THE GEOLOGY AND ORE DEPOSITS OF THE JOHNNY M MINE,

AMBROSIA LAKE DISTRICT, GRANTS, NEW MEXICO

by

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Submitted in Partial Fullfillment
of the Requirements for the Degree of
Master of Science in Geology

New Mexico Institute of Mining and Technology

Socorro, New Mexico

December 1980

Dedicated to my Parents

ABSTRACT

The sedimentary features and structures present in the Westwater Canyon Sandstone Member of the Morrison Formation exposed in the Johnny M Mine indicate that the sediments were deposited by a system of aggrading braided streams. The Poison Canyon sandstone, a sandstone horizon in the lower Brushy Basin Member of the Morrison Formation, was probably the result of deposition in a complex environment of meandering and braided streams. Paleocurrent direction indicators, such as fossilized log orientation, foreset azimuths, and the axis of cross-beds and channel scours, suggests that the local paleostream flow was to the east with a slight component to the south.

The uranium mineralization is intimately associated with 1) local accumulations of carbonaceous (humate) matter derived from the decay of organic material, such as trees and plants, present in the fluvial environment; and 2) paleostream channels preserved in the Jurassic rocks.

The ore elements were derived from leaching of air-fall tuffs and ash, which were introduced into the fluvial systems during volcanic activity in the western U.S. The mobile ore element ions were reduced and concentrated by humic acids and bacteria present in the fluvial system, and ultimately remobilized in the system into the forms present today. The uranium is thus envisioned as forming either, essentially on the surface as the sediments were being deposited, or at very shallow (20 feet, 6 m) depth.

TABLE OF CONTENTS

TABLE OF CONTENTS continued

TABLE OF CONTENTS continued

LIST of ILLUSTRATIONS

LIST of ILLUSTRATIONS continued

LIST of ILLUSTRATIONS continued

LIST of ILLUSTRATIONS continued

PREFACE

Purpose and Scope

In light of the recent revival of interest in uranium, many proposals have been made concerning the ages of the various uranium deposits, the environments of deposition of the host sediments, the source of the ore elements, and the mechanisms of transportation and deposition of the uranium. The chief purpose of this paper is to provide a thorough description of one of the newest mines in the Ambrosia Lake District, the Johnny M Mine, and to use this data to reconstruct the paleoenvironment of the host rocks, and the conditions that lead to the development of the ore deposits. Since this study is limited to one mine, the findings may not be widely applicable over the entire Grants Uranium Region, but the author believes that they are pertinent to the Ambrosia Lake District. At any rate, the data and conclusions should be useful to any further thinking.

Chapters I and II contain a summation of data that the author has liberally borrowed from various sources. The rest of the paper mainly contains data and ideas for which the writer is solely responsible.

Methods

The author was employed as a geologist at the Johnny M Mine during the summer of 1977 specifically for the purpose of collecting data and generating ideas, all of which to be used in this paper. During the course of the following year, the writer spent sveral weeks in the mine collecting additional data for this paper.

Acknowledgements

Many people assisted me in the preparation of this paper, and to them I wish to express my sincere thanks and appreciation.

Clay T. Smith, my advisor and thesis committee head at New Mexico Institute of Mining and Technology, was instrumental in the generation of my thesis topic and in supplying me with numerous ideas and recommendations, and for this I express my deepest thanks. I wish to sincerely thank John E. Motica, Vice-President, Geology, Ranchers Exploration and Development Corp., Albuquerque, N.M., for giving me the opportunity to conduct my studies and supplying me with necessary funds. The geologists at the Johnny M Mine, N. M. Naiknimbalker, chief geologist, and Mark Malkoski, mine geologist, provided invaluable consultation and constructive conmments, and to them I am indebted. I also express thanks to Walt Ashwill, Dave Fitch, and Art Ehrenberg, all of Ranchers, for their ideas and time. Gratitude is also given to the other members of my thesis committee, John MacMillan, Chris Rautman, and Dave Norman, for their constructive criticism and time.

The use of the X-ray fluorescent equipment and computer time was graciously given to me by the New Mexico Bureau of Mines and Mineral Resources. The cost of the preparation of the thin-sections was paid for by a Geoscience Department fund.

Many other persons who have assisted me are not mentioned here, but their contributions are warmly remembered.

CHAPTER I

INTRODUCTION

Location and Access

The Grants Uranium Region, also known as the Grants Mineral Belt (Hilpert and Moench, 1960), is a strip of land about 30 miles (48 km) wide and 100 miles (161 km) long, lying north of and approximately parallel to Interstate Highway 40 (see Fig. 1). It extends southeast from a point north of Gallup, New Mexico, to the western edge of the Rio Grande Trough, about 20 miles (32 km) west of Albuquerque, New Mexico. The Ambrosia Lake District, a major part of this region, is located in the central part, about 20 miles (32 km) north of Grants, New Mexico (see Fig. 1).

The Johnny M Mine, a joint venture of Ranchers Exploration and Development Corporation and Houston Natural Gas Company, is situated at the southeast edge of the Ambrosia Lake District, on Sections 7 and 18, T. 13N, R. 8W, in McKinley County, New Mexico. The mine is easily accessible via N.M. State Highway 53. The shaft (Fig. 2) is located 1.1 miles (1.8 km) north of this road via a well-maintained dirt road.

History

Ranchers Exploration drilled the first hole in Section 7 in late 1968. By the end of 1972, 302 holes were drilled and logged, and the North side ore bodies were delineated. The ore bodies in Section 18 were initially drilled out by United Nuclear Corporation and sold to Ranchers in 1972 (Naiknimbalkar, N.M., personal communication, March 1978).

The shaft for the Johnny M Mine (named for its discoverer John E. Motica) was started in 1972 and finally completed in August 1974. The

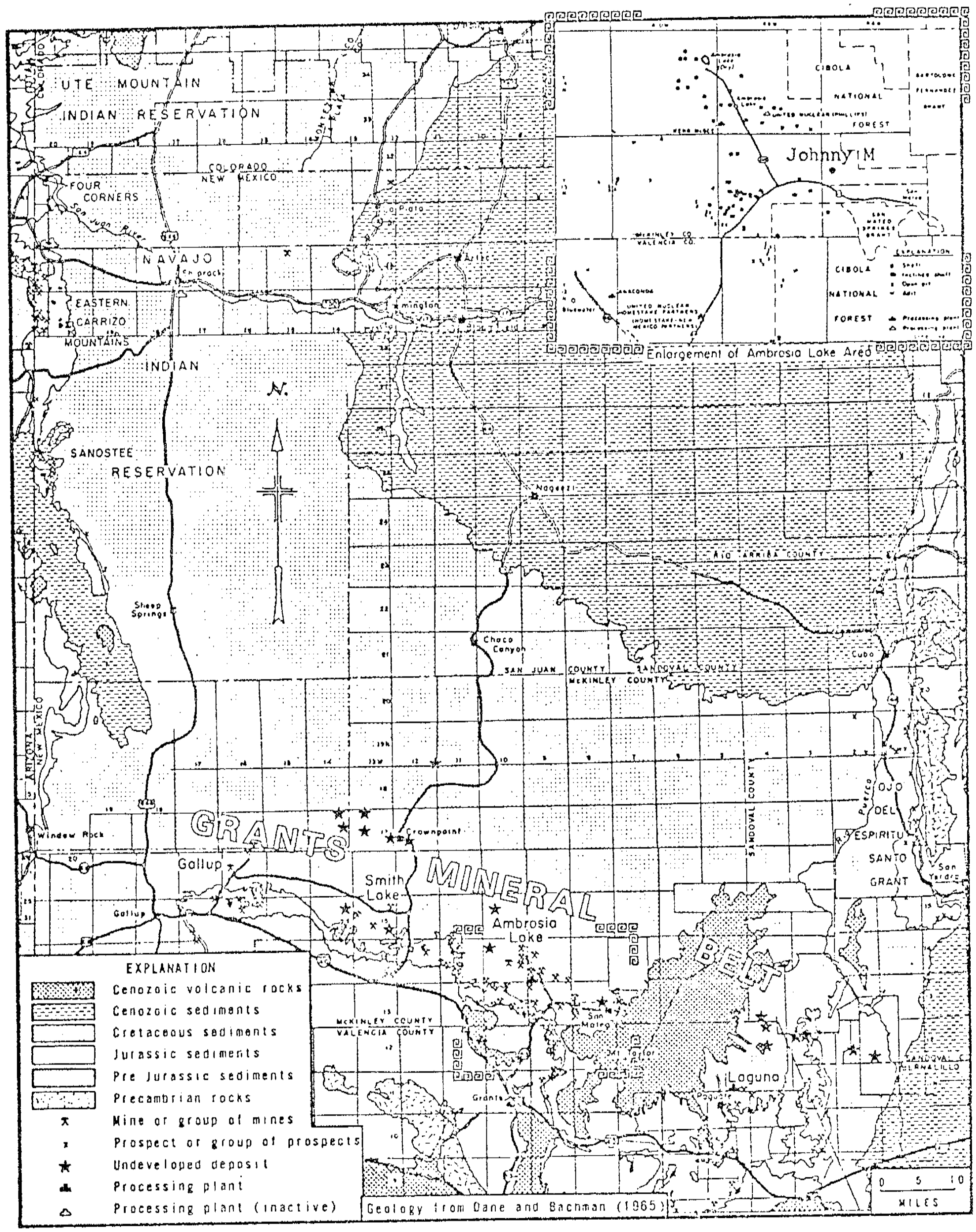

Fig. 1 - Location of the Grants Uranium Region (modified from Chenoweth, 1977)

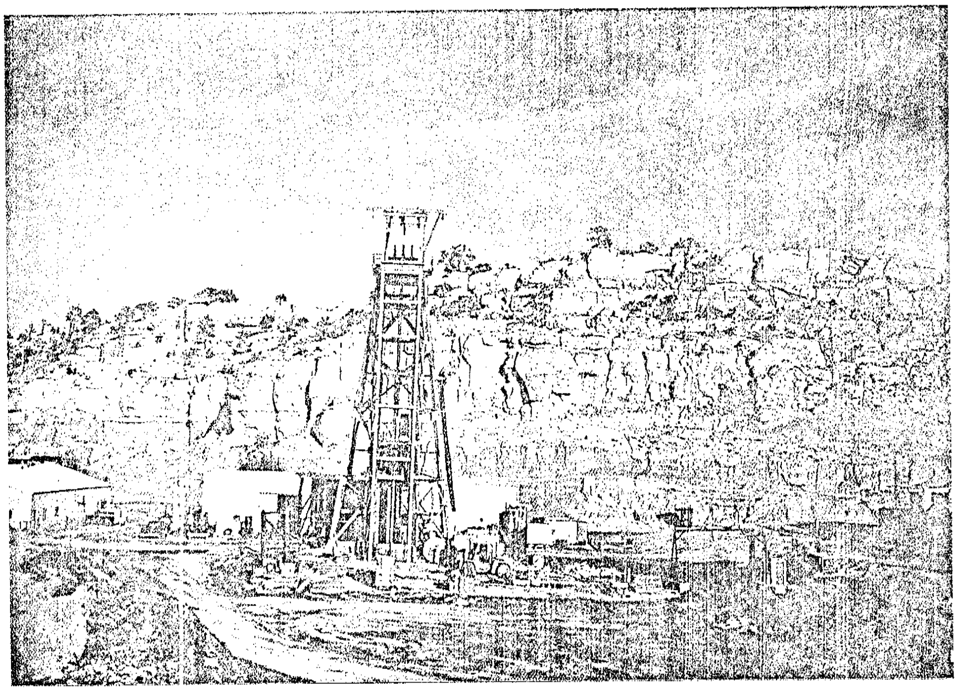

Fig. 2 - The headframe of the Johnny M Mine

first pound of uranium ore was recovered in May 1976. Full production was reached during the summer of 1977.

CHAPTER II

GENERAL GEOLOGY

Surface Features

The major part of the Ambrosia Lake District is in a belt of sediments dipping gently (1° to 3°) to the northeast. These sediments crop out in a series of west-northwest trending ridges, mesas and broad valleys. Most ridges or cuestas are capped by the Jurassic Todilto Limestone, the Cretaceous Dakota Sandstone (Fig. 3), or the Cretaceous Gallup Sandstone. The shaft of the Johnny M Mine is located about 1000 feet (305 m) south of a ridge capped by the Gallup Sandstone (Fig. 4).

Mount Taylor (Fig. 5), a Cenozoic volcano with a summit elevation of 11,389 feet (3,471 m), is located at the extreme southeastern edge of the Ambrosia Lake District (see Fig. 1). Basalt and andesite flows of the Mount Taylor volcanic field cover the south-central portion of the Grants Uranium Region.

Throughout this area, elevations are typically between 6,000 feet (1,829 m) and 8,000 feet (2,438 m). The local relief is no more than 300 feet (91 m), except near Mount Taylor, where relief may exceed 2,000 feet (610 m).

The valleys are open and moderately covered by short grass; much of this land is used for grazing cattle. Mesas and ridges are sparsely covered with vegetation, mostly small juniper and pinon trees. Pine forests are conspicuous and abundant above 8,000 feet (2,438 m) on Mount Taylor.

The climate around Grants, New Mexico is semi-arid, with a yearly precipitation around 10 inches (25 cm). While generally mild, the summer temperatures can exceed 100°F (37.8°C) and winter temperatures

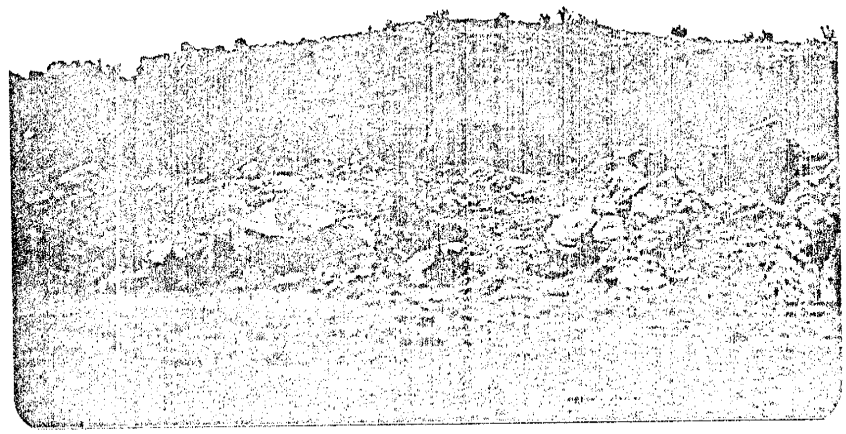

Fig. 3 - Dakota Sandstone capping a ridge

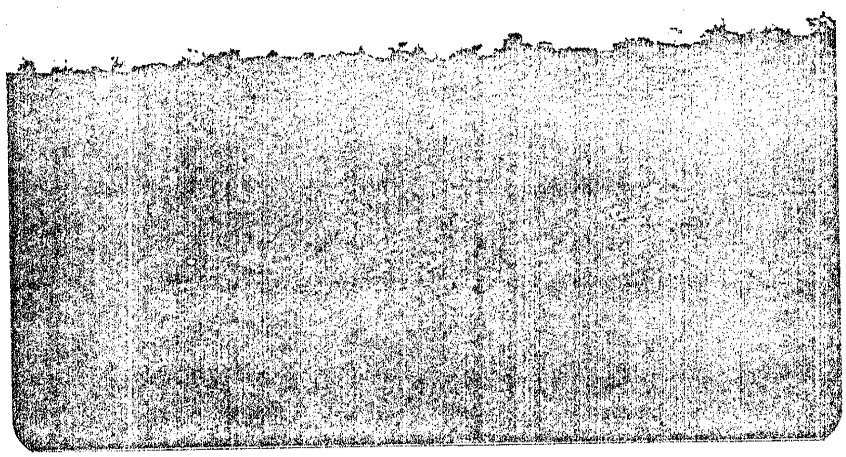

Fig. 4 - Gallup Sandstone capping a ridge
at the Johnny M Mine

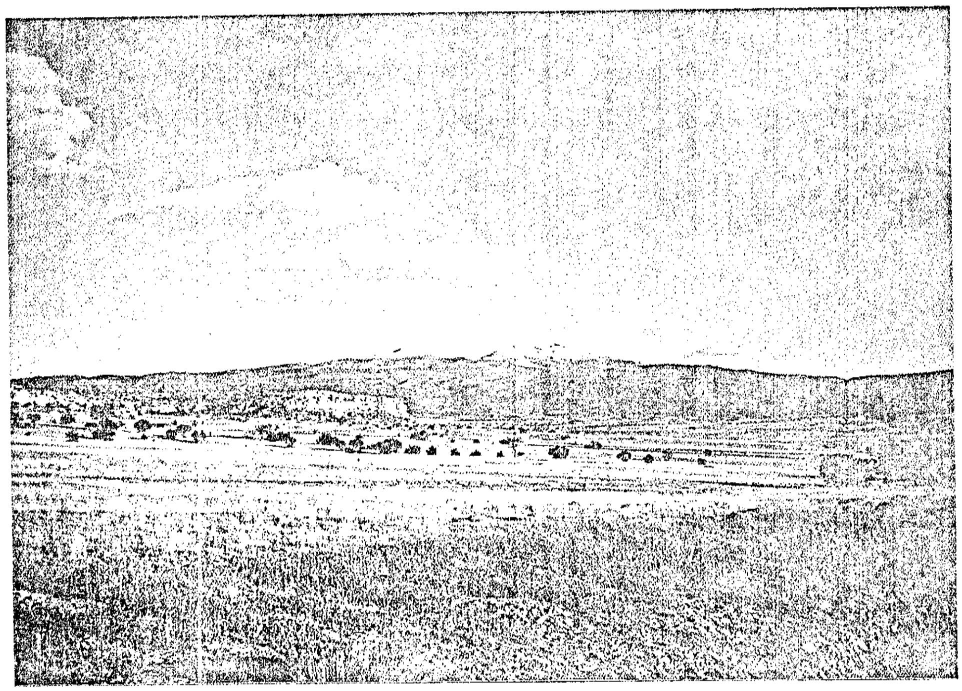

Fig. 5 - Mount Taylor, looking southeast

may drop to 15°F below zero (-26°C) for short periods.

Stratigraphy

The sedimentary rocks exposed in the Grants Uranium Region range in age from Pennsylvanian to Cretaceous. Associated intrusive and extrusive rocks of the Mount Taylor and Zuni volcanic fields are of Tertiary and Quaternary ages.

The Paleozoic sediments are dominantly brown and red clastic rocks, presumably of shallow marine or continental origin. The total thickness is about 1,700 feet (518 m), and they are exposed on the flanks of the Zuni Mountains, overlying a Precambrian core (Smith, 1954).

Of the sedimentary rocks that are exposed in the area, uranium deposits are found only in a few of the units of Jurassic and Cretaceous age (Fig. 6). The Middle Jurassic rocks are, in ascending order, Entrada Sandstone, Todilto Limestone, Summerville Formation, and Bluff Sandstone, all assigned to the San Rafael Group. The Morrison Formation, of Late Jurassic age, and the Dakota Sandstone of Late Cretaceous age complete the mineralized units. This sequence is about 1,000 feet (305 m) thick and unconformably overlies approximately 100 feet (30 m) of red eolian sandstone of the Wingate Formation, in turn underlain by 1,000 feet (305 m) of siltstone and other fine clastics of the Chinle Formation, both of Late Triassic age.

The Jurassic rocks are unconformably overlain by the Dakota Sandstone, and then successively by the Mancos Formation and the Mesa Verde Group, which includes the Gallup Sandstone, the Crevasse Canyon Formation, and Hosta Sandstone. The Mancos Shale and the Mesa Verde Group consist of some 2,000 feet (610 m) of Late Cretaceous marine and nonmarine shales, sandstones, and coal beds.

SYSTEM	AGE	FORMATION	URANIUM DEPOSITS
Cretaceous	Early and Late Cretaceous	Dakota Sandstone	Scattered small deposits, generally near base and closely related to carbonaceous material.
		Unconformity	
Jurassic	Late Jurassic	Morrison Formation	Contains about 95% of all the known uranium reserves in the Grants Uranium Region.
		Bluff Sandstone	Contains no deposits.
		Summerville Formation	Contains scattered deposits at base, generally where underlying Todilto Limestone is mineralized.
		Todilto Limestone	Contains many small and some fairly large deposits in the limestone member.
		Entrada Sandstone	Contains scattered small deposits at top of formation, generally where overlying Todilto Limestone is mineralized.
		Unconformity	
Triassic	Late Triassic	Wingate Sandstone	Contains no deposits.

Fig. 6 - Stratigraphic column of the rock units that contain uranium deposits in the Grants Uranium Region (modified from Hilpert, 1963)

The volcanics of the Mount Taylor and Zuni Mountains volcanic fields form the cap rock of the eastern half of the Region.

A brief description of the uranium-bearing rocks in the Grants Uranium Region is given below. A more detailed description of the ore-bearing rocks exposed in the Johnny M Mine is given on page 26 ff.

Entrada Sandstone

The Entrada Sandstone, the basal unit of the San Rafael Group, is the lowermost uranium-bearing unit. It disconformably overlies the Upper Triassic Wingate Sandstone and ranges from 150 feet (46 m) to 250 feet (76 m) in thickness. The Entrada Sandstone consists of an upper unit of reddish-orange, fine-grained sandstone with thick sets of large-scale cross-beds, and a lower unit of red and gray siltstone. Scattered uranium mineralization is found, mostly in the upper part associated with ore bodies in the overlying Todilto Limestone.

Todilto Limestone

The Todilto Limestone, which is comformable and generally gradational with the Entrada Sandstone, is composed of two members. The basal limestone member is from 0 to 40 feet (12 m) thick and fairly widespread. It consists of laminated and thin-bedded, gray, fetid, fine-grained limestone with some interbeds of siltstone at the base, and a few thin seams of gypsum near the top. The upper gypsum-anhydrite member is 90 feet (27 m) thick, and is more restricted in areal extent. This member is conformable and gradational with the underlying limestone member.

The Todilto Limestone contains some small and some fairly large ore deposits in the Ambrosia Lake District. The ore is confined to the limestone member.

Summerville Formation

The Summerville Formation, 50 feet (15 m) to 220 feet (67 m) thick, generally consists of a lower silty member and an upper sandy member. The lower unit is a sequence of soft, reddish-brown mudstone, and thin-bedded, silty sandstone that locally contains gypsum. It grades upward into the upper sandy member, which consists of reddish-brown and pale-brown, fine-grained, even-bedded sandstone, and some interbedded siltstone.

The Summerville Formation contains a few scattered uranium deposits at the base, usually where the underlying Todilto Limestone is mineralized.

Bluff Sandstone

The Bluff Sandstone, 130 feet (40 m) to 400 Feet (122 m) thick, intertongues with the underlying Summerville Formation, and the contact between the two is rather arbitrary. The contact is generally selected between the uppermost persistent siltstone and overlying thick-bedded sandstone.

The Bluff Sandstone consists of pale-brown to pale-red, fairly well-sorted, fine- to medium-grained, well-cemented quartz sandstone. It forms massive, smooth, rounded cliffs above the talus covered slopes and ribbed cliffs of the Summerville Formation. Thick sets of large-scale, trough cross-beds are characteristic of the upper part. The lower part grades into smaller-scale sets of cross-beds and some flat beds.

The Bluff Sandstone contains no known uranium deposits.

Morrison Formation

In the Grants Uranium Region, the Upper Jurassic Morrison Formation consists of three members, in ascending order, Recapture Shale, Westwater Canyon Sandstone, and Brushy Basin Shale.

The Recapture Shale Member, which is conformable on the Bluff Sandstone, ranges in thickness from 50 feet (15 m) to 200 feet (61 m), and averages 150 feet (46 m) thick. The Recapture Member is mostly distinctive gray and grayish-red beds of sandstone, siltstone, mudstone, and some thin beds of limestone. The beds range from a foot (30 cm) to several feet thick, and some sandstone beds are 10 feet (3 m) thick. The sandstone is soft, clayey, poorly sorted, and fine- to medium-grained. It is commonly ripple-laminated and thin-bedded.

The Recapture Shale contains a few, very small, low grade uranium deposits.

The Westwater Canyon Sandstone Member generally intertongues with the Recapture Shale Member. The Westwater Canyon sandstone ranges from 50 feet (15 m) to 300 feet (91 m) thick, with an average thickness of approximately 150 feet (46 m) (Kittel and others, 1967). The average thickness in the vicinity of the Johnny M Mine is approximately 155 feet (47 m). It is mostly a light, yellow-brown to gray-tan, fine- to coarse-grained, poorly sorted, cross-bedded, arkosic sandstone. Small lenses of pebbles and some thin seams of gray-green claystone and siltstone are present. Grains of pink feldspar are conspicuous in hand specimen. Silicified bones and silicified or carbonized trees are locally abundant. The cross-bedding is generally of small- to medium-scale trough sets.

The Westwater Canyon sandstone contains 90% of the large uranium ore deposits in the Grants Uranium Region.

The Brushy Basin Shale Member conformably overlies and intertongues with the Westwater Canyon sandstone. The Brushy Basin shale is generally 20 feet (6 m) to 350 feet (107 m) thick, with the average thickness in the vicinity of the mine being 110 feet (34 m). It consists of greenish-gray claystones with interbedded sandstone and a few thin beds of limestone. The sandstone beds are similar in color and lithology to those of the Westwater Canyon Sandstone Member. These beds range from 1 foot (30 cm) to several tens of feet in thickness.

Uranium deposits of significant value have been found and mined in a lower sandstone lens (locally called the Poison Canyon sandstone), and an upper sandstone lens (locally called the Jackpile sandstone) of the Brushy Basin Shale Member .

Dakota Sandstone and overlying Cretaceous rocks

The Dakota Sandstone, a prominent cliff former in the Grants area, unconformably overlies the Morrison Formation. It ranges from 10 feet (3 m) to 150 feet (46 m) thick. The Dakota Sandstone consists mostly of tan to gray, well-cemented, quartz sandstone, dark-gray carbonaceous shale, and local lenses of conglomerate and impure coal. The sandstone is generally medium-grained, clean, and contains numerous small molds of carbonized plant fragments. The sand grains are rounded and cemented with silica.

A few, very small uranium deposits occur in the Dakota Sandstone, mostly near the base.

The Dakota Sandstone is conformably overlain by approximately 1,000 feet (305 m) of Mancos Shale, a succession of Upper Cretaceous dark-gray marine shales. The Mancos Shale is in turn overlain by about 1,000 feet (305 m) of marine and non-marine shales, sandstones, and coal beds of the Mesa Verde Group of Upper Cretaceous age. None of the Cretaceous sediments above the Dakota Sandstone have any apparent relation to the uranium deposits.

General Structural Geology

The Grants Uranium Region extends in a NW-SE trend, 30 miles (48 km) wide and 100 miles (161 km) long, along the southern edge of the San Juan Basin in northwestern New Mexico. It extends from the Gallup sag on the west to the Rio Grande trough on the east. The principal mineralized region is found along the Chaco Slope, a northeast dipping homoclinal structure, which is the southern structural flank of the San Juan Basin (Kelley, 1951). The Chaco Slope lies between the Central Basin to the north and the Zuni Uplift to the south. The Ambrosia Lake District occupies a faulted and folded part of the Chaco Slope. The regional northeast dip of 3° is modified in many places by folds and faults (see Figs. 7 and 8).

The principal regional structures of the Ambrosia Lake District are the Zuni Uplift and the Acoma sag. The Zuni Uplift is a broad northwest trending upwarp asymmetrical to the southwest. The uranium region cuts across the northern edge of the uplift and is approximately parallel to its trend. The Acoma sag is a broad, flat, downwarp that slopes very gently to the north between the Zuni Uplift to the west and the Puerco fault belt to the east. The McCartys syncline, near the margin of the Zuni Uplift, forms the axis of the sag. Near its eastern end, the uranium region crosses the Acoma sag into the Puerco fault belt and dissipates at the western edge of the Rio Grande trough.

