct association of uraninite and montroseite has been found; so direct determination of age relationships have not been possible. There is a suggestion that uraninite may be earlier; all the montroseite examined is on strongly etched quartz grains with no evidence of replacement, whereas, uraninite seems to have replaced some quartz, perhaps contemporaneously with the etching of quartz elsewhere.

The period of ore formation possibly began with dissolution of quartz. While this was taking place, pyrite began to be deposited; and, later, uraninite was deposited simultaneously with pyrite. This stage was followed by deposition of montroseite, and this was followed in turn by the deposition of authigenic quartz. Small amounts of galena, sphalerite, bornite, and probably molybdenite and cobalt sulfides were deposited during the epoch of ore mineralization, but their age relationships have not been established.

The primary ore in the Monument No. 2 channel, therefore, appears to have been largely uraninite and montroseite, with small quantities of sulfides, and a siliceous gangue in a siliceous country rock. From the

age determinations and the regional geology it may be seen that the ore formed at a depth of several thousand feet. The primary ore was thus protected from oxidation for a considerable time, until erosion cut away most of the overlying rocks and circulating ground water began to bring atmospheric agents down to the site of the ore deposit.

The beginning of oxidation is surmised by many geologists to be the period of uplift and erosion that has produced the many great canyons and mesas of the southwest. Since its inception oxidation has been relatively continuous, probably at an ever increasing rate until the present.

Although a continuous range of oxidation products may be traced from primary ore to thoroughly oxidized ore, it is convenient to consider the process in stages, based on major mineral assemblages observed in the ore. Although the stages appear to be fairly definite, the boundaries between the stages are indistinct.

The primary ore has been described above. Only small amounts of this type of ore have been found in the ore deposit in the Monument No. 2 channel, and all occurrences were in the workings on South Ridge.

The first distinct oxidation stage is marked by very dark ore, commonly blue black, with locally a dark-greenish or brownish cast. This oxidation stage is commonly referred to as the corvusite stage after the vanadium mineral that predominates in this type of ore and which is largely responsible for the blue-black color. Associated minerals include becquerelite, tyuyamunite, navajoite, uraninite, rauhite, hewettite, and pyrite. The minerals are mostly fine grained and intimately mixed, and in most places individual minerals cannot be

recognized except under the microscope or after various separatory techniques; frequently no distinction is possible. Tyuyamunite, particularly, is hidden by the dark colors of the other minerals.

The vanadium has been oxidized from  $V^{3+}$  in montroseite to  $V^{4+}$  in corvusite with a few minerals oxidized to  $V^{5+}$ . Continued oxidation of corvusite would convert all the vanadium to  $V^{5+}$  in the minerals navajoite, hewettite, rauvite, and tyuyamunite. Of these navajoite is probably the first formed, as it represents essentially a simple vanadium oxide, whereas, calcium has been added in hewettite, and both calcium and uranium in rauvite and tyuyamunite. As navajoite  $\checkmark$  is

---

$\checkmark$  Evans, H. T., Jr., in preparation, The crystal chemistry and mineralogy of vanadium, in Garrels, R. M., and Larsen, E. S., 3d, Mineralogy and geochemistry of the Colorado Plateau uranium ores: U. S. Geol. Survey Prof. Paper 320.

---

formed, however, only in a highly acid environment (pH about 2) its occurrence may have been governed by this factor.

Concurrently with the oxidation of the vanadium, uranium would be oxidized from  $U^{4+}$  to  $U^{6+}$ . Some oxidation may have taken place earlier by auto-oxidation. Apparently the uranium oxidized more slowly than the vanadium, as relicts of uraninite are left after the vanadium seems to be entirely oxidized. Pyrite appears to be largely unchanged through the corvusite stage, although in places the presence of iron sulfates indicates oxidation is taking place. The ilsemannite found along with the iron sulfate suggests that perhaps an early molybdenum mineral is oxidized during this stage.

The corvusite stage is represented by the ores in the incline no. 2 workings and in the southern two-thirds of the South Ridge workings (fig. 29). Those workings near the surface on Main Ridge contained no corvusite-type ore, although in some places corvusite-type ore underlay these upper workings.

The second oxidation stage (following the corvusite stage) is represented by dark-blackish-brown to medium-brown ore, in which all the vanadium is in the  $V^{5+}$  state; and all the uranium, except for scattered relicts of uraninite, is in the  $U^{6+}$  state. Minerals present are tyuyamunite, rauvite, hewettite, limonite, and small amounts of uraninite, becquerelite, uranophane, and pyrite. The second oxidation stage represents the completion of the oxidation of the vanadium, and considerable mixing of uranium and vanadium and other ions to form combined minerals. It is represented by border zones a few feet wide around areas of corvusite-type ore.

The third oxidation stage is represented by tyuyamunite-type ore. This ore, which is the most abundant and widespread type in the ore deposit in the Monument No. 2 channel, ranges in color from dark reddish brown through various lighter browns to bright yellow; a small amount of grayish ore with disseminated yellow tyuyamunite is also classed with this type. The chief minerals, beside the quartz of the host rock, are limonite and tyuyamunite, with smaller amounts of hewettite, rauvite, and a little relict pyrite. A few scattered relicts of uraninite rimmed with becquerelite or uranophane have been found in this type of ore, and all the autunite, metazeunerite, and carnotite found in the mine have been in this type of ore. The tyuyamunite-type ore apparently results from

continued oxidation of pyrite and continued recombination of the elements of the earlier minerals such as hewettite, rauvite, and becquerelite to form the more stable tyuyamunite.

The fourth oxidation stage results from the action of these re-combinations, and gives an ore containing little more than limonite, tyuyamunite, and perhaps a little hewettite. This is just the type of ore that is found throughout the uppermost workings and locally near the cliff faces where the deposit has been cut through by the canyons; these are the places where the ore has been longest and most completely exposed to oxidation.

Although oxidation and alteration of the ores in the ore deposit in the Monument No. 2 channel have been extensive, there has been relatively little overall movement of the metals. The primary minerals, particularly uraninite, appear to have oxidized nearly in place, and combination of the oxidation products has taken place with little migration. Vanadium appears to be more mobile than uranium; the secondary vanadium minerals hewettite and steigerite have been found along joints as much as 25 feet from ore, whereas, uranium minerals along joints are much closer to the ore. Small samples of ore show differing contents of the daughter products of uranium, but the ratios of these elements in bulk samples of ore are near the equilibrium values.

Monument No. 1 channel

Monument No. 1-Mitten No. 2 mine and Monument No. 1 Annex

Introduction

In 1954, the Monument No. 1 channel (fig. 14, channel no. 36) was the scene of intensive mining activity, primarily as the result of a discovery of a new ore body in channel sediments formerly thought to be barren. Before that, in the period 1942 to 1950, the major producer was the Monument No. 1 mine, operated by the Vanadium Corporation of America. This mine was in the basal sediments at the east end of a large channel remnant. The ore deposit pinched out and in 1950 mining was discontinued and the adits were caved as a safety measure. From then until 1953, the area lay unclaimed, although some work was done in another small mine about a quarter of a mile distant. This mine, known as the Monument No. 1 Annex, is in a weakly mineralized mass of the Shinarump member of the Chinle formation about 150 feet long and 50 feet wide.

During 1952, several Navajo Indians reprospected the area of the Monument No. 1 mine. Production records do not exist and it is assumed that no ore was produced. In 1953, a new mine, the Mitten No. 2, owned by the Foutz Mining Company (now the Industrial Uranium Company) was opened in the flank of the west part of the channel remnant. The mine was in weakly mineralized ground and produced less than 100 tons of ore. In early 1954, however, a new ore body was discovered in this part

of the channel sediments as a result of a drilling program by the Foutz Mining Company, and as of January 1955, it was this ore body which was being mined through the new Monument No. 1-Mitten No. 2 mine workings.

#### Location and accessibility

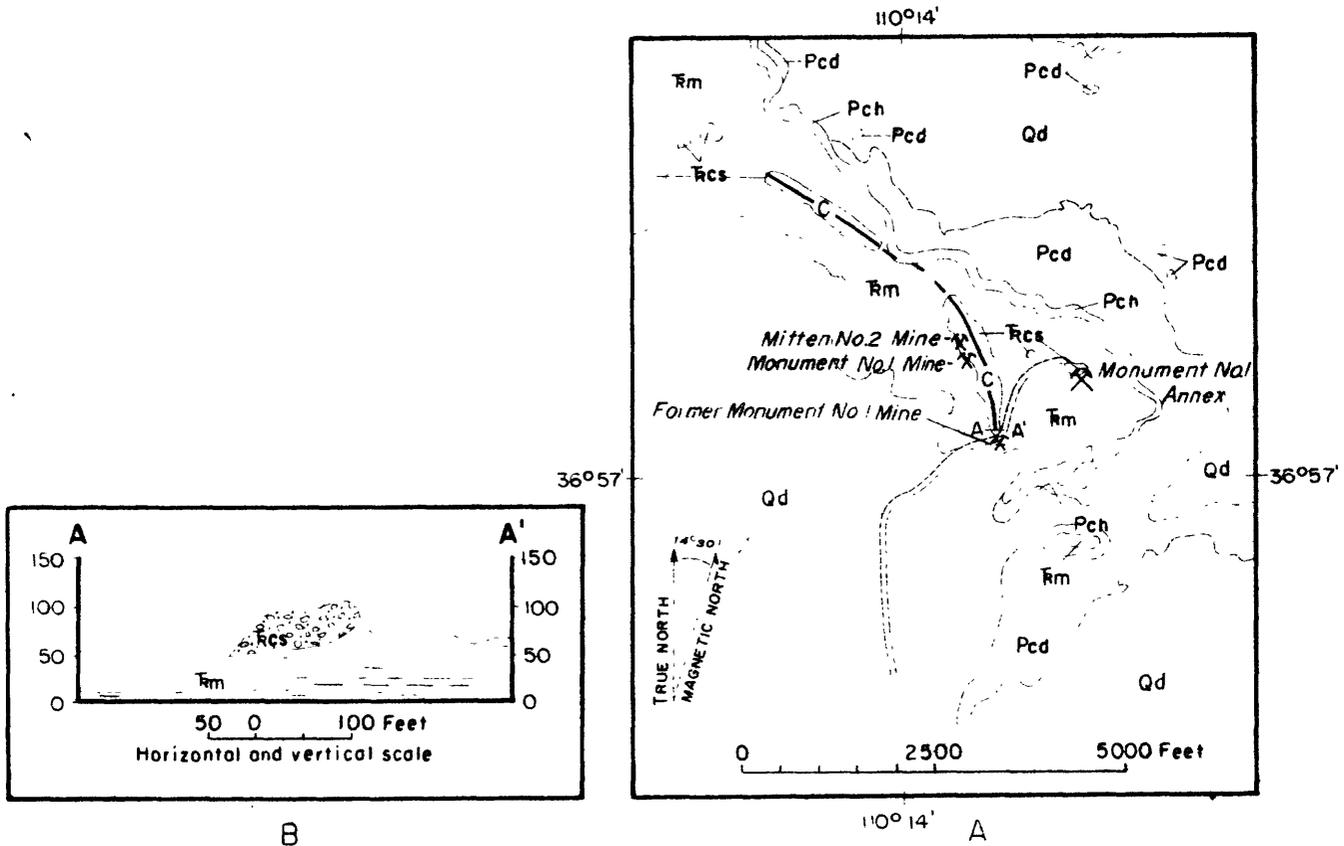
The center of the Monument No. 1 area is at latitude  $36^{\circ} 57' 24''$  N. and longitude  $110^{\circ} 14'$  W. The area is on a prominent ridge west of the Kayenta-Mexican Hat road (fig. 1; Navajo Indian Reservation Route No. 1). The mines are reached by an ungraded trail that leads northwest from the Kayenta-Mexican Hat road and which ascends to the mine portals by a series of switchbacks.

#### Geology

The ridge is capped by remnants of the Shinarump member of the Chinle formation which stand about 30 feet above the general ground surface formed on the Moenkopi formation (fig. 32). Scattered across this Moenkopi surface are deposits of unconsolidated eolian sand as much as 10 feet thick.

Most of the Shinarump member has been eroded from the area near the Monument No. 1 mine, and it is only to the west, near Oljeto Wash, that the Shinarump member is preserved. There, however, it is concealed beneath a dune sand and alluvial cover that may be as much as 80 feet thick, although it likely averages 20 feet.

The Shinarump member forms the gently dipping east flank of the asymmetrical Oljeto syncline (p. 127) and dips average  $3^{\circ}$  to the southwest.



EXPLANATION

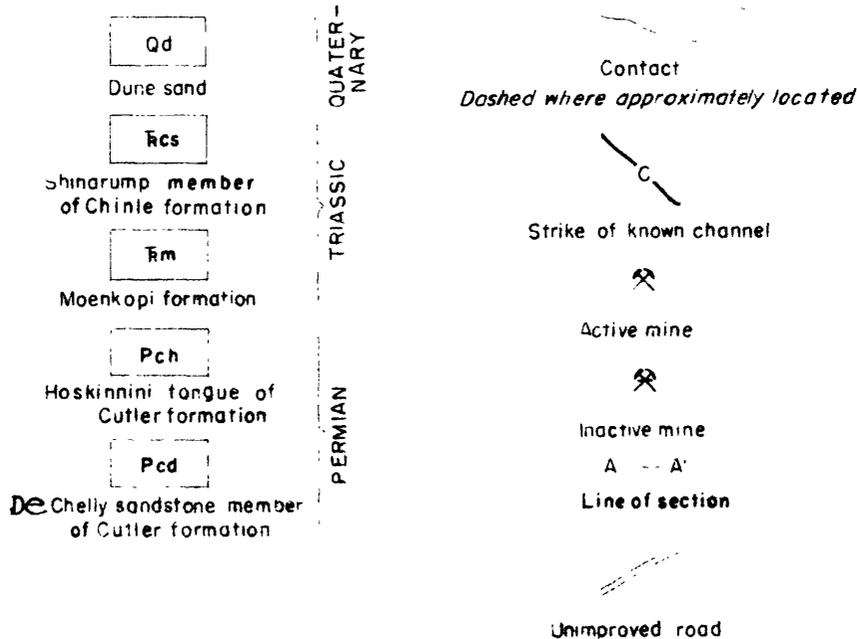


FIGURE 32.--GEOLOGIC MAP AND CROSS SECTION OF THE MONUMENT NO. 1 CHANNEL. THE TWO CHANNEL REMNANTS OF THE SHINARUMP MEMBER FORM TOPOGRAPHIC HIGHS. THE CHANNEL CURVES TO THE NORTHWEST. IT IS UNCERTAIN IF THE MONUMENT NO. 1 ANNEX IS IN A PART OF THE SAME CHANNEL.



11

Channel

Remnants of the Shinarump member represent part of a former wide-spread sheet of conglomeratic sandstone. Dissection, however, has been so extensive that the uppermost beds of Shinarump member as well as part of the subjacent strata of Moenkopi age have been largely removed (fig. 32B). The result is that channel sediments now appear as two ridges whose alignment is to the northwest (fig. 32A). The two ridges, however, do not everywhere reflect the true width of the channel, for locally, part of the channel sediments have been eroded. When these remnants are viewed in cross section, it is apparent that in places only the east flank of the channel is preserved (figs. 32B and 33). Extrapolating from the channel remnants preserved, the channel is estimated to have been about 250 feet wide and to have been cut about 50 feet into the Moenkopi formation. The channel curves to the northwest (fig. 32A). The southern channel remnants, which contain the mine workings, trend about N. 10° W., and the northern remnant trends about N. 55° W.

Sediments in the Monument No. 1 channel have the same appearance as sediments of the Shinarump member found elsewhere in the Monument Valley area, Arizona. The basal conglomeratic sandstone grades vertically into a massive sandstone in the uppermost beds. Conglomerate lenses are scattered through the channel sediments. They retain their identity only for short distances, grading laterally into massive sandstones. In a few places, small scours, filled with conglomeratic sandstone, have been cut into the massive sandstone that forms the uppermost channel sediments.



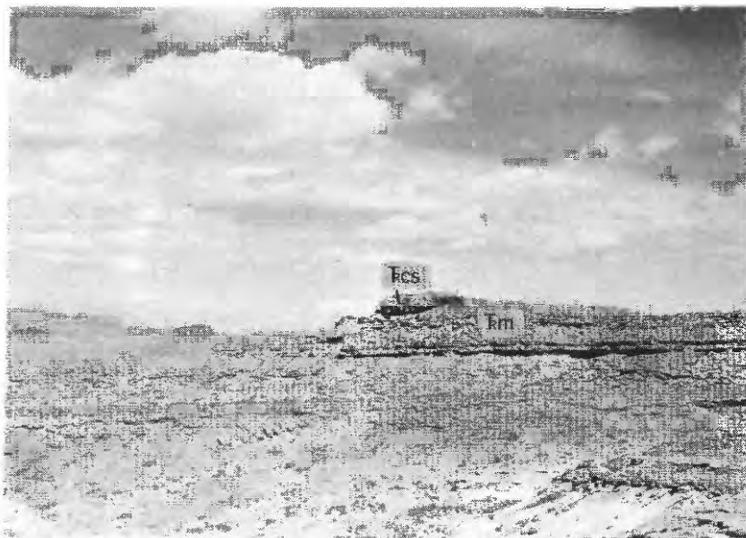


Figure 33.--Photo showing the isolated mass of the Shinarump member of the Chinle formation (Rcs) that forms the south remnant of the Monument No. 1 channel. Rm - Moenkopi formation. Mine dump marks the approximate location of the Vanadium Corporation of America's former Monument No. 1 mine.



Three lithologic types can be differentiated in the basal channel sediments; these are (1) a trash-pocket conglomerate, (2) a calcite-cemented sandstone, and (3) a silica-cemented sandstone (fig. 34). The trash-pocket conglomerate consists of well-rounded pebbles of quartz, chert, and quartzite, as well as angular claystone fragments and fossil plant matter, all in a matrix of coarse-grained sandstone. The calcite-cemented sandstone, is a light-tan hard massive crossbedded unit well cemented by calcium carbonate. These calcite-cemented sandstone lenses are composed of well-rounded fine to coarse grains of quartz, chert, and quartzite in an exceedingly tight carbonate cement. The quartz grains lack authigenic overgrowths in marked contrast to those grains in the silica-cemented sandstone. The third lithologic type, the silica-cemented sandstones are composed of rounded to angular coarse grains of quartz, chert, and quartzite all enclosed in a loosely knit matrix of chalcedonic cement. A characteristic feature is authigenic overgrowths on the quartz grains.

Inclusions in the basal channel sediments consist of silicified wood, ranging from small fragments to logs over 2 feet in diameter and 10 feet long, as well as large amounts of carbonaceous matter and clay pebbles. Also included are angular fragments of light-gray siltstone interpreted as having been derived from the Moenkopi formation. Measurements of the trend of 15 silicified logs in the channel sediments indicate a range from N.  $10^{\circ}$  W. to N.  $85^{\circ}$  W., although most of the logs are aligned collinear with the N.  $10^{\circ}$  W. strike of the channel.

The upper surface of the channel fill is irregular, marked by depressions as much as 20 feet in diameter and 4 feet deep, and by rounded hummocks which rise about 20 feet above the general surface.





Figure 34.--Photo showing the three lithologic types represented in basal channel sediments: Tp - trash-pocket conglomerate; Cc - calcite-cemented sandstone; and Sc - silica-cemented sandstone.



Near the southernmost exposure of channel sediments, a concentration of silicified logs on the surface is surrounded by very dark limonite-colored sediments. This limonitic coloration is not confined to one locality, for elsewhere on the surface smaller limonite-colored areas are exposed. Unweathered exposures of channel sediments lack the limonite coloration (fig. 35).

The channel is underlain by an altered zone in the uppermost strata of the Moenkopi formation that is about 2 feet thick along the channel flanks and increases in thickness to almost 5 feet below the channel. In the uppermost part of the altered zone beneath the channel minute quantities of secondary copper minerals such as azurite, malachite, and chrysocolla are along the bedding planes and fill small fractures.

The possible significance of the altered zone is being investigated Weeks, 1952b). Specimens of both the red unaltered and the gray altered Moenkopi formation were chemically analyzed. Mrs. Weeks reports: "At Monument No. 1 mine, both red and gray clay contain quartz, hydromica, chlorite, and kaolinite. Chemical determinations of total iron, ferric and ferrous iron, titanium dioxide, and vanadium pentoxide, made by R. G. Milkey, showed that in all suites of samples total iron and ferric iron are higher in the red than in the adjacent gray sample. Although the ferrous-ferric ratio is higher in all the gray samples than in the adjacent red clay, the ferrous iron does not vary significantly between the red and gray of each set. To alter the red clay to gray, only 1 percent more or less of ferric iron pigment would have to be leached from the red. Hematite is too small in quantity or too fine grained to show in X-ray patterns of natural red clays."





Figure 35.--Photo showing limonite-impregnated sediments along fractures in the Monument No. 1 channel fill.



Mrs. Weeks sought but found no evidence for or against a relationship of the altered zone to ore mineralizing solutions.

Sediments in the Monument No. 1 Annex are similar to those filling the Monument No. 1 channel except that light-gray oval clay pebbles, about half an inch long are in a matrix of coarse-grained sandstone. The clay pebbles are so alined as to give an impression of rudimentary horizontal bedding. Yellow uranium minerals are disseminated in the interstices of the sandstone near the pebbles but are absent elsewhere. A banded appearance results, with yellow mineralized bands about 1 inch wide alternating with white barren bands, also about 1 inch wide. Close examination near some of the clay pebbles indicates that in some yellow uranium minerals impregnate the sandstone to their very edges. In others a halo about a quarter of an inch thick devoid of uranium minerals surrounds them.

Trash pockets of fossil plant matter are common in the sediments of the Monument No. 1 Annex. These pockets appear in cross section as irregular thin strips of black coaly substance (vitrain?). In plan view, these pockets show as impressions of reedlike plant material in the sandstone.

#### Uranium-vanadium ore bodies

Two ore bodies have been discovered in the basal channel sediments of the south channel remnant. They are separated from one another by barren sediments. Little is known about the size, shape, and distribution of the ore body mined by the Vanadium Corporation of America at the former Monument No. 1 mine (fig. 32). The second ore body, currently being

mined through the Monument No. 1-Mitten No. 2 mine portals (fig. 32) is near the north end of the south channel remnant. It is about 675 feet long, about 75 feet wide, (although, in places it is as wide as 120 feet), and ranges in thickness from 1 foot to as much as 18 feet, (although, it averages 7 feet in thickness). This ore body trends N. 30° W., and is collinear with the channel trend. In both longitudinal and cross section the ore body appears planoconvex or biconvex, with its base commonly conforming to the channel floor.

In places, both the trash-pocket conglomerate and the silica-cemented sandstone contain ore and form ore bodies. Barren calcite-cemented sandstone lenses commonly are intercalated in the ore body (fig. 34). The ore is brilliant blue black, principally due to the widespread distribution of the vanadium mineral, corvusite. Scattered irregularly through the ore body are specks of yellow, green, and blue, representing secondary uranium (tyuyamunite), copper-vanadium (volborthite), and copper (azurite, malachite) minerals. Copper minerals are common in the south part of the Monument No. 1 mine workings but are not found in the Mitten No. 2 mine workings. Semiquantitative spectrographic analyses of the basal channel sediments, however, indicate that copper is widespread.

Mineralogy

The following minerals were collected from channel sediments exposed near the former Monument No. 1 mine:

Apatite(?)	$\text{CaFCa}_4(\text{PO}_4)_3$	Rare
Autunite	$\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 12\text{H}_2\text{O}$	Rare
Azurite	$\text{Cu}_3(\text{OH})_2(\text{CO}_3)_2$	Rare
Carnotite	$\text{K}_2(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 1-3\text{H}_2\text{O}$	Rare(?)
Calcite	$\text{CaCO}_3$	Common
Chlorite	$\text{Mg}_5(\text{Al,Fe})(\text{OH})_8(\text{Al,Si})_4\text{O}_{10}$	Rare
Chrysocolla	$\text{CuSiO}_3 \cdot 2\text{H}_2\text{O}$	Rare
Hydromica	$\text{KAl}_2(\text{OH})_2\text{AlSi}_3(\text{O,OH})_{10}$	Rare to common
Kaolinite	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	Rare(?)
Limonite	$2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$	Common
Malachite	$\text{Cu}_2(\text{OH})_2\text{CO}_3$	Rare
Metatorbernite	$\text{Cu}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$	Rare
Montmorillonite	$(\text{MgCa})\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 5\text{SiO}_2 \cdot n\text{H}_2\text{O}$	Rare
Pyrite	$\text{FeS}_2$	Common
Torbernite	$\text{Cu}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 12\text{H}_2\text{O}$	Rare
Tyuyamunite	$\text{Ca}(\text{UO}_2)(\text{VO}_4)_2 \cdot 7-10\frac{1}{2}\text{H}_2\text{O}$	Common
Zippeite	$(\text{UO}_2)_2\text{SO}_4(\text{OH})_2 \cdot 4\text{H}_2\text{O}$	Rare

Essentially the same minerals are found at Monument No. 1 Annex.

The following minerals were collected from the Mitten No. 2 mine:

Apatite	$\text{CaFCa}_4(\text{PO}_4)_3$	Rare
Azurite	$\text{Cu}_3(\text{OH})_2(\text{CO}_3)_2$	Rare to common
Calcite	$\text{CaCO}_3$	Common
Carnotite	$\text{K}_2(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 1-3\text{H}_2\text{O}$	Rare
Chalcanthite	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	Rare
Chalcedony	$\text{SiO}_2$	Rare to common
Chalcocite	$\text{Cu}_2\text{S}$	Rare
Chrysocolla	$\text{CuSiO}_3 \cdot 2\text{H}_2\text{O}$	Rare to common
Corvusite	$\text{V}_2\text{O}_4 \cdot 6\text{V}_2\text{O}_5 \cdot n\text{H}_2\text{O} (?)$	Common
Hewettite	$\text{CaV}_6\text{O}_{16} \cdot 9\text{H}_2\text{O}$	Rare
Malachite	$\text{Cu}_2(\text{OH})_2\text{CO}_3$	Common
Metatorbernite	$\text{Cu}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 8-12\text{H}_2\text{O}$	Rare
Metatyuyamunite	$\text{Ca}(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 7-10\frac{1}{2}\text{H}_2\text{O}$	Common
Pyrite	$\text{FeS}_2$	Common
Rauvite	$\text{CaO} \cdot 2\text{UO}_3 \cdot 5\text{V}_2\text{O}_5 \cdot 16\text{H}_2\text{O} (?)$	Rare
Roscoelite	$(\text{Al}, \text{V})_2\text{AlSi}_3(\text{K}, \text{Na})\text{O}_{10}(\text{OH}, \text{F})_2$	Rare
Tyuyamunite	$\text{Ca}(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 7-10\frac{1}{2}\text{H}_2\text{O}$	Common
Volborthite	$\text{Cu}_3(\text{VO}_4)_2 \cdot 3\text{H}_2\text{O} (?)$	Common

## PROSPECTS IN THE MONUMENT VALLEY AREA, ARIZONA

The Monument Valley area has been examined thoroughly by white and Navajo prospectors, and few mineralized outcrops remain unclaimed. Those channel exposures that show copper or uranium minerals (fig. 14 and table 3) generally have had some development work completed in the form of roads or small adits. The U. S. Atomic Energy Commission has investigated several of these prospects by diamond drilling. As of July 1953, the U. S. Geological Survey had done no physical exploration in the Monument Valley area, Arizona, beyond several geophysical surveys launched primarily to secure geologic information.

Two areas seem most promising, Hunts Mesa and Mitchell Mesa. The U. S. Atomic Energy Commission completed a drilling program in November 1952, on Hunts Mesa. Thirty-two holes were drilled. Of these, only two holes penetrated mineralized ground and in neither was the material of ore grade.

Witkind and Thaden (1954) have recommended both geophysical and diamond-drilling programs for Mitchell Mesa.

Hunts Mesa

Hunts Mesa is a small mesa in the Monument Valley area, Arizona. At least two channels (fig. 14, channel nos. 56 and 57) crop out at the base of the Shinarump member which caps the mesa, and it is within channel sediments so exposed that uranium and copper minerals have been found (fig. 36).

Hunts Mesa is in Navajo County at latitude  $36^{\circ} 53'$  N. and longitude  $110^{\circ} 03'$  W. The mesa top is reached by two roads, one of which was completed in 1953. The other road is a jeep trail. No ore has been shipped from the mesa.