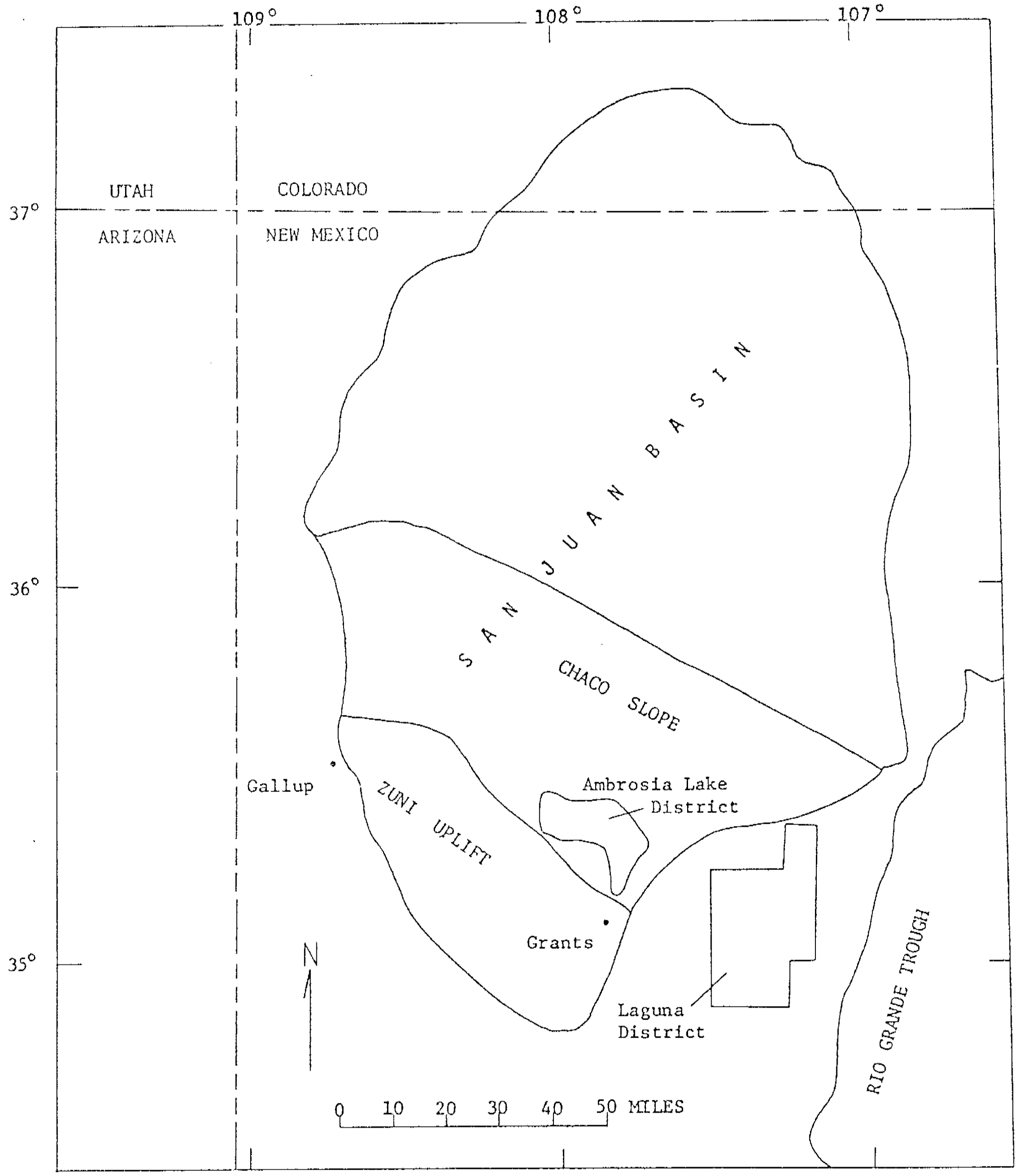

Fig. 7 - Location of the San Juan Basin and the Ambrosia Lake District (modified from Santos, 1970)

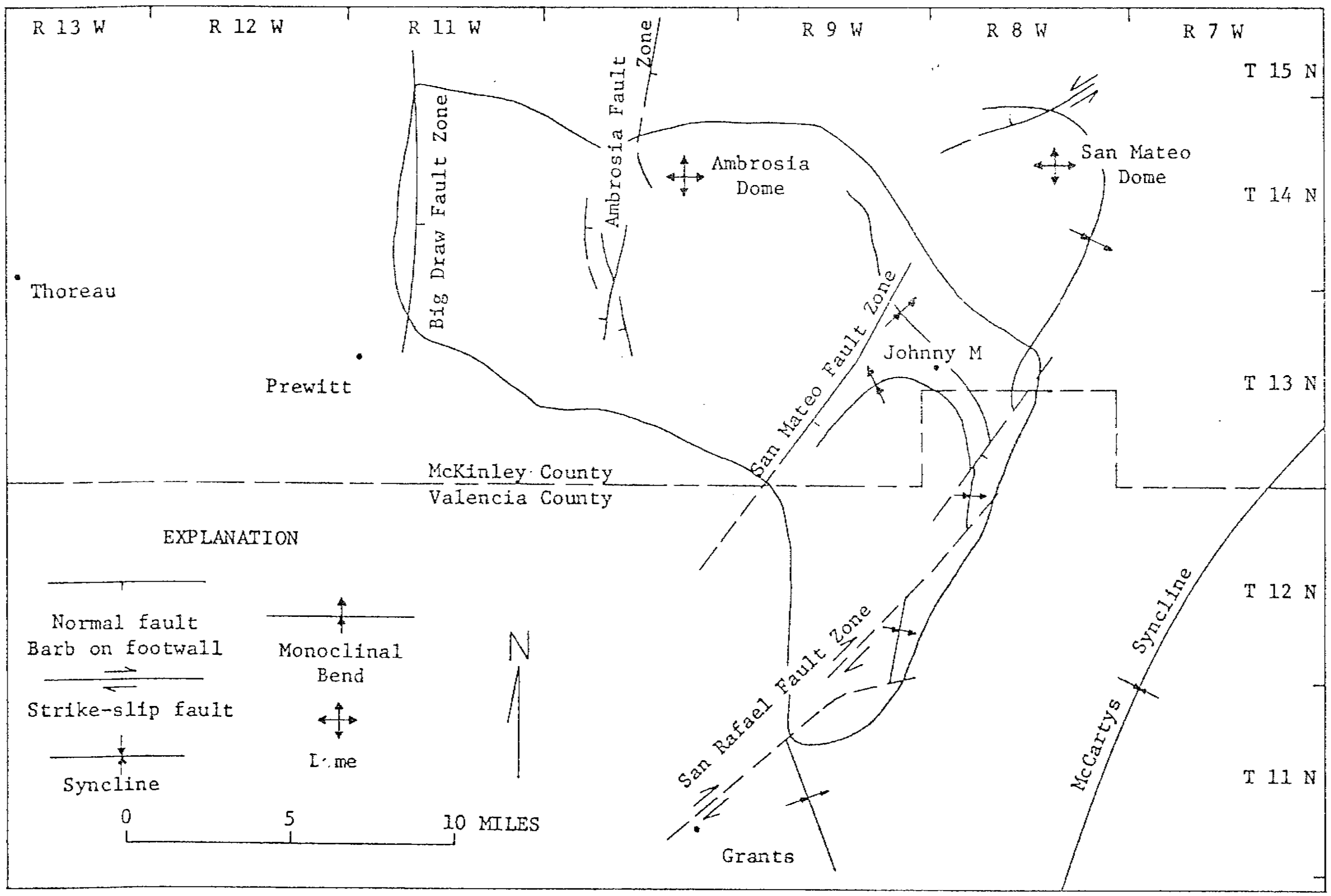

Fig. 8 - Structural geology of the Ambrosia Lake District (modified from Santos, 1970)

The major deformation of the region probably occurred in Laramide (Late Cretaceous-Early Tertiary) time and gave rise to the Zuni Uplift and the San Juan Basin. At this time, the principal folds and faults in the Ambrosia Lake District were formed and the gentle regional dips were established (Kelley, 1963). The faults and associated folds of the Puerco fault belt, and the Rio Grande trough were formed and structurally defined in Pliocene time (Kelley, 1963). Some faults that dislocate the Mount Taylor volcanics may be as late as Pliocene or early Pleistocene.

The eastern and northeastern parts of the Zuni Uplift are broken by numerous radial faults. The Ambrosia Lake District is structurally bounded to the west by the Big Draw fault zone and to the east by the San Rafael fault zone (see Fig. 8).

The San Rafael fault zone, striking northeast through Grants, is the largest fault zone in the region. This zone is comprised of several faults which fracture the eastward dipping west flank of the McCartys syncline (Santos, 1970). The movement along the fault zone is essentially vertical, as the downthrown east side is displaced approximately 1,000 feet (305 m) vertically along the fault zone 3 miles (5 km) northeast of Grants.

The San Mateo fault zone, downthrown to the east, has a maximum vertical displacement of 450 feet (137 m) where it strikes northeastward. Strata on the downthrown side dip about 12° toward the fault plane. Strata on the upthrown west side appear to abut the fault plane with little or no drag (Santos, 1970).

The Ambrosia fault zone, also downthrown to the east, strikes nearly due north, where the maximum vertical displacement is about 350 feet

(107 m) (Santos, 1970). As in the San Mateo fault zone, strata on the downthrown side dip toward the fault plane, whereas the strata on the upthrown side abut the fault plane with little or no drag.

The Big Draw fault zone strikes northeastward in the Zuni Mountains, curves, and strikes due north, north of Interstate 40, at the extreme western edge of the Ambrosia Lake District. The fault is downthrown on the east, with a maximum stratigraphic throw of 600 feet (183 m) (Smith, 1954).

West of the Ambrosia Lake District, the Bluewater fault zone strikes due north. An en echelon pattern is developed in which each successive fault surface shows its maximum separation either northwest or southeast of the preceding fault surface (Smith, 1954). Maximum stratigraphic throw along the Bluewater fault zone ranges from 200 to 400 feet (61 to 122 m), although the average is probably less than 100 feet (31 m).

Many folds are also present in the Grants Uranium Region. Folds in strata of Jurassic age that are not reflected in the overlying Dakota Sandstone are called pre-Dakota folds. These structures are presumed to have formed during the deposition of the Morrison Formation or slightly thereafter. Folds that involve the Dakota Sandstone are called post-Dakota folds, and probably developed during the Laramide deformation of the region.

The McCartys syncline is the largest post-Dakota fold in the region, and bounds the Ambrosia Lake District on the east. This fold is asymmetrical, and the dips that form the steeper west limb develop a maximum structural relief of about 1,600 feet (488 m). The crest of the monocline trends northward, and is offset at three places by the San

Rafael fault zone.

Ambrosia dome, the next largest post-Dakota fold in the district, is an asymmetrical triangular fold with steep flanks on the south and west, and a gentle flank on the northeast. The steep western flank is cut by the Ambrosia fault zone, producing a maximum structural relief of 1,150 feet (350 m).

Pre-Dakota folds are present in the Laguna District to the southeast of the Ambrosia Lake District (see Fig. 7). Two sets of folds occur: a major set which trends to the east and northeast, and a minor set which trends northward (Moench and Schlee, 1967). Folds of the major set are sinuous and have an amplitude of several hundred feet. Folding is believed to have begun during or shortly after Todilto Limestone deposition, and to have continued through to very latest Jurassic and possibly Early Cretaceous time.

No pre-Dakota folds of the magnitude of those in the Laguna District occur in the Ambrosia Lake District. None have been observed in outcrop; and if any do exist in the subsurface, they are too subtle to be indicated by drill hole data (Santos, 1970).

Collapse Structures

Collapse structures are common in the Bluff, Summerville, and Morrison Formations in the Ambrosia Lake District and also in the nearby Laguna District. The peculiar structures are circular in plan and vertical to near vertical in orientation. They are usually bounded by one or more concentric ring faults. The material within the structures is displaced downward and may consist of brecciated fragments of sandstone and mudstone, a disaggregated mixture of mudstone and sandstone, or bedded material in which the beds sag toward the middle of the collapse. The structures are known to be as much as 200 feet (61 m) in diameter and more than 300 feet (91 m) in depth. No collapse structures are known that have a base which penetrates the Todilto Limestone or whose top penetrates the Dakota Sandstone (Kittel and others, 1967).

In the Ambrosia Lake District, the collapse structures are not associated with folds as they are presumed to be in the Laguna District. These structures are clustered in an area where the Recapture Shale Member of the Morrison Formation is unusually thick, 240 feet (73 m), compared with 125-145 feet (38-44 m) elsewhere. Three of the collapse features are close to the San Mateo fault zone, and their existence may be related to the faulting there. Elsewhere in the district, there is no obvious relationship between faults and collapse structures. Most of these structures occur where the Dakota Sandstone has been removed by erosion, but drill hole data indicates that these structures are probably all pre-Dakota in age (Clark and Havenstrite, 1963).

Igneous Rocks

The principal igneous rocks in the region include a variety of rather extensive basaltic flows and shallow intrusive rocks. Diabase dikes and sills are fairly common in the Laguna District; most of these are less than 10 feet (3 m) wide, but a few that branch from plugs are several tens of feet wide. Sills are found at many stratigraphic horizons in the district. Dike trends are principally northerly and northwesterly; maximum known length is about 10 miles (16 km).

Numerous basaltic necks occur in or adjacent to the Mount Taylor volcanic field. Most of these probably fed volcanoes, and several sections of partly dissected cones and feeder necks are exposed along the edge of Mesa Chivato and lesser volcanic-capped mesas. These necks may consist of solid lava, lava breccia, or lava-sedimentary mixed breccias.

An elliptically shaped dome, one to one and one-half miles (2.4 km) in diameter, is present in East Grants Ridge, about seven miles (11 km) northeast of Grants. The central part of the dome is aphanitic, lithophysae-bearing, flow-banded rhyolite surrounded by a peripheral-chilled sheath of obsidian and perlite (Kittel and others, 1967).

CHAPTER III

GEOLOGY of the HOST ROCKS

Introduction

The Johnny M Mine produces uranium from two members of the Morrison Formation. Most mines in the Ambrosia Lake District are mining ore either from the Westwater Canyon sandstone or from sandstones in the Brushy Basin Member; however, at the Johnny M, both members are being mined.

The mine is separated into two sections, the North side and the South side, as Ranchers personnel call them. The North side, situated in Section 7, produces ore exclusively from the Westwater Canyon sandstone. The South side, in Section 18, produces ore from both the Westwater Canyon sandstone and the Brushy Basin Member. The approximate outlines of the ore bodies in their respective sections are shown in Figs. 9a and 9b.

Interpretation of Stratigraphy using Self-Potential and Resistivity Logs

Interpretation of stratigraphy in the Johnny M Mine was done using Self-Potential (SP) and Resistivity logs. In general, these logs give a clear indication of the subsurface geology and formation contacts. A typical log from the Johnny M Mine is shown in Fig. 10.

The first prominent marker horizon that the author used for correlation is the base of the Dakota Sandstone. This marker is nearly always very distinct.

The base of the Brushy Basin Shale Member is designated at the bottom of a prominent shale horizon, known as the "K" shale to geologists

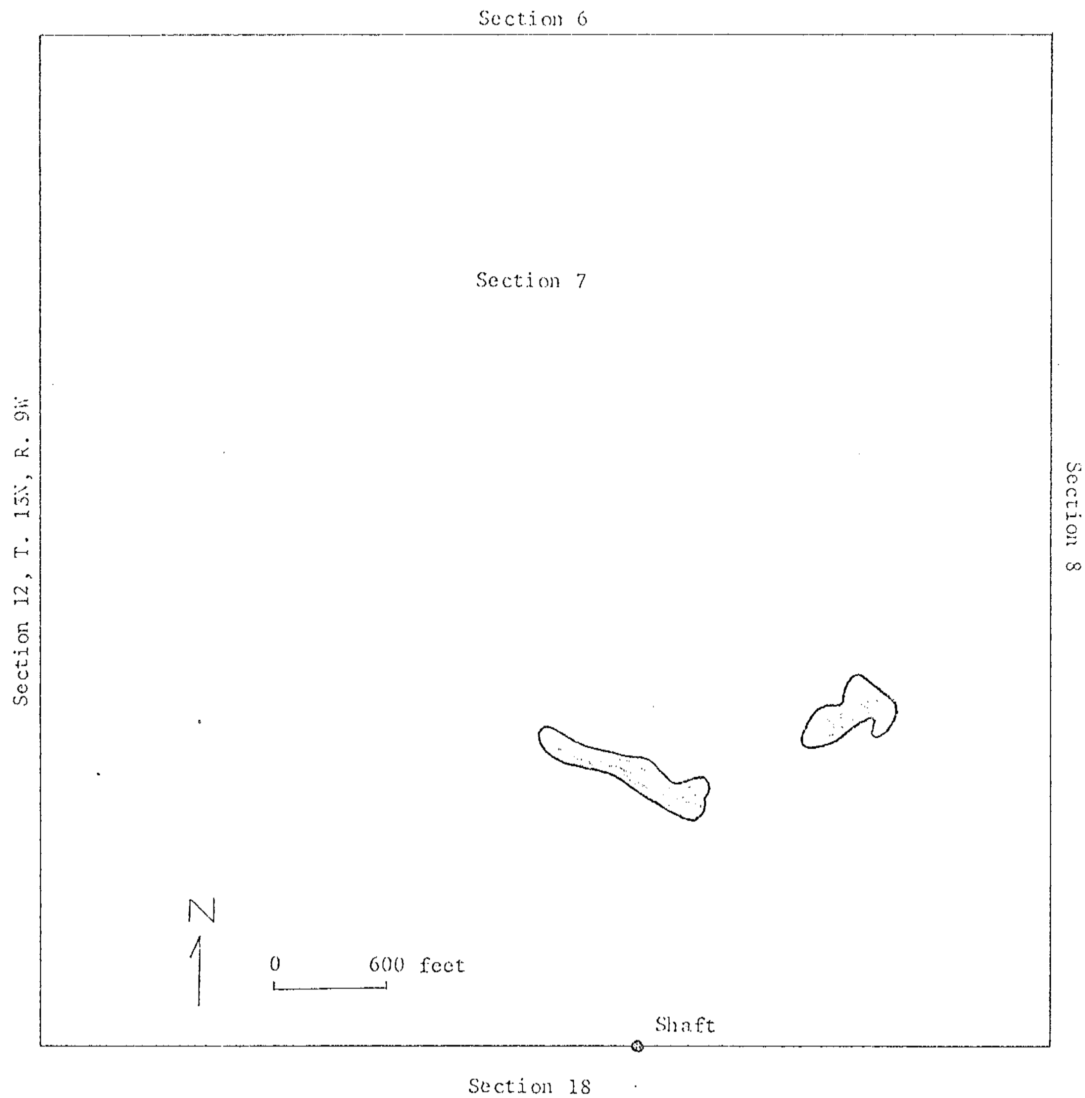

Fig. 9a - Plan view of the North side ore bodies

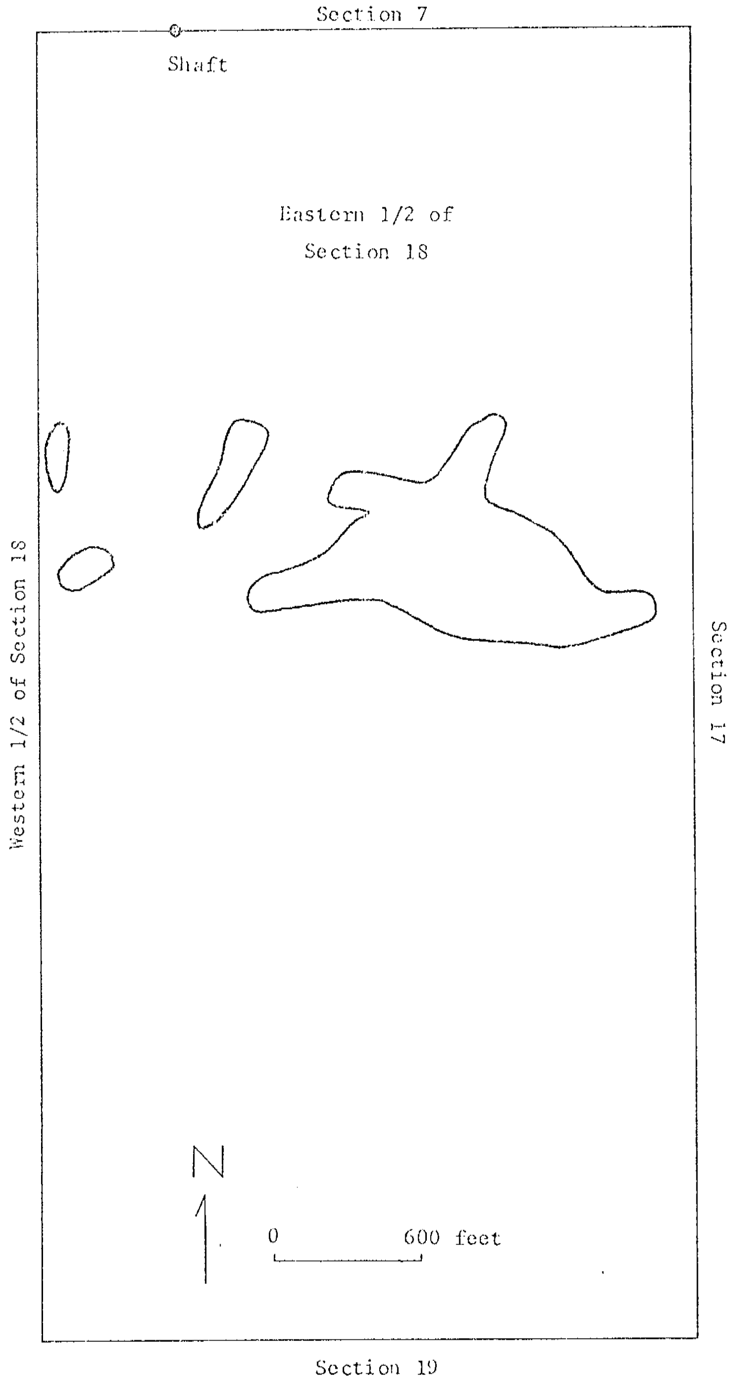

Fig. 9b - Plan view of the South side ore bodies

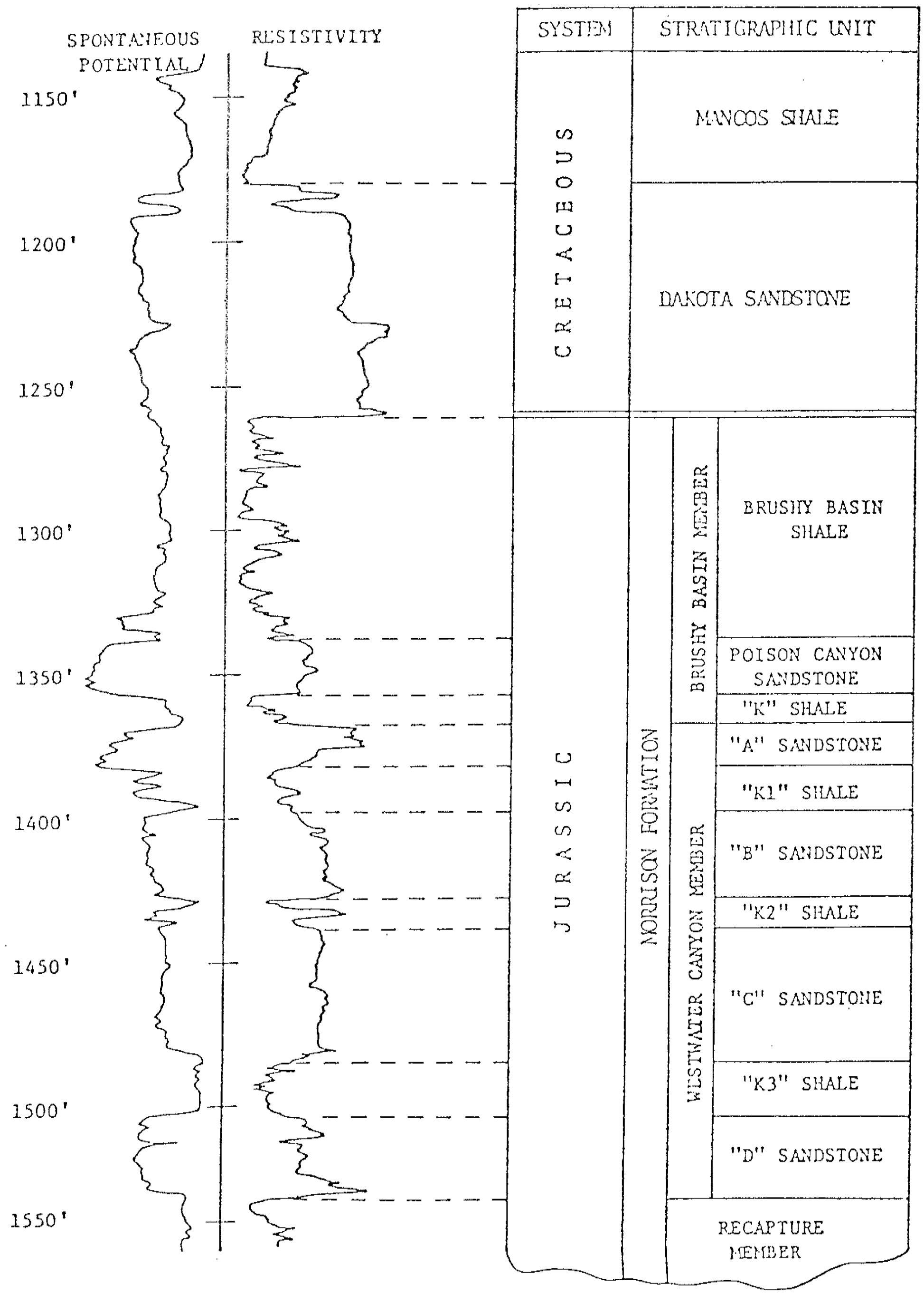

Fig. 10 - Log from the Johnny M Mine

in the Grants Region. The sandstone unit directly above the "K" shale is interpreted as the Poison Canyon sandstone, a term of economic usage in the Ambrosia Lake District for the basal sandstone horizon of the Brushy Basin Shale Member. Some geologists (e.g. Santos, 1970) favor classifying the Poison Canyon sandstone and "K" shale as part of the Westwater Canyon Sandstone Member; however, in this report the upper contact of the Westwater Canyon Sandstone Member is placed at the base of the "K" shale.

The Westwater Canyon sandstone typically has three to four prominent sandstone horizons separated by shale (claystone) zones. These sandstone units are usually given various letter names, such as "A", "B", and "C" sand, by the different mining companies. The shale zones, which are only traceable for short distances, are commonly referred to, from top down, as the "K1" shale, "K2" shale, and so on.

The top of the Recapture Shale Member, which is not exposed in the mine, is usually placed at the top of a thick shale horizon below the basal sandstone unit of the Westwater Canyon sandstone. The thickness of the Westwater Canyon sandstone is used as a guide to the placement of the Recapture shale contact, as the Westwater Canyon sandstone is commonly between 140 feet (43 m) and 180 feet (55 m) thick in the vicinity of the mine.

General Stratigraphy in the vicinity of the mine

In the vicinity of the Johnny M Mine, the upper two members of the Morrison Formation, the Westwater Canyon sandstone and the Brushy Basin shale, have a total thickness of 265 feet (88 m). The Westwater Canyon averages 155 feet (51 m) in thickness, while the Brushy Basin averages 110 feet (36 m) thick, but these thicknesses vary over Sections 7 and 18.

Host rocks for the ore deposits being mined are the upper two sandstone horizons of the Westwater Canyon ("A" and "B" horizons in Fig. 10), and the Poison Canyon sandstone of the Brushy Basin Member. The majority of the ore is in the "A" sandstone horizon and in the Poison Canyon sandstone, but some of the richest ore was found in the "B" sandstone horizon of the Westwater Canyon sandstone.

The upper sandstone horizons of the Westwater Canyon ("A" and "B") are of varied thicknesses throughout the area, but near the ore bodies they average about 20 feet (7 m) thick. In between these sandstone horizons there usually exists a shale zone, often referred to as the "Kl" shale (see Fig. 10). This shale zone is usually continuous, but at times it is absent. This shale is usually 10-12 feet (4 m) thick.

The Westwater Canyon Sandstone Member and the Brushy Basin Shale Member are separated by a continuous shale layer known as the "K" shale (fig. 10). This shale is very similar to the shale present in the upper Brushy Basin shale, therefore the "K" shale is considered the lowest shale unit of the Brushy Basin Shale Member. The thickness is relatively uniform, commonly 8 to 12 feet (3-4 m).

The Poison Canyon sandstone, which rests directly on the "K" shale, tapers from 70 feet (23 m) thick in the northern part of Section 7, to a feather edge in the southern part of Section 18. Where the Poison Canyon is mined, its thickness is approximately 12 feet (4 m).

Above the Poison Canyon sandstone is the thick, main shale zone of the Brushy Basin. Thickness varies considerably, but averages 90 feet (30 m) near the ore bodies. Thickness is greater where the Poison Canyon sandstone is thin, and vice versa.

The relationships between the various stratigraphic horizons are illustrated in Appendix F.

Westwater Canyon sandstone

Sandstone

The sandstones of the upper Westwater Canyon have the composition of an arkose; feldspars comprise about 35% of the rock. The sandstone layers may be horizontally bedded or complexly cross-bedded. The cross-bedding is associated with scour-and-fill structures, foreset development, and erosion surfaces or diastems which extend for distances up to 50 feet (16 m).

Sandstone varies unpredictably from weakly to strongly indurated (principally cemented by calcite), and varies widely in grain size, sorting, and roundness. Changes in texture and structure within beds, and from one bed to another are common. Claystone fragments up to 2 inches (5 cm) in length are dispersed in some of the coarser-grained sandstone units. Claystone cobble conglomerates one to two feet (30 to 60 cm) thick are fairly common along diastems.

Permeability appears to be quite high. Water derived from the Westwater Canyon sandstone is constantly being pumped out of the mine workings. Small diameter probe holes drilled upward and outward frequently yield flows of several gallons per minute.

Plant remains, and fossil trees and bones are especially widespread in the Johnny M Mine. Fragments of logs, branches, and twigs are abundant along with separate accumulations of leaves and reed-like plant stems. The smaller pieces are usually coalified, whereas the larger logs are commonly silicified. Dinosaur bones are also conspicuously abundant.

Claystone

The claystone, which is present in layers interbedded in the sandstones, can occur in various shades of green and red. Fresh claystone is commonly dark green, whereas weathered claystone is a light grayish-green, with irregularly shaped reddish-colored lenses. Weathered claystone is very fragile and powdery, breaking up when handled. Fresh, dry claystone is blocky, having a smooth, almost soapy, feel with little grittiness, and a waxy sheen; it is usually sectile. The claystone consistently contains a small proportion of non-clay detrital particles, and the balance is composed of fine-grained clay minerals probably derived from alteration of volcanic ash.

Boundaries between areas of red and green claystone are sharp, but always irregular in nature, and they tend to cross the bedding at any angle. The red claystone is harder and more brittle than the green claystone and more resistant to breakdown in water. Moist, weathered claystone clasts of any type dessicate within a few days and split into chunks.

A variety of textures exist in thin-sections of the claystone. They commonly contain up to 10%-15% of subangular, fine sand-size quartz and feldspar particles. These coarser particles are most frequently randomly scattered through the clay, but may be concentrated in very fine laminae. Clay particle outlines are indistinct, even at magnifications of 100X. Some orientation of the clay particles is indicated by a tendency to show extinction parallel to the bedding in polarized light.

A very interesting feature of the claystone zones is the existence of a mantling effect of colors on individual clay galls. A common feature is to see a gall, 1 foot (.3 m) across, with a red core and a green mantle (Fig. 11a). The inverse color scheme, a green core with a red mantle is also observed, but it is not nearly as common (Fig. 11b).

Sedimentary Structures and Features

Following are descriptions of the sedimentary features that the author observed while working underground.

Channel-fill cross-bedding

Cross-beds may be produced by the filling of small alluvial or erosional channels, such as may be present in a braided stream environment. A trough-shaped, scoured channel is filled by thin sets of laminae conforming to the shape of the channel floor (McKee, 1957). In a later phase, this trough-shaped channel, with its conformable laminae, is partially eroded, and a new, younger trough is produced, which is ultimately filled by another set of thin laminae. This is schematically shown in Fig. 12 and illustrated in Fig. 13. This sedimentary feature is conspicuous in the sandstones of the mine. Most of these features are of medium- to large- scale, as the individual sets are usually 5 cm or more in thickness.

Systems of channel-fill cross-bedding can vary greatly in size, ranging from 3 cm thick and .3 m across to nearly 1 m thick and 5 m long. In these systems, there tend to be several individual channels that are filled by the trough-shaped beds. These beds range from 1 to 3 cm in thickness. Frequently, some graded bedding exists within each bed, with subtle changes from coarser to finer material. This sequence is repeated up through the trough. Overall, the sorting is moderate (Folk, 1968) within the graded beds.

Fig. 11a - Clay gall with a red core and green rim

Fig. 11b - Clay gall with a green core and red rim

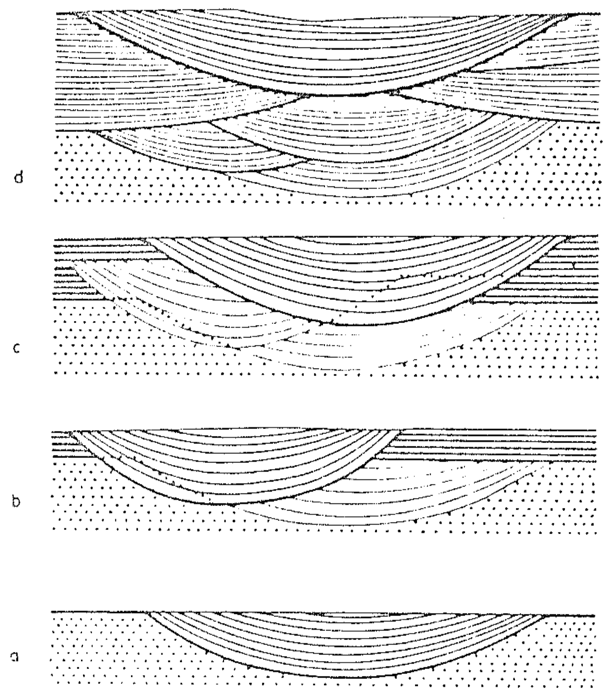

Fig. 12 - Scheme demonstrating the development of channel-fill cross-bedding (Fig. 153, Reineck and Singh, 1975)

Fig. 13 - Channel-fill cross-bedding as seen in the mine

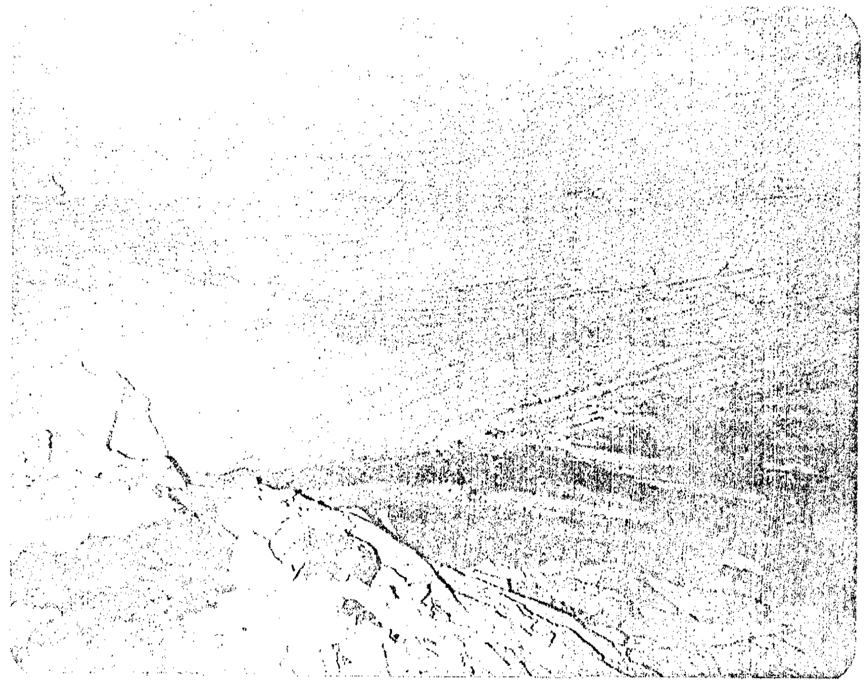

Fig. 14a - Foresets separated from cross-beds by a diastem; the yellow material is zippeite

Fig. 14b - Small scale diastem cutting off foresets; hammer head is just above a diastem average size being about 1/4 inch (.6 cm). The gravel is commonly composed of chert, pink feldspar, and granitic and claystone fragments. The coarsest material is confined to the extreme basal layer about 2 inches (5 cm) thick and grades into finer material upward. The sorting is moderate to well (Folk, 1968) for this coarse layer, apparently due to the winnowing out of the finer material, and then becomes poorer upward. Organic material, such as pieces of carbonized branches, leaves, and reeds, are commonly concentrated about a foot (30 cm) above the basal layer, seemingly deposited after all the fines were winnowed out.

Graded Bedding

Graded beds are sedimentation units characterized by a gradation in grain size, from coarse to fine, upward from the base to the top of the unit. Pettijohn (1957) discusses the two types of grading possible: a) the decrease in the grain size upward as a result of the addition of successive increments of material, each of which is finer than the preceeding. This is probably the result of sedimentation from a current gradually decreasing in velocity and competence; b) the finer material is distributed throughout, with the coarser grains gradually decreasing upward. This is a product of sedimentation from a suspension in which all sizes are carried, and out of which they settle.

The second type of graded bedding (b) is apparently the dominant type present in the sands exposed in the mine, however, this feature is subtle and not easily perceptible. This graded bedding is pervasive throughout the horizontally bedded sands. Each bed incorporates a sequence of coarser to finer material, with this being repetitive over several feet vertically. In a particularly good exposure, a 2 foot (.6 m) sequence of coarse sediment had thin (1-2 inches, 2-5 cm) beds of much finer material interlayered within. The change from the coarse to the fine sand was abrupt, almost knife sharp, but this is rare to see.

Reverse graded bedding, where the finer material grades upward into the coarser material was not observed in the mine exposures.

Horizontal Bedding

The most abundant and conspicuous type of bedding present in the Westwater Canyon sands is evenly layered sand composed of parallel and almost horizontal sand layers up to 1 inch (2.5 cm) in thickness. Individual layers are usually horizontal or slightly inclined due to deposition on originally inclined surfaces. The layers can commonly be traced up to 12-15 feet (4-5 m). Bedding is commonly marked by alternating sequences of graded beds. Bedding ranges from very thin-bedded to thin-bedded (Reineck and Singh, 1975).

The fine- to medium-grained sandstones show the best developed horizontal bedding. Occasionally, a 1-2 cm thick layer of coarse sand is present, interlayered with the normal sequence of bedding. This feature is probably due to deposition during a single flood stage. Different sets of evenly laminated sands are frequently separated from each other by very low angle erosional surfaces.

Scour and Fill

A conspicuous and interesting sedimentary feature present in the Westwater Canyon sands is the scour and fill structure. This occurs where the older horizontally bedded sands are eroded by a fast moving stream of water, and, in place of the eroded material, sediment is deposited by the stream.

These scour and fill structures range in size from 1 foot to 20 feet (25 cm to 6 m) across. The contact with the lower sand bed is concave upward, forming the apparent trough shape of the eroding channel (Figs. 15a and 15b). The channel fill sand sequence usually extends upward from up to 3 feet (1 m) to where another scour and fill feature is present or the horizontal bedding is resumed.

Scour and fill structures, which are generally produced on the channel bottom, are good aids in the determination of paleocurrent direction, because the longer axis runs parallel to the general current direction.

Ripple-Marks

Ripple-marks are very rare in the Westwater Canyon sands exposed in the mine. It is assumed that they are erased with each new rush of water, and being superficial in nature, would not be easily preserved, or that ripples never formed because the sediment was coarse sand.

Ripple-marks, or more correctly, casts of ripple-marks have been observed in only one small area within the mine. These small-scale ripples (Reineck and Singh, 1975) have a height of approximately 2 mm and a length of 3 cm. The size of the ripples and the fact that they were formed in a fine-grained sandstone indicates that they were formed in a quieter water environment.

No dependable flow direction was obtainable.

Current Lineation

Current lineation, a bedding plane feature consisting of a stream lining effect of sand grains on smooth bedding planes, is extremely rare. Only one set of lineations was observed. The lack of lineations

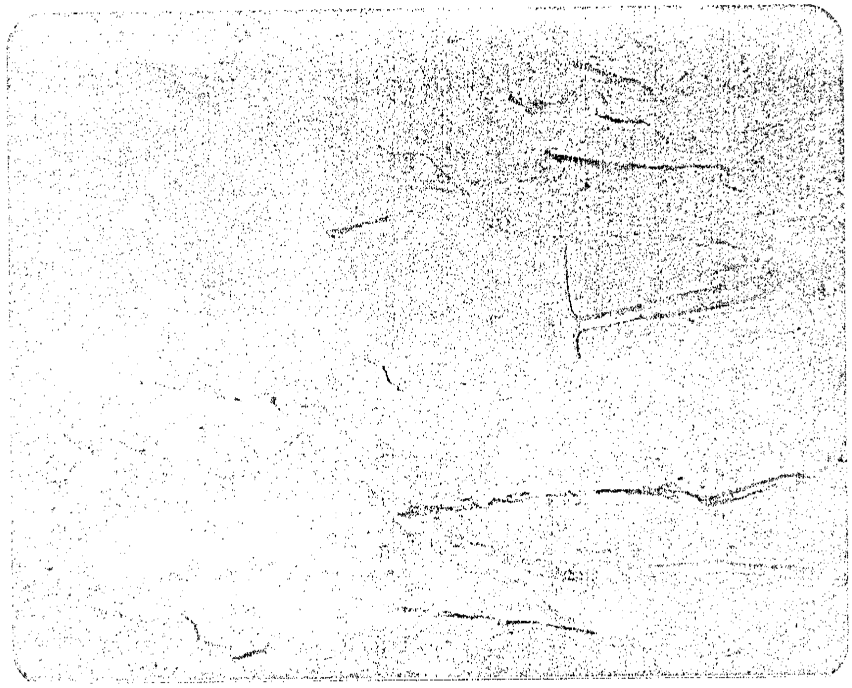

Fig. 15a - Hammer head points to scour contact between fine-grained sand below and coarse-grained sand above

Fig. 15b - Pencil points to scour surface between cross-bedded fine-grained sand below and coarse-grained sand above may be due to the very poor bedding plane exposures in the mine, as well as the difficulty of observing this structure.

Slump Features

Slump structure is a general term which includes all the penecontemporaneous deformation structures resulting from movement or displacement of already deposited sediments, mainly under the action of gravity (Reinck and Singh, 1975). Slumping of a sediment mass may result in the breakage and transportation of sediment, producing a chaotic mixture of different types of sediments, such as mud fragment clasts embedded in a sandy matrix, or vice-versa.

The slumping of mud layers is locally abundant in the mine. It is not unusual to have large, angular mudstone clasts or galls in a mixture of coarse-grained sandstone. These slump structures (Fig. 16) produced by gravity probably originated on the oversteepened banks of a channel. Occasionally, thin claystone layers can be observed disrupted and the angular clasts, up to an inch (2.5 cm) long, intermixed in the upper zone of the underlying sandstone bed. Distorted or contorted bedding within the sandstone beds is not a common feature.

Trash Piles

Squyres (1970) coined a term, "trash piles", for large, local accumulations of small, carbonized plant fragments within the Westwater Canyon sandstone. These features are also abundant in the sandstone horizons in the Johnny M Mine (Fig. 17).

These trash piles are large sedimentary accumulations up to 30 feet (10 m) wide and 10 feet (3.1 m) thick of various types of carbonized plant remains, such as reeds, grasses, and small branches (Fig. 18).

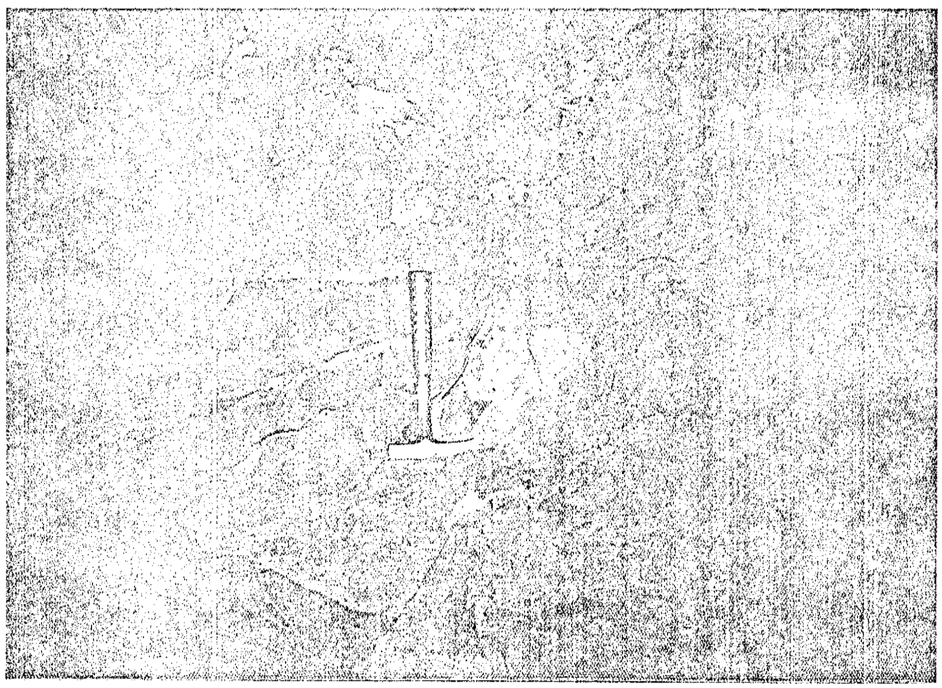

Fig. 16 - Slump structure - red clay galls in a sandy matrix

Fig. 17 - Trash pile - the dark brown material is uranium mineralization, and the white is kaolinite

Fig. 18 - Coalified organic debris commonly found in a trash pile

The matrix is usually a poorly sorted, gray, very friable, fine- to medium-grained sandstone that lacks any distinctive bedding. The organic debris tends to be uniformly distributed throughout the trash pile.

Trash piles consistently have low grade uranium mineralization - 0.04% to 0.10% U_3O_8 - probably due to the abundance of organic debris.

Claystone Cobbles

Conspicuous in several sandstone units are claystone or mudstone clasts, commonly called clay "galls". Sizes range from 1/8 inch to 2 inches (12 mm to 5 cm) but may be larger. The galls tend to be subangular and elongate. The long dimension of the galls, especially the small ones, are conformable with the bedding planes, thus giving the appearance of being deposited along the sand grains (Fig. 19a).

In addition to the smaller clay galls, mudstone clasts are present that range up to 3 feet (1 m) thick and tens of feet (several meters) in lateral extent. Here are found large clasts, up to 2 feet (.6 m) long, which are subangular fragments of once thick mudstone accumulations (Fig. 19b) in a quiet part of a channel system, possibly behind a big point bar on the inside of a meander loop. The mudstone layer broke up as a result of differential compaction prior to lithification. These galls must have formed in situ, since they are much too large to have been transported any significant distance. Sand usually fills the interstices between the galls.

Texture

The sandstones vary widely in texture. Grain size can vary from a very fine-grained sandstone to a sandstone with abundant pebbles (the Udden-Wentworth scale, see Blatt and others, 1972) through a vertical rib distance of 6 feet (2 m). The majority of the sand grains

Fig. 19a - Elongate, green clay galls concentrated along the bedding planes of a coarse-grained sandstone; the white nests are kaolinite

Fig. 19b - Large clay galls representing break-up of a claystone accumulation fall within a size range of .125 mm to .75 mm, which puts it in the range of fine to coarse sand. Taking into account all the different sandstone beds, the author estimates that the median grain size is about .4 mm, making it a medium sand.

Sorting is also variable, and there is a definite relationship between grain size and sorting. The coarser, conglomeratic sandstones are characterized by poor sorting (Fig. 20), with a phi Standard Deviation (where phi = $\log_2 d$, where d = diameter in mm) of 1 to 2 (Folk, 1968). This poor sorting is probably characteristic of flood stages, after which all the sediment is rapidly deposited together. The finer-grained sandstones are well-sorted, with a phi Standard Deviation of .40 to .50 (Folk, 1968). This sorting allows the finer sands to have permeability as good as that of the poorly sorted coarser sandstones. Overall, the sandstone sorting factor is phi S.D. = 1.00, somewhere between poorly sorted and moderately sorted.

An interesting feature of these sandstones is the fabric, particularly the grain to grain contact. While few grains, as viewed in thin-section, actually touch one another, the sandstones are probably grain supported. The overall spacing between the grains is usually less than half the diameter of the average grain. The grains that do touch meet on a point and not along a line. The lack of grain to grain contact is very evident in thin-sections of high-grade ore bearing sandstones. Here, the grains actually appear to be floating in a matrix of humate matter (Fig. 21). This floating is also apparent in barren sandstones that are well-cemented with calcite. It does not appear as if the calcite replaced a previous matrix, since there are no "ghosts" present. This could imply that the calcite was introduced during or shortly after

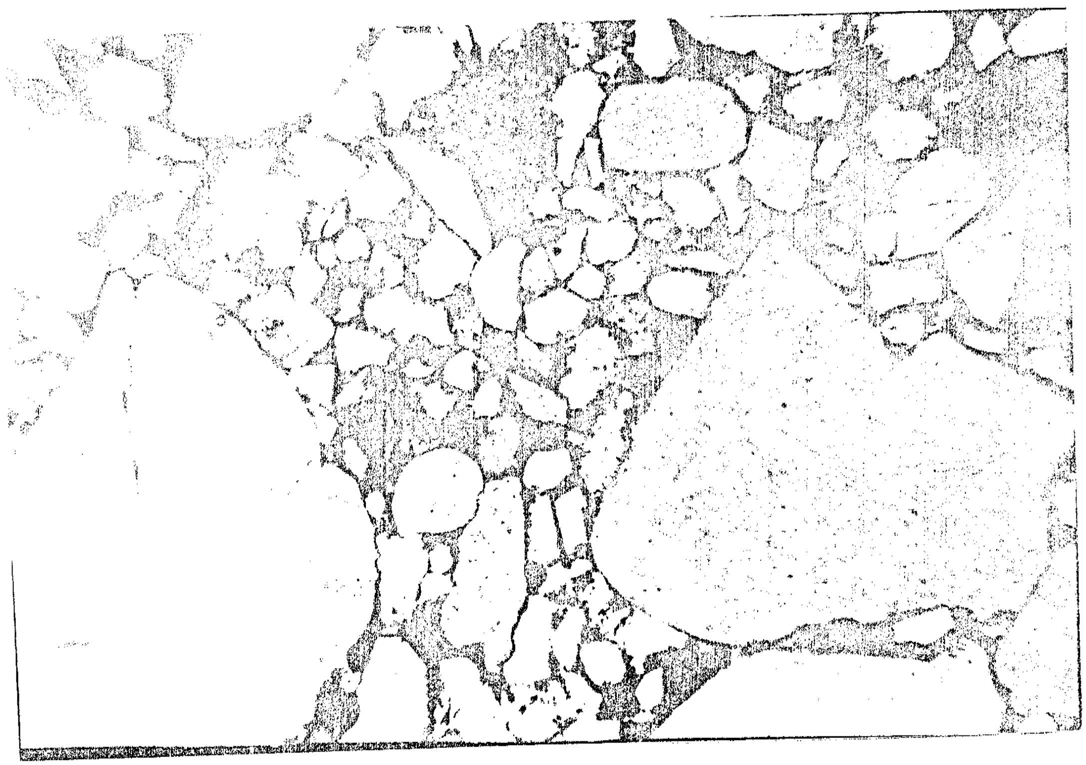

Fig. 20 - Poor sorting in a coarse-grained sandstone (2.5X)

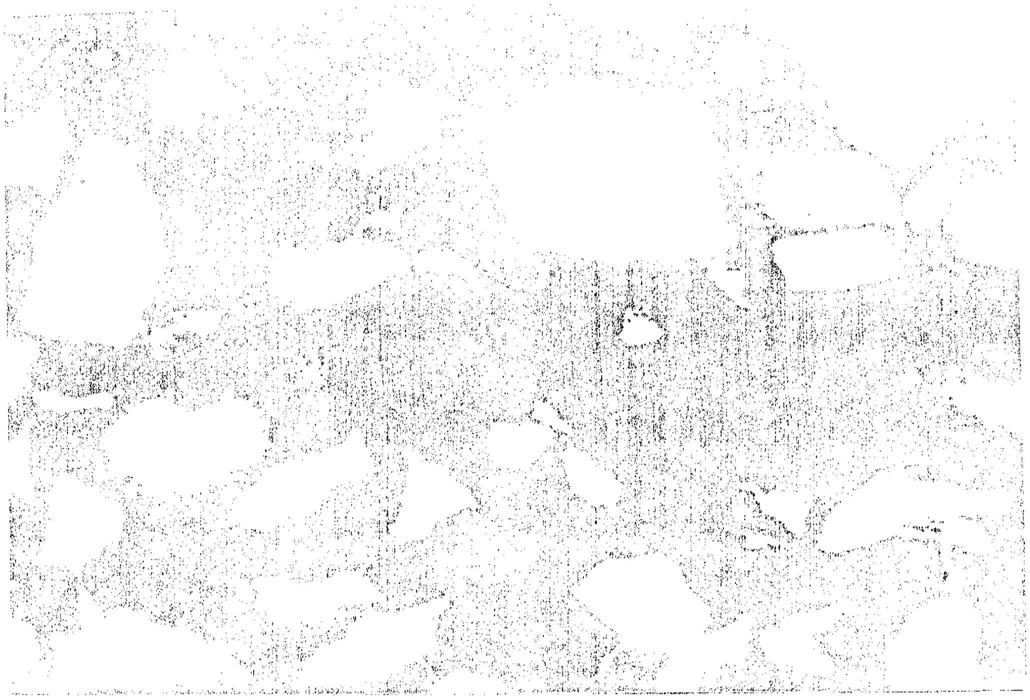

Fig. 21 - Detrital grains appear to be floating in a matrix of humate matter (2.5X)

deposition of the sands. In some thin-sections of ore-bearing sandstones, the relationship between the humate matrix and the sand grains suggests that the grains were deposited into the humate mass, since the distance between grains can be as much as 1.5 mm.

Color

The most variable feature of the Westwater Canyon sandstone horizons is the color. The predominant color is a light yellow-tan, but the whole spectrum of colors includes gray-brown, reddish-brown, gray-green, bleached tan, light gray, and red. No obvious pattern exists in the distribution of colors, except that sandstone adjacent to the ore bodies tends to be bleached gray-tan, whereas the sandstone is a distinctive red color away from the ore bodies.

The color of the sandstone may be uniform over some distance, but more commonly, it varies vertically in the rib. It is common to see a fine-grained yellow-tan sandstone overlain by a dark gray-green coarse-grained sandstone, or any other combination. Abrupt color changes typically correspond to either a change in the grain size of the sands, or in the amount of mudstone galls or lenses present. No one color is characteristic of any one feature.

Locally abundant in the sandstones are thin (up to 2 cm) streaks of red or green extending horizontally across an otherwise uniform horizon (Fig. 22). These streaks or bands may occur singly or in clusters. They may extend laterally for up to 20 feet (6 m), but they usually are not extensive. These bands may be either red or green in any one area, or the colors can be intermixed.

The only application of color to exploration for ore within the mine is that a thick sequence of red sands implies the disappearance of the ore zone.

Fig. 22 - Variable color scheme in medium-grained sandstone

Cement

Calcite is the major cementing agent in the Westwater Canyon sands, and it occurs as lenses rather than as a continuous, pervasive intergranular material. Where present, calcite transforms soft, friable sandstones into well-indurated rock. When a mudstone layer is present in a sandstone horizon, the most cemented sandstone zone will most likely be immediately above the mudstone layer, extending upward from 1 foot to 4 feet (.3 m to 1.3 m). It appears that the less permeable mudstone layer acted as a barrier for the cementing fluids. The contact between the well-indurated and friable sandstones is commonly a gradational one, extending over a zone of 1 to 2 feet (.3 m to .6 m).

Chert is occasionally present as a cementing agent, but is volumetrically unimportant. Interstitial clay is important in some beds, as it may be the only cementing agent. These sands are of course the most friable of the sandstones. In red sandstones, ferric oxides may also act as a cementing agent along with calcite.

Fossils

Fossils are very abundant in the Westwater Canyon sands exposed in the mine. Trees, branches, dinosaur bones, and grasses are encountered during mining.

Trees and branches range in size from 2 inches (5 cm) long and 1/2 inch (1.3 cm) across, to over 50 feet (17 m) long and 3 feet (1 m) across (Fig. 23). Most of these trees are completely replaced by silica and are barren of uranium. Carbonized trees and branches may be highly mineralized. A 100 lb. (45 kg) fragment of a tree collected during this study ran 16% U_3O_8. On some trees, the bark is almost perfectly preserved, looking fresh enough to burn. Knots are also clearly visible on some trees.

Fig. 23 - Largest fossil tree trunk exposed in the mine

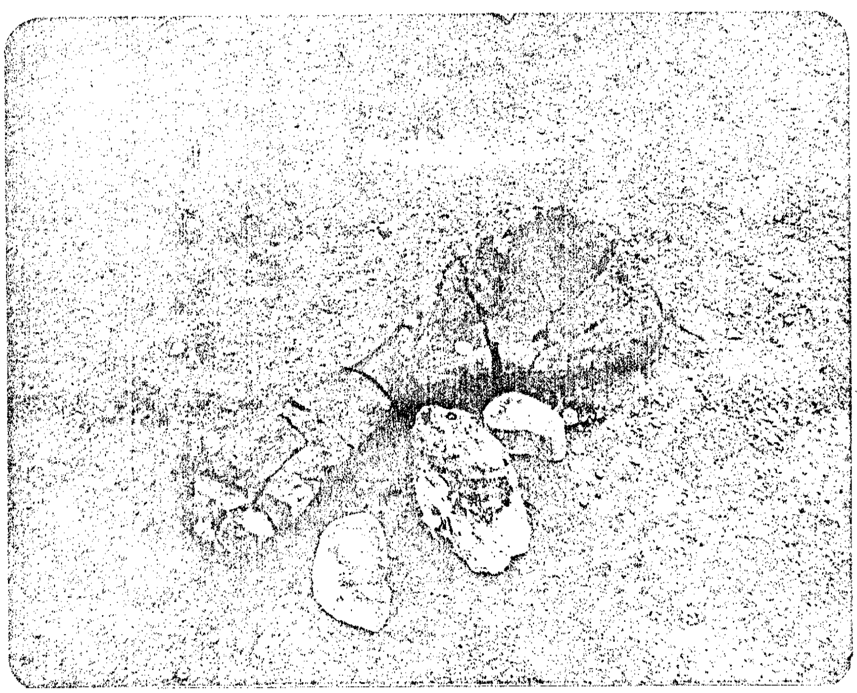

Fig. 24 - Sample of bones collected from the mine; the largest bone in the picture is a reconstruction of several small pieces

Dinosaur bones are particularly interesting. They range in size from a few inches to 12 feet (4 m) long (Fig. 24). The most commonly preserved specimens are the thigh and rib bones of these Upper Jurassic creatures. One observation made (Malkoski, M., mine geologist, personal communication, March 1978) was a rib bone, in full curvature, sticking out of a pillar. Practically all the bones observed are replaced by silica. In some cases the preservation is so good that the bone structure is visible to the unaided eye. Most of these bones are unmineralized; if any do contain any uranium it is in a thin carbonized crust around the fossil.