Sedimentary rocks exposed range from the Organ Rock tongue of the Cutler formation of Permian age at the base of the mesa to the Shinarump member of the Chinle formation of Triassic age at the top. Most of the Shinarump member, however, is concealed beneath sand dunes, and outcrops are best along the mesa rim. The thickness of the Shinarump member varies from place to place. Along the southeast edge of the mesa it is but 2 or 3 feet thick, whereas, along the northeast edge it is as much as 75 feet thick.

The mesa is near the crest of the Agathla anticline (fig. 2), and the strata are almost horizontal.

In many places around the mesa uppermost strata of the Moenkopi formation contain small cracks which are filled with sediments of the Shinarump member. These cracks are almost vertical and follow a zig-zag course as they penetrate as much as 20 feet into the underlying Moenkopi formation. They thicken erratically but in general taper from a width of about 6 inches at the base of the Shinarump member to where they pinchout. In a few localities secondary copper minerals, principally malachite and chrysocolla, fill interstices in the upper 3 to 4 feet of the cracks.

At least two channels crop out along the north rim of the mesa, although more may be concealed beneath the thick talus concealing the base of the Shinarump member (fig. 36). The main channel (no. 57) strikes about east, is about 300 feet wide, and has been cut about 50 feet into the underlying Moenkopi formation. The other channel (no. 56) is much smaller and crops out in two places along the north rim. It strikes about N. 80° E., is about 50 feet wide, and has been cut about 20 feet

into the Moenkopi formation. In general, the main channel is broad and relatively shallow. Its flanks dip about  $5^{\circ}$ . The smaller channel, however, has much steeper flanks and appears to be cut as a very narrow "V" into the underlying Moenkopi formation. Whether or not these two channels are related is unknown.

Sediments in both channels consist predominantly of a dark-gray conglomeratic sandstone, with conglomeratic material near the base grading upward into a coarse- to medium-grained sandstone near the top. The sediments are crossbedded and contain silicified wood, carbonaceous wood fragments (vitrain?) dark-purple to gray clay pebbles (possibly fragments of Moenkopi), and tan fine-grained siltstone pebbles of unknown origin.

Mineralized rock crops out at two of the channel exposures (fig. 36) and consists principally of channel sediments impregnated with secondary copper and uranium minerals. This impregnation appears as minute specks of azurite, malachite, and tyuyamunite(?) filling interstices. Clay pebbles in these mineralized exposures have been partly replaced by both copper and uranium minerals. Some of the clay pebbles show concentric zoning involving these minerals. One clay pebble half an inch in diameter is surrounded by a black zone about one-eighth of an inch thick of what may be chalcocite, which in turn is surrounded by a one-quarter inch ring of mixed secondary copper and yellow uranium (tyuyamunite?) minerals. Beyond this mixed copper tyuyamunite(?) ring, the sandstone is barren.

Grab and channel samples were collected for analysis by geologists of the U. S. Atomic Energy Commission (AEC) and the U. S. Geological Survey (USGS). The results of assays completed on the samples are listed below. Locations of samples are shown on figure 36.

Organization	Sample No.	U <sub>3</sub> O <sub>8</sub>	V <sub>2</sub> O <sub>5</sub>	Cu
AEC	13754	4.78	6.12	0.51
AEC	13755	0.14	0.96	0.10
AEC	13756	0.06	1.26	2.69
USGS	MV-8	0.01	0.66	8.96
USGS	MV-9	0.32	1.39	4.37

Samples collected from basal channel sediments at three outcrops along the north rim of Hunts Mesa contained the following minerals:

Azurite	$\text{Cu}_3(\text{OH})_2(\text{CO}_3)_2$	Rare to common
Calcite	$\text{CaCO}_3$	Common
Carnotite	$\text{K}_2(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 3\text{H}_2\text{O}$	Rare?
Chalcocite?	$\text{Cu}_2\text{S}$	Rare
Chrysocolla?	$\text{CuSiO}_3 \cdot 2\text{H}_2\text{O}$	Rare to common
Corvusite?	$\text{V}_2\text{O}_4 \cdot 6\text{V}_2\text{O}_5 \cdot n\text{H}_2\text{O}$	Rare
Jarosite	$\text{K}_2\text{Fe}_6(\text{OH})_{12}(\text{SO}_4)_4$	Common
Limonite	$2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$	Common
Malachite	$\text{Cu}_2(\text{OH})_2\text{CO}_3$	Rare to common
Torbernite	$\text{Cu}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 12\text{H}_2\text{O}$	Rare
Tyuyamunite	$\text{Ca}(\text{UO}_2)(\text{VO}_4)_2 \cdot n\text{H}_2\text{O}$	Rare to common

Mitchell Mesa

Mitchell Mesa is a large irregularly shaped mesa in the north-central part of the Monument Valley area, Arizona (fig. 2). The mesa is capped by the Shinarump member of the Chinle formation, and yellow uranium minerals are in sediments filling a channel at the base of the cap rock. The mesa is rimmed by sheer cliffs, and access to the top can be gained at only one locality, and there, only across talus slopes and smooth steep walls of consolidated sedimentary strata. The cost of constructing a truck trail to the mesa top would be high.

Mitchell Mesa is in Navajo County at latitude  $36^{\circ} 58'$  N. and longitude  $110^{\circ} 07'$  W. The mesa is about 2 miles south of the Arizona-Utah State line, and about 7 miles southeast of Goulding's Trading Post, Utah (fig. 1).

Strata forming Mitchell Mesa range from the Organ Rock tongue at the base to the Shinarump member at the top. Around the mesa crest, the Shinarump member is about 50 feet thick except where channels have been cut into the Moenkopi formation; in these places the Shinarump member is as thick as 120 feet.

Mitchell Mesa is on the crest of a small unnamed anticline; consequently, the strata are nearly horizontal.

Channel sediments crop out around the edges of the mesa (fig. 37). Of these exposures, three are so aligned as to leave little doubt that they are exposures of a single channel that strikes about  $N. 65^{\circ} W.$ , is about 350 feet wide, and has been cut about 75 feet into the Moenkopi formation (fig. 17). This channel is considered to be the main channel and is called Mitchell Mesa channel No. 1 (fig. 14 and table 3, no. 51).

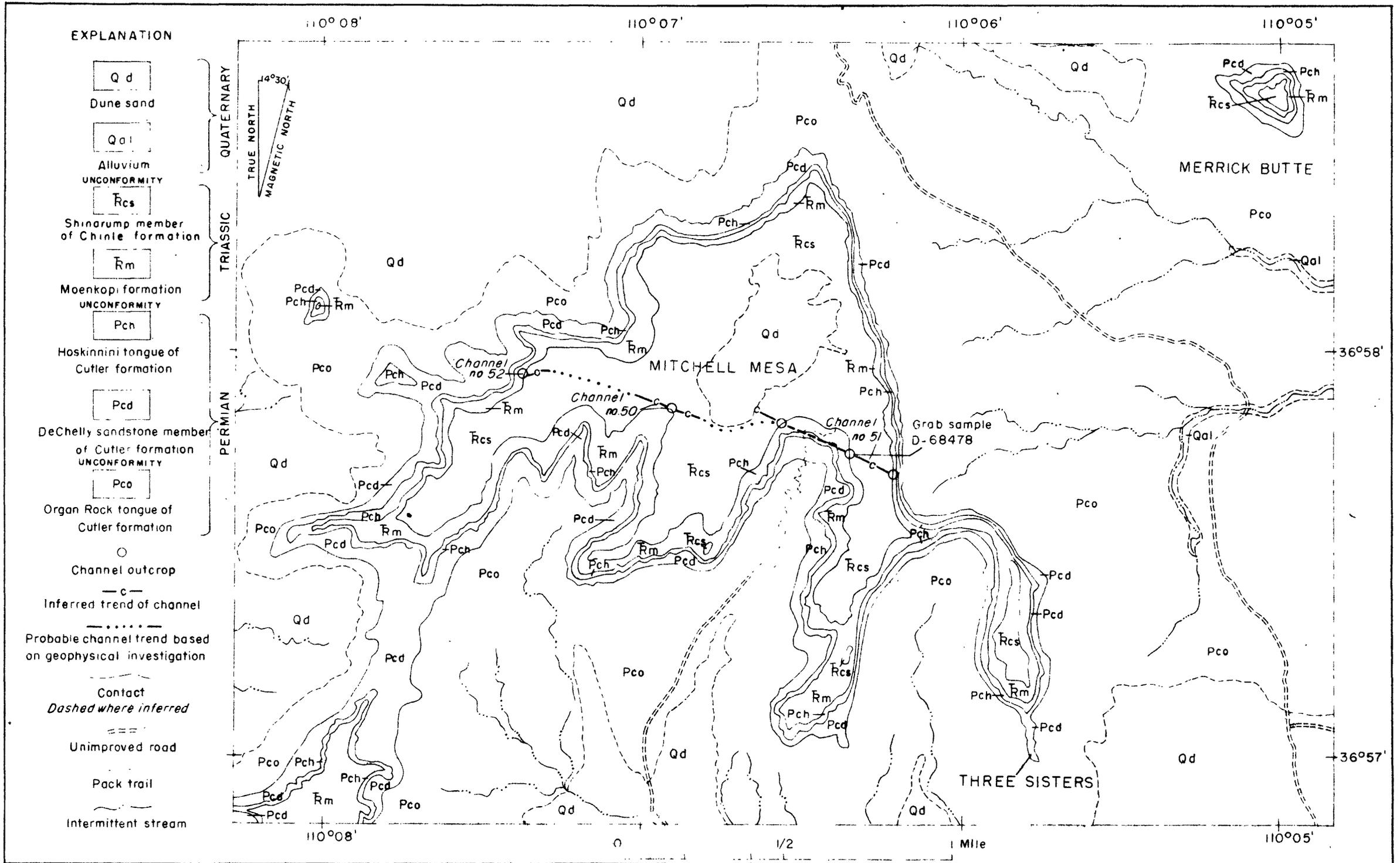
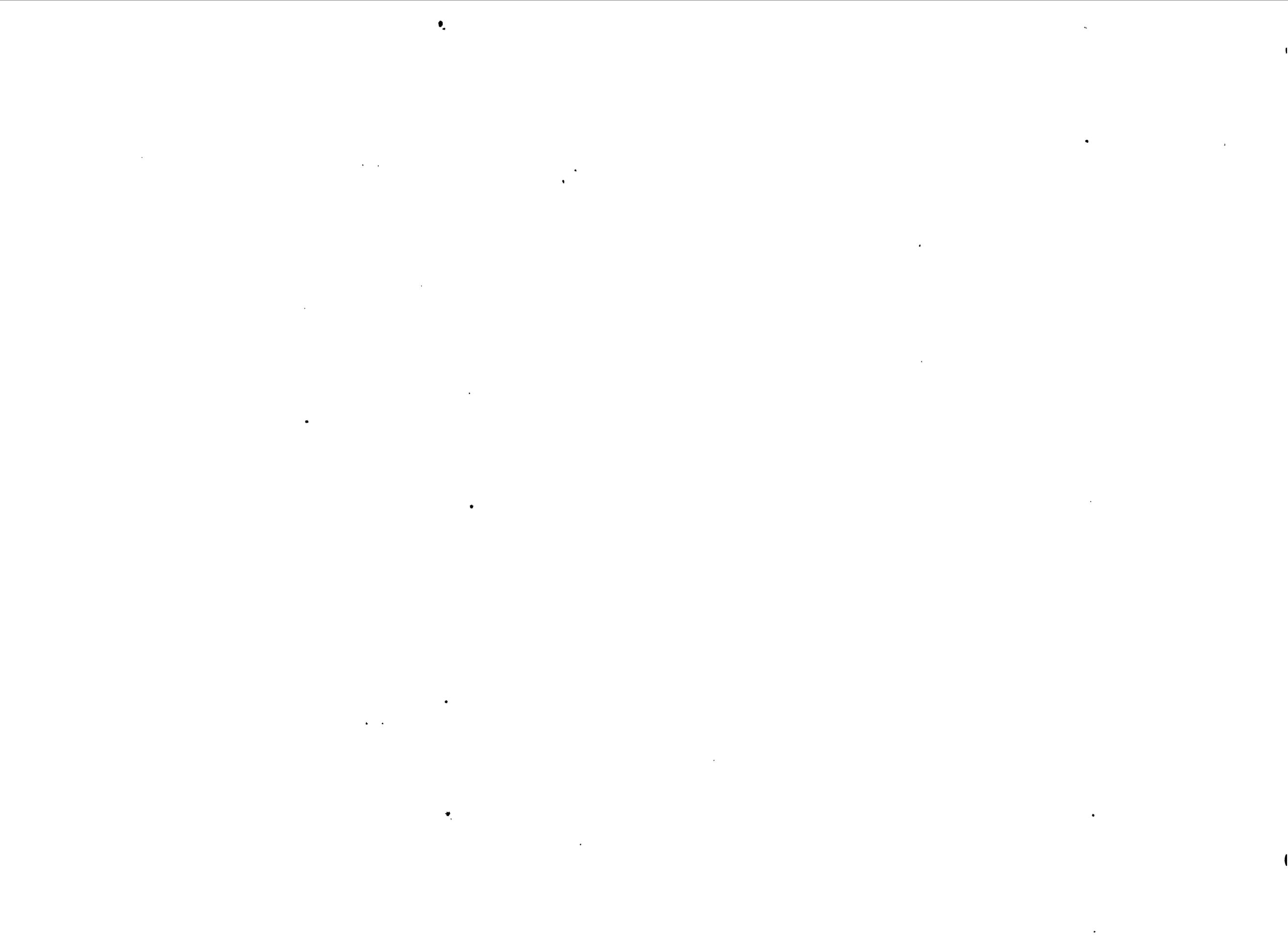


FIGURE 37.--GEOLOGIC MAP OF MITCHELL MESA ON WHICH THE CENTERLINES OF THE KNOWN CHANNELS HAVE BEEN DRAWN. PROBABLE RELATIONSHIP OF CHANNELS IS SUGGESTED BY GEOPHYSICAL MEASUREMENTS.