Carbonized remnants of reeds and grasses are locally abundant in grayish, organic rich, sandstones known as trash piles. The remnants are basically carbon remains that have been lithified into the sandstone. Fragments are usually 1 to 2 inches (2.5 to 5 cm) long, but never more than 5 inches (12 cm).

The two most interesting fossils that have been collected in the mine are fresh-water clams, and what appears to be a tooth. The clams, embedded in a coarse-grained sandstone, have been identified (Balk, C., personal communication, March 1978) as a member of the genus Unio, possibly of the species felchi. These clams are relatively common in the Upper Jurassic Morrison Formation of Colorado, but have never been reported in the Ambrosia Lake District. The habitat of these clams is interpreted (Balk, C., per. comm.) as fresh-water streams. Shells of the specimens collected in the mine are remarkably well preserved and in one piece. Only minor erosional wear on these shells indicates that their site of deposition was relatively close to their living grounds.

The fossil that appears to be a tooth was collected from a green claystone above a sandstone horizon. The tooth, only 1/4 inch (.6 cm) in the longest dimension, is well preserved and shows very little erosional wear. It is probably from a carniverous dinosaur, since the point on it is sharp.

Mineralogy

Detrital Minerals

The proportions of detrital minerals in the Westwater Canyon sandstones of the mine vary within wide limits; feldspar is usually between 25% to 40% of the total, with quartz comprising most of the remainder. Thus these sandstones are considered arkosic.

Quartz, on the average, composes approximately 61% of the detrital minerals, but can range from 35% to 71%. Most grains are clear and free of fractures, but some have inclusions of dust and a rare bubble. The extinction patterns commonly are uniform, but occasionally a strained pattern is observed. Quartz overgrowths occur but are uncommon. The roundness of the grains varies considerably from rare singly terminated crystals to very well-rounded grains, but most fall between subangular and subrounded (.3 to .5 on the chart in Krumbein and Sloss, 1955). The grain sizes rarely exceed 1.5 mm.

Orthoclase, the next most abundant mineral, comprises 13% of the detrital minerals. The orthoclase is commonly cloudy, more rounded than quartz, and contains fractures. Occasionally, some alteration, probably to sericite, is seen along the borders. Grain sizes are similar to those of quartz, with orthoclase more commonly occurring as larger grains.

Roundness ranges from angular (rare) to rounded, with the typical grain somewhere between subangular and subrounded.

The large pink grains that are conspicuous in hand specimen (page 12) are microcline, and comprise 8.5% of the detrital minerals. Microcline grains are usually very fresh, only rarely showing clay alteration. Polysynthetic twinning, or "grid-iron" twinning, characteristic of microcline is very well-developed (Fig. 25). Microcline grains are usually larger than adjacent grains of other minerals, and may be as large as 20 mm. Angular crystal laths are relatively common. It is surprising to see subrounded quartz grains next to angular microline grains. This possibly can be explained by the microcline crystal being in a larger pebble and ultimately being weathered out further from the source, thus the grain would show less erosional wear. The average microcline grain is commonly subrounded to subangular.

The plagioclase feldspar (14.5% of the detrital minerals) present in the Westwater Canyon sands is sodic. The extinction angles on the albite twinning for crystals cut normal to 010 range from 18^{o} to 30^{o}, with the majority of the angles being between 20^{o} and 25^{o} (Michel-Levy method). This, along with the positive optic sign, indicates that the plagioclase is principally in the composition range An_{0-50}, with the majority of the plagioclase being andesine. The grains are very closely twinned, but no zoning was observed. Plagioclase is more intensely altered than potash feldspar, with many grains being completely coated by a thin layer of alteration clay, probably a kaolinite or smectite. The grain shapes and sizes are comparable to that of microcline, except that the upper size limit is 2-3 mm. Grains of antiperthite, stringers of orthoclase intergrown in andesine, are present.

About 3% of the sandstone particles are rock fragments, mostly chert, with subordinate volcanic, granitic, limestone, and quartzite

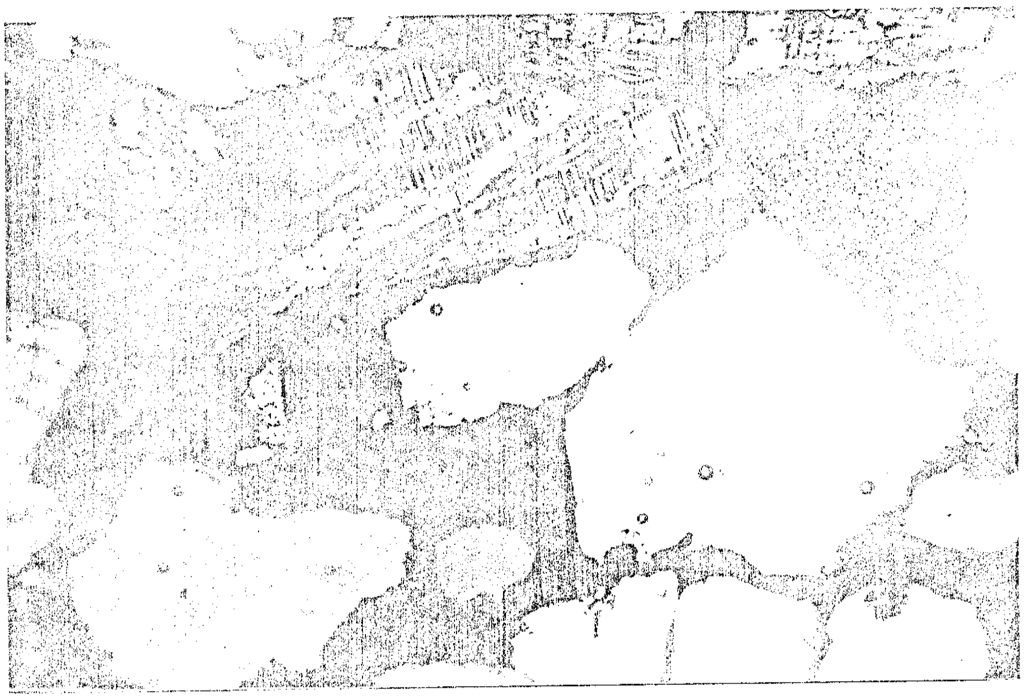

Fig. 25 - Microcline grain exhibiting polysynthetic or "grid-iron" twinning; the light grains are quartz (2.5X)

fragments. Chert grains, which may be as large as 15 mm in diameter, are often conspicuous in hand specimen. The chert grains are rounded and apparently quite fresh. Rare volcanic detritus consists mostly of semi-spherical masses of low-birefrigent clay minerals. A few identifiable sanidine grains are present, and these were almost completely dissolved leaving an empty shell.

Biotite and chlorite are present but uncommon in the 30 thin-sections examined by the author. Biotite appears slightly altered, and the chlorite exhibited its anomalous blue interference color.

The only heavy detrital mineral identified was apatite, and this was in only one thin-section. Pyrite, extensively altered to hematite but showing cubic form, exists but is rare. Magnetite and ilmenite are conspicuously absent from these sandstones.

Authigenic Minerals

The description of the minerals that follows is of the minerals that occur in the Westwater Canyon sands regardless of mineralization. The minerals that are intimately associated with the ore bodies will be covered in the section that describes the ore deposits.

Kaolinite - Kaolinite is pervasive throughout the mine, occurring in all sandstone horizons. The kaolin occurs as disseminated blebs or nests, ranging in size from a few millimeters to a couple of centimeters. These nests are composed of clean, white, well-crystallized kaolinite, filling the interstices of the sandstones and frequently surrounding several sand grains. The nests do not necessarily form around only feldspar grains; therefore it can be assumed that they do not form in situ, but rather the kaolinite flakes were transported some distance prior to deposition.

Nests are disseminated throughout all the sands, but are larger and more prevalent in coarser-grained sands. The nests may be either randomly distributed in the sands or follow sedimentary structures, such as bedding (Fig. 26a). Kaolinite nests, particularly in the coarser sands, follow the bedding. If many nests follow the bedding, the appearance is more of a linear belt than that of a series of individual blebs (Fig. 26b).

Where kaolinite nests are abundant, they may occupy about 5% of the volume of the sandstone; kaolin makes up about 40% of the volume within a particular bleb. Kaolinite also has been observed filling very small, narrow fractures in sandstone and cracks in carbonized wood. Kaolinite may coat smaller pieces of carbonized fossils.

When kaolinite nests are present in a sandstone that is penetrated by uranium mineralization, there is no physical difference to these nests as compared to the nests occurring in the barren sandstone. The kaolinite is definitely post-ore, since the nests are on top of the ore, and not coated by it. The source of the kaolinite is most likely plagioclase that is present in the sands themselves, as alteration is present on most of the plagioclase viewed in thin-section.

Calcite - Calcite, in addition to acting as the major cementing agent, occurs as small rhomb-shaped crystals filling fractures within the sandstones and claystones. Crystals are typically clear and well-defined, and may be as large as 1 cm. Calcite is also present in cracks in fossil trees and bones.

Barite - Barite occurs as honey-colored, tabular crystals up to 1 cm in length, and is limited to fractures in sandstones and claystones that occur in and near ore. The most visible barite crystals occur where

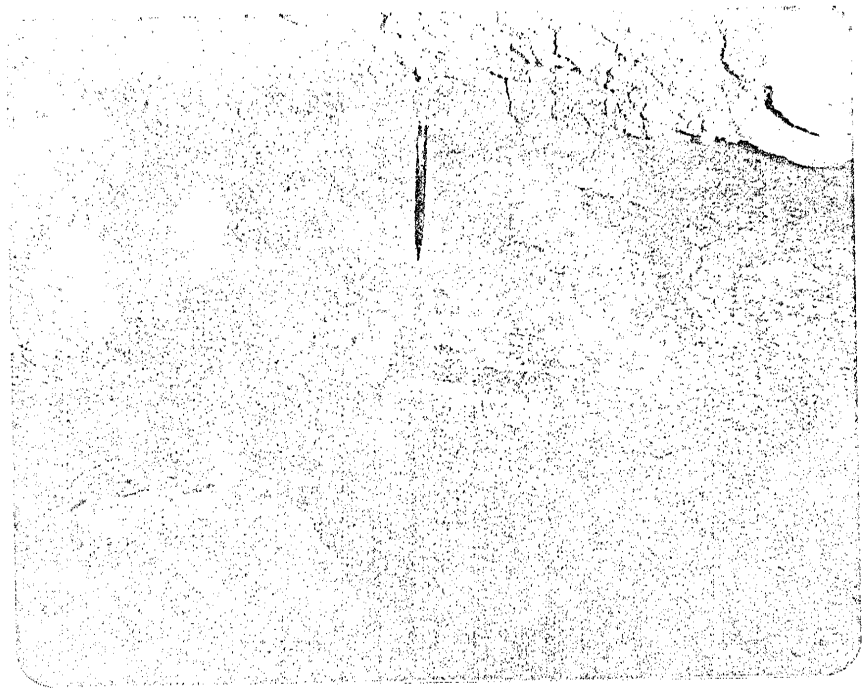

Fig. 26a - Large kaolinite blebs in a coarse-grained sandstone

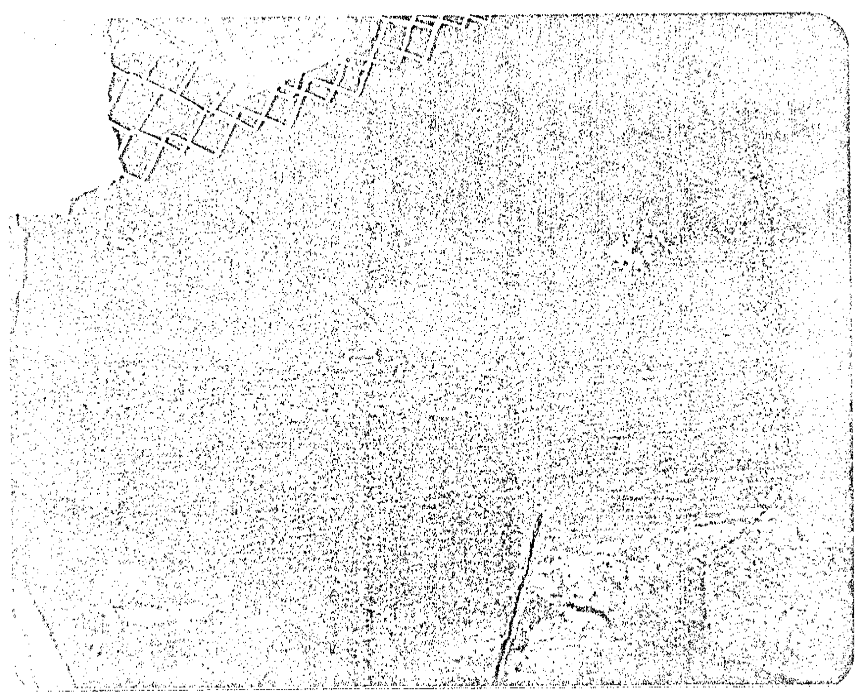

Fig. 26b - Kaolinite blebs, defining the bedding, appearing as linear belts the fracture crosses the ore pod, but they are also present along the fracture away from the ore. Sometimes, the crystals are coated with a very thin layer of what is presumed to be uranium mineralization.

Pyrite - Pyrite is not particularly abundant in the Westwater Canyon sands exposed in the mine. It may be present in fractures, in ore-bearing sandstones, in barren sandstones, and in claystones. The form is typically that of very small cubes arranged in pockets as a thin dusting perched on detrital grains in the sandstone. Their presence is revealed by their high reflectance. The pyrite exposed on the surfaces of the mine workings is typically fresh with no hematitic staining around or in the clusters.

Silica - Silica overgrowths on detrital quartz grains are pervasive throughout the mine and locally abundant, but actually comprise a very small fraction of the total rock. Overgrowths may be present on every quartz grain in a particular area, and impart a characteristic sparkle to the rock, but more commonly, they occur only on isolated grains.

Silica also occurs in the form of silicified wood and bones, which are widespread and abundant (see section on fossils, page 49). The larger detritus, such as trees and bones, are always silicified, either completely or in the center along with a carbonized periphery, whereas the smaller fragments are commonly carbonized.

Poison Canyon sandstone

The Poison Canyon sandstone is a gray to tan, generally poorly sorted, medium- to very coarse-grained and locally conglomeratic sandstone. The general composition is that of an arkose, with feldspars composing about 30% of the detrital grains.

The Poison Canyon sandstone typically is horizontally bedded with thin laminae of very coarse clastics interbedded with the finer material, but locally it is complexly cross-bedded. Cementing agents, mostly calcite, are irregularly distributed, yielding areas of friable sandstone and other areas that are very well-indurated. Grain size, and degree of roundness and sorting may vary considerably within beds, or from one bed to another. Claystone fragments are present along the bedding planes of the coarser material, but are not nearly so abundant as in Westwater Canyon sandstones. Larger claystone fragments, up to 20 cm long, are irregularly dispersed throughout the sand horizon but are rather rare.

Organic debris, abundant in Westwater Canyon sands, is very rare in the Poison Canyon sands. Trash piles do not appear here, and small pieces of carbonized plants and trees are rare.

The permeability is such as to support a considerable flow of water, as evidenced while drilling probe holes upward and outward.

Sedimentary Structures and Features

Compared to the Westwater Canyon sandstone, the Poison Canyon contains fewer sedimentary features. Features in common include channel-fill cross-bedding, foresets, graded bedding, horizontal bedding, and scour and fill features. These features are not as conspicuous nor as abundant as they are in the Westwater Canyon sands. The discussion given of these features on pages 31-37 is valid for the Poison Canyon sandstone, therefore the reader is referred to those pages. The Poison Canyon sandstone is conspicuously lacking in channel-lag deposits, slump features, mudstone cobble conglomerates, and especially trash piles.

A unique feature of the Poison Canyon sandstone is the existence of what appear to be scours in the top of the "K" shale, immediately below the Poison Canyon. These scours are broad, shallow features extending up to 100 feet (33 m) across. These scours indicate a change in depositional environment from the low energy processes that deposited the "K" shale, to an active fluvial system that deposited the Poison Canyon sands. The scours are the result of the first major channels to develop during the deposition of the Poison Canyon sandstone.

Texture

Texture of the Poison Canyon sands is varied. Grain sizes vary greatly from bed to bed and within beds. Within a vertical distance of 4 feet (1.4 m), the rock may change from a medium-grained sandstone to a sandstone with abundant pebbles (Udden-Wentworth scale). The majority of the sand grains fall within a range of .25 mm to 1.25 mm, between medium- and coarse-grained. The median grain size is probably near.65 mm, a coarse sand on the Udden-Wentworth scale. Thus the Poison Canyon sandstone is coarser-grained than the Westwater Canyon sandstone exposed in the mine.

Sorting within the Poison Canyon sandstone beds is as varied as in the Westwater Canyon sands. The coarsest sands are the most poorly sorted, within an overall phi S.D. of 1 to 2 (Folk, 1968). The finer sediments are better sorted, usually exhibiting a phi S.D. of .4 to .6. Overall, the Poison Canyon sandstone has a phi S.D. of 1.25, making it a poorly sorted sandstone on Folk's (1968) scale.

The fabric of the Poison Canyon sandstone is very similar to that of the Westwater Canyon, especially in that the sandstone is grain supported. Grains floating in the matrix are not as prevalent here as in the Westwater Canyon sands, but they do exist.

Color

The color of the sandstones is extremely consistent, being shades of gray and tan. Actually, the Poison Canyon gives the appearance that it has been entirely bleached, because there is essentially no red sandstone exposed. The dominant color is a light gray-tan; only rarely are green sandstones encountered.

Cement

As in the Westwater Canyon sandstones, calcite is by far the most abundant cementing agent. Its occurrence is unpredictable and spotty, occurring mostly as lenses rather than as a continuous sheet. Calcite tends to be more abundant at the bottom of the sandstone, concentrated along the contact with the "K" shale. Where calcite cement is not present, the sandstone is very friable. A gradational contact usually exists between the well-indurated and friable sandstones, extending over a zone of 1 to 2 feet (.3 to .6 m).

Chert is also a cementing agent locally, but it is volumetrically unimportant. Interstitial clay is the only cementing agent in the more friable sandstones.

Fossils

The Poison Canyon sandstone is virtually devoid of fossils. At most, only a dozen fragments of trees and grasses have been found. This is in surprising contrast to the fossil-rich Westwater Canyon sands, considering that both are fluvial sandstones.

Mineralogy

Detrital Minerals

The proportions of detrital minerals in the Poison Canyon sandstone fall into a small range, with feldspar making up about 30% of the detrital grains. Therefore, this sandstone is arkosic, similar to the Westwater Canyon sands.

Quartz is by far the most abundant mineral in the Poison Canyon sandstone, averaging 69% of the detrital minerals. The amount of quartz is fairly constant, ranging from 60% to 76%. Quartz grains are clear and fracture free, with rare inclusions or bubbles. Uniform extinction patterns are the rule, with only a very small number of grains exhibiting a strained pattern. As might be expected in a fluvial system, the roundness of the grains varies, but the majority of the grains fall between subangular and subrounded (.3 to .5 on the chart in Krumbein and Sloss, 1955), with a general tendency towards the subrounded category. The size of the quartz grains rarely exceeds 25 mm.

The second most abundant mineral is orthoclase, which averages 20% of the detrital minerals. These orthoclase grains are cloudier than quartz grains (due to alteration); they also contain some fractures. Sericite, an alteration product, is present along the borders of some of the grains. The orthoclase grains tend to be a little larger than the quartz, and are also more rounded. Grain shapes range from subangular to rounded, with most of the grains being subrounded. Perthite, orthoclase with blebs of albite, is irregularly present.

Microcline, which tends to form the largest grains in any one hand specimen, averages 4.5% of the detrital minerals in the Poison Canyon sandstone exposed in the mine. Microcline grains are very fresh, with prominent polysynthetic or "grid-iron" twinning. Angular crystals laths are fairly common, with grains up to 20 mm in diameter being common. Generally, microcline grains are larger than the adjacent grains. The majority are subangular to subrounded, with most being subrounded.

Plagioclase feldspar averages 4.5% of the detrital minerals. The extinction angles observed on the albite twinning range from 19^{o} to 28^{o}, and the optic signs are positive, thereby indicating that the plagioclase is sodic, having the composition of andesine. The grains are twinned, although not as closely as in the Westwater Canyon sands; no zoning was observed. Many grains are altered, thinly covered with a clay, probably kaolinite or a smectite. Lath-shaped grains are common, and most grains are subangular to subrounded. Grains rarely exceed 4 mm in diameter.

About 2% of the sandstone particles are rock fragments, mostly chert, with some granitic and volcanic fragments. Chert grains are commonly rounded and fresh, and may be as large as 15 mm across. The volcanic detritus is similar to that encountered in the Westwater Canyon sands, being spherical masses of undifferentiable clay minerals. Sanidine grains are rare, the visible ones being largely dissolved and leaving empty shells.

Biotite occurs as thin flakes, and is randomly dispersed throughout the sands. Pyrite is also present, but is commonly altered to hematite. As in the Westwater Canyon sands, magnetite and ilmenite are absent.

Authigenic Minerals

Since the authigenic minerals present in the Poison Canyon sandstone are the same as in the Westwater Canyon sands, the reader is referred to page 53 for the descriptions.

Structure

There is a striking contrast between the North and South sides of the mine as far as structure is concerned. The North side has virtually no major structures, whereas the South side is extensively faulted.

The North side is cut by several small normal faults, with an occasional reverse fault present. A typical normal fault with a displacement of 3 feet (1 m) is shown in Fig. 27. Most of these faults are accompanied by a thin zone of fault gouge. All the faults are post-ore as the ore bands are always offset by the faults. No ore has been found along the fault planes. The majority of the faults are high angle, with fault plane dips in the range of 50^{o} to 85^{o}. Fault planes strike consistently in a north-northeast direction, with a range from N10^{o}W to N40^{o}E, with the average strike around N10^{o}E.

An interesting structural feature present on the North side is a subtle monocline on the northeastern edge of the ore body. The monocline is approximately 100 feet (33 m) long and 30 feet (10 m) deep (as much as could be seen and deduced from the mine workings). Whereas the average dip of the beds in the mine is 3^{o}, the beds along the monocline dip at an average of 35^{o} in a N40^{o}E direction (Fig. 28). The monocline dies out rapidly as it is not present in the mine workings 25 feet (8 m) below. Some ore, with an average grade of 0.06% U_3O_8, is present in the sands of the monocline. The ore tends to follow the bedding closely as shown in Fig. 28. The contact between ore and waste is gradational in the down dip direction.

The South side of the mine is more intensely faulted than the North side (Appendix - Plates I and II). There are several faults or fault zones present with displacements up to 75 feet (25 m). In an east-west

Fig. 27 - Normal fault with the downthrown side on the right; displacement is about 3 feet (1 m); the fault plane trends N10°E

Fig. 28 - Monocline - the beds are dipping 35° to the northeast; the ore (black) follows the bedding

direction across the middle of the ore body, a series of northward striking faults causes the strata to be step-faulted down to the east. The total displacement across the fault series is about 93 feet (31 m) as shown in Fig. 29. All these faults are normal, with very steeply (Fig. 30) dipping fault planes (65^{o}E to 85^{o}E). Strike is generally in a north-northeast direction, with a range from N10^{o}W to N20^{o}E.

The fault zone on the east side of Fig. 29 is of particular interest. Total displacement is on the order of 70 feet (23 m) as indicated by study of the SP and Resistivity logs. The only observed faults in the area yield a total displacement of about 30 feet (10 m), therefore, an undetected fault or fault zone is present that has a total stepping down to the east displacement of 40 feet (13 m). This fault zone is probably 100 feet (33 m) wide.

In addition to these major faults there are minor faults with displacements from several inches to 3 feet (8 cm to 1 m). These faults are also normal, with dips from 60^{o}E to 85^{o}E, and striking from N5^{o}W to N20^{o}E, with one very small vertical fault striking N45^{o}W.

All these faults are post-ore and probably of Laramide age. As may be seen from the major fault zone map (Appendix - Plate III) the trend of the faults is to the north-northeast, and are probably associated with a northeast splinter of the San Mateo Fault zone (Fig. 8).

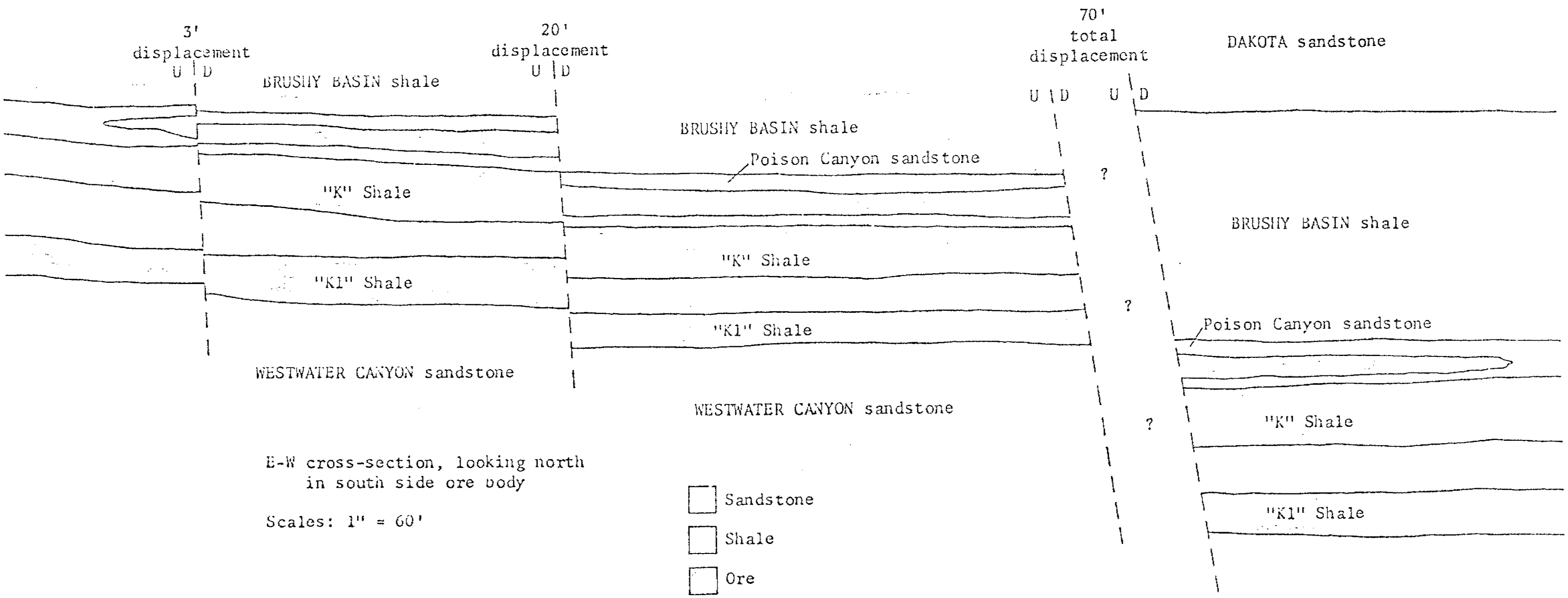

Fig. 29 - Illustration showing the step-faulting present in the South side ore body

Fig. 30 - Near vertical fault with a displacement of about 30 feet (10 m); the Brushy Basin (on left) is downthrown against the upper Westwater Canyon on right; the fault plane trend is N5°E

Paleostream Channels

Remnants of paleostream channels or channel-like deposits occur commonly in the sandstones exposed in the mine. Most of these features are small, such as channel scour troughs, on the order of 10 feet (3 m) across and up to 20 feet (6 m) long. Locally a channel deposit complete with a well defined basal conglomerate (see page 33), can be traced for up to 75 feet (25 m) long, and up to 35 feet (12 m) across. A couple of these larger channels have a distinct bank developed, as shown in Fig. 31. These channel banks are rare, but they can be detected either visually or through interpretation of long-hole drilling within the mine.

Since the mine workings are limited to those areas that show uranium mineralization, it is often hard to get data on the lateral extent of any possible channel system. The writer prefers to use the term channel system in describing the sandstones, because we are most likely dealing with not one major channel but an aggrading system of braided streams. Even without a distinctive channel scour to follow, one can usually identify a channel deposit by the presence of relatively variable, coarser-grained sediment that is strongly cross-bedded over a lateral distance of up to 100 feet (33 m). These zones often grade laterally into more uniform, finer-grained, horizontally bedded sandstone on either side. Numerous intersecting erosion surfaces are characteristic within the channel system. Claystone conglomerates, trash piles, and coarse plant and fossil detritus are more abundant here than elsewhere. Larger trees and bones tend to be accumulated along the outer extremities of the channel.

Stream channel directions implied by the sandstones of the Morrison Formation have been the subject of much study. Santos (1963) states that

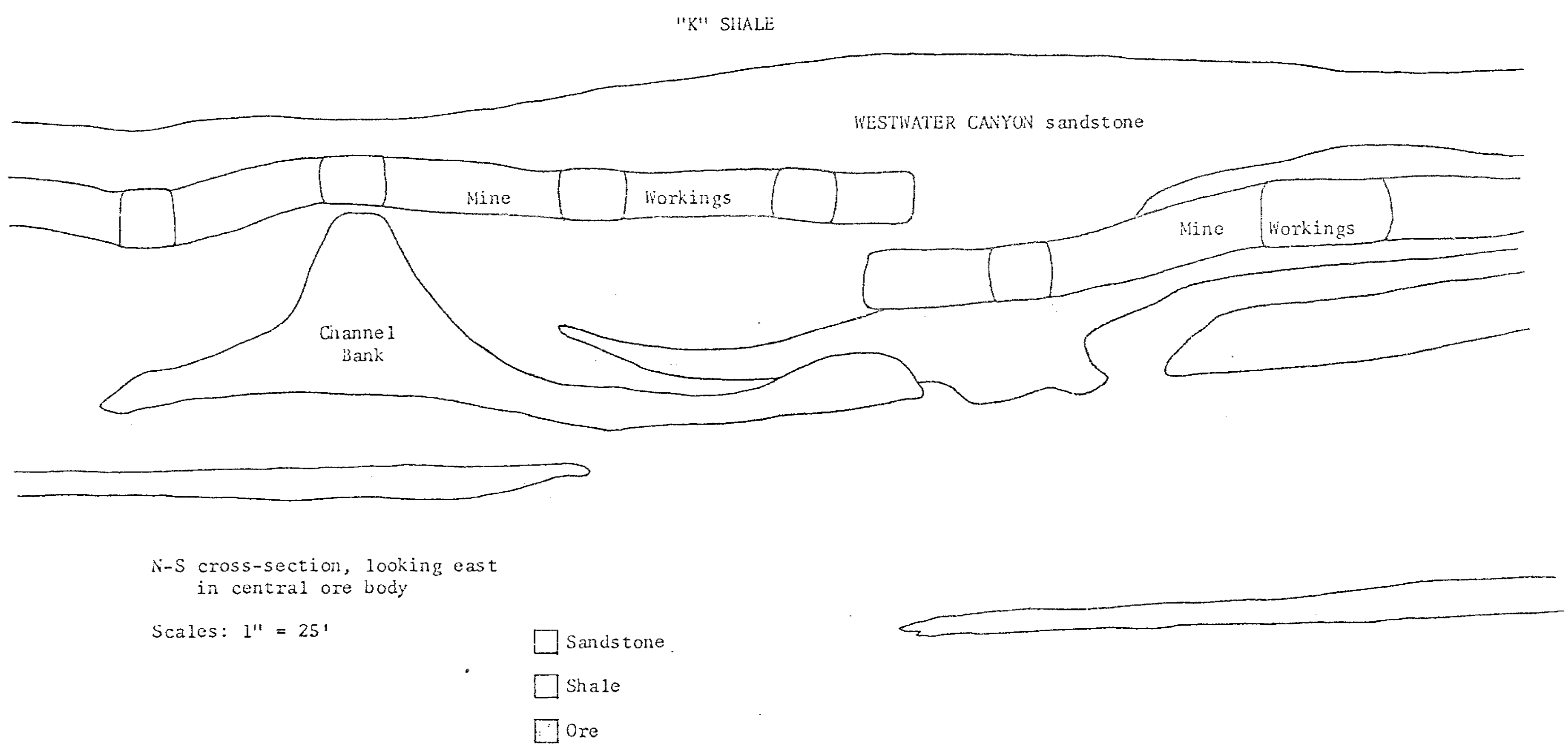

Fig. 31 - Illustration of a channel bank

the current lineations in many mines of the Ambrosia Lake District indicate that the lower two-thirds of the Westwater Canyon sandstone was deposited by streams oriented in a northwest-southeast direction, and the streams that deposited the upper one-third were oriented northeast-southwest. He did not reach any conclusions as to the streamflow direction. Granger and others (1961) also used current lineations to deduce a northeasterly-southwesterly flow in the upper parts of the Westwater Canyon and in the Poison Canyon sandstones. Squyres (1970) states that structures present in the Ann Lee Mine clearly indicate stream flow was to the southeast in the upper Westwater Canyon. Rapaport (1963), using cross-bed directions, log orientations, and heavy mineral lineations, showed that current flow during Poison Canyon deposition was to the east. Campbell (1976) states that the average bearings of paleocurrents in the Westwater Canyon indicate a northeasterly trend, but occasional averages are directed either northwesterly or southeasterly. Care must be taken in using Campbell's interpretations because his data was collected over a large area of Morrison outcrop. Riese (1977), in his study of the Morrison Formation near the Gulf Mount Taylor Project, states that the streams which deposited those sediments flowed to the southeast.

Oriented sedimentary structures of various kinds are abundant in the mine workings of the Johnny M. These include foreset dip azimuths, the long axis of channel scours, the axis of channel-fill cross-beds, and the long axis orientation of trees and bones. The directional resultants of these sedimentary features are generally quite consistent in any particular channel, and as it turns out, consistent throughout large regions of the mine.

The author collected directional data from all areas of the mine over a period of several months to determine if there was one major stream flow direction in this part of the Morrison Formation. This data was then fed into a computer program called Paleostat, for the vectoral analysis of the paleocurrent direction. The mine was broken down into four areas for ease of data separation: central ore body, 800-2, 800-3, and south side. These areas are shown in Figs. 32a and 32b. The analysis proved very interesting.

The central ore body, which is contained in the uppermost sandstone horizon of the Westwater Canyon (see Fig. 10), has a strong streamflow orientation of 112° east of north, with 80% of the data falling in the range of 60°-150°. This directional analysis was based on 96 measurements of scour trends, log orientations, and foreset dip azimuths.

The south side data is all from the Poison Canyon sandstone. Since there are very few logs present, the analysis was based on 62 measurements of foreset dip azimuths and the axis of channel-fill cross-bedding. This data yielded a presumed flow direction of 102° east of north, with 86% of the data falling between 30°-180°. There was obviously a greater spread on the measurements, nonetheless, a stream flow to the east is strongly indicated.

The data for the other two areas, 800-2 and 800-3, is not as abundant as for the first two areas, and thus the results are not as reliable. The lack of data is because these stopes are older and many areas are closed off. With 30 measurements of log orientations and scour trends in 800-2 (which is contained in the uppermost sandstone horizon of the Westwater Canyon), there is an indication that the stream orientation was northeast-southwest, but a reliable flow direction was

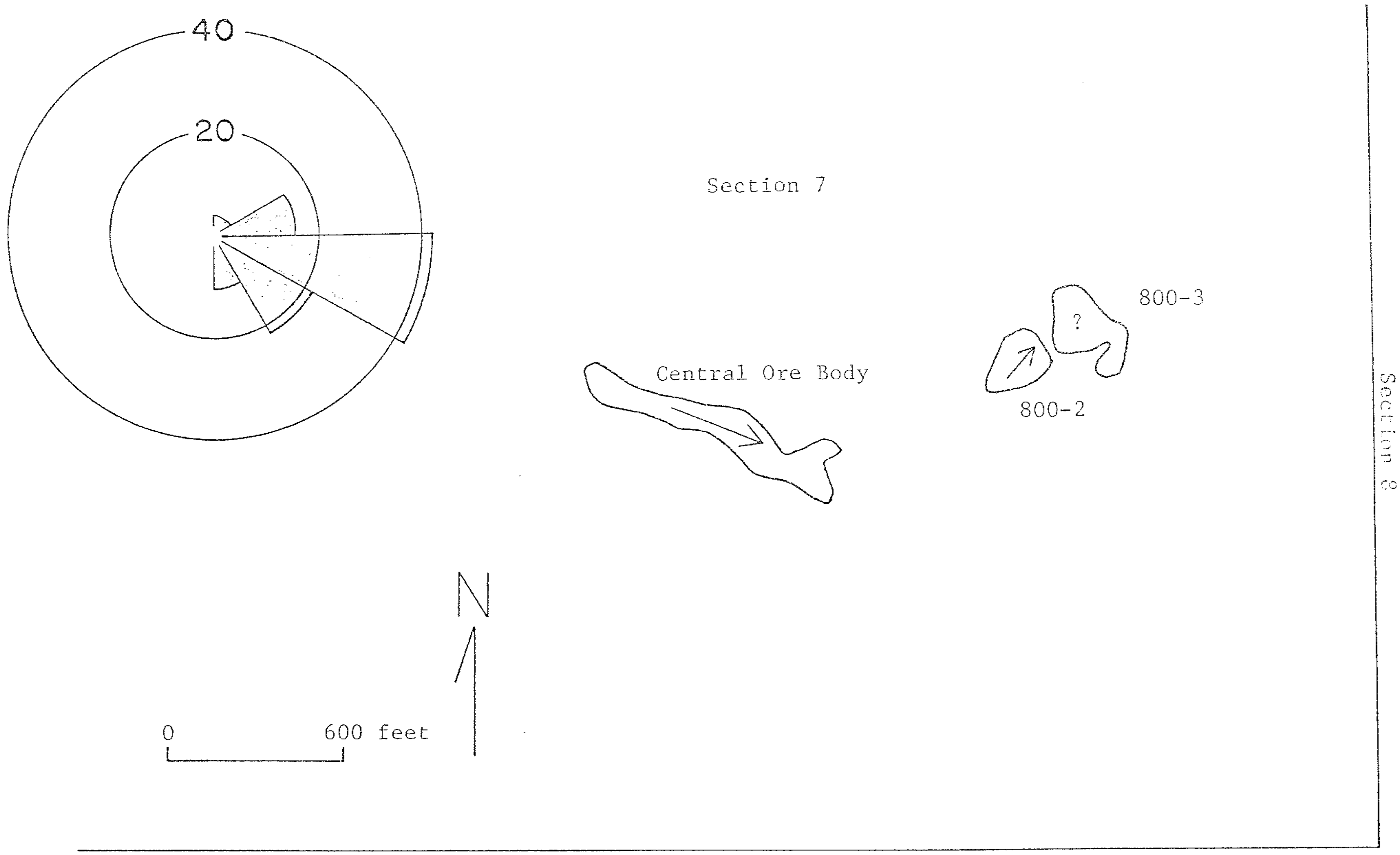

Fig. 32a - Orebodies in the North side and their paleo-current direction (rose diagram is in number of measurements)

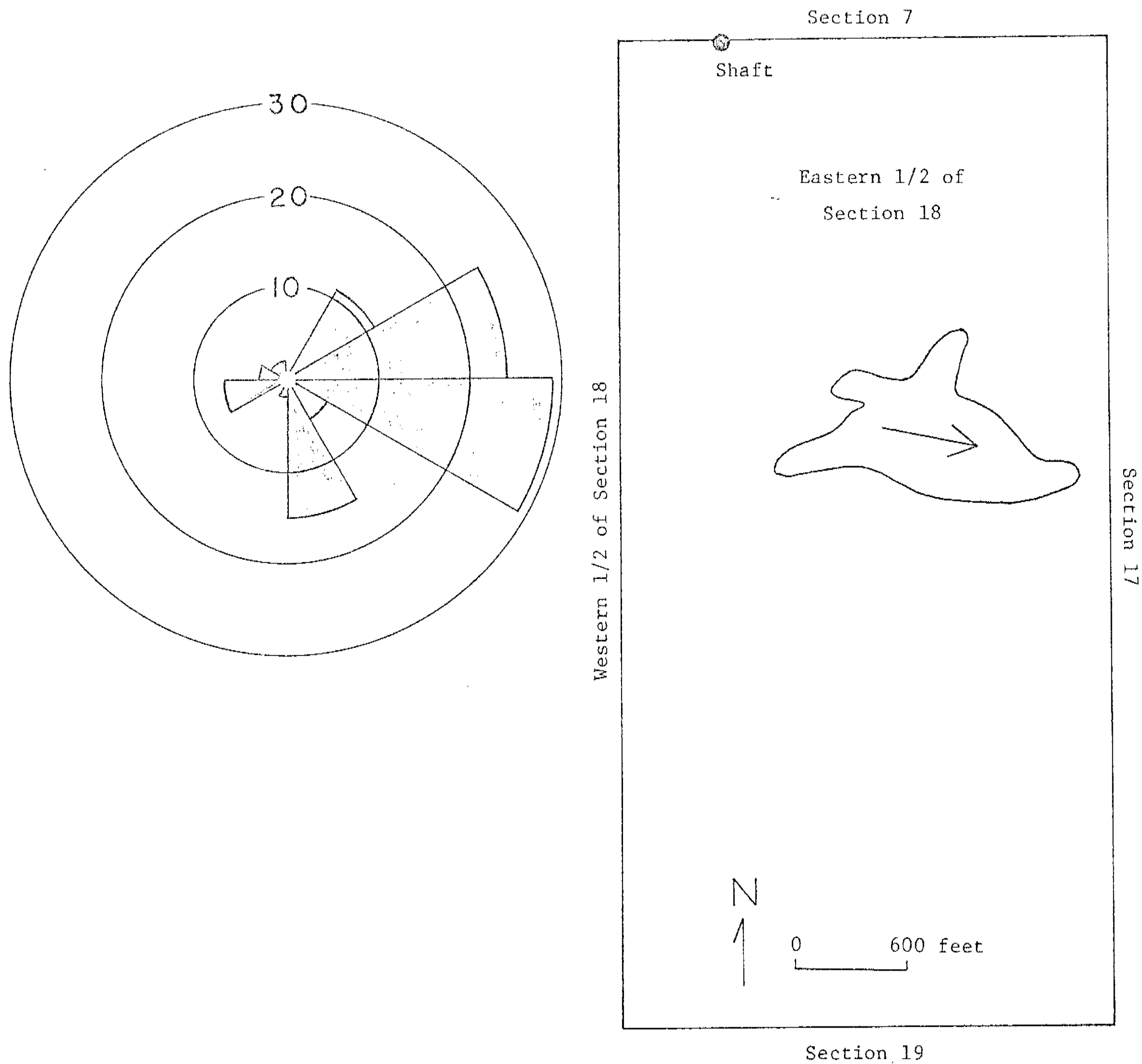

Fig. 32b - South side orebody and the paleocurrent direction (rose diagram is in number of measurements) not obtained (the author tends to believe the flow was to the northeast). There is wide dispersion in the data from 800-3. This may be attributed to the fact that this area of the mine is in the two upper sandstone horizons of the Westwater Canyon, and thus two different stream systems could have been encountered. Without corraborative data, all that can be said is that 75% of the data falls in the range 0°-150°, thereby indicating an easterly trend.

In summary, sedimentary evidence present in the sandstone horizons in the Johnny M Mine indicates that most of the stream systems that deposited the sediments flowed in a predominantly easterly direction (Figs. 32a & 32b). As the channels were part of a complex braided stream system, some dispersion in the channel orientation would be expected. Since the Johnny M Mine is situated right on line between the old main body of the Ambrosia Lake District and the Gulf Mount Taylor Project, this paleocurrent data provides an additional link. The author is fairly convinced that with all the new data available, the streams that deposited the sediments of the upper Westwater Canyon sandstone and the Poison Canyon sandstone flowed eastward, with a slight component to the south.

Environments of Deposition of the Morrison Formation

The first major interpretation of the depositional environment of the Morrison Formation was by Mook (1916). Mook interpreted the Morrison Formation as a broad alluvial plain, formed by a number of individual, coalescing fans, with lakes forming locally. He likened the Morrison deposits to the great alluvial plains of eastern China.

Stokes (1944) agreed in general with Mook's interpretation but states that Mook did not take into account the part played by volcanic ash in building up the Morrison Formation, as indicated by bentonites.

Craig and others (1955), McKee and others (1956), and Harshbarger and others (1957) all concluded that the Morrison Formation in northwestern New Mexico was deposited primarily in a continental fluvial environment with streams flowing to the north and/or northeast from a source area in southwestern New Mexico known as the Mogollon Highlands.

Craig and others (1955) state that the facies distribution of the Westwater Canyon Sandstone Member indicates that it was deposited as a broad fan-shaped alluvial plain. The unit was formed by an alluviating distributary system of braided channels, and represents a continuation of Recapture deposition. The Westwater Canyon differs, however, in that it consists of much coarser material than the Recapture. This is thought to reflect a rejuvenation of the source area in west-central New Mexico. As the source was reduced and ceased furnishing coarse material, Brushy Basin sediments were spread over the area of deposition of the Westwater Canyon sandstone. Craig and others (1955) also note that the abundance of fossil plant and dinosaur remains suggests that the climate was humid.

Hilpert (1963) summarizes the views of some writers in the district:

> "Studies of the lithologies and sedimentary structures of the Morrison by Craig et al. (1955) indicate that the sediments were largely derived from a landmass in east-central Arizona and west-central New Mexico and were deposited by an aggrading system of northeastward flowing streams. The sediments of the Brushy Basin Member were probably deposited in a mixed lacustrine and fluvial environment in which the fluvial material probably came largely from the Mogollon Highland to the south (Harshbarger et al., 1957)."

Santos (1970) states that the composition of the clastic material in the Morrison units indicates that they were derived from sedimentary, igneous, and metamorphic terranes. The Recapture Member is regarded as a fan-shaped alluvial plain constructed by aggrading streams carrying clastic material to the northeast and east. Rejuvenation of the source area (postulated to have been south of Gallup) resulted in the deposition of a blanket of coarser sand - the Westwater Canyon Sandstone Member - over northwest New Mexico. The trend of current lineations in the Ambrosia Lake District indicates that in this area the streams that deposited the sands flowed east-southeast during deposition of lower Westwater sands, and northeast during deposition of upper Westwater sands.

Flesch (1975) shows that the genetic sequences of the Westwater Canyon resemble relatively rapidly aggrading stream sequences deposited by wide but shallow, low sinuosity, sandy, braided streams (Fig. 33). Problems exist, according to Flesch, in definitely stating that the Westwater Canyon streams were braided, for they lack planar (tabular) cross-stratification typical of transverse bars, and characteristics of longitudinal bars. Most longitudinal bars, however, have been described for gravelly, braided streams, whereas the Westwater Canyon units are mostly medium-grained sands.

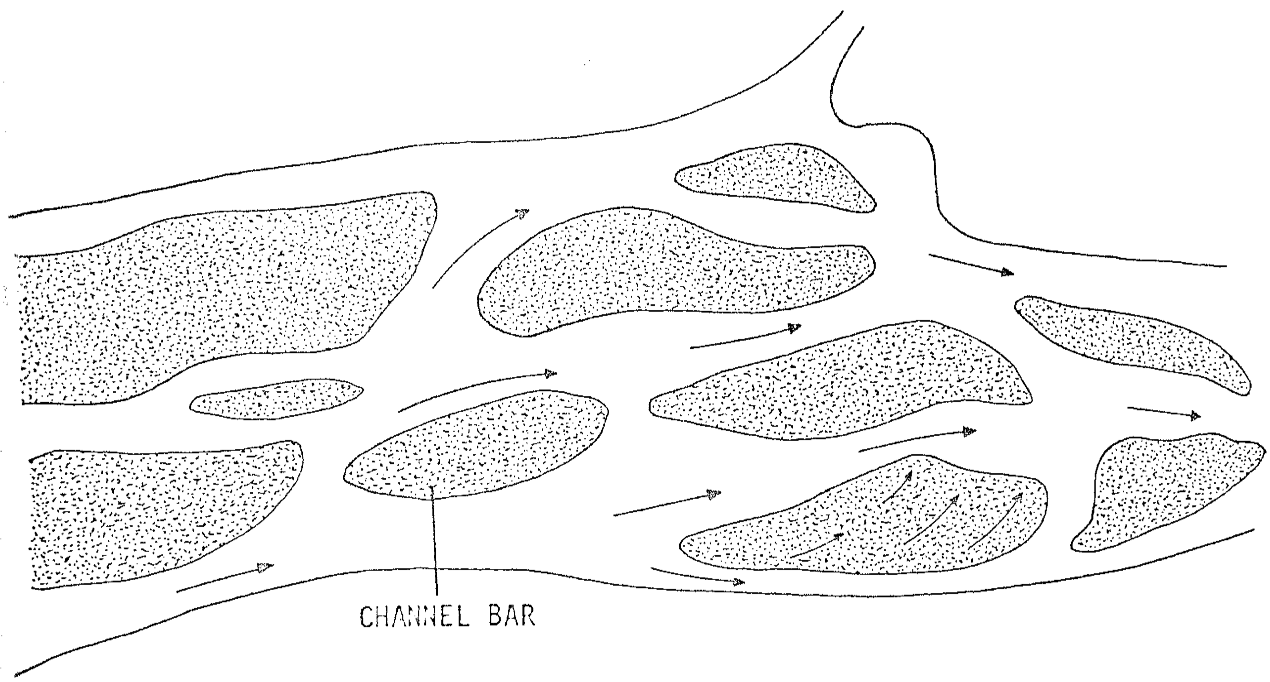

Fig. 33 - Schematic drawing of an idealized braided stream (modified after Reineck and Singh, 1975)

The sedimentologic characteristics of Westwater Canyon sandstones are somewhat unique in that they resemble neither well-documented meandering nor braided streams, but appear to fall somewhere in between. The repetitive internal sequence of scoured surface - trough filling - horizontal stratification - clay drape, argues against meandering (Flesch, 1975). Since the sandstone units are widespread, if they did not originate as superimposed loop deposits, they must have originated as shallow, widespread river systems containing smaller scale, braided or anastomosing streams.

Flesch (1975) also states that a model of meandering streams with extensive floodplain deposits containing temporary fresh water ponds best explains the Brushy Basin Shale Member. Claystone units are thick and extensive with occasional thin micrite beds and contain randomly intermixed, discontinuous sandstone units of local to more widespread extent and variable texture (silt to gravel). Streams of varying magnitude existed, from small accessory stream channels tens of feet in width, to more persistent, larger streams up to a few hundred feet in width (possibly locally of low sinuosity?). Streams which deposited the more persistent sandstone units may have had an overall meandering pattern. Sediment deposition occurred principally during flood stage, at which time point bars were drowned and the streams took on a low sinuosity pattern.

Campbell (1975) states that the Westwater Canyon sandstone in northwestern New Mexico should be regarded as a fluvial sheet sandstone. This sandstone body consists of coalescing fluvial channel systems that in turn are composed of still smaller coalescing individual channels.

Campbell concluded that the Westwater Canyon probably formed by the coalescing of braided stream deposits.

Based on a review of the literature and on personal observation in the mine and in outcrop, the author concludes that the Westwater Canyon Sandstone Member of the Morrison Formation was formed by an aggrading system of low sinuosity braided streams. This interpretation is supported by the following data: 1) low dispersion of paleocurrents, 2) paucity of silts and muds in the section, and 3) the high width to depth ratios of the channel scours. These streams flowed on broad, coalescing alluvial fans emanating outward from a source (Mogollon Highlands) in west-central New Mexico. While the major flow was to the north and northeast, filling and choking of these channels probably caused braided, perhaps ephermal distributaries to spill laterally off the flanks of the fan (Granger, 1968). These newly created streams would then yield the easterly depositional trends that are evident in the Ambrosia Lake District, in the Johnny M Mine, and in the Mount Taylor area.

The Brushy Basin Shale Member, with its laterally uniform, blanket-like shale units, and random, discontinuous sandstone units (Poison Canyon sandstone), was probably deposited in an environment of meandering streams with extensive floodplains, dotted with an occasional small fresh water lake. This interpretation is supported by: 1) the relatively high dispersion of paleocurrents, 2) paucity of extensive sandstone units in the section, and 3) the low width to depth ratios of the channel scours.

CHAPTER IV

ORE DEPOSITS

The uranium ore consists essentially of sandstone that is impregnated by a dark, tarry-looking organic substance which coats sand grains and fills interstices. The uranium is contained within the organic material. There are occurrences of organic material that contain no uranium mineralization, but never has uranium mineralization been found that has not been intimately associated with some type of organic material.

The color of the ore ranges from a light gray-brown to a very dark black. There is a direct relationship between the thickness of the grain coating (and ore grade) to the color of the mineralization: the darker the color, the higher the U_3O_8 content. With practice, a person can visually estimate the grade of the ore with good accuracy from .05% to 1% U_3O_8, and with lesser accuracy as the ore grade exceeds 1%.

The average grade of the ore from the Ambrosia Lake District, discounting dilution during mining, is about .20% U_3O_8. The Johnny M ore has an average grade of .40% to .45%, with ore ranging from .05% to over 2% U_3O_8. Sub-ore grade material, less than .05%, is also abundant and widespread in the mine.

Vanadium occurs associated with the uranium ore, although in lesser concentrations. Vanadium ranges from .02% V_2O_5 in very low-grade uranium ore, to 1.25% V_2O_5 in high-grade uranium ore. Molybdenum, copper, selenium, and arsenic, listed in order of decreasing abundance, also are concentrated in the uranium mineralization. Iron is much more abundant than all the elements (except for uranium), but there is little change in its concentration between ore and the surrounding sediments.

Squyres (1970), in his review of the Grants Uranium Region, states that at least two generations of uranium ore are present: an early generation that is displaced by Laramide faulting, and a later generation which has been directed and controlled by the faults, as opposed to displacing the ore. Even though there are several major fault zones and numerous small faults with a north-south trend (see structural section) cutting the stratigraphy in the Johnny M, the ore is only displaced rather than diverted by the faults. Therefore, it is assumed by the author that all the uranium ore in the Johnny M is early. It will be mentioned later that some of the ore in the mine has been remobilized, but this is not connected to faulting.

The uranium ore that occurs in the Poison Canyon sandstone is slightly different in form and distribution than the ore which occurs in the Westwater Canyon sandstone. Therefore, the author will treat each separately.

Westwater Canyon Ore

Form

The ore bodies shown in Fig. 32a define regions which enclose all known currently commercial grade ore. The uranium mineralization is not consistent throughout the individual ore bodies, being composed of numerous ore pods.

The overall trend of the ore bodies is linear. The central ore body (see Fig. 32a) is about 1000 feet (333 m) in length and up to 200 feet (66 m) in width. The thickness of the ore body varies as the ore is not confined to one specific level in the horizon, which is the uppermost sandstone horizon in the Westwater Canyon sandstone, but it is usually no more than 15 feet (5 m) thick at any one location. The lateral extent of this ore body is more predictable than is the thickness. This shows up well in mine drilling programs where no ore is encountered laterally outside the defined regions of the ore body, whereas up and down probe holes sporadically strike ore.

The other two bodies, 800-2 and 800-3, contain ore that is complexly layered in the two upper sandstone horizons of the Westwater Canyon. The two ore zones are often separated by a 5-10 foot (2-3 m) shale zone ("Kl" shale). While the ore bodies are distinct in themselves in their respective horizons, they can be stacked on top of one another.

In plan view, ore bodies 800-2 and 800-3 lack any truly definable shape but tend to be ellipsoidal. Ore body 800-2, which is situated in the same horizon as the central ore body, is the oldest ore producing stope in the mine and is now closed down. The gross dimensions of the ore body were 300 feet (100 m) long and 200 feet (65 m) wide at the widest point. This ore body contained some of the richest ore encountered in the mine.

Ore body 800-3 is a unique stope in that the ore occurs in the two upper sandstone horizons of the Westwater Canyon. This is not the result of one continuous ore body, but rather the interfingering of two distinct ore zones. Overall, the ore bodies are linear to ellipsoidal in plan, being about 600 feet (200 m) in length and up to 300 feet (100 m) wide. Since the ore occurs in two different levels, the stope is 60 feet (20 m) high in places.