It is symmetrical in cross section and is considered typical of channels in the Monument Valley area, Arizona. A fourth channel exposure (fig. 37, channel no. 50) is farther west and is a longitudinal section along a channel flank. This channel strikes about N.  $70^{\circ}$  W., is estimated to be about 350 feet wide, and has been cut about 50 feet into the Moenkopi formation. The channel is named the Mitchell Mesa channel No. 2 (figs. 14 and 37 and table 3, no. 50). A fifth channel strikes about N.  $82^{\circ}$  E., is about 300 feet wide, and has been scoured about 70 feet into the underlying Moenkopi formation. It is referred to as the Mitchell Mesa channel No. 3 (figs. 14 and 37 and table 3, no. 52). Geophysical work completed in 1954, suggests that all of these channels join and trend northwest across the mesa top (fig. 37).

Channel sediments consist predominantly of a light-gray to buff massive coarse-grained sandstone that grades locally to conglomeratic sandstone. Near the base of the channel, many rounded clay pebbles about 2 inches in diameter are in a matrix of coarse-grained sandstone. In places these clay pebbles have weathered out, leaving the more resistant cemented sandstone in the form of a fretwork that is local in extent.

Beneath the channel, a light-gray altered zone, about 4 feet thick, is in the reddish-brown siltstone beds of the Moenkopi. This zone thins along the channel flanks.

At the base of Mitchell Mesa channel No. 1 (fig. 37, channel no. 51) yellow uranium-vanadium minerals are in a friable coarse-grained conglomeratic sandstone and form a seam about 4 feet long and a quarter of an inch thick. Surrounding the seam is a mass of black material, tentatively

identified as a mixture of vanadium minerals and carbonaceous matter, that impregnates the conglomeratic sandstone and forms an irregular mass 6 to 8 feet in diameter.

Following heavy rains a small seep appears at the mineralized locality. This seep may represent ground-water movement through basal channel sediments; the direction of ground-water flow presumably reflecting the westerly slope of the channel floor. It is suggested that these uranium-vanadium minerals may represent redeposition of material leached from a uraniferous deposit updip.

Geologists of the U. S. Atomic Energy Commission and the U. S. Geological Survey have examined the mineralized outcrop. One grab sample (USGS--D-68478) was collected from the basal sediments at the point indicated in figure 37 and submitted for analysis to L. P. Rader, Jr., who reported: 0.59 percent eU and 0.71 percent U, and stated that "The sample probably contains small amounts of organic material... The yellow uranium mineral is a mixture of tyuyamunite."

This grab sample is not representative of the exposure of mineralized channel sediments. It does, however, indicate the presence of uranium minerals in concentrations commensurate with other favorable prospects in the Monument Valley area, Arizona.

The following minerals have been identified tentatively from samples collected at the base of Mitchell Mesa channel No. 1:

Azurite	$\text{Cu}_3(\text{OH})_2(\text{CO}_3)_2$	Rare
Calcite	$\text{CaCO}_3$	Common
Jarosite	$\text{K}_2\text{Fe}_6(\text{OH})_{12}(\text{SO}_4)_4$	Common
Limonite	$2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$	Common
Malachite	$\text{Cu}_2(\text{OH})_2(\text{CO}_3)$	Rare
Metatyuyamunite	$\text{Ca}(\text{UO}_2)_2(\text{VO}_4)_2 \cdot n\text{H}_2\text{O}$	Rare
Torbernite	$\text{Cu}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 12\text{H}_2\text{O}$	Rare
Tyuyamunite	$\text{Ca}(\text{UO}_2)(\text{VO}_4)_2 \cdot n\text{H}_2\text{O}$	Rare
Vanadium minerals		Rare to common

#### Koley Black area

This area (fig. 14) is known by various names; in this report it is referred to as the Koley Black area, after the name of the original claimant. During the course of a U. S. Atomic Energy Commission airborne radioactivity survey in the Monument Valley area, (Cummings, 1952), two anomalies were recorded over the Koley Black area. Each area of anomaly was named; one is known as "Cold;" the other, as "Sheep." The area known as "Cold" is shown on figure 19 as channel no. 45. It is uncertain which of the remaining channel outcrops is known as "Sheep;" likely it is channel no. 44. At the time of its drilling program in the Monument Valley area, the U. S. Atomic Energy Commission named the area "Cold Mesa."

The Koley Black area at latitude  $36^\circ 48' 42''$  N., and longitude  $110^\circ 09' 18''$  W., is in Navajo County, Ariz., about 3 miles southeast of Agathla Peak and a similar distance due north of the Porras dikes (fig. 2).

The area is about 8 miles northeast of Kayenta, Ariz. Consolidated sedimentary strata exposed in the Koley Black area range from the DeChelly sandstone member of the Cutler formation, under the valley floors, to the Shinarump member of the Chinle formation, which forms the general upland surface. The Shinarump member in this area is about 25 feet thick, although it thickens to 45 feet or more as a result of channeling. In places on the upland surface the Shinarump member thins laterally as a result of erosion; in these localities the underlying Moenkopi formation forms the surface.

The ground surface is veneered by a thin mantle of sand that thickens locally to 5 feet or slightly more. In places, irregular hummocks of the Shinarump member rise 20 to 30 feet above the general ground surface.

The area is on the south flank of the Agathla anticline, and the strata dip about  $5^{\circ}$  to the south.

A maze of channels is exposed in this area (fig. 19). They range in width from channels 35 feet wide to others that exceed 250 feet in width. The major geologic problem, as shown in figure 19, has been to relate the 4 channels noted in the southeast part of the area to the 7 channels in the northwest part. Data on the channels are given in table 3. Their orientation and spatial distribution are shown on figure 14. All of the channels strike northwest, and this suggests that they may be part of the same channel network. In general, the larger channels are in the southeast part of the area, and it appears probable that one or more of these larger ones may have branched to form the smaller channels.

Sediments filling the channels are coarse conglomerate beds near the base which grade upward into conglomeratic sandstone and coarse-grained sandstone beds near the top. Silicified wood is buried in channel

sediments as fragments and as logs as much as 2 feet in diameter. Also included are small pod-shaped masses of a black coaly substance (vitrain?) surrounded by conglomeratic sandstone. Limonite stains the surface of the channel sediments but does not appear to have penetrated the sandstone.

The Koley Black channels are underlain by a green to light-gray altered zone about 1 foot thick in the uppermost Moenkopi siltstone beds. The altered zone thickens slightly below the channels.

Four of the Koley Black group of channels contain small amounts of copper in basal channel sediments (table 3). No abnormal radioactivity was noted in a ground check by U. S. Geological Survey personnel, although the airborne radioactivity survey conducted by the U. S. Atomic Energy Commission reported two anomalies (i.e., "Sheep" and "Cold") over the Koley Black area (Cummings, 1952). These anomalies were then checked by U. S. Atomic Energy Commission ground personnel; their results were negative.

A diamond-drilling program was completed in April 1952, by the U. S. Atomic Energy Commission across the largest of the channels in the area (fig. 19, channel no. 45, and fig. 38). Seventeen holes were drilled directly behind the outcrop; no mineralized ground was found.

A geophysical program was undertaken, under the supervision of W. E. Davis, by Rudolph A. Black and Wayne H. Jackson of the U. S. Geological Survey. Field work was completed in July 1952, and the interpretations of the geophysical investigation substantiate several of the geologic interpretations made concerning channels. The concave upward end of channel no. 45 (fig. 19B) indicates that some channels are not continuous (p. 135). On the basis of the resistivity work channel no. 45





Figure 38.--Photo looking north at the Koley Black channel (no. 45). Men at the base give scale. The channel is about 270 feet wide and has been cut about 30 feet into the underlying Moenkopi formation.  $R_m$  - Moenkopi formation;  $R_{cs}$  - Shinarump member of the Chinle formation.



appears to end 350 feet behind the face of the outcrop. The habit of a major channel to divide into subsidiary channels (p. 139) seems well confirmed by the resistivity interpretations of channel nos. 38, 39, and 40 (fig. 19B). The existence of deeper scours in the floors of channels (p. 141) is also confirmed as shown by the elongate scour in the main channel southeast of channel nos. 38, 39, and 40.

Two geophysical techniques were used; one involved electrical resistivity measurements; the other, gravity measurements. Details on techniques used and the results obtained have been reported by Black and Jackson (1954). The interpretations (fig. 19B) are based on the resistivity data.

The following minerals have been identified from samples of basal channel sediments collected in the Koley Black area:

Azurite	$\text{Cu}_3(\text{OH})_2(\text{CO}_3)_2$	Rare
Calcite	$\text{CaCO}_3$	Common
Jarosite	$\text{K}_2\text{Fe}_6(\text{OH})_{12}(\text{SO}_4)_4$	Common
Limonite	$2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$	Common
Malachite	$\text{Cu}(\text{OH})_2(\text{CO}_3)$	Rare
Manganese (in dendrites)		Rare to common
Muscovite	$(\text{H},\text{K})\text{AlSi}_3\text{O}_{10}$	Rare

#### Alfred Miles channel No. 1

The Alfred Miles channel No. 1 (figs. 14 and 39 and table 3), among the largest noted, can be traced for about 4 miles in Arizona and Utah. The channel is intersected by deep canyons and broken into segments; channel sediments crop out in several localities (fig. 39) and it is on these exposures that claims have been staked by various prospectors.



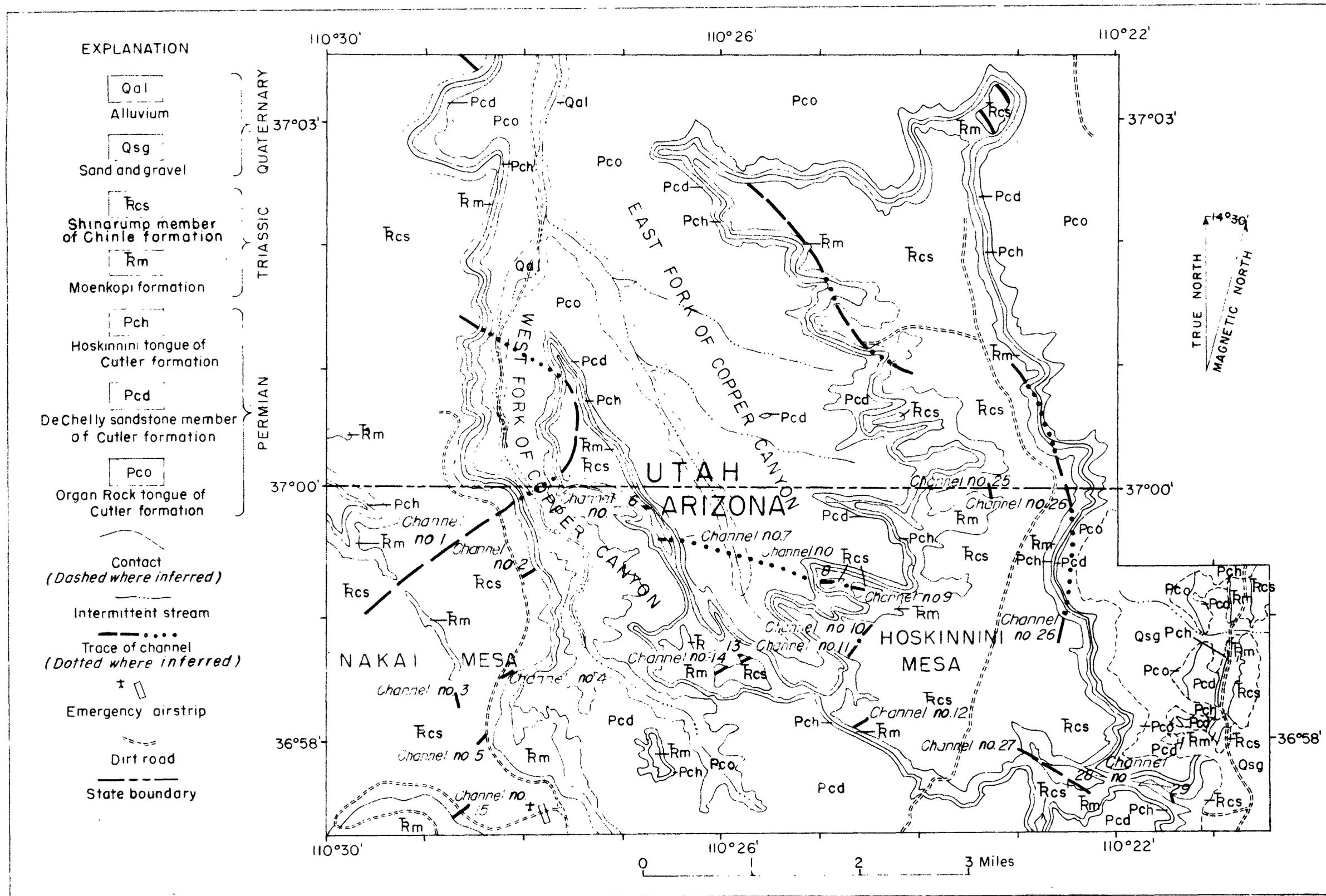


FIGURE 39.—GEOLOGIC MAP OF THE SOUTH END OF THE COPPER CANYON AREA SHOWING DISTRIBUTION OF CHANNELS ON PARTS OF NAKAI AND HOSKINNINI MESAS. DATA FOR NUMBERED CHANNELS ARE GIVEN IN TABLE 9. CHANNELS NOS. 27 AND 28 ARE KNOWN AS THE "CHANNELS AT SOUTHEAST EDGE OF HOSKINNINI MESA." THE LOCATION OF THE CHANNELS IN UTAH WERE DETERMINED BY RICHARD Q. LEWIS, SR., AND DONALD E. TRIMBLE, U.S. GEOLOGICAL SURVEY.



The channel is known by several names; among them are the Todechenee channel, the Nakai Mesa channel (Gregg, 1952), the Peninsula channel, and the Alfred Miles channel.

The part of the channel within Arizona is in Navajo County, at latitude  $36^{\circ} 59' 48''$  N. and longitude  $110^{\circ} 28' 6''$  W. Water and supplies are remote. The channel remnants on both the Arizona and Utah parts of Nakai Mesa are accessible by a graded dirt road. Parts of the channel are on a narrow projection of Hoskinnini Mesa, however, and these can be reached by a pack trail that extends along the projection from the southwest edge of Hoskinnini Mesa (fig. 39). Another route to these channel exposures makes use of the floor of Copper Canyon. An ungraded dirt road extends westward from the Oljeto Trading Post, Utah (fig. 1), and ends at the base of the steep slopes that underlie the channel remnants on the projection.

Consolidated sedimentary strata exposed in the Alfred Miles channel No. 1 area range from the Organ Rock tongue of the Cutler formation at the base of the Mesa to the Shinarump member of the Chinle formation which forms the canyon rims. About 90 feet of the Shinarump member is exposed, and it commonly stands as a vertical cliff. Where there are channels, the Shinarump member thickens to 120 feet or more.

On Nakai Mesa the Shinarump member is covered by dune sand that ranges in thickness from a thin film along mesa edges to 15 feet back from the rim. There is practically no sand cover on the projection of Hoskinnini Mesa, and the surface of the Shinarump member is pitted with depressions as much as 20 feet wide and 5 feet deep and marked by irregular hummocks that rise about 20 feet above the general ground surface.

The Alfred Miles channel No. 1 describes a broad curve (fig. 29). In Arizona its trend is about N. 50° E., but as it is traced northeastward it curves and where it re-enters Utah, its trend is to the northwest. The channel is about 2,150 feet wide, (fig. 16 and 40) and has been cut about 70 feet into the Moenkopi formation. Channel sediments consist predominantly of massive uniform-textured, coarse-grained sandstone that forms cliffs. A few small conglomerate lenses are in the basal sediments. Claystone boulders, cobbles, and pebbles make up the coarse material. These fragments range in size from small rounded chips about a quarter of an inch in diameter to angular boulders as much as 5 feet in long dimension. In places where the clay fragments have weathered out, the sandstone matrix remains as a fretwork. Much of the clay has been derived from the Moenkopi formation. These fragments can be found in various stages of alteration, from those that are all red and show no alteration, to others that are totally altered and are grayish green. An altered zone, in the uppermost strata of the Moenkopi formation below the channel, ranges in thickness from 2 to 8 inches. This is one of the few channels noted in the Monument Valley area, Arizona, where the altered zone did not thicken under a channel.

A series of anomalies were discovered during an airborne radioactivity survey conducted by the U. S. Atomic Energy Commission (Cummings, 1952). Despite the anomalies only sparse amounts of uranium minerals were found impregnating the channel sediments at one spot along the east face of Nakai Mesa (Fred Todechenee claim). Secondary copper minerals have been found at the base of several remnants of the Alfred



Figure 40.--Photo looking northeast across the West Ford of Copper Canyon showing broad deep Alfred Miles channel No. 1. Channel is about 2,150 feet wide and about 70 feet deep. Pco - Organ Rock tongue of the Cutler formation; Pcd - DeChelly sandstone member of the Cutler formation; Pch - Hoskinnini tongue of the Cutler formation; Rm - Moenkopi formation; and Rcs - Shinarump member of the Chinle formation.



Miles channel No. 1. Secondary copper minerals (azurite, malachite), that impregnate sandstone and replace wood, are along the base of the channel where it crops out on the projection of Hoskinnini Mesa. Similar occurrences have been noted at the channel outcrop on the east face of Nakai Mesa. In a few places copper minerals coat clay galls and, where the galls have been removed, the copper minerals remain on the walls of the molds so formed. Malachite was found also in the fractures and bedding planes of the siltstones and claystones in the altered zone of the Moenkopi formation directly underlying the mineralized localities.

During the summer and fall of 1952, the U. S. Atomic Energy Commission undertook a diamond-drilling program on Nakai Mesa (figs. 39 and 41). Thirty-nine holes were drilled, totalling about 5,600 feet. Only one hole penetrated mineralized ground. A short adit dug subsequently, to investigate the type and degree of mineralized rock found by this one drill hole, penetrated what "appeared to be a halo surrounding a fossil log" (written communication, Grand Junction Exploration Branch of the U. S. Atomic Energy Commission for October 1952). An area extending about 3,100 feet back from the rim was investigated by two rows of drill holes behind the outcrop. No attempt was made to drill along the length of the channel.

Discussing the geology of the mineralized deposits found along the base of this channel, (Gregg 1952) states: "Mineralization occurs in the bottom of channels, usually on one side and generally in a roll or gouge where logs and organic trash collect. Generally mineralization is directly above a muddy Moenkopi siltstone, the upper layers of which may



110° 28' 30"

## EXPLANATION

- 5763  
U.S. Atomic Energy Commission drill hole
- x 5733  
U.S. Bureau of Reclamation geophone station
-  Escarpment
- 5750  
Contour line  
Base of Shinarump  
member of Chinle formation
- Approximate centerline of channel

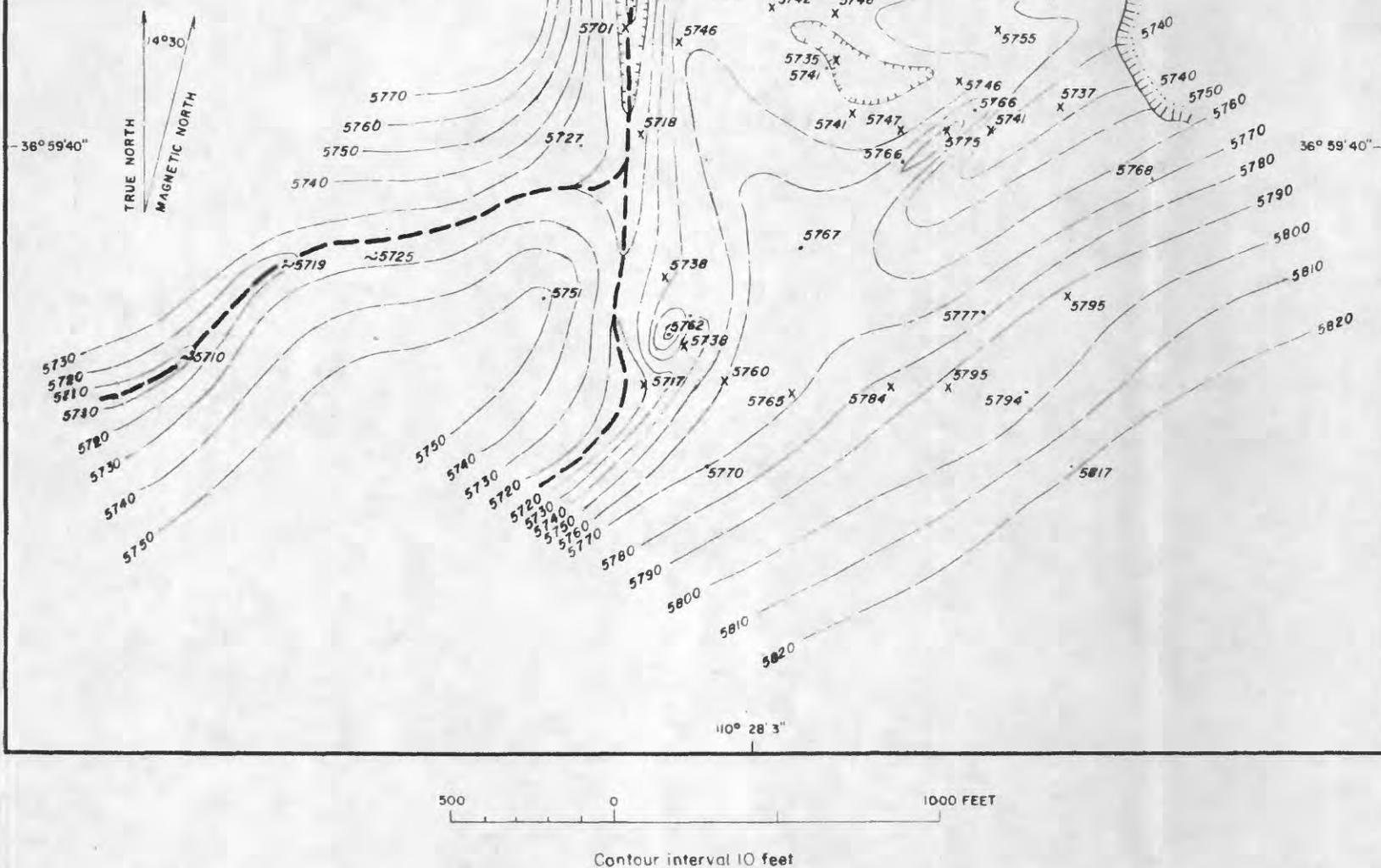
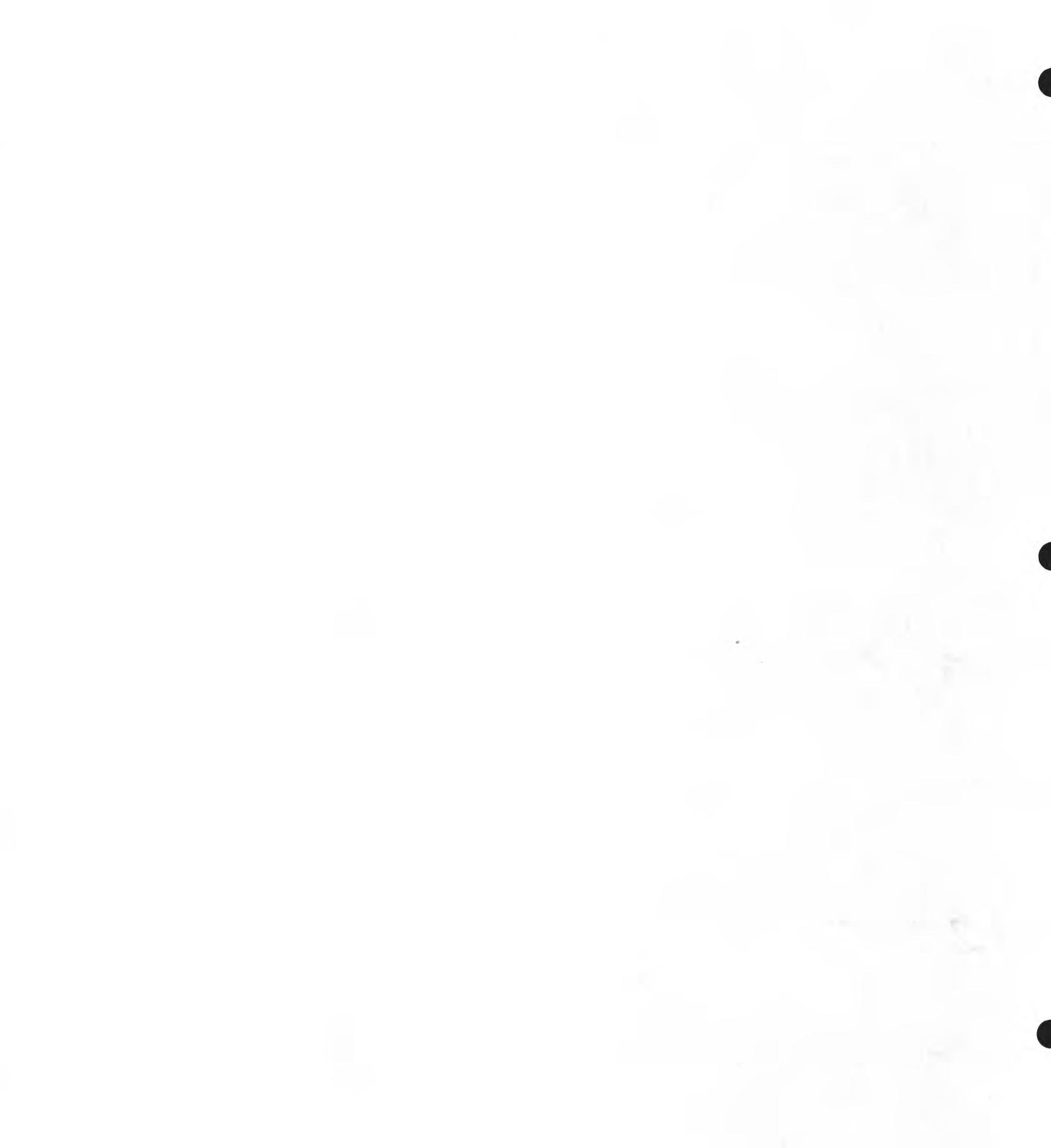


FIGURE 41.--POSSIBLE TREND OF THE ALFRED MILES CHANNEL NO. 1 BASED ON SEISMIC REFRACTION AND DRILLING DATA SUPPLIED BY DART WANTLUND, U.S. BUREAU OF RECLAMATION. DRILL-HOLE DATA FROM U.S. ATOMIC ENERGY COMMISSION DRILLING PROGRAM ON NAKAI MESA (C. CLARE GREGG, WRITTEN COMMUNICATION, 1952). CONTOURS ON THE BASE OF THE SHINARUMP MEMBER OF THE CHINLE FORMATION.



be also mineralized. The important associations seem to be carbon in the form of logs of wood trash; and copper, usually as malachite, although many outcrops revealing the characteristic color of copper mineralization contain no uranium."

During August and September 1952, the U. S. Bureau of Reclamation undertook, on behalf of the U. S. Atomic Energy Commission, a seismic survey of that part of Nakai Mesa underlain by the Alfred Miles channel No. 1. Results are shown in figure 41. Complete details on results obtained and methods used are contained in an unpublished report by the U. S. Bureau of Reclamation (Dart Wantlund and R. D. Casey, 1952). In essence, the survey indicated that the channel bifurcated with a smaller part extending almost due west, and the major part of the channel curving sinuously to the southwest. Additional holes were drilled upon completion of the seismic survey to corroborate the findings. Mineralized ground was not penetrated in these drill holes.

The suite of minerals identified from the basal channel sediments filling the Alfred Miles channel No. 1 is characteristic of mineralized outcrops in the Monument Valley area, Arizona.

Autunite(?)	$\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 10-12\text{H}_2\text{O}$	Rare
Azurite	$\text{Cu}_3(\text{OH})_2(\text{CO}_3)_2$	Rare
Calcite	$\text{CaCO}_3$	Common
Carnotite(?)	$\text{K}_2(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 3\text{H}_2\text{O}$	Rare
Jarosite	$\text{K}_2\text{Fe}_6(\text{OH})_{12}(\text{SO}_4)_4$	Common
Limonite	$2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$	Common
Malachite	$\text{Cu}_2(\text{OH})_2\text{CO}_3$	Rare
Torbernite	$\text{Cu}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 12\text{H}_2\text{O}$	Rare

Cecil Todechenee channel

At one locality, along the base of the east flank of Skeleton Mesa (fig. 2), a small remnant of the Shinarump member of the Chinle formation is exposed in a deep re-entrant. At the base of this remnant is a longitudinal exposure of mineralized sediments that forms the south flank of the Cecil Todechenee channel (fig. 14 and table 3, channel no. 21). A small adit has been opened about 20 feet into the base of the channel. As far as is known, ore has not been shipped from this channel.