The ore bodies are not one continuous zone of uranium ore but rather consist of individual ore pods that occur in various shapes (Figs. 34a, 34b, 34c, 34d). The predominant ore pod form is that of elongated,

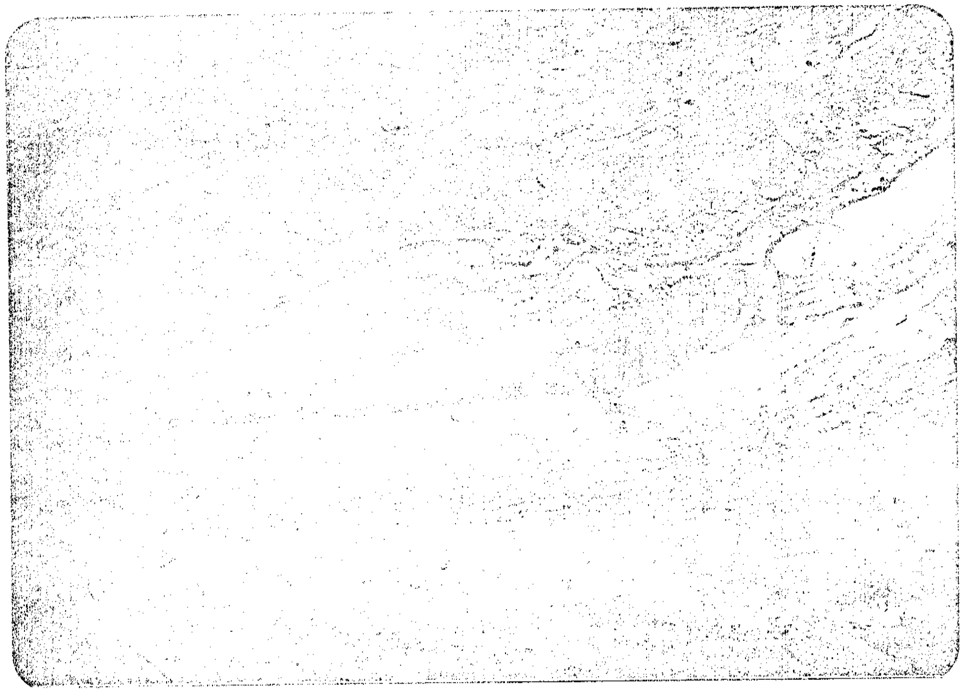

Fig. 34a - Ore pod in a fine-grained sandstone; note the red band above and to the right of the pod

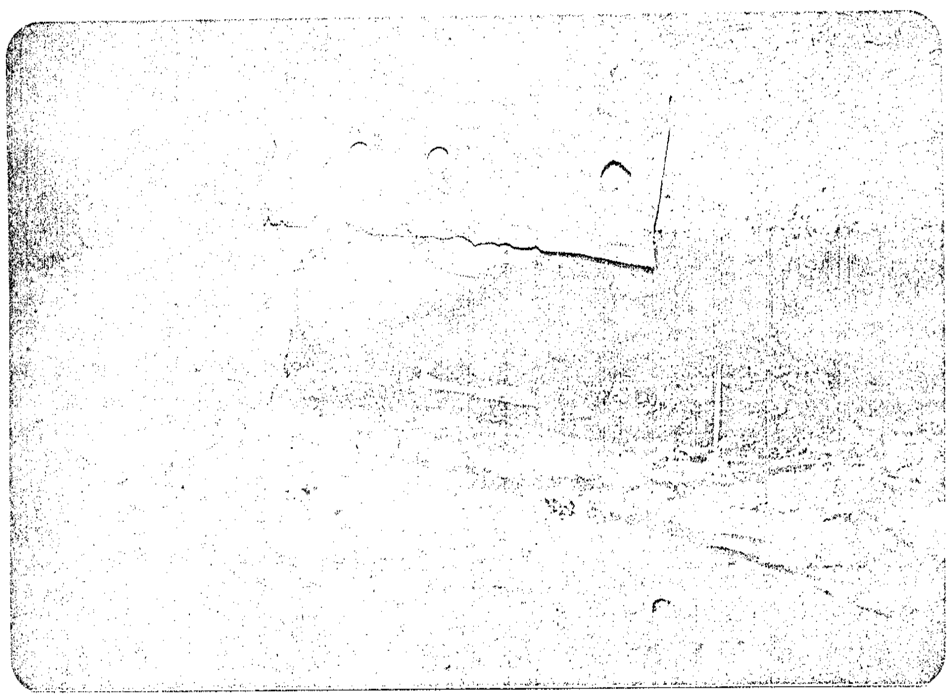

Fig. 34b - Ore pod in a medium-grained sandstone; note the red band below the pod. This form is the most characteristic of the ore pods in the Westwater Canyon

Fig. 34c - Ore pod, looking south; note the red band below and to the right of the pod

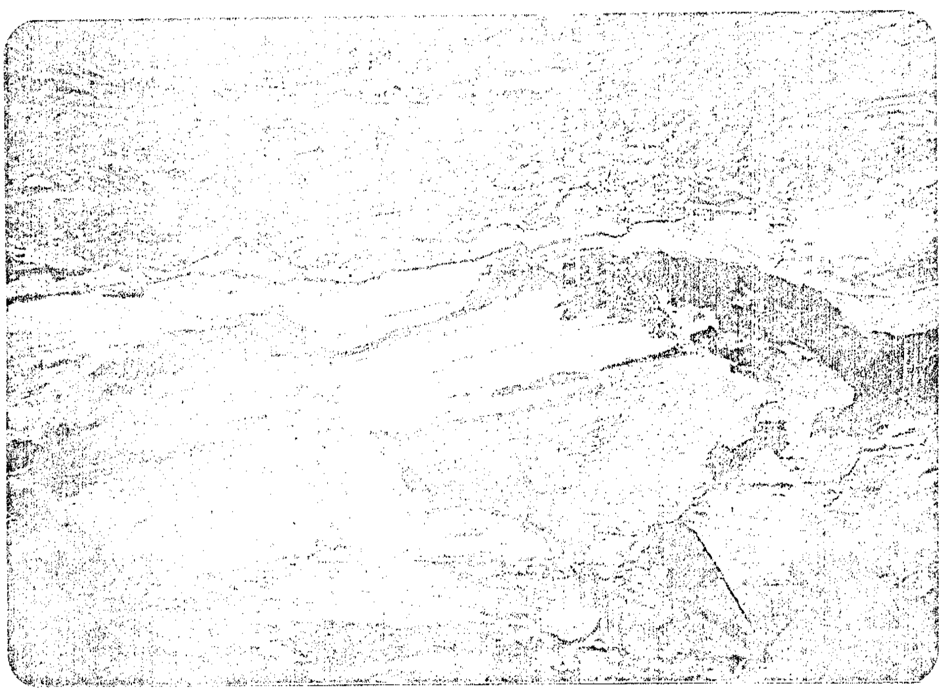

Fig. 34d - Complex ore pod; note the red band above the pod tongue-like lenses that can range from 3 feet (1 m) to over 30 feet (10 m) long (Fig. 35). These pods are commonly lenticular in cross section with a length-to-width ratio of 2:1 to 25:1. The thickness of any given individual ore pod is usually less than 5 feet (1.6 m). Numerous thin ore pods may occur together, resulting in complex forms.

Blanket ore is a term given to very long, thin ore pods that are irregular in ore content and unpredictably undulate or "roll" through the sandstone horizons (Figs. 36a and 36b). The pod usually only deviates about 6 feet (2 m) from some horizontal plane. This blanket ore is commonly situated in the lower part of the exposed sandstone layer, usually occurring atop a claystone zone if one is present. Calcite cement usually separates the ore from the claystone zone.

Since it is difficult to view the ore pods in three dimensions, a trend is not always obtainable; when an ore pod trend is visible or projectable, the elongation is commonly parallel or subparallel to the overall trend of the entire orebody. This is especially evident in the central ore body.

The ore pods, especially the smaller ones, are generally uniform in ore composition, and have sharp boundaries with the surrounding barren rock. The U_3O_8 content of the sandstone at the ore boundary can decrease several hundred-fold in a distance of 2 inches (5 cm). Some contacts are knife-edge sharp. Some of the pods are patchy and ill-defined, and these generally are much lower in U_3O_8 content than the more uniform ore pods. The smaller, more homogenous ore pods are consistently the richest ones, commonly containing over 1% U_3O_8. The richer ore pods also contain the most calcite cement. The cement usually extends beyond the ore boundary for one or two feet (.3 to .6 m) and

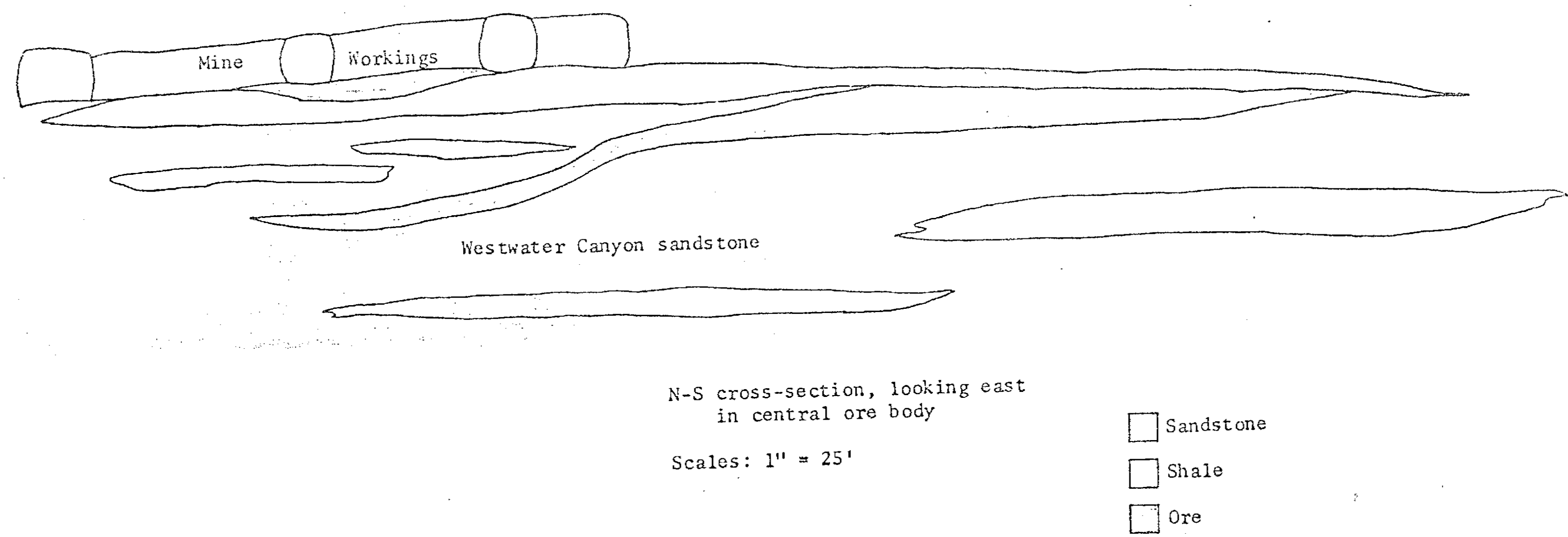

Fig. 35 - Overall form of the ore pods in the Westwater Canyon

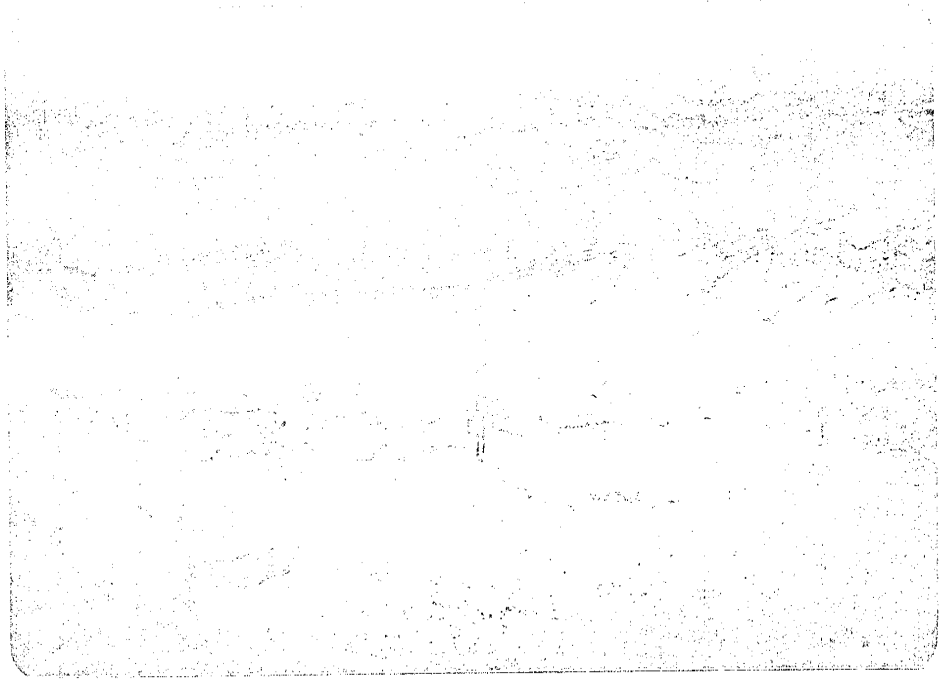

Fig. 36a - Typical blanket ore

Fig. 36b - Blanket ore

then gradually dies out into more friable, barren sandstone. The larger ore blankets are more friable than the smaller pods, but much better indurated than the average barren sandstone.

Uranium mineralization is always present in a sandstone host, regardless of grain size of the sandstone. Ore occurs in the sandstone matrix of clay gall conglomerates, but the ore is strictly confined to the sand matrix and only on one occasion has the ore penetrated the clay. Only one clay gall isolated in sandstone contained very minor uranium mineralization.

Miscellaneous Features

Ore Rolls - The term roll, synonymous with ore roll, is applied to any curving surface which cuts across the bedding of the host rocks (Squyres, 1970). Crescent-shaped ore pods, similar to the overall geometry of the classical Wyoming-type roll, occur in the Johnny M Mine, but on a very much smaller scale. These rolls are very rare and may be as much as 12 feet (4 m) long and 4 feet (1.3 m) high (Fig. 37). This roll has a distinct head with two tails extending outward, which are usually interpreted to point in the direction from which the ore fluids came. The roll was elongated nearly parallel to the trend of the central ore body. The convex side (front) of the roll has a sharp contact with barren, bleached sandstone, whereas the concave side (back) of the roll has a more diffuse contact and is feathery. The ore is evenly distributed throughout the roll. The tails tend to feather out into the host sands. Sandstone immediately adjacent to the ore roll is bleached tan-gray, whereas sandstone further out around the roll is gray-green, suggesting that the bleaching effect is probably associated with the formation of the ore roll.

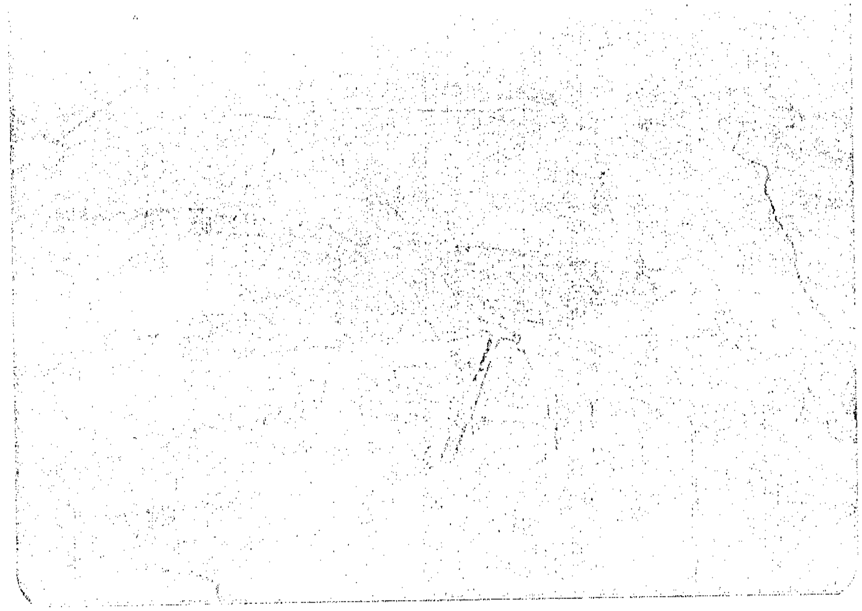

Fig. 37 - Ore roll; the trend is to the southeast

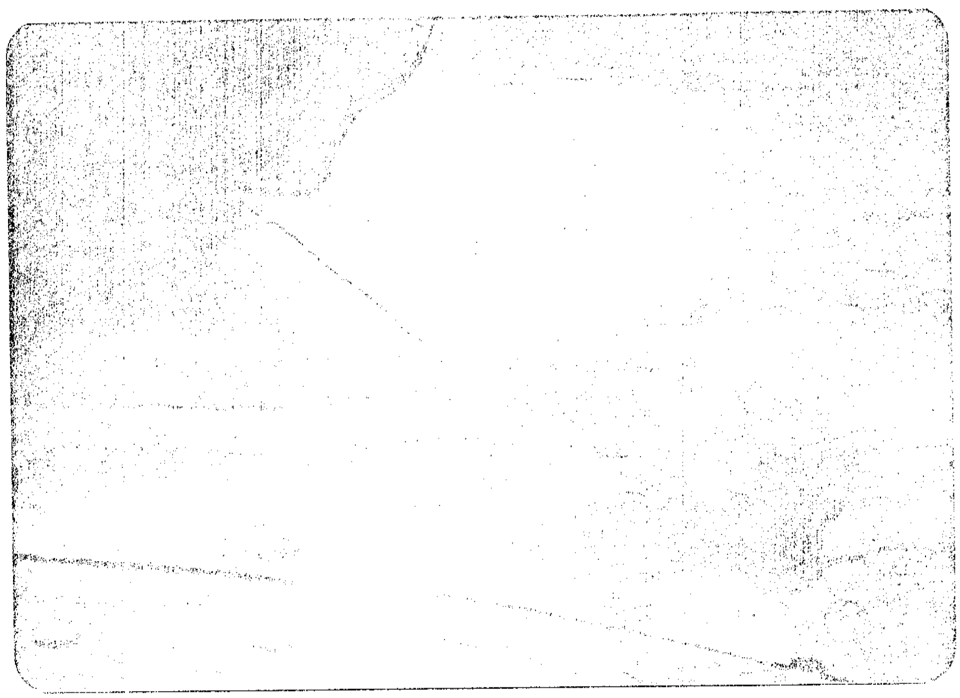

Fig. 38 - Ore pod resembling an ore roll but the head and tails are not well-developed

There exist other features that resemble rolls, but they are not as well-developed into a crescent-shape. One of these features is shown in Fig. 38. Shown is an ellipsoidal pod of ore with a non-ore center. The head and tails are not distinctly developed. The convex side of the pod has a sharp contact with the surrounding sand, whereas the inner boundaries are more diffuse. This pod is uniformly enriched in uranium except for the clay gall and calcified sphere of sandstone. The pod is highly calcified and therefore, well indurated. The sandstone becomes more friable gradually outward, along with a gradual decrease in percent of U_3O_8.

Directional Features - While most ore pods are situated in a sandstone host with no apparent connection to any specific feature, an occasional ore pod is intimately associated with fossil trees. The ore is formed as a halo around the tree, with a distinctive tailing effect pointing in the presumed paleocurrent directon. There is much more ore on the "lee" side of the tree than on the current side. The fossilized log itself is not necessarily mineralized, but a thin crust around the log usually contains some mineralization. This tailing effect is an uncommon feature, but where present, the trend of the tail is subparallel to the overall trend of the ore body.

Iron Bands - Accompanying nearly every well-defined, uniform ore pod is a red band, apparently oxidized iron pigment in the sandstone. This band is usually present along all or most of the periphery of the pod (Figs. 34a,b,c,d), and if not, it is commonly restricted to the "front" and/or bottom of the pod. This red band, which is usually continuous, never actually comes in contact with the ore, as there is always a thin (1/2", 1.3 cm) space between the red band and the ore.

The total iron content of this band is commonly higher than the total iron content of the ore and surrounding sediments.

Concentric Ore Pod - On only one occasion has the author seen a feature that is described below and shown in Fig. 39. This is a spherical pod of high-grade ore, completely enveloping an extremely well-cemented (by calcite) sphere of low-grade ore. The lithology of the host sandstone, medium-grained arkosic sand, is the same across the whole sphere. The whole pod is well-cemented, but the center is more indurated than the richer ore. The calcite cement is pervasive throughout the whole area, making the corresponding red band above the sphere well indurated also. The ore is 4.0% U_3O_8, and the central part is 0.2%, by no means barren, but considerably less than the surrounding ore. The contact between the high- and low-grade ore is almost knife-edge sharp.

The author found this feature intriguing. It could be a cross section through an ore roll, perpendicular to the trend and oblique to the trend of the roll which would yield the typical crescent-shape. Unfortunately, no side view was available. This feature could also be representative of a tube-like flow of ore fluids, with the ore forming peripherally to the center. The center was probably the fastest stream of fluids, with the ore "growing" outward.

Poison Canyon Ore

Form

Poison Canyon ore is different than Westwater Canyon ore in that it is more massive and very rarely occurs as the small individual pods so common in the Westwater Canyon. The individual ore pods are much

Fig. 39 - Concentric ore pod; the light colored center is low-grade ore whereas the black outer shell is high-grade ore; note the red band above the ore pod; looking west

more extensive, continuous, thicker and more uniform in the Poison Canyon. Ore pods are commonly 50 feet (15 m) long, 25 feet (8 m) wide, and up to 6 feet (2 m) thick, although the average ore pod is thinner. The length-to-width ratio ranges from 3:1 to 10:1. It is not unusual for an ore pod or lens to extend the entire thickness of the Poison Canyon sandstone, about 12 feet (4 m), being sandwiched between the "K" Shale and the Brushy Basin. The best way to describe the ore form is sheet- or manto-like (Figs. 40a and 40b). The trend of the sheets of ore are parallel to the overall trend of the ore body.

Where the ore does not occur as one thick mass across the entire thickness, it is usually a thin layer (2 feet, .6 m) at the base of the Poison Canyon, overlying the "K" Shale. Also, ore can be found anywhere in the sandstone horizon, in the middle with barren sand on either side, and also in the top part directly below the Brushy Basin. When the ore is near the "K" Shale, it is never in direct contact with it - there is a calcite cemented zone up to 4 inches (10 cm) thick that separates ore and shale.

Besides the basic shapes and forms expressed by the Poison Canyon ore, there are other differences in comparison to the Westwater Canyon ore. Poison Canyon ore is distinctly lower in U_3O_8 content. Grades of 1% are common; grades of 2% or more are very rare. The overall grade of the Poison Canyon ore is lower than the grade of the Westwater Canyon ore, but since the Poison Canyon ore is extensive, the lower grade is of little concern.

Calcite cement is pervasive throughout the Poison Canyon, but the ore is not quite as well-indurated as Westwater Canyon ore. Locally,

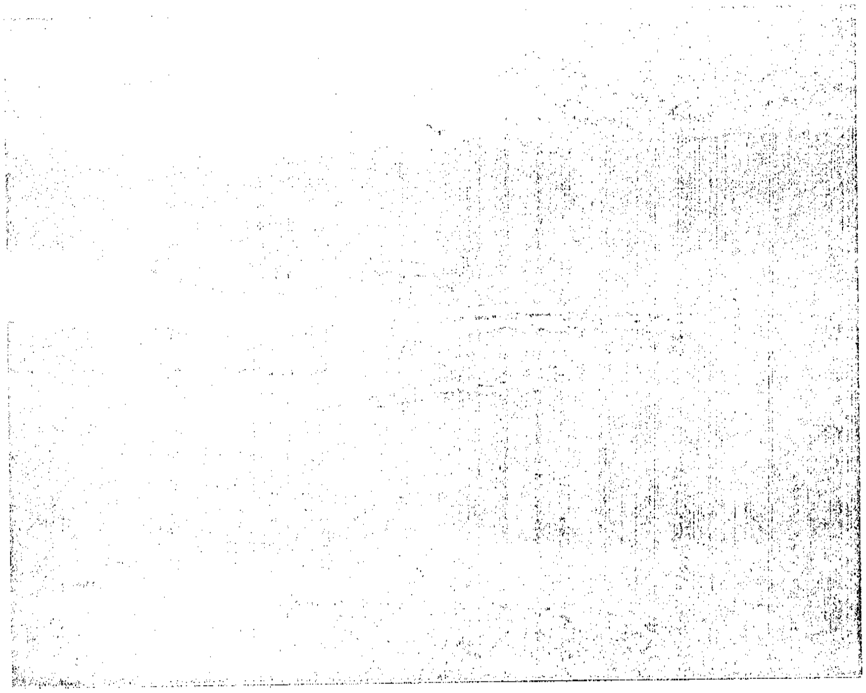

Fig. 40a - Typical Poison Canyon ore

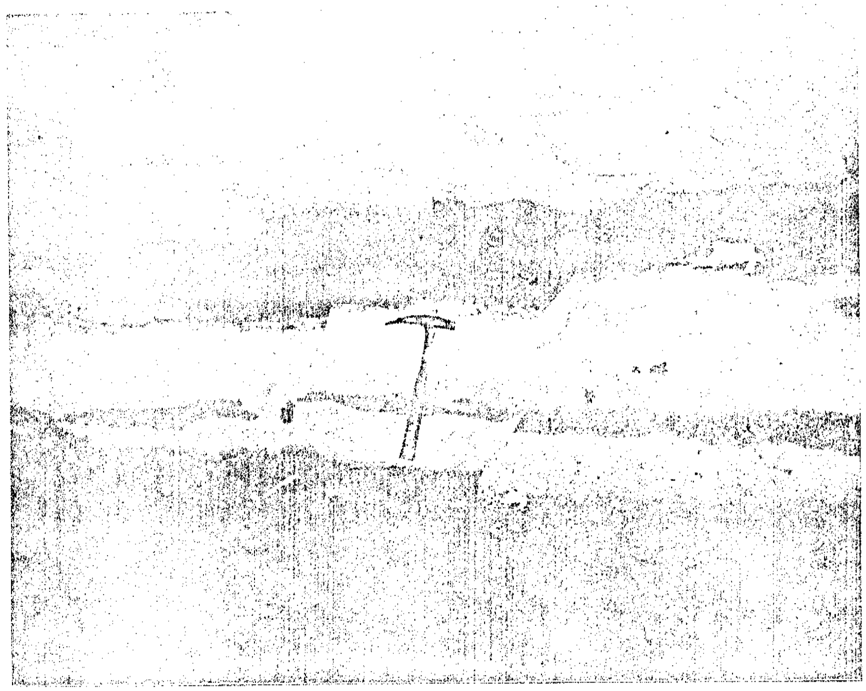

Fig. 40b - Poison Canyon ore; the thin gray band under the hammer is molybdenum-bearing the ore is quite hard, but overall, the ore is more friable than the Westwater Canyon ore.

The most obvious difference between ore bodies in the Poison Canyon and the Westwater Canyon is the significant lack of organic detritus such as trees, bones, and trash piles in the Poison Canyon sands. There have been only two or three pieces of carbonized debris found in the Poison Canyon sandstone.

Miscellaneous Features

Features such as ore rolls and directional indicators do not occur in the Poison Canyon. The iron bands common around the ore pods in the Westwater ore are rare and poorly developed in the Poison Canyon ore.

Mineralized Clay Galls - There exist a few clay galls that are impregnated with uranium mineralization. Usually this only occurs in clay galls that are isolated in massive pods of ore.

Relation to Stratigraphy, Sedimentary Features and Structure

Ore bodies in the Johnny M Mine are not subject to any definite stratigraphic control, except that the overall orientation of the ore bodies and the orientation of most of the ore pods is consistent with the orientation of fluvial sedimentary features. While no one major stream channel has or can be accurately mapped, the sandstone near and in the ore bodies tends to be more prominently cross-bedded, coarser-grained, contains more fossil detritus, and in general exhibits more channel associated characteristics than the sandstones at a greater distance from ore. It is thus inferred that the ore-bearing horizons occur in at least part of a complex fluvial system.

Since there is a relationship between the location of ore and channels, it is usually inferred that ore dies out at the boundary of a channel system. The presence of a channel does not necessarily signify that ore exists, but by the same token, ore does not tend to occur in commercial quantitites outside the channel systems.

Individual ore pods can occur either 1) suspended within thick sandstone beds separated from adjacent sedimentary surfaces by a few feet of barren sandstone, 2) resting on the upper surface of a claystone bed, 3) intermixed with a claystone cobble conglomerate, or 4) localized on a laterally persistent scour surface. Thin layers of ore which occur in thick sandstone beds are more apt to be associated with erosional surfaces and thin claystone zones.

Although ore locally does conform to bedding or to an erosional surface (Fig. 41), ore pods consistently transect all types of sedimentary structures, including lithologic changes, cross-bedding, and scour surfaces, as shown in Fig. 42. The ore boundary that transects sedimentary features is usually sharp and there is no change in grade or morphology of the ore across the feature. The most common sedimentary feature that the ore transects is a lithologic variation, most noticably a change from a coarse-grained sandstone to a fine-grained sandstone (Fig. 42). Typically, ore which closely follows bedding or another sedimentary feature eventually dips down and crosses that feature. Overall, the author has observed no small-scale sedimentary feature that exerts any significant control on the emplacement of ore.