The Cecil Todechenee channel is in Navajo County, Ariz., at latitude  $36^{\circ} 53' 24''$  N. and longitude  $110^{\circ} 24' 48''$  W. A graded dirt road passes within 500 yards of the claim. This road extends west from Navajo Indian Reservation Route No. 1 (Kayenta-Mexican Hat road) and follows Adahchijiyahi Canyon onto Todechenee bench where it turns north, passes the Todechenee claim, and ascends Hoskinnini Mesa (fig. 2). A short connecting road could be bulldozed to the claim site with little expense.

Consolidated sedimentary strata exposed near the claim range from the DeChelly sandstone member of the Cutler formation to the Navajo sandstone. These strata form the gently dipping west flank of the asymmetrical Organ Rock anticline (p. 127); strata exposed at the claim dip about  $3^{\circ}$  to the west.

Although only a part of the south flank of the channel is exposed, it is estimated that the channel trends about east, is about 100 feet wide, and has been cut about 20 feet into the Moenkopi formation. The Shinarump member is about 40 feet thick. Channel sediments consist predominantly of a cream-colored coarse-grained sandstone, speckled with small limonite stains.

In the mineralized zone the channel sediments are conglomeratic and enclose gray claystone fragments and considerable quantities of silicified and carbonized wood. The largest zone of high radioactivity conforms to what apparently is a log 6 to 8 inches in diameter and about 6 feet long. Another spot of high radioactivity does not seem to be related to plant matter.

A sample from a small ore pile assayed 0.23 percent  $U_3O_8$  (Gregg, 1952). A 3-foot channel sample assayed 0.02 percent  $U_3O_8$ , and 0.27 percent  $V_2O_5$ . Grab samples ran as high as 0.24 percent  $U_3O_8$  and 1.49 percent  $V_2O_5$  (Cutter and Leonard, 1952).

From samples of the channel sediments exposed at the Cecil Todechenee claim, the following minerals have been tentatively identified.

Calcite	$CaCO_3$	Common
Carnotite	$K_2(UO_2)_2(VO_4)_2 \cdot 1-3H_2O$	Rare
Corvusite(?)	$V_2O_4 \cdot 6V_2O_5 \cdot nH_2O$	Rare
Jarosite	$K_2Fe_6(OH)_{12}(SO_4)_4$	Common
Limonite	$2Fe_2O_3 \cdot 3H_2O$	Common
Malachite	$Cu_2(OH)_2CO_3$	Rare
Tyuyamunite	$Ca(UO_2)_2(VO_4)_2 \cdot nH_2O$	Rare

#### Channels at southeast edge of Hoskinnini Mesa

Channel nos. 27 and 28 of figures 14 and 39, and table 3 will be considered as a unit, for their general trend suggests that they are part of the same channel. Channel no. 27, known to geologists of the U. S. Atomic Energy Commission as Hoskinnini No. 1, is at latitude  $36^{\circ} 57' 48''$  N. and longitude  $110^{\circ} 22' 48''$  W. Channel no. 28, at latitude  $36^{\circ} 57' 30''$  N. and longitude  $110^{\circ} 22' 12''$  W., is known to U. S. Atomic Energy Commission geologists as Crescent (Cummings, 1952).

The channels crop out on the southeast edge of Hoskinnini Mesa, and are easily accessible from a graded dirt road on the mesa top. The road extends west from Navajo Indian Reservation Route No. 1 (Kayenta-Mexican Hat road), follows Adachijiyahi Canyon to Todicheenie bench, crosses Todicheenie and adjacent uplands, and finally ascends Hoskinnini Mesa.

Exposed consolidated sedimentary strata range from the Organ Rock tongue of the Cutler formation along the base of Hoskinnini Mesa, to the Shinarump member of the Chinle formation which forms the mesa cap. The Shinarump member, which overlies the Moenkopi formation, forms a vertical cliff about 50 feet high and is veneered by dune sand which ranges in thickness from a thin film to a cover more than 20 feet thick.

These strata form the asymmetrical Organ Rock anticline with its gently dipping west flank and steeply dipping east flank. The two channels crop out near the crest of the structure.

Channel no. 27 (Hoskinnini No. 1) strikes about N. 65° W., is about 250 feet wide, and has been cut about 75 feet into the Moenkopi formation. Channel sediments seem to be predominantly light-gray massive coarse-grained sandstone with small amounts of included silicified wood. A longitudinal section of the channel is exposed, but along much of its length the altered zone in uppermost strata of the Moenkopi formation is covered by debris or not exposed. No uranium minerals or abnormal radioactivity were noted.

Channel no. 28 (Crescent) strikes about N. 45° W., is about 150 feet wide, and has been cut about 50 feet into the Moenkopi formation. Channel sediments consist predominantly of light-gray crossbedded medium-grained sandstone with local lenses of conglomerate near the channel's base. Blue

and green secondary copper minerals (malachite and azurite) are scattered widely in the basal sediments, and limonite stains the outcrop and the joints. Radioactivity (0.05-MR per hour) is only slightly above background (0.03-MR per hour).

Anomalies were reported over these remnants by the U. S. Atomic Energy Commission's airborne radioactivity survey and were subsequently ground checked by U. S. Atomic Energy Commission personnel. Their findings were negative (Cummings, 1952).

The following minerals have been tentatively identified from samples collected at these channel outcrops.

Azurite(?)	$\text{Cu}_3(\text{OH})_2(\text{CO}_3)_2$	Rare
Calcite	$\text{CaCO}_3$	Common
Hematite	$\text{Fe}_2\text{O}_3$	Rare
Jarosite	$\text{K}_2\text{Fe}_6(\text{OH})_{12}(\text{SO}_4)_4$	Common
Limonite	$2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$	Common
Malachite	$\text{Cu}_2(\text{OH})_2\text{CO}_3$	Rare

#### OIL AND GAS POSSIBILITIES

Only two tests for oil and gas have been completed in the Monument Valley area, Apache and Navajo Counties, Ariz. (fig. 42 and table 6 index nos. 1 and 2), and in only one (index no. 2) was there any show of oil or gas, even though both penetrated strata (fig. 43) that produce in adjacent areas. Of the other tests completed near the Monument Valley area most have been unsuccessful, although a few in the nearby Mexican Hat field (once known as the San Juan oil field) produced small amounts of



.



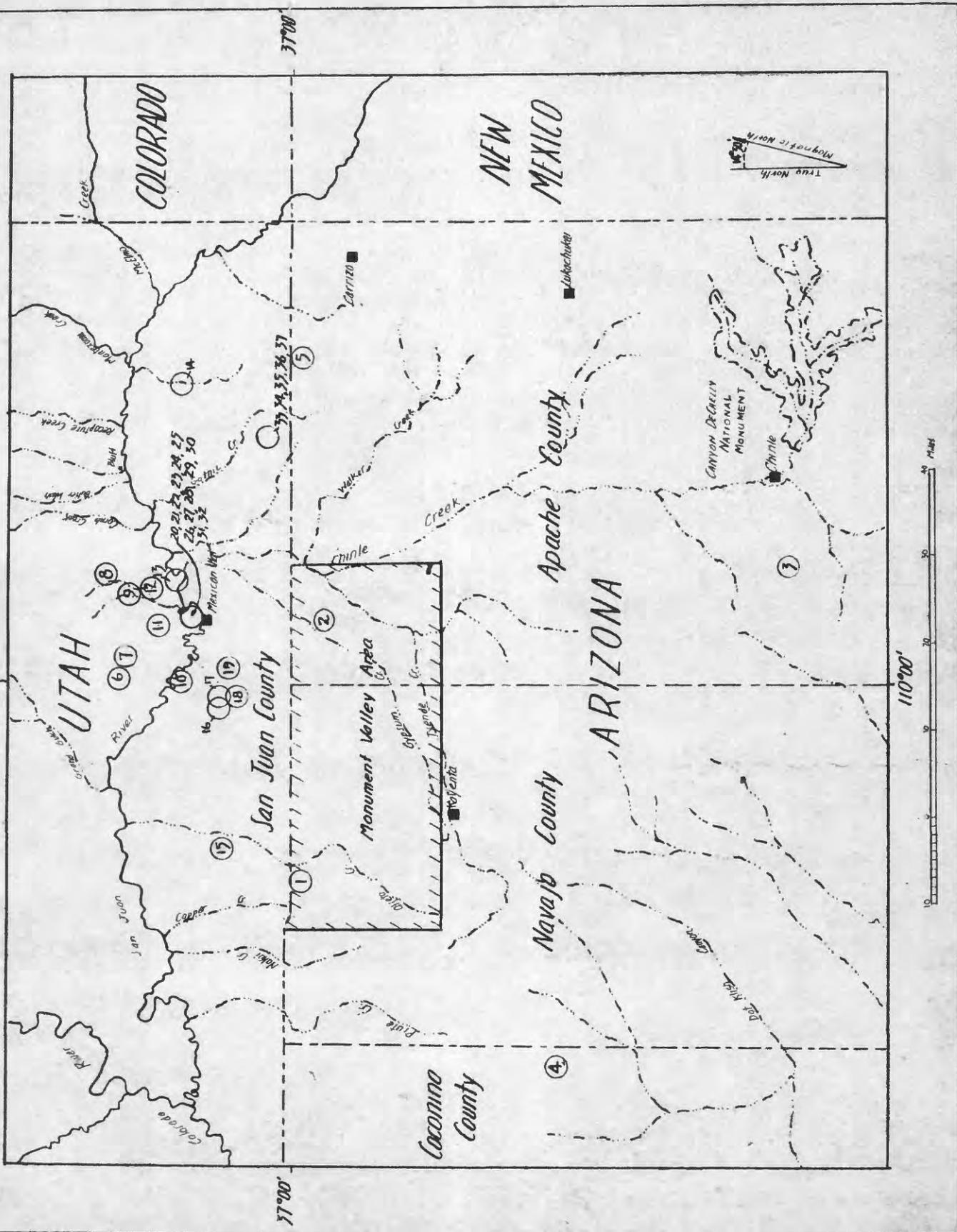


FIGURE 42.--LOCATION OF TEST WELLS DRILLED IN AND ADJACENT TO THE MONUMENT VALLEY AREA, APACHE AND NAVAJO COUNTIES, ARIZ.



oil before 1930. After 1930, interest in the commercial oil and gas possibilities of the area waned and drilling ceased. In 1948, interest in northeastern Arizona and southeastern Utah revived and several oil companies began to test promising structures. In 1954, the Shell Oil Company completed two successful tests about 50 miles to the northeast.

Although oil seeps have been known in this general region since 1882 (Woodruff, 1910, p. 98), oil in commercial quantities was first produced from the Mexican Hat oil field in 1908. Since then about 115 wells have been drilled in the field; of these only a few were successful and the more significant ones have been listed on table 6. Production was principally from the Hermosa formation (Pennsylvanian) with minor oil and gas from the Rico formation (Pennsylvanian and Permian?). The field has been described previously by Woodruff (1910), Baker (1936), and Hansen and Bell (1949). The nearest active field is the Boundary Butte field in San Juan County, Utah (T. 43 S., R. 22 E.), about 35 to 40 miles to the northeast. Here, production of both oil and gas is from the Coconino sandstone (the age equivalent of the DeChelly sandstone of the Cutler formation) in an elongate northwest-trending anticline on the southwest flank of the Paradox Basin.

In the Mexican Hat oil field, most of the first wells drilled were extremely shallow and were intended to test the Rico and Hermosa formations. Subsequently deeper tests were completed, and it was soon determined that in places the sedimentary rocks were as thin as 2,000 feet. In the course of drilling oil and gas shows were found at several horizons, although major production was either from the Rico or Hermosa

formations. The oil was in a structural syncline and production was hampered by low porosity in the lenticular sandstone beds and by low hydrostatic pressure (Hansen and Bell, 1949, p. 198).

Of the wildcat tests completed near the Monument Valley area only the two Shell tests were successful. The first of these, Shell's test No. 2, East Boundary Butte is in sec. 3, T. 41 N., R. 28 E., Apache County, Ariz., and was completed as a gas producer (table 6). The second well, Shell's No. 2 Desert Creek is in sec. 35, T. 41 S., R. 23 E., San Juan County, Utah, and was completed as an oil well. Both wells produced from the Hermosa formation.

The most recent test in the Monument Valley area was in sec. 34, T. 42 N., R. 18 E., Navajo County, Ariz., (unsurveyed) on the crest of the Organ Rock anticline (fig. 2). The test, known as Navajo A-1, was a joint venture by the Texas, Sinclair, and Skelly Oil Companies and penetrated 4,523 feet to the Elbert formation (late Devonian) before it was abandoned as a dry hole (table 6). There were no shows of oil or gas. The log of the hole is published here in full by courtesy of these oil companies.

Sample description of the Texas, Sinclair, and Skelly Oil Companies' well, Navajo A-1, sec. 34, T. 42 N., R. 18 E., Navajo County, Ariz.

## MESOZOIC ERA

### TRIASSIC PERIOD

<u>Shinarump formation</u>	0-93	(93 feet)
0-50 (50)	Sandstone, white, medium-coarse grained	
50-93 (43)	Sandstone, white, medium-coarse grained, with some light-gray shale stringers, conglomeratic at base. Some milky and amber chert.	

MESOZOIC ERA--ContinuedTRIASSIC PERIOD--Continued

Moenkopi formation 93-263 feet (170 feet)

93-190 (97) Shale, brown-maroon.

190-212 (22) Siltstone, buff, slightly limy.

212-263 (51) Shale, brown, slightly sandy.

PALEOZOIC ERAPERMIAN PERIOD

Cutler formation 263-2207 feet (1944 feet)

Hoskinnini member 263-336 feet (73 feet)

263-290 (33) Sandstone, red-white, very fine grained,  
slightly limy.

290-300 (10) Shale, brown, sandy.

300-326 (26) Siltstone, red-brown, slightly limy and  
conglomeratic.

326-336 (10) Shale, brown, sandy.

DeChelly member 336-697 feet (361 feet)

336-360 (24) Sandstone, red-tan, fine-grained, limy,  
trace of milky chert.

360-410 (50) Sandstone, red-tan, fine-medium grained,  
slightly conglomeratic.

410-490 (80) Sandstone, pink, medium-grained, slightly  
conglomeratic and limy.

490-500 (10) Shale, brown.

500-697 (197) Sandstone, pink-tan, medium- to coarse-  
grained, slightly conglomeratic and limy.

PALEOZOIC ERA--ContinuedPERMIAN PERIOD--ContinuedCutler formation-Continued

<u>Organ Rock member</u>	697-1325 feet	(628 feet)
697-910 (213)	Shale, red, hard, sandy, micaceous.	
910-930 (20)	Sandstone, white, medium-grained.	
930-1325 (395)	Shale, red, very sandy, slightly limy.	
<u>Cedar Mesa member</u>	1325-1835 feet	(519 feet)
1325-1400 (75)	Sandstone, pink-white, very fine grained, limy.	
1400-1480 (80)	Sandstone, light-gray to white, very fine grained, limy.	
1480-1650 (170)	Sandstone, orange-pink, very fine to fine-grained, some free quartz grains, hard-friable, limy, with some red shale stringers.	
1650-60 (10)	Shale, red, sandy, limy.	
1660-1750 (90)	Sandstone, orange-gray, fine-grained, limy, with some red and green shale stringers.	
1750-80 (30)	Shale, red, micaceous, limy.	
1780-1835 (55)	Sandstone, orange, very fine grained, limy, with red shale stringers.	
<u>Halgaito member</u>	1835-2207	(372 feet)
1835-2130 (295)	Shale, red, limy, interbedded with some gray limestone and pink-gray sandstone. Traces of green shale.	

PALEOZOIC ERA--ContinuedPERMIAN PERIOD--ContinuedCutler formation --ContinuedHalgaito member --Continued

2130-2207 (77) Shale, red-brown, limy, sandy, with some stringers of red and gray limestone.

Rico formation 2207-2785 feet (578 feet)

- 2207-2310 (103) Sandstone, white-pink, fine-grained, limy, interbedded with some red and brown shale and gray limestone.
- 2310-60 (50) Shale, red, sandy, limy, with some limestone and sandstone stringers.
- 2360-80 (20) Sandstone, white-pink, fine-grained, limy.
- 2380-2490 (110) Shale, red, limy, sandy, with some stringers of limestone.
- 2490-2555 (65) Limestone, gray-green, fine-crystalline, sandy, with some red shale stringers.
- 2555-2590 (35) Sandstone, white to gray, medium-grained, limy, hard to friable.
- 2590-2600 (10) Shale, red, sandy.
- 2600-10 (10) Shale, purple, sandy, micaceous.
- 2610-40 (30) Limestone, white to light-gray, fine- to medium-crystalline, slightly oolitic.
- 2640-60 (20) Sandstone, white, fine-grained, friable.
- 2660-70 (10) Shale, red, limy, sandy.
- 2670-2700 (30) Limestone, tan to light-gray, fine crystalline dense, slightly sandy.

PALEOZOIC ERA--ContinuedPERMIAN PERIOD--ContinuedRico formation--Continued

- 2700-10 (10) Shale, red, limy.
- 2710-60 (50) Sandstone, white, fine- to medium-grained.
- 2760-70 (10) Shale, red, interbedded with red-gray limestone and white sandstone.
- 2770-85 (15) Sandstone, purple-gray, limy.

PENNSYLVANIANHermosa formation

2785-3488 feet (703 feet)

- 2785-95 (10) Limestone, light-gray to gray, dense, sandy.
- 2795-2820 (25) Sandstone, white to light-gray, fine-medium grained, limy, interbedded with red shale and some gray chert.
- 2820-2980 (60) Limestone, light- to dark-gray, dense, siliceous, interbedded with amber, gray, and milky chert, and gray sandstone.
- 2980-3225 (45) Limestone, white to light-gray, fine crystalline to dense, sandy, interbedded with amber and milky chert, and red and brown shale.
- 3225-3280 (55) Limestone, gray-brown, medium crystalline, slightly oölitic, some honeycombed, interbedded with amber chert and gray sandstone.
- 3280-3450 (30) Limestone, white to light-gray, medium to fine crystalline, some honeycombed and chalky, interbedded with amber chert, gray sandstone, and some calcite.

PENNSYLVANIAN--ContinuedHermosa formation--Continued

3450-3488 (38) Limestone, white to light-gray, dense, with some amber chert.

Molas formation 3488-3585 feet (97 feet)

3488-3515 (27) Limestone, light-gray, dense, interbedded with amber chert and green shale.

3515-50 (35) Shale, green and purple, interbedded with some light-gray limestone, and amber chert.

3550-80 (30) Shale, red-maroon.

3580-85 (5) Shale, purple.

MISSISSIPPIANMolas formation--Continued 3585-4077 feet (492 feet)

3585-3670 (85) Limestone, white, chalky, with some amber chert, and red-purple shale.

3670-3740 (70) Limestone, light-gray to white, fine crystalline to chalky, oölitic, with some gray dolomite and milky chert.

3740-3820 (80) Dolomite, tan to dark-gray, fine crystalline to sucrose, with some limestone and calcite.

3820-3855 (35) Limestone, dolomitic, white, coarse to crystalline.

3855-3900 (45) Dolomitic, white to light-gray, fine crystalline to sucrose with some white and amber chert, interbedded with light-gray limestone.

MISSISSIPPIAN--ContinuedMolas formation--Continued

3900-4077 (177) Dolomite, white to gray, fine crystalline to  
sucrose, interbedded with chalky limestone.

DEVONIAN 4077-? (Drilled 446 feet)

Upper Devonian

4077-4192 (115) Limestone, white to light-gray, fine crystalline  
to dense, some chalky, interbedded with red,  
purple, and green shale.

(Lower Devonian) Elbert 4192-? (Drilled 331 feet)

4192-4260 (68) Dolomite, tan to gray, coarse crystalline to  
dense, with some milky chert, interbedded with  
red and green shale.

4260-75 (15) Shale, purple, limy, with some gray dolomite.

4275-4370 (95) Dolomite, gray to dark-gray, coarse crystalline  
to dense, with some milky and amber chert, and  
traces of green shale.

4370-4425 (55) Dolomite, dark-gray to black, coarse crystalline,  
interbedded with gray sandstone.

4425-40 (15) Sandstone, white to light-gray, fine grained,  
glauconitic.

4440-75 (35) Dolomite, tan to gray to black, fine to medium  
crystalline, slightly sandy, with some thin  
gray sandstone and red shale stringers.

4475-95 (20) Sandstone, red, fine-grained, arkose, slightly  
limy.

DEVONIAN--Continued(Lower Devonian)--Continued

4495-4523 (28) Dolomite, tan to gray to black, fine to medium crystalline, dense, slightly siliceous, with some interbedded amber and milky chert, and light-gray limestone.

Total depth 4523 feet in Elbert formation

The other test in this area is in sec. 7, T. 41 N., R. 23 E., Apache County, Ariz., (unsurveyed) and was completed in 1924, on the crest of the Gypsum Creek dome (fig. 2). The well, known as the Midwest 1 Gypsum, was drilled by the San Juan Oil and Development Company to a depth of 2,083 feet. It started in the Halgaito tongue of the Cutler formation and was bottomed in the Elbert formation. It was abandoned as a dry hole.

The depth to <sup>crystalline</sup> rocks over most of the Monument Valley area (fig. 43) probably does not exceed 6,000 feet, and many parts of the area can be tested by relatively shallow drilling. The area seems to be in a favorable structural location, for its major part is astride the southern end of the Monument upwarp; its east edge is on the southwest flank of the Paradox Basin; and its south edge abuts the north rim of the Black Mesa Basin. Although the sedimentary cover is thin, the rocks thicken rapidly to the northeast, south, and west. Favorable host rocks for oil and gas accumulations include strata of Hermosa and Rico, as well as Devonian and Cambrian age.

Although possible oil-bearing strata underlie the area, uncertainty exists as to which type structures are favorable. Many of the tests in this part of Utah and Arizona have been on the crests of local structures.

As most were dry holes, it has been suggested (Baker, 1936, p. 98) that the troughs of the syncline, rather than the anticlinal crests, are favorable sites for oil accumulation. Baker notes that current theories of oil migration suggest that oil will migrate to the crests of anticlines if water is abundant in the reservoir rocks. Conversely, a lack of water will result in the oil moving to the synclinal troughs. This is well-demonstrated in the Mexican Hat oil field. Despite this viewpoint most of the recent tests, including the successful Shell tests, were on anticlinal crests.

As yet there has not been sufficient exploratory work in this general area to warrant a specific statement on this problem. Many of the wells drilled on the crests of anticlines were either dry holes or encountered water or gas. However, as the area was deformed in Tertiary time, it seems likely that the original oil accumulations have been either displaced or dispersed. As yet, no thorough test has been completed on structural terraces, stratigraphic traps (such as the reef limestone at the base of the Hermosa; Wengerd, 1951), or near faults to appraise these features as possible oil reservoirs. Until more drilling has been done, a conclusive answer cannot be given as to the potentialities of the area for oil and gas.

The favorable location of the area in terms of regional structure, the presence of oil-bearing strata, and the many possible oil traps, all suggest that the Monument Valley area is a likely site for oil and gas accumulations in the concealed Paleozoic rocks. If nothing else, the success of the two Shell wells re-emphasizes the promising oil and gas possibilities of this sector of the Four Corners area.

SELECTED BIBLIOGRAPHY

- Allen, J. E., and Balk, Robert, 1954, Mineral resources of Fort Defiance and Tohatchi quadrangles, Arizona and New Mexico: N. Mex. Bur. Mines and Mineral Res. Bull. 36, 192 p.
- Allen, V. T., 1930, Triassic bentonite of the Painted Desert: Am. Jour. Sci. 5th ser., v. 19, p. 283-288.
- Baker, A. A., 1933, Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, 95 p.
- \_\_\_\_\_, 1936, Geology of the Monument Valley-Navajo Mountain region, San Juan County, Utah: U. S. Geol. Survey Bull. 865, 106 p.
- \_\_\_\_\_, 1946, Geology of the Green River Desert-Cataract Canyon region, Emery, Wayne, and Garfield Counties, Utah: U. S. Geol. Survey Bull. 951, 122 p.
- Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., 1936, Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183, 66 p.
- Baker, A. A., Dobbin, C. E., McKnight, E. T., and Reeside, J. B., Jr., 1927, Notes on the stratigraphy of the Moab region, Utah: Am. Assoc. Petroleum Geologists Bull., v. 11, p. 785-808.
- Baker, A. A., and Reeside, J. B., Jr., 1929, Correlation of the Permian of southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado: Am. Assoc. Petroleum Geologists Bull., v. 13, p. 1413-1448.
- Balk, Robert, 1954, Kimberlitic tuff plugs in northeastern Arizona: Am. Geophys. Union Trans., v. 35, p. 381.

- Bryan, Kirk, 1920, Origin of rock tanks and charcos: Am. Jour. Sci., 4th ser., v. 50, p. 188-206.
- Callahan, J. T., 1951, The geology of the Glen Canyon group along the Echo Cliffs, Arizona: Plateau, v. 23, p. 49-57.
- Camp, C. L., 1930, A study of the phytosaurs with description of new material from western North America: Calif. Univ. Mem., v. 10, 174 p.
- \_\_\_\_\_, 1936, A new type of small bipedal dinosaur from the Navajo sandstone of Arizona: Calif. Univ. Dept. Geol. Sci. Bull., v. 24, p. 39-55.
- Camp, C. L., Colbert, E. H., McKee, E. D., and Welles, S. P., 1947, A guide to the continental Triassic of northern Arizona: Plateau, v. 20, 9 p.
- Camp, C. L., and VanderHoff, V. L., 1935, Small bipedal dinosaur from the Jurassic of northern Arizona (abs.): Geol. Soc. America Proc. 1934, p. 384-385.
- Chester, J. W., 1951, Geology and mineralization of Hunt's Mesa, Monument Valley, Arizona: U. S. Atomic Energy Comm. RMO-801, 9 p., issued by U. S. Atomic Energy Comm. Tech. Inf. Service Extension, Oak Ridge, Tenn.
- Coffin, R. C., 1921, Radium, uranium, and vanadium deposits of southwestern Colorado: Colorado Geol. Survey Bull. 16, 231 p.
- Craig, L. C., Holmes, C. N., Cadigan, R. A., Freeman, V. L., Mullens, T. E., and Weir, G. W., 1955, Stratigraphy of the Morrison and related formations, Colorado Plateau region, a preliminary report: U. S. Geol. Survey Bull. 1009-E, p. 125-168.