Claystone zones commonly separate ore pods that are stacked. Interfingering of ore pods occurs where ore is at different levels in close proximity to one another, so the ore is confined to one specific layer

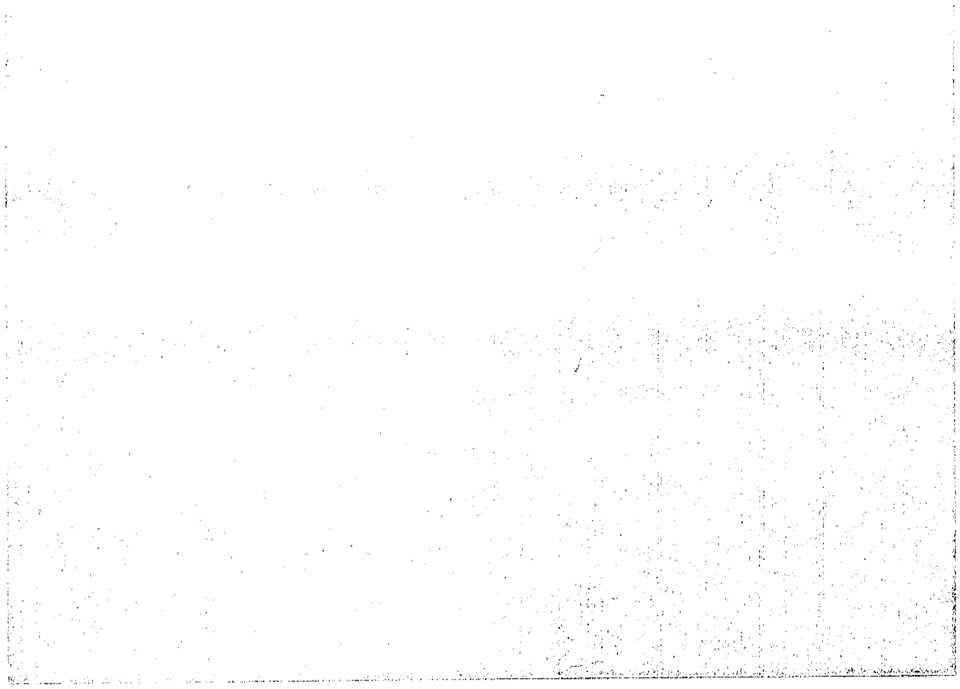

Fig. 41 - Pencil points to ore that is confined to scour surface; note how the ore bifurates when the two scours meet

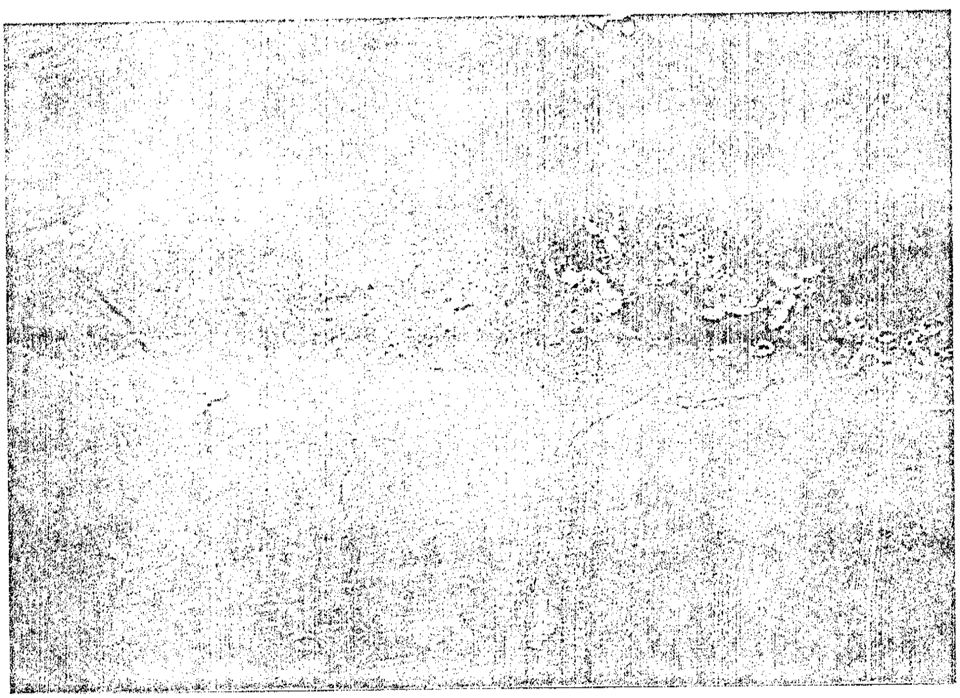

Fig. 42 - Ore transecting different sandstone lithologies; the white material is kaolinite

in the bed. Overall, the occurrence of ore pods is randomly distributed throughout the ore body, indicating the lack of specific beds or sedimentary features controlling the ore emplacement.

There are two features that appear to have some influence on the location of ore pods. Persistent claystone zones usually exist as a basal barrier to blanket ore. Tracing this claystone zone may lead to more ore. Trash piles are commonly in close proximity to major ore pods, the ore pods lying in a presumed down current directon. These trash piles are assumed by the author to be the major source of the humate material associated with the uranium ore.

Ore bodies that occur in the Poison Canyon sandstone are under much greater stratigraphic control. The Poison Canyon sandstone, which has an average thickness of 10 feet (3.3 m) in the mine workings, is consistently bounded by two impermeable shale layers, the "K" Shale below and the shales in the Brushy Basin above. Any ore present exists between these two shale layers. The majority of the ore occurs in the basal part of the horizon. There appears to be a correlation between ore occurrence and a persistent coarse-grained sandstone bed within the Poison Canyon. The ore is not strictly confined to this one particular extensive bed, but the ore appears to be preferentially situated in or very close to this bed.

The relation between ore and faulting is very straight foward; faults cut and displace ore, with no apparent ore movement along the fault plane (Fig. 43). The extensive faulting does affect mine planning as the fault zones are avoided due to their weakness. Faulting consistently displaces Poison Canyon ore down to the east, and this also affects the mining.

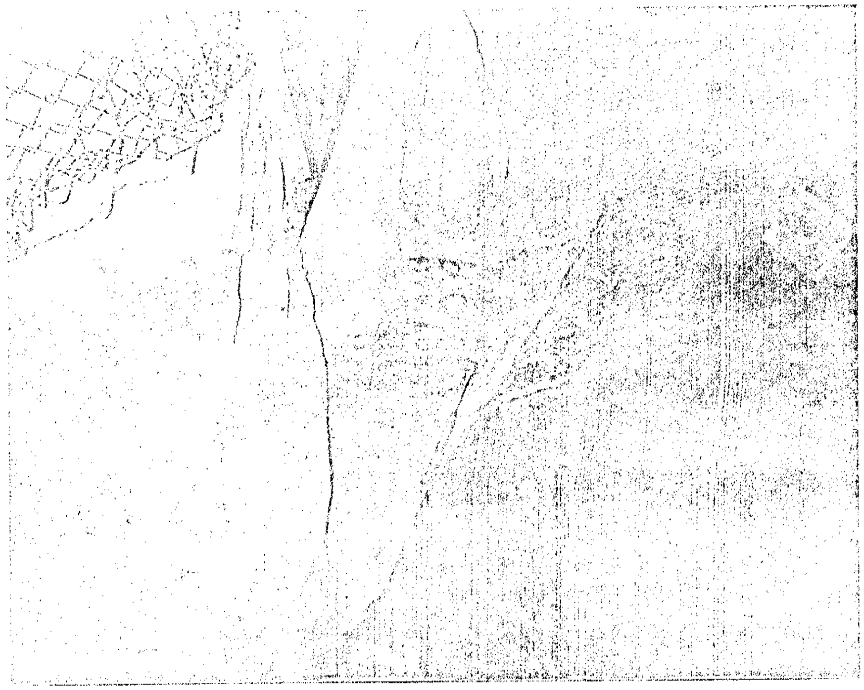

Fig. 43 - Fault cutting off Poison Canyon ore; displacement is 10 feet (3.3 m); fault trends N5^{o}E

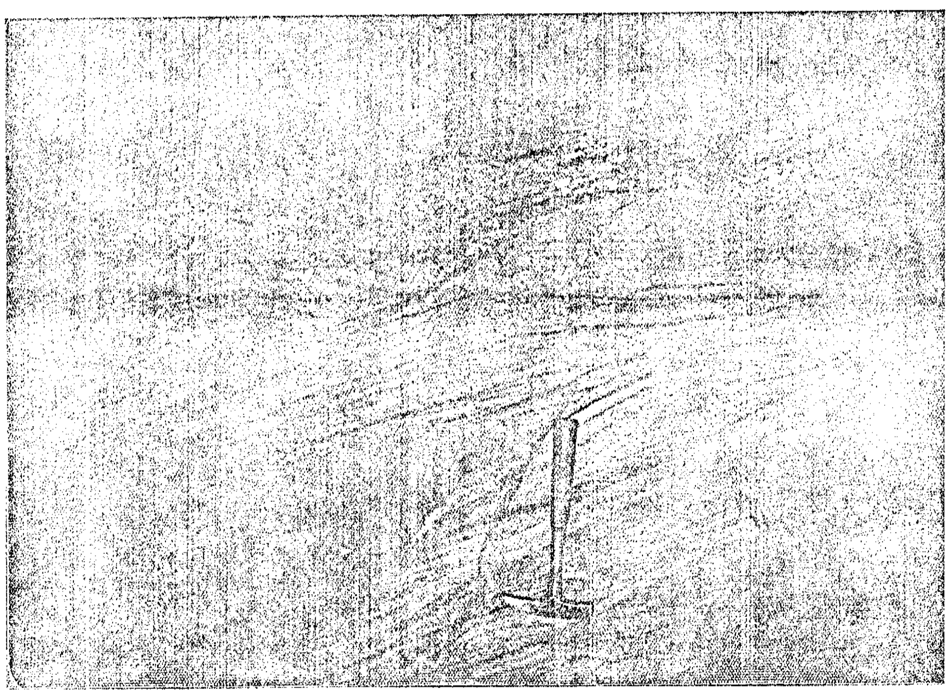

Fig. 44 - Molybdenum-bearing material impregnating certain bedding planes

Associated Jordisite

Squyres (1970) states that a black amorphous substance identified as jordisite (MoS_2) exists in close association with primary ore bodies in the Grants Region. Squyres implies that jordisite is quite abundant in the Ambrosia Lake District, but the author did not encounter a significant amount of jordisite in the Johnny M Mine.

However, where jordisite occurs in the mine, it is much more abundant in association with Poison Canyon ore than with Westwater Canyon ore. The jordisite in the Westwater Canyon occurs in a feathery pattern, selectively impregnating certain laminae of the bedded sandstone adjacent to an ore pod (Fig. 44). The jordisite "feathers" extend outward peripherally from the ore pod but are never in direct contact with the ore; there being an inch (2.5 cm) or so of barren sandstone between the ore and jordisite.

Jordisite associated with the Poison Canyon ore is much more massive and extensive (Fig. 45). Instead of feathery masses, the jordisite occurs as layers, commonly 6 inches (15 cm) thick, and rarely over a foot (30 cm) thick. Again there is a narrow band of barren sandstone separating ore and jordisite.

The jordisite, which commonly exhibits a brownish-gray color, has a molybdenum content that ranges from .03% to .08%, and the U_3O_8 content can be as high as .06%.

Overall, jordisite is locally abundant within certain ore pods, but it is volumetrically unimportant in the mine workings.

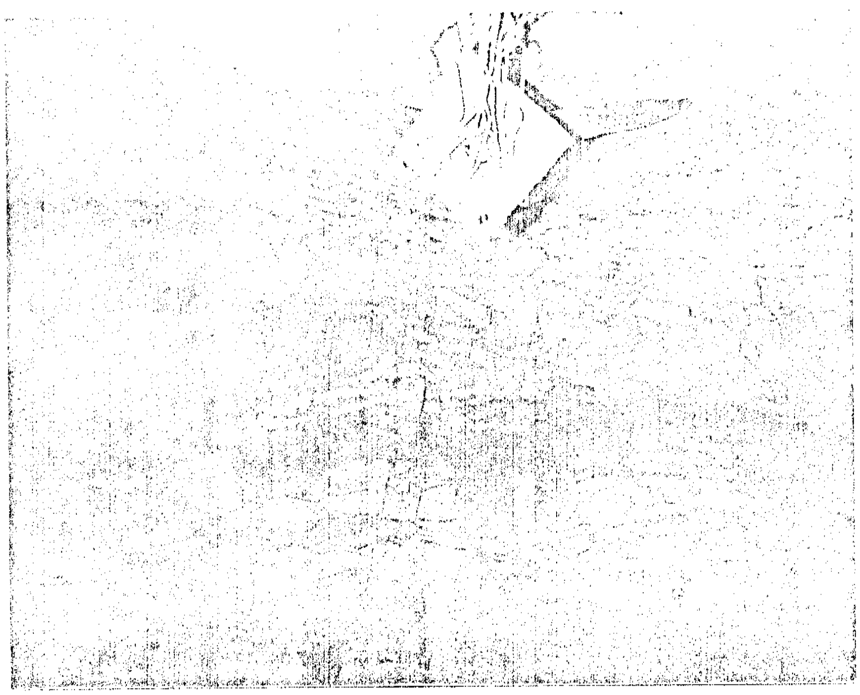

Fig. 45 - Molybdenum-bearing material (gray) adjacent to Poison Canyon ore (black)

Mineralogy of the Ore Deposits

Organic Substances

The organic material that is so closely connected with the uranium ore bears a close physical resemblance to tar or an asphalt-like substance. After studies on this material were conducted (Granger and others, 1961, Moench and Schlee, 1967), it was concluded that the organic substance originated as humates, rather than as some form of hydrocarbon. As defined by Vine and others (1958), humates are salts of humic acids and humic acids have been defined as brown or yellow organic matter extracted from decaying plant material by alkaline solutions.

The term humate is now widely applied to the solid residues of water-soluble humic substances, regardless of its present state or mechanism of precipitation. Squyres (1970) goes through a detailed summary of the means by which the humates have been identified, so the reader is referred to that paper. The author agrees with Squyres that the organic substance which is intimately associated with the uranium ore deposits in the Grants Region are humates or were derived from humic substances.

Uranium Minerals

Granger (1963) and Squyres (1970) applied the name coffinite to the uranium mineral that is being mined in the Grants Region. This author does not believe that the uranium should be called coffinite, because the uranium probably does not occur as a mineral. There is a good possibility that the uranium exists as part of an uraniferous organic complex (Motica, J. E., pers. comm., Aug. 23, 1978). Theories about uranium formation do not require that the uranium occur as a mineral, in fact, it would probably be easier to explain if the uranium did not occur as a mineral. The author has talked with R. Della Vale (University of New Mexico, pers. comm., July 15, 1978) whose work substantiates the author's view that the uranium occurs as part of an organic complex and not as a mineral. Uranium probably exists as the mineral coffinite to a minor degree in the uranium ore, which would yield the reported X-ray pattern of coffinite. More conclusive work and open-minded thinking is needed before anything definite should be said about the form of uranium in the ore deposits.

Uranium also occurs as the oxide material zippeite ($2UO_3 \cdot SO_3 \cdot 5H_2O$) (Granger, 1963), in the form of bright yellow aggregates of minute radiating needles (Fig. 46). Zippeite is not abundant, but where it occurs it is a thin, earthy-looking, fragile coating or crust on exposed sandstones. It is evident that this mineral was formed after mining was initiated, since it is only found on exposed surfaces in older workings.

Vanadium Minerals

No vanadium minerals have been observed in the Johnny M Mine, even though there is abundant vanadium present (see chemical analysis, Appendix B). Vanadium occurs as either a part of the organic complex, a submicrocrystalline form of the mineral montroseite ($V_2O_3 \cdot H_2O$) (Granger, 1963), or possibly as submicrocrystalline carnotite ($K \cdot (UO_2)_2 \cdot (VO_4)_2 \cdot 3H_2O$).

The ratio of uranium to vanadium ranges from 1:2 in low-grade ore to 12:1 in high-grade ore. Vanadium is also present in small amounts (0.02%) in samples virtually void of uranium.

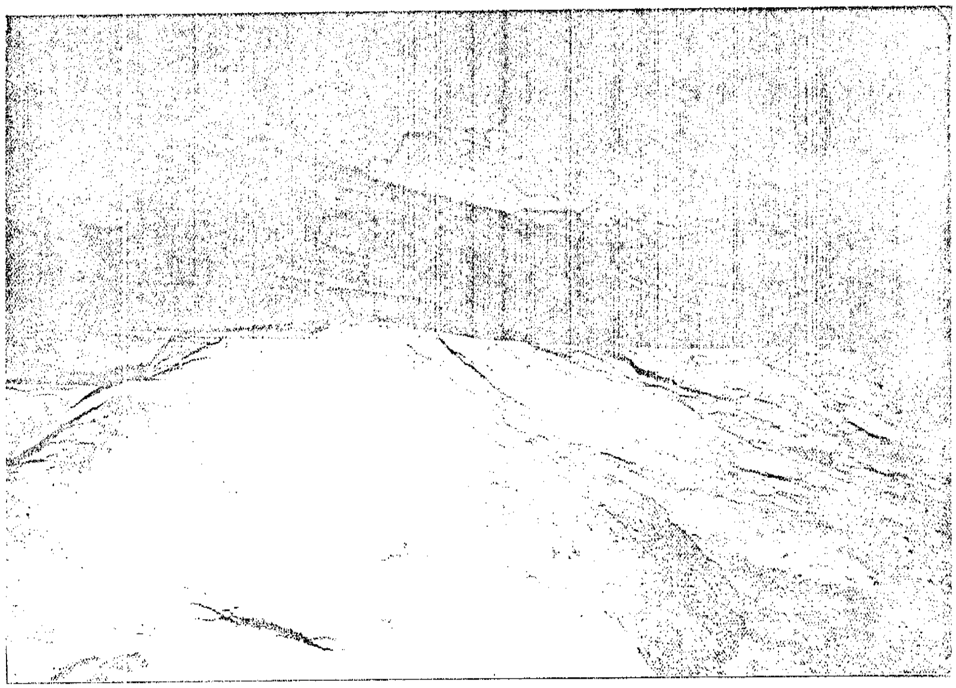

Fig. 46 - Zippeite

Molybdenum Minerals

Jordisite, amorphous MoS_2, has already been described in this paper as occurring adjacent to some ore pods. Granger (1963) states that jordisite cannot be positively identified because it is fine-grained or amorphous, difficult to separate, and produces no diagnostic X-ray pattern.

Molybdenum also occurs as the oxide mineral ilsemannite ($Mo_3O_8 \cdot nH_2O$) (Granger, 1963), as a thin, blue coating composed of fibrous, needle-like, radiating crystals (Fig. 47). This mineral yielded the highest amount of molybdenum of any sample analyzed, 0.7%, and contained 0.25% vanadium, 0.2% copper, and had no detectable U_3O_8. Ilsemannite is more abundant in Poison Canyon ore, but is rare in the mine.

Selenium Minerals

Native selenium occurs as minute acicular crystals up to a few millimeters long, perched as tufts on sand grains. It occurs in various parts of the mine but is rare. The most common occurrence is in close proximity to ore pods. Chemical analyses indicate that selenium not only occurs as crystals, but is also incorporated in the humate material. Selenium is not present in barren sandstone, but can be as rich as 1.0% in high-grade ore. There is a direct relationship between the amount of uranium present and the abundance of selenium.

Arsenic Minerals

The distribution of arsenic in and around ore is similar to that of selenium, and the abundance of the two elements is also similar, though arsenic is less apt to occur in concentrations over 0.07%. No specific arsenic minerals have been identified in the Johnny M Mine.

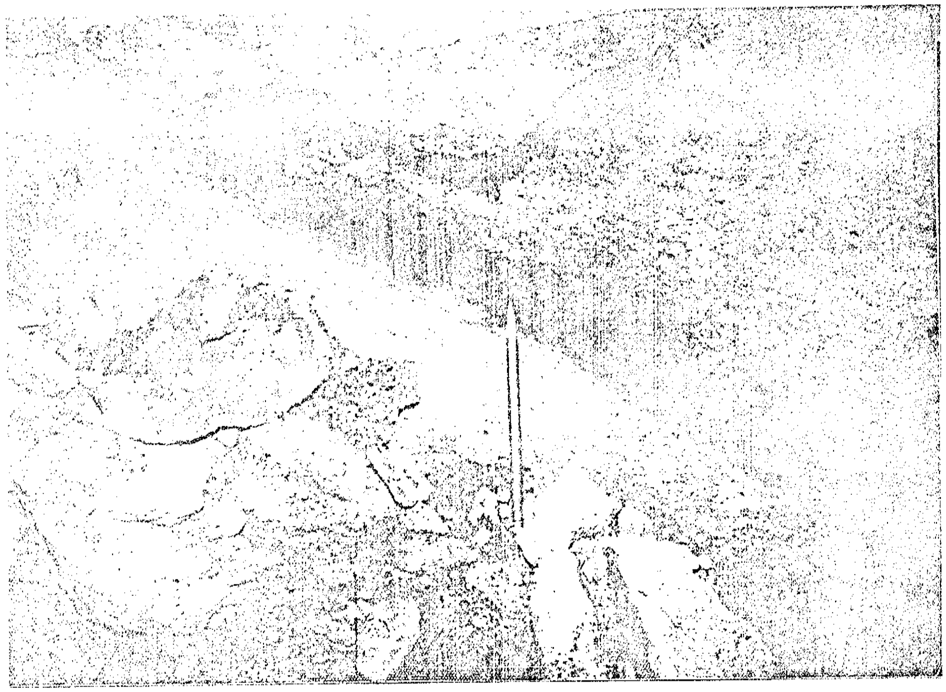

Fig. 47 - Pencil points to ilsemannite

Copper Minerals

No copper minerals have been identified in the mine, but copper does exist in the ore bodies, with a slight tendency to increase in the ore pods themselves. Within the limits of the ore bodies the concentrations of copper can be as high as 200 ppm, with the average about 100 ppm. There appears to be a depletion of copper laterally away from the ore bodies (outside the channel), with concentrations falling as low as 1 ppm.

Pyrite

Pyrite is pervasive throughout the entire mine, but is not very abundant. It occurs either disseminated in the sandstone or clustered on clay galls. The pyrite usually occurs as a thin, dusty film on sandstone grains, with crystals being less than .2mm wide. The pyrite crystals on the clay galls are also fine-grained, but larger grains do occur. Cubes are the most abundant form. Pyrite also occurs along the edges of claystone beds and in fractures and joints within the beds.

Pyrite is much more abundant in the Poison Canyon sandstone than it is in the Westwater Canyon sandstone. It is more abundant near ore, and somewhat concentrated in ore pods as compared with adjacent barren sandstone. The pyrite grains coat the ore without being coated or stained by the humate material. Thin films of pyrite can be found along the sides of open fractures in carbonized wood, either near or away from ore.

Ore Controls

Sedimentary

The idea of ore controls has always been an intriguing one since understanding of the ore control processes allows for more successful exploration for additional ore. Santos (1963) gives a brief overview of sedimentary ore controls for the Ambrosia Lake District. Following are my interpretations of ore controls as interpreted from features present in the Johnny M Mine.

On a large scale the one major sedimentary ore control is the presence of a well-developed, quartz-rich, arkosic, fluviatile sandstone. This type of sandstone is the main host for ore in the Grants Region, therefore one must encounter this horizon before ore can be found. Within this sandstone there are a number of smaller scale features which may be important to the depositional control of the ore: diastems, bedding planes, grain size and sorting, calcite cement, and humate material.

The author concludes that diastems, bedding planes, grain size, sorting, and calcite cement do not play any significant role in ore control processes. Humate material is the one feature that exerts considerable control over the ore emplacement.

This humate matter is present in every sandstone uranium mine in the Grants Region (Granger, 1968). Granger (1968) also states that all this humate material has been mineralized to some extent with uranium, and conversely, no uranium of undisputedly primary origin has been found away from humate matter.

All this is certainly true in the Johnny M Mine. All the ore that has been or is being mined is intimately associated with black to dark brown humate material in the sandstones; no ore has been found in sandstone devoid of this humate matter. It is common to find patches of black material that looks like ore and actually consists of very low-grade mineralization.

The intimate relationship between the uranium ore and humate material strongly suggests that the humate matter is the most important control in the deposition of the uranium ore.

Structural

Structure has been mentioned as an ore control (Clark and Havenstrite, 1963). In the Johnny M Mine there are no structural features that appear to control the ore. The faulting encountered in the mine offsets ore bodies as much as it offsets stratigraphic units. Where the ore abuts a fault plane there is such minute amounts of ore contained within the fault plane that virtually no movement of ore after faulting has occurred. Consequently, there is no "stack" ore present in the Johnny M Mine. Joints and fractures also cross-cut the ore in the same manner as do the faults.

CHAPTER V

SYNTHESIS of the ORE

The preceding sections of this study are mostly descriptive, but the following sections represent an attempt to reconstruct the formation of the ore bodies, and the conditions under which they formed. This part is highly interpretive, although the author relies on existing literature and personal observation.

AGE of the ORE

By using several parameters it is possible to bracket the age of the formation of the uranium ore deposits.

Structural Evidence - Faulting in the southern San Juan Basin has been related to the structural deformation associated with the Zuni Uplift. This tectonic episode is speculated to have taken place in Laramide time (Late Cretaceous - Early Tertiary) (Kelley, 1963). Since the ore bodies in the Grants Region are displaced by some of these faults, which radiate northward from the Zuni Mountains, it can be deduced that the uranium ore deposits were formed before the faulting occurred, and thus a minimum age of pre-Laramide is thereby indicated for the ore bodies.

Stratigraphic Evidence - Collapse structures present in the Ambrosia Lake District have been studied by Granger, Santos and others (1961) and they concluded that the ore, which is localized around the cylindrical features, is probably pre-Laramide, the inferred age of the collapse structures.

The Dakota Formation and approximately the upper 30 feet (10 m) of the Morrison Formation are not displaced by the collapse structures in the Cliffside Mine (Clark and Havenstrite, 1963), although beds a few tens of feet lower show full displacements. The collapse structures and the associated ore must therefore have been formed during the deposition of the Morrison Formation.

A pre-Dakota age was established for the uranium ore in the Paguate Mine in the Jackpile Sandstone (Nash and Kerr, 1966). They described a section of ore-bearing sandstone at the top of the Jackpile sandstone that is truncated by a pre-Dakota erosion surface. These geologic relations are clear enough to establish a definite pre-Dakota age for the ore.

Radioactive Dating - In 1963, Miller and Kulp, using U^{235} : Pb^{207} ratios, calculated ages near 210 m.y. for the uranium deposits in Triassic rocks on the Colorado Plateau, and about 110 m.y. for deposits in the Morrison Formation. They concluded that the ore deposits formed soon after deposition of their host rocks.

Granger (1963) estimated an age of about 100 m.y. for the uranium deposits in the Ambrosia Lake District, but noted that this is probably a minimum age.

Della Vale (pers. comm., 1978) has been doing a geochemical study of several ore bodies in the Grants Region. His preliminary age determinations indicate that the ore deposits become successively younger going up the section in the Morrison Formation. The ages obtained range from 155 m.y. to 140 m.y., and suggest that the ore formed during or immediately after deposition of the host sands.

Summary - The previous discussion proves that the ore deposits studied formed before deposition of the Dakota Sandstone. Also, most evidence strongly indicates that the ore deposits formed sometime between deposition of the host sands and deposition of the uppermost Morrison Formation.

Source of the Ore

Ever since the Grants Region has been known to be one of the richest uranium regions in the world, there has been much speculation on the origin of the uranium and associated ore elements. The major hypotheses concerning the source of the ore in sandstone-type uranium deposits are: 1) ascending uraniferous hydrothermal solutions, 2) leaching of granitic rocks which are assumed to be the source of the sediments, 3) leaching of the host sediments by groundwater, 4) leaching of volcanic ash deposited synchronously with the host sediments, 5) leaching of the bentonitic shales (Brushy Basin) stratigraphically above the host sediments by groundwater.

Hydrothermal Source

The hydrothermal (specifically telethermal) hypothesis is based on the premise that the metals were initially derived from a deep-seated magmatic source and were carried laterally by groundwater to favorable depositional sites. The major objection to this idea is the lack of source rocks of sufficient age and the lack of feeder zones for the hydrothermal solutions. Squyres (1970) concisely lists several other objections to this hypothesis. The author believes that a hydrothermal source for the ore elements is unfounded.

Granitic Leach

Granitic rocks are known to be relatively rich in uranium. Turekian and Wedepohl (1961) determined that the average uranium content of granite is 3 ppm, whereas Senftle and Keevil (1947) found an average value of 4 ppm. Granites containing several tens of ppm occur (McKelvey and others, 1955; Masursky, 1962). A study on cores and samples of the Granite Mountains in Wyoming was made by Stuckless and others (1977).

The Granite Mountains are known to have unusually high concentrations of uranium (9.8 ppm). Rosholt and others (1969) calculated, by ratios of radiogenic lead daughter products to percentage of uranium in this granite, that it is 80% deficient in uranium, and there is an average loss of 20 grams per kilogram - enough to supply 1000 times the uranium reserves plus production in Wyoming. Stuckless and others (1977) mention that the percentage of uranium in a granite will increase with increasing silica and alkali content. It can probably be safely assumed that given a large enough granitic mass, enough uranium exists to account for all the uranium found in the Grants Region.

The presence of adequate amounts of uranium in a granite does not necessarily qualify it as a potential source rock. It is also necessary that the uranium be available for leaching at some time during the history of the parent rock. Stuckless and others (1977) propose several ways in which uranium loss may occur in a granite.

1. Loss due to granulite facies metamorphism which drives out connate waters.
2. Loss due to weathering, but they deem this process unlikely because of the depths to which uranium loss was observed.
3. Loss to dilantancy (Goldich and Mudrey, 1972), in which uplift releases overburden pressure and water is given off, taking uranium with it.
4. Loss at grain to grain boundaries.

Actually, the first three processes are mechanisms for loss of uranium at grain to grain boundaries.

A major part of the uranium in granitic rocks is concentrated in accessory minerals such as sphene and zircon. Sphene, zircon, and other uranium-bearing minerals are highly resistant to weathering, and are little affected by leaching. Therefore, even though they may be transported into a favorable sedimentary environment, these minerals resist dissolution and thus their uranium content is not readily available for the ore-forming processes.

The remainder of the uranium occurs along grain to grain boundaries, and in interstices, or is attached to various silicates, such as mica and feldspar. These silicate minerals may yield their uranium content during weathering, transportation, and incorporation into sedimentary rocks, but much of the feldspar in the Grants Region is still quite fresh (Squyres, 1970), as well as in the sands of the Johnny M Mine.

The uranium present at grain boundaries in granitic rocks is readily leachable. In a study of the Sierra Nevadas, Brown and others (1953) estimated that about half of the uranium content was leachable just by pouring water over the crushed granite. By using a more acidic leachate, he was able to remove even greater amounts of uranium. However, most of this easily available uranium is probably put into solution during weathering at the outcrop, where it has a good chance of becoming part of the surface run-off, and thereby becomes dispersed and diluted.