- Daugherty, L. H., 1941, The Upper Triassic flora of Arizona, with a discussion of its geologic occurrence by H. R. Stagner: Carnegie Inst. Washington Pub. 526, Contr. Paleontology, 108 p.
- Dorn, C. L., 1949, Developments [in oil and gas] in Rocky Mountain region in 1948: Am. Assoc. Petroleum Geologists Bull., v. 33, p. 827-836.
- Dutton, C. E., 1880, Report on the geology of the high plateaus of Utah: U. S. Geol. and Geog. Survey Rocky Mtn. Region, 307 p.
- Finch, W. I., 1953, Geologic aspects of the resource appraisal of uranium deposits in the pre-Morrison formations of the Colorado Plateau, an interim report: U. S. Geol. Survey TEI-328A, 35 p., issued by U. S. Atomic Energy Comm. Tech. Inf. Service Extension, Oak Ridge.
- \_\_\_\_\_, in preparation, Geology of the uranium deposits in Triassic rocks of the Colorado Plateau: U. S. Geol. Survey Bull.
- Finnell, T. L., 1957, Structural control of uranium ore at the Monument No. 2 mine, Apache County, Arizona: Econ. Geology, v. 52, no. 1, p. 25-35.
- Fischer, R. P., 1947, Deposits of vanadium-bearing sandstone: Colorado Mineral Res. Board [Bull.], p. 451-456.
- Fischer, R. P., and Hilpert, L. S., 1952, Geology of the Uravan mineral belt: U. S. Geol. Survey Bull. 988-A, p. 1-13.
- Gilluly, James, 1929, Geology and oil and gas prospects of part of the San Rafael Swell, Utah: U. S. Geol. Survey Bull. 806, p. 69-130.
- Gregg, C. C., 1952, Reconnaissance and investigational drilling on Hoskinnini and Nakai Mesas, San Juan County, Utah, and Navajo County, Arizona: U. S. Atomic Energy Comm. RMO 987, 10 p. [Microcard copy on file in U. S. Atomic Energy Comm. depository libraries]

- Gregory, H. E., 1913, The Shinarump conglomerate: Am. Jour. Sci., 4th ser., v. 35, p. 424-438.
- \_\_\_\_\_, 1915, The igneous origin of the "glacial deposits" on the Navajo Reservation, Arizona and Utah: Am. Jour. Sci., 4th ser., v. 40, p. 97-115.
- \_\_\_\_\_, 1916, Garnet deposits on the Navajo Reservation, Arizona and Utah: Econ. Geology, v. 11, p. 223-230.
- \_\_\_\_\_, 1917, Geology of the Navajo country--a reconnaissance of parts of Arizona, New Mexico, and Utah: U. S. Geol. Survey Prof. Paper 93, 161 p.
- \_\_\_\_\_, 1938, The San Juan country, a geographic and geologic reconnaissance of southeastern Utah, with contributions by M. R. Thorpe and H. D. Miser: U. S. Geol. Survey Prof. Paper 188, 123 p.
- \_\_\_\_\_, 1950, Geology and geography of the Zion Park region, Utah and Arizona: U. S. Geol. Survey Prof. Paper 220, 200 p.
- Gregory, H. E., and Moore, R. C., 1931, The Kaiparowitz region, a geographic and geologic reconnaissance of parts of Utah and Arizona: U. S. Geol. Survey Prof. Paper 164, 161 p.
- Gruner, J. W., and Gardner, Lynn, 1952, Mineral associations in the uranium deposits of the Colorado Plateau and adjacent regions with special emphasis on those in the Shinarump formation; in Annual report for 1951-1952, Pt. 3: U. S. Atomic Energy Comm. RMO-566, 40 p., issued by U. S. Atomic Energy Comm. Tech. Inf. Service Extension, Oak Ridge, Tenn.
- Hack, J. T., 1942, The changing environment of the Hopi Indians of Arizona: Harvard Univ., Peabody Mus. Archeol. and Ethnologic Papers, v. 35, 85 p.

- Hager, Dorsey, 1954, Some notes on oil and gas developments in Utah, Nevada, and Arizona: Mines Mag., v. 44, no. 11, p. 79.
- Hansen, G. H., and Bell, M. M., 1949, The oil and gas possibilities of Utah: Utah Geol. and Mineralog. Survey, Salt Lake City, Utah, 341 p.
- Harshbarger, J. W., Repenning, C. A., and Jackson, R. L., 1951, Jurassic stratigraphy of the Navajo country, in N. Mex. Geol. Soc. Guidebook of the south and west sides of the San Juan Basin, New Mexico and Arizona: N. Mex. Geol. Soc., 2d Field Conf., p. 95-99.
- Huddle, J. W., and Dobrovolsky, Ernest, 1945, Late Paleozoic stratigraphy of central and northeastern Arizona: U. S. Geol. Survey Oil and Gas Inv. Prelim. Chart no. 10.
- Hunt, A. P., 1953, Archeological survey of the La Sal Mountain area, Utah: Univ. Utah Anthropological Papers. no. 14.
- Hunt, C. B., 1955, Recent geology of Cane Wash, Monument Valley, Arizona: Science, v. 122, p. 583-585.
- Hunt, C. B., assisted by Paul Averitt and R. L. Miller, 1953, Geology and geography of the Henry Mountains region, Utah: U. S. Geol. Survey Prof. Paper 228, 234 p.
- Imlay, R. W., 1948, Characteristic marine Jurassic fossils from the western interior of the United States: U. S. Geol. Survey Prof. Paper 214-B, p. 13-33.
- Longwell, C. R., Miser, H. D., Moore, R. C., Bryan, Kirk, and Paige, Sidney, 1923, Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, p. 1-23.
- Marble, J. P. (Chairman), 1950, Report of the Committee on the measurement of geologic time, 1949-50: Natl. Research Council, Div. Geology and Geography, 118 p.

- Mathews, E. B., 1917, Submerged "deeps" in the Susquehanna River:  
Geol. Soc. America Bull., v. 28, p. 335-346.
- McKee, E. D., 1934, An investigation of the light-colored cross-bedded sandstones of the Canyon DeChelly, Arizona: Am. Jour. Sci., 5th ser., v. 28, p. 219-233.
- \_\_\_\_\_, 1936, Triassic pebbles in northern Arizona containing invertebrate fossils: Am. Jour. Sci., 5th ser., v. 33, p. 260-263.
- \_\_\_\_\_, 1945, The Coconino sandstone--its history and origin: Carnegie Inst. Washington Pub. 440, p. 77-115.
- \_\_\_\_\_, 1951a, Triassic deposits of the Arizona-New Mexico border area, in Guidebook of the south and west sides of the San Juan Basin, New Mexico and Arizona: N. Mex. Geol. Soc., 2d Field Conf., p. 85-92.
- \_\_\_\_\_, 1951b, Sedimentary basins of Arizona and adjoining areas: Geol. Soc. America Bull., v. 62, p. 481-505.
- \_\_\_\_\_, 1954, Stratigraphy and history of the Moenkopi formation of Triassic age: Geol. Soc. America Mem. 61.
- McKee, E. D., Evenson, C. D., and Grundy, W. D., 1953, Studies in sedimentology of the Shinarump conglomerate of northeastern Arizona: U. S. Atomic Energy Comm. RME-3089, 48 p., issued by U. S. Atomic Energy Comm. Tech. Inf. Service Extension, Oak Ridge, Tenn.
- Miser, H. D., 1925, Geologic structure of San Juan Canyon and adjacent country, Utah: U. S. Geol. Survey Bull. 751D, p. 115-155.
- \_\_\_\_\_, 1924, The San Juan Canyon, southeastern Utah, a geographic and hydrographic reconnaissance: U. S. Geol. Survey Water-Supply Paper 538, 80 p.

- Newberry, J. S., 1861, Geological report, in Ives, J. C., Report upon the Colorado River of the West: U. S., 36th Cong., 1st sess., S. Doc.---- and H. Doc. 90, pt. 3, 154 p.
- Prommel, H. W. C., and Crum, H. E., 1927, Salt domes of Permian and Pennsylvanian age in southeastern Utah and their influence on oil accumulation: Am. Assoc. Petroleum Geologists Bull., v. 11, p. 373-393.
- Reeside, J. B., Jr., and Bassler, Harvey, 1922, Stratigraphic sections in southwestern Utah and northeastern Arizona: U. S. Geol. Survey Prof. Paper 129-D, p. 53-77.
- Shoemaker, E. M., 1953, Collapse origin of the diatremes of the Navajo-Hopi Reservation (abs.): Geol. Soc. America Bull., v. 64, p. 1514.
- Smith, C. T., 1951, Problems of Jurassic stratigraphy of the Colorado Plateau and adjoining regions, in Guidebook of the south and west sides of the San Juan Basin, New Mexico and Arizona: N. Mex. Geol. Soc., Field Conf., p. 99-102.
- Smith, J. F., Jr., Hinrichs, E. N., and Luedke, R. G., 1952, Progress report on geologic studies in the Capitol Reef area, Wayne County, Utah: U. S. Geol. Survey Trace Elements Inv. Rept. 203, 29 p., issued by U. S. Atomic Energy Comm. Tech. Inf. Service Extension, Oak Ridge, Tenn.
- Sterrett, D. B., 1909, Mineral Resources of the United States, 1908: U. S. Geol. Survey Pub., pt. 2, p. 823-828.
- Stewart, J. H., 1957, Proposed nomenclature of part of Upper Triassic strata in southeastern Utah: Am. Assoc. Petroleum Geologists Bull., v. 41, p. 441-465.

Stewart, J. H., Williams, G. A., Albee, H. F., and Raup, O. B., in preparation, Stratigraphy of Triassic and associated formations in part of the Colorado Plateau region, with a section on Sedimentary petrology by R. A. Cadigan: U. S. Geol. Survey Bull.

Stieff, L. R., and Stern, T. W., 1952a, Identification and lead-uranium ratio ages of massive uraninites from the Shinarump conglomerate, Utah: Science, v. 115, p. 706-708.

Stieff, L. R., and Stern, T. W., 1952b, and 1953, Lead-uranium ages of some uraninites from Triassic and Jurassic sedimentary rocks of the Colorado Plateau (abs.): Geol. Soc. America Bull., v. 63, p. 1299-1300; Am. Mineralogist, v. 38, nos. 3 and 4, p. 359-360.

Stieff, L. R., Stern, T. W., and Milkey, R. G., 1953, A preliminary determination of the age of some uranium ores of the Colorado Plateau by the lead-uranium method: U. S. Geol. Survey Circ. 271, 19 p.

Stokes, W. L., 1944, Morrison formation and related deposits in and adjacent to the Colorado Plateau: Geol. Soc. America Bull., v. 55, p. 951-992.

\_\_\_\_\_, 1950, Pediment concept applied to Shinarump and similar conglomerates: Geol. Soc. America Bull., v. 61, p. 91-98.

Umbach, P. H., and Barnes, F. C., 1952, Developments in Arizona, western New Mexico, and northern New Mexico in 1951: Am. Assoc. Petroleum Geologists Bull., v. 36, p. 1147-1156.

\_\_\_\_\_, 1953, Developments in Arizona, western New Mexico, and northern New Mexico in 1952: Am. Assoc. Petroleum Geologists Bull., v. 37, p. 1376-1383.

- Wantlund, Dart, and Casey, R. D., 1952, Field tests for the U. S. Atomic Energy Commission on the use of the seismic geophysical method for tracing "buried channels" in the Monument Valley area, Arizona: U. S. Bur. of Reclamation, Eng. Geology Br., Geol. Rept. G-123, 68 p.
- Waters, A. C., and Granger, H. C., 1953, Volcanic debris in uraniferous sandstones and its possible bearing on the origin and precipitation of uranium: U. S. Geol. Survey Circ. 224, 26 p.
- Weeks, A. D., and Thompson, M. E., 1954, Identification and occurrence of uranium and vanadium minerals from the Colorado Plateaus: U. S. Geol. Survey Bull. 1009-B, p. 13-62.
- Weeks, A. D., Thompson, M. E., and Sherwood, A. M., 1955, Navajoite, a new vanadium oxide from Arizona (abs.): Science, v. 119, p. 326; Am. Mineralogist, v. 40, p. 207-212.
- Wengerd, S. A., 1951, Reef limestones of Hermosa formation, San Juan Canyon, Utah: Am. Assoc. Petroleum Geologists Bull., v. 35, p. 1038-1051.
- Wengerd, S. A., and Strickland, J. W., 1954, Pennsylvanian stratigraphy of Paradox Salt Basin, Four Corners region, Colorado and Utah: Am. Assoc. Petroleum Geologists Bull., v. 38, p. 2157-2199.
- Welles, S. P., 1947, Vertebrates from the upper Moenkopi formation of northern Arizona: Calif. Univ., Dept. Geol. Sci., Bull., v. 27, p. 241-294.
- Williams, Howel, 1936, Pliocene volcanoes of the Navajo-Hopi country: Geol. Soc. America Bull., v. 47, p. 111-172.

Witkind, I. J., 1956a, Channels and related swales at the base of the Shinarump conglomerate, Monument Valley, Arizona: U. S. Geol.

Survey Prof. Paper 300, p. 233-237.

\_\_\_\_\_, 1956b, Uranium deposits at base of the Shinarump conglomerate, Monument Valley, Arizona: U. S. Geol. Survey Bull. 1030-C, 130 p.

Woodruff, E. G., 1910, Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, p. 76-104.

UNPUBLISHED REPORTS

- Chester, J. W., 1951, Geology and mineralization of Hunt's Mesa, Monument Valley, Arizona, with recommendations for exploratory drilling: U. S. Atomic Energy Comm. RMO-691.
- Chester, J. W., and Donnerstag, P. H., 1953, Drilling in the Monument Valley area of Arizona and Utah: U. S. Atomic Energy Comm. RMO-830.
- Cummings, W. L., 1952, Airborne radioactivity survey of part of the Navajo Indian Reservation of Utah and Arizona: U. S. Atomic Energy Comm. RMO-808.
- Cutter, R. C., and Leonard, J. H., 1952, Preliminary reconnaissance report 130, Grand Junction Exploration Branch, U. S. Atomic Energy Commission.
- Lewis, R. Q., Sr., and Trimble, D. E., in preparation, Geology and uranium deposits of Monument Valley, San Juan County, Utah: U. S. Geol. Survey Bull.
- Mullens, T. E., in preparation, Geology of the Clay Hills area, San Juan County, Utah: U. S. Geol. Survey Bull.
- Stieff, L. R., and Stern, T. W., 1951, The identification and lead-uranium ratio ages of massive uraninites from the Shinarump conglomerate, Utah: U. S. Geol. Survey Trace Elements Memo. Rept. 317.
- Weeks, A. D., 1952a, Summary report on mineralogic studies of the Colorado Plateau through April 30, 1952: U. S. Geol. Survey Trace Elements Memo. Rept. 431.

- Weeks, A. D., 1952b, Summary report on Colorado Plateau clay studies through April 30, 1952: U. S. Geol. Survey Trace Elements Memo. Rept. 437.
- Witkind, I. J., McKay, E. J., Johnson, D. H., Finnell, T. L., Claus, R. J., and Johnson, D. L., 1951, Preliminary report on geologic studies in the Monument Valley area, Arizona: U. S. Geol. Survey Trace Elements Memo. Rept. 318.
- Witkind, I. J., and Thaden R. E., 1954, Recommendations for an exploration program on Mitchell Mesa, Monument Valley area, Arizona: U. S. Geol. Survey Trace Elements Memo. Rept. 577.
- Witkind, I. J., Thaden, R. E., and Lough, C. F., 1953a, Preliminary report on geologic investigations in Monument Valley area, Arizona, 1952: U. S. Geol. Survey Trace Elements Memo. Rept. 536.
- \_\_\_\_\_, 1953b, Interim report on geologic investigations in the Monument Valley area, Arizona: U. S. Geol. Survey Trace Elements Memo. Rept. 492.