Considering that a granitic mass could viably be the source for the uranium in sandstone-type deposits, we must now consider the processes by which the uranium is transferred from the granitic mass to favorable sites of deposition. The two proposed processes would fall into two categories, syngenetic and epigenetic.

The syngenetic hypothesis basically involves the transportation of uraniferous sediments to be deposited as a uniformly mineralized sand and later be reconcentrated in more favorable zones. Zitting and others (1957) proposed that the Westwater Canyon sandstone is composed of arkosic sands derived from an uranium-rich granite. Since the depositional environment was in a closed basin, the uranium-rich waters were not lost to the ocean, and the uranium was maintained in the system. The uranium would then conceivably be available to be trapped by whatever means (Zitting and his coworkers mention asphaltic deposits under the Ambrosia Lake dome), and the ore deposits would eventually be formed.

The possibility exists that the uranium was derived epigenetically from the leaching of granites that are not the source rocks of the sediments. It is presumed that the sediments of the San Juan Basin "lapped" onto an ancestral Zuni Mountains highland somewhere south of Gallup, N.M. (Rappaport, 1952). The central core of the present Zuni Mountains is Precambrian granite (Smith, 1954), and it is assumed that the ancestral Zuni Mountains (if they ever existed) would have been underlain by Precambrian granite also. This core might have had sufficient uranium to supply and form the ore deposits in the Morrison Formation. While no work has been published to date on the possibility of the Zuni granite as a source rock for uranium, the study on the Granite Mountains of Wyoming (Stuckless and others, 1977) might be applicable to the Zuni Mountains. It is possible that sometime during the erosional history of the ancestral Zuni Mountains the uranium-rich core was exposed, and due to weathering or the other ways outlined by Stuckless and others (1977), a substantial amount of the uranium was released into the groundwater system and thus became available for ore formation.

Volcanic Ash Leach

Volcanic tuffs are known to be anomalously rich in uranium, even richer than granites. Denson (1952) published analyses on several tuffs and tuffac[illegible] whole contents of uranium varied from a few ppm to 40 ppm, with an average value of about 20 ppm. This data shows that volcanic tuffs and tuffaceous sediments have a potential at least as good, if not better than granites as a source for uranium.

White and Waring (1963) have indicated that a significant percentage of the trace elements on surfaces of fresh volcanic ash can be easily removed by leaching. Ash transported by air and deposited into sediments, or water-borne for a short distance without appreciable weathering, has a good chance of yielding its readily available trace elements directly into fluvial deposits. Scott and Barker (1962) have shown that groundwater samples from granitic and tuffaceous terranes show a range of uranium concentrations from less than 0.1 ppb to several tens of ppb, and an average of about 5 ppb. These values are considerably above the average for all groundwater samples. In a study of the uranium content of groundwater in South Dakota and Wyoming, Denson and others (1950) give 92 analyses of water samples from tuffaceous Oligiocene and Miocene sediments exclusive of known mineralized zones, in which the average uranium content was 35 ppb. They also noted that the samples contain greater than normal amounts of molybdenum, vanadium, copper, selenium, and arsenic, and concluded that the uranium and other elements were derived from the associated tuffaceous material.

The uranium present in the glassy matrix of shards and other volcanic detritus has a high probability of being released into the fluvial system during the decomposition of the glass. The uranium present in volcanic ash and tuffs appears to be more readily available than the uranium in granitic rocks, and thus more likely to become available in an environment conducive to the formation of uranium ore deposits.

Assuming that volcanic ash can be a source of the ore elements, processes of ore element transfer from the ash or tuff to favorable environments of deposition must be considered. Again the processes can be separated into syngenetic and epigenetic.

The syngenetic model involves the near simultaneous deposition of the sediments and the volcanic ash. The uranium and other ore elements are derived from the leaching of the volcanic ash by rainfall, and are transported by the fluvial system to favorable environments within the associated sediments that are continuously being deposited.

The epigenetic hypothesis proposes a model in which the uranium is derived from bentonitic mudstones in the Brushy Basin Shale Member by the action of groundwater leaching. The groundwater is visualized as leaching the uranium from the volcanic ash layers and transporting the ore elements down fluid gradient to be deposited in favorable environments within the sandstone horizons below. Squyres (1970, p. 200) states that this process took place "while Morrison sediments were still being deposited a few hundred feet higher."

Summary and Comparison

The following is a summary and comparison of the different hypotheses as to the possible source rocks and processes for uranium ore solutions.

1. Hydrothermal
2. Granite leach
    a. Syngenetic
        1. concentration of uranium after deposition as disseminated mineralization throughout the host rock from which it is also derived
    b. Epigenetic
        1. groundwater leaching of uranium rich granites and subsequent transportation into environments favorable for deposition

3. Volcanic ash leach
   a. Syngenetic
      1. near simultaneous deposition and concentration of uranium derived from air-fall tuffs
   b. Epigenetic
      1. groundwater leaching of the bentonitic mudstones in the Brushy Basin shale

The hydrothermal hypothesis, as stated before, is not regarded as viable for a source of the ore elements in the Morrison Formation.

The granite leach theories are viable but the major stumbling block is the source of the elements associated with the uranium: copper, vanadium, molybdenum, arsenic, and selenium. Due to the close association of these elements to uranium, the proposed source of the uranium is also presumably the source for these other elements. This is where a granite leach hypothesis starts to fall short. While vanadium, molybdenum, and copper can be accounted for by leaching of a granite, selenium and possibly arsenic are present in insufficient amounts in a granite. It is hard to imagine how a granite with a selenium content of 0.05 ppm could be a significant source of that element in adjacent sediments. Arsenic is rarely present above 2.0 ppm in granites, thus the large amounts of arsenic present in the uranium deposits (up to 700 ppm) cannot be easily accounted for but may be possible.

Disregarding the deficiencies of selenium and arsenic in a granite, let us now take a look at the processes involved for the ore formation. The syngenetic theory is viable except for the critical point as to why the uranium ions and detritus destined to become host rocks for the ore are not separated during transportation. If the uranium is easily leachable from the grain to grain boundaries, then with the onset of weathering, the uranium would be dispersed and diluted in the fluvial system. Still, much of the uranium would eventually reach favorable depositional sites, and through extensive concentration the uranium needed for the ore deposits could conceivably be collected.

The epigenetic theory is widely applicable, but it calls for the availability of a granitic mass after the sediments have already been deposited. This is possible in the postulated Zuni Mountains, but since these have been eroded, no further studies can be conducted. Also, the dispersion and dilution problems faced in the syngenetic theory is just as prominent here.

The volcanic leach theory is more reasonable than the granite leach theory. The problem of accessory ore elements, especially arsenic and selenium, does not exist with a volcanic ash source. Vanadium, molybdenum, and copper are just as abundant in ash as they are in granites, but arsenic and selenium are much more abundant in volcanic ash. The volcanic material contains about 5 times as much arsenic as the average granite, and selenium can be as much as 200 times more concentrated in ashes than in average granites although arsenic and selenium have high concentrations in alkaline granites.

The syngenetic theory appears to have the best possibilities as to being the ultimate source of the ore elements. Once the air-fall tuff has been deposited over a wide area, the surficial elements are quickly stripped by rainfall. The climate during deposition of the Morrison Formation was probably moist, as evidenced by the abundance of trees, dinosaur bones, and plant fragments. Once the elements are in solution in the surface runoff, they are brought to fluvial systems where they can be concentrated into ore deposits. There is going to be dispersion and dilution, but since the average volcanic ash is up to six times as rich in uranium as the average granite, this loss is not significantly prohibitive.

The epigenetic theory is plausible but the author feels that it has some drawbacks. Although the Brushy Basin shale is bentonite-rich (presumably being derived from air-fall tuffs), the author wonders how ore elements are going to be leached from a consolidated shale and then transported down the section. The Brushy Basin is an extremely tight green shale, with a permeability that is and probably was very low. The author is reluctant to accept that uraniferous solutions are going to percolate thru the Brushy Basin (in places over 100 feet (33 m) thick) and deposit the ore elements in favorable sandstone horizons below. Another drawback is the fact that the Brushy Basin is still anomalously high in uranium and rather uniformly at that (Smith, C. T., pers. comm., 1978). If this was the source for the uranium it might be expected that the Brushy Basin would be depleted in uranium or at least not uniformly anomalously high. Also, since the ash is easily leachable, one might assume that while the Brushy Basin was accumulating, much of the ore elements would be washed into the surface runoff and thus not be available for later leaching.

Conclusions

Based on the following arguments, the author believes that a volcanic ash is a more plausible source for uranium and other ore elements than a granitic rock.

1. Granitic rocks are a possible source for most of the ore elements associated with uranium, but are probably not an adequate source for selenium and arsenic, whereas volcanic ash is probably an adequate source for all elements.

2. Uranium in granite occurs either in accessory minerals (sphene and zircon) and silicates (micas) and thus unavailable for ore formation, or present along grain to grain boundaries and likely to be released during

weathering at the outcrop and thus dispersed and diluted in the surface runoff. Uranium in volcanic ash is more likely to be released in an environment favorable to ore deposition.

3. Groundwater data tend to confirm that uranium can be derived from volcanic detritus more readily than from granites.

Of the two theories utilizing volcanic ash as the source of the ore elements, the author strongly prefers the syngenetic model for the following reasons:

1. By having the uraniferous air-fall tuffs being deposited at or near the same time as the host sands, the uranium is immediately put into a system with favorable environments for ore formation without long transportation required.

2. Leaching uranium from a bentonitic mudstone (Brushy Basin shale) that is 100 feet (33 m) thick and has a very low permeability, and then having the groundwater transport this ore material to favorable sandstone horizons below is a process that the author finds hard to accept.

3. If the Brushy Basin shale is actually the source for all the uranium in the Grants Region, then how can it be explained that the Brushy Basin is uniformly anomalously high in uranium.

4. During deposition of the Brushy Basin, it is likely that, due to rainfall, a substantial amount of the uranium would be lost to surface runoff, and thus would not be available later on.

In summary, the author contends that the most plausible source of the uranium and associated ore elements in the sandstone-type uranium deposits in the Grants Region is volcanic ash, and the ore elements were released to the host sediments contemporaneously with deposition of the latter.

Genesis of the Humate Material

Through chemical and infrared analyses (Granger and others, 1961; Moench and Schlee, 1967), the carbonaceous matter that is intimately associated with the uranium ore has been shown to be very similar to coals and humic acids, promoting the conclusion that it is a residue from a water-soluble humate derived from decaying plant material. There is no convincing evidence that the carbonaceous matter is a petroleum residue or that it is closely related to hydrocarbons.

Humates are best described as mixtures of organic compounds with variable atomic structures and compositions that are leached from decaying vegetation by alkaline solutions (Motica, J. E., pers. comm., July 19, 1978). Humate materials are widely distributed in nature, and arise from the chemical and biological degradation of plant material (Gamble and Schintzer, 1973). Christman and Minear (1971) have stated that organic materials appear to be present to some extent in most natural waters and in some cases are sufficiently concentrated to make the water yellow or brown in color. Christman and Ghassemi (1966) and Sarkanen (1963) have suggested that these organic materials are dissolved from living woody tissues, decaying wood, soil organic matter, or a combination of these. Stumm and Morgan (1970) have indicated that the range of concentrations of organic materials in surface waters is 0.1 to 10 mg/liter. Very extensive humate deposits in northwest Florida are derived from the leaching of surface vegetation and are probably accumulating at the present time in many localities (Swanson and Palacas, 1965). The practical importance of organic matter in surface waters is also indicated by the publication of a colorimetric method of analysis for what are described as "tannin, lignin, tannin-like, lignin-like compounds, or hydroxylated aromatic compounds (Taras and others, 1971).

Source

Granger (1968) outlined three proposed sources for the humate matter:

1. The "Dakota source hypothesis" - an extrinsic epigenetic source from decaying vegetation that contributed to the carbonaceous beds in the lower parts of the Dakota Sandstone. The Morrison Formation was directly overlain by a boggy vegetated terrain prior to final reworking and deposition of the Dakota Sandstone, and humic derivatives from the decaying vegetation were carried downward and laterally into sandstones of the Westwater Canyon and transported to regions where they were precipitated.

2. The "syngenetic source hypothesis" - an extrinsic penecontemporaneous source from decaying vegetation along the streams that deposited the Westwater Canyon sediments. Humic material derived from decaying vegetation along the stream courses dissolved in the stream waters and underflow waters, but were precipitated along an interface between underflow and more stagnant ground waters.

3. The "interval source hypothesis" - an intrinsic diagenetic source from decaying vegetation that was deposited (syngenetically) with the Westwater Canyon sediments. The dissolved humic materials then precipitated wherever they came in contact with precipitating agents.

While Granger supports the "Dakota source hypothesis", the author sees the humate matter present in the ore bodies as originating from the leaching of vegetal matter (trees, grasses) existing along the stream courses and incorporated within the sediments, rather than by introduction from an external source. Therefore, the author supports a combination of the "syngenetic source" and the "internal source" hypotheses.

The most obvious evidence in the Johnny M Mine in support of this hypothesis is the close spatial relationship between fossil plant material and the humate occurrences. This relationship is present in the individual ore pods and even in the small clusters of fossilized woody fragments in the trash piles. Squyres (1970) states that in many mines in the Grants Region ore lies only a few tens of feet from large accumulations of carbonized wood. This observation also exists in the Westwater Canyon ore bodies in the Johnny M Mine. Ore can sometimes be seen adjacent to a log, showing clearly that the log contributed the humate matter that trapped the uranium. The majority of the richer ore pods are closely related to accumulations of fossil trees and plants, with the ore occurring below and away from the organics. With the presence of trash piles, numerous fossil trees and grasses, and other organic detritus in the Westwater Canyon sandstones, it is very easy to derive the necessary amount of humate material for the accumulation of the known ore bodies.

Transport and Precipitation

Migration of humate as a colloid in an aqueous solution has been documented. Colloidal humic acid particles are about 0.02 microns in diameter, small enough to be suspended in surface waters and to permit easy passage through permeable sandstone. Humic acids, unless flocculated to a gel, could be carried some distance in streams or in groundwater.

Precipitation of the humic acids could be the result of several possible mechanisms. Black and Christman (1963) have verified that the humic matter found in water is negatively charged. As the humic acids migrate in the surface water, accumulation of an abundance of absorbed cations (mostly divalent, Squyres, 1970) would tend to cause flocculation. Reduction of pH, as a result of oxidation of some of the organic matter, may have had an effect on flocculation. One other possibility is that the humic acids polymerized spontaneously, as demonstrated by Pommer and Breger (1960).

When humic acids are flocculated in the laboratory, the particles settle and combine to form an amber-colored gel with a high water content (Squyres, 1970). The gel is coherent, but very soft and weak. Once a humate is flocculated into a gel, it is still capable of limited migration due to its low viscosity. Polymerization and dehydration would eventually render the gel immobile. Once in the solid form, humic matter is difficult to remobilize except in highly alkaline solutions. Swanson and Palacas (1965) point out that total consolidation of the humate can actually take place without the influence of heat or radiation. The conversion of the gel to its present insoluble state took place after the humate deposits had concentrated the uranium and became consolidated.

Environmental Conditions

pH

The general environment during the deposition of the Morrison sediments was probably mildly alkaline, with pH values kept near 8.5 by hydrolysis reactions and carbonate equilibria. This is supported by several lines of thought.

According to Krauskopf (1967) water cannot remain in contact with silicate minerals for any length of time without becoming alkaline through hydrolosis reactions such as:

$$4KAlSi_3O_8 + 22H_2O = Al_4Si_4O_{10}(OH)_8 + 4K^+ + 8H_4SiO_4 + 4OH^-$$

(feldspar + water = clay + soluble products, including hydroxyl ion)

The formation of silicic acid (H_4SiO_4) would keep the pH from rising much above 9:

$$H_2O + SiO_2 \text{ (quartz)} + OH^- = H_3SiO_4^-$$

$$H_4SiO_4 \text{ (aq)} + OH^- = H_3SiO_4^-$$

Assuming that the source of the Morrison sediments is granitic, this interaction between water and the silicates would start at weathering and continue through deposition. Hydrolysis of volcanic ash present in the environment would tend to maintain an alkaline pH in the water.

Garrels and Christ (1965) showed by calculation and measurement that pure water equilibrated with calcium carbonate and atmospheric CO_2 reaches a pH of about 8.4. The system is buffered and resists decreases in pH chiefly by the reactions:

$$CaCO_3 + H^+ = Ca^{++} + HCO_3^-$$

$$HCO_3^- + H^+ = H_2CO_3$$

In its course from outcrop to depositional site the surface waters and upper zone of the groundwater would undoubtedly come in contact with calcite, such as limestone lenses in small lake deposits. This would contribute to maintain a pH of around 8.0.

Probably the best line of evidence for an alkaline fluvial system in the Morrison sediments is the analogy with measured pH values of waters in similar sediments today. Among the analyses by White and others (1963), pH values of 7 to 9 are consistently found in groundwaters from sandstones, arkoses, and finer-grained clastic sediments. pH values of present-day groundwater from the Morrison Formation are clustered around 8 (Garrels and others, 1959).

Ore Formation Processes

Mobilization of the Ore Elements

Volcanic ash can be easily leached of its elemental constituents. White and Waring (1963, p. K9) write "relatively high concentrations of minor elements can be leached by distilled water from volcanic ash. Much leachable material was...condensed on associated ash..."

White and Waring (1963) cite analyses of natural and experimental leachates of freshly fallen ash. The ash contained tens of hundreds of ppm of easily leached minor elements, and the experiments indicated that the elements were largely absorbed on the surfaces of the ash particles. While the minor elements cited were associated with chloride, fluoride, and sulfate, it is very likely that uranium and the associated ore elements also collect on the surfaces of the ash particles (during eruption of the ash), and are deposited with the ash. This idea fits well with the syngenetic theory of a volcanic ash source, and with the belief that the uranium is concentrated during the deposition of the host sediments.

Ore Elements in Solution and Subsequent Concentration

Uranium leached from a volcanic ash and released into an aqueous medium would be solubilized in the hexavalent state as UO_2^{++} or as a complex, e.g. $[UO_2(CO_3)_3]^{-4}$ (Szalay, 1964). Laboratory investigations have demonstrated that UO_2^{++} and other cations of medium or high atomic weight are strongly fixed by humic acids (Szalay and Szilagyi, 1967). Due to the strong sorption of these cations, low concentrations of heavy cations (e.g. UO_2^{++}) migrating in natural waters which come into contact with the humic acids may become concentrated by a factor of 10,000 (Szalay and Szilagyi, 1967).

Until recently, the structure of humic acids in nature was poorly known. Jennings and Leventhal (1977) have experimentally determined the structure of at least one humic acid, with a chemical formula of $C_{249}O_{82}H_{320}N_{13}S_2$. They point out that there are numerous sites available to interact with soluble oxidized uranium species such as UO_2^{++} and $UO_2(OH)^+$. This fixation would be a reversible cation-exchange process with a geochemical enrichment factor of about 10,000 as previously stated (Szalay, 1958). The resulting organic structure due to the emplacement of the uranium ion into the structure of the humic acid is referred to as an uranyl humate by Vine and others (1958).

This uranyl humate could probably form in both surficial waters and in very near surface groundwater that is in direct contact with the stream water. Theoretically, this uranyl humate could migrate in the fluvial system for some distance before flocculation occurs. Flocculation (precipitation) of the uranyl humates would occur when the alkaline solution was rendered more acidic and/or there was a moderate concentration of divalent cations (e.g. UO_2^{++}) (Vine and others, 1958). The simultaneous reduction of sulphate by bacteria present in the organic humate would reduce the pH (Trudinger, 1971):

$$SO_4^{--} + 8_e^{-} + 9H^+ \underset{\text{bacteria}}{=} HS^- + 4H_2O$$

The combination of the reduction in pH and the abundance of cations would ultimately cause precipitation of the humate, and once flocculated, the humate forms a gel-like substance that eventually becomes a hard, brittle solid.

The cation-exchange process established for the accumulation of UO_2^{++} does not seem immediately applicable to the fixation of vanadium. The most stable form of vanadium in natural waters is the mobile meta-vanadate anion VO_3^-, but anions could not be directly fixed by humic acids, even in trace amounts (Szalay and Szilagyi, 1967). This anion is reduced to the quadrivalent state $(VO_2)^{++}$ when the dilute aqueous solution comes into contact with humic acids or other reducing agents. The cations produced are then available for absorption on the humic acids by a process such as that established for UO_2^{++}, with a geochemical enrichment factor of at least 50,000 (Szalay and Szilagyi, 1967). VO_2^{++} is the most probable cation to form because its formation requires only modest reducing conditions.

Molybdenum would probably be present in the aqueous solution as the anion MoO_4^{--}, along with arsenic as $HAsO_4^{--}$, and selenium as SeO_4^{--} or SeO_3^{--} (Squyres, 1970). Each of these elements form a stable dissolved species, and is capable of migration in solution under oxidizing conditions. Since there is little correlation between molybdenum and organic carbon in the primary ore bodies, it is therefore safe to conclude that molybdenum was precipitated by reaction with H_2S (HS^- in alkaline solutions). The fact that the only important molybdenum mineral is a sulfide (jordisite, MoS_2), the peripheral relation of jordisite to ore or to the humate matrix, and the isotopic composition of the sulphur (Squyres, 1970) all support this view. Arsenic and selenium have distribution patterns roughly similar to that of molybdenum, but with a tendency to be more concentrated in the richer uranium ore pods. Arsenic and selenium are effectively precipitated from dilute, weakly alkaline solutions by HS^-, and probably are precipitated by a process similar to the vanadium reduction outlined above. Since selenium sulfide is unstable and decomposes to elemental selenium, the occurrence of elemental selenium as acicular crystals is explainable.

Calcite should continuously be precipitating in the fluvial system, especially in the groundwater. The humate masses would be a source of HCO_3^-, due to the generation of CO_2 by slow oxidation in the decaying process:

$$CO_2 + H_2O = H_2CO_3$$
$$H_2CO_3 = HCO_3^- + H^+$$

With Ca^{++} being present in concentrations of up to 10 ppm (Squyres, 1970) in the aqueous solutions, and the pH of the system being around 8, calcite should form at least in moderate amounts:

$$Ca^{++} + 2HCO_3^- = CaCO_3 + H_2O + CO_2$$

Thus calcite would be forming essentially in the same system as the ore elements. The calcite would precipitate to some degree regardless of the ore processes, as there are Ca^{++} ions present in natural waters. The relationship between rich uranium ore and the abundance of calcite cement suggests to the author that the calcite formation somehow plays a role in the concentration of uranium and the precipitation of the uranyl humates. Perhaps some Ca^{++} ions are absorbed by the humic acids and help in the flocculation process, and calcite is subsequently precipitated during or after the process.

Scenario of the Ore Formation

Following is a compilation of the various previous discussions molded into the processes that the author envisions as resulting in the sandstone-type uranium deposits of the Grants Uranium Region, with special implications to the observations made in the Johnny M Mine.

Volcanic ash brought to northwestern New Mexico by westerly wind patterns were presumably derived from extensive volcanogenic activity in the western United States during deposition of the Morrison Formation (Chapin, C. E., pers. comm., July 19, 1978). This air-fall tuff would be deposited in the region where the Morrison sediments would be accumulating. Deposition of the ash in the fluvial system would initiate leaching of the ore elements, and subsequent release into the stream water and near surface groundwater. Due to the extensive areal extent of the air-fall tuff, surface runoff would also contain some ore elements in solution due to leaching of the ash by rainfall.

The fluvial system that was depositing the Morrison Formation contained much vegetation. Vegetation would accumulate in local backwater swamps, oxbow lakes, and on exposed bars. The trash piles would most probably be formed in the backwater swamps or oxbow lakes that still have tie-ins to the active sedimentation system. Constant decay of the organic material would release humic acids into the fluvial system.

The presence of clay galls can be accounted for by two processes. One is that the galls represent rip-up material from previously deposited mudstone layers that were eroded and then deposited by a high-velocity current. Another explanation is that the galls represent desiccation fragments from a once continuous mudstone layer, and their "boudinage-type" appearance is probably due to compaction, while still wet, by overlying sediments.

By the processes already discussed, the uranium and ore elements would be absorbed and reduced by the humic acids present and uraniferous organic complexes would form. These complexes would form in the surface waters and easily permeate the recently deposited sands and thus enter the near surface groundwater. The migration of these uranyl humates would be impeded by mudstone layers which would act as permeability barriers. Clay galls would not be expected to be mineralized by the uranyl humates because of the lower permeability.

The uranyl humates would ultimately form a gel and eventually become insoluble. The "floating grain" matrix previously described is evidence that the humate gel can form in the fluvial system while deposition of the sediments is still proceding. That the uraniferous organic complexes can form and precipitate at or very near the surface is inferred from the fact that ore bands are truncated by a later scour, indicating the ore processes occur essentially on the surface (Figs. 48a and 48b). Most uranyl humate complexes migrate into the groundwater where they are ultimately flocculated. The various shapes attained by the individual ore pods are the result of the different flow patterns of the groundwater.

Since the uranium is envisioned as forming in the surficial waters, the ore pods might be expected to conform very closely to the sedimentary structures, but this is not the case in the Johnny M Mine. This is easily explained by the migration habits of the humate complex. As the humate complex is in the process of forming a gel it migrates in the water and passes through the permeable sandstones. Since the sediments are newly deposited and unconsolidated, the permeability would tend to be uniform throughout the sediments. The migrating gel would then pass through the sediments without regard for cross-bedding or other sedimentary structures. The humate complex would then coalesce into the form we see today, with curving boundaries truncating sedimentary structures.

The red iron band so typically associated with the Westwater Canyon ore pods is probably the result of a complex interaction between the migrating, oxidized ore-bearing fluids and reduced groundwater. The red bands would probably form sometime during the later stages of the humate complex flocculating process.

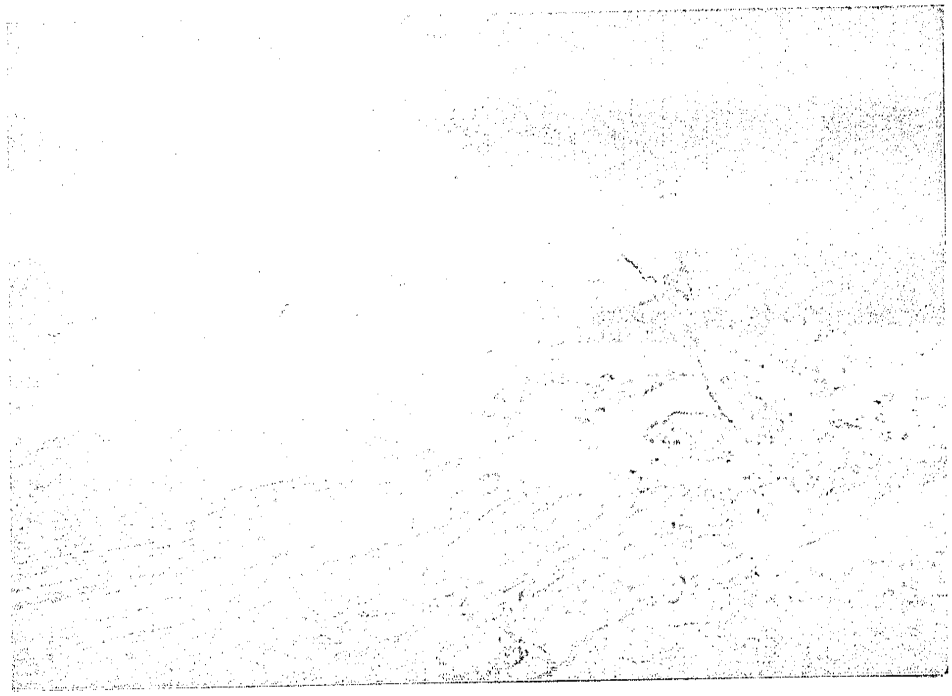

Fig. 48a - Banded uranium ore truncated by a scour and fill feature

Fig. 48b - Same as above

The occurrence of clay galls with red cores and green rims (Fig. 11a) can be explained by the interaction of the humic acid complexes with the clay galls themselves. The only significant difference that has been found between the red and green clays in a gall, other than color, is the difference in total iron. The red clays are significantly higher in total iron than the green clays (see Appendix B). Weeks (1951), in a study of red and gray (green) clays from the Morrison Formation, found that the total iron and ferric iron content are considerably higher in the red than in the gray (green) clay. Assuming that a clay gall was originally homogeneously red, it appears that the green rim is the direct result of removal and reduction of iron from the clay gall. This removal and reduction of iron may be attributable to humic acids present in the groundwater (Motica, J. E., pers. comm., July, 1978). The humic acids would remove and reduce the iron in galls it came in contact with. The clay galls with a green core and red rim were probably completely reduced, and at a later time were reoxidized.

Once buried under sediments, the uranium may undergo further secondary chemical changes in the course of the long geological processes of coalification and fossilization (Szalay, 1958). Secondary enrichment and mineralization may take place according to local conditions. The host rocks themselves may undergo changes after burial. The various color schemes present in the uranium-bearing sandstones (Fig. 22) are probably caused by either diagenesis or later groundwater movements.

While the processes that deposited the uranium ore are the same for the Westwater Canyon and Poison Canyon ore bodies, there may be a slight difference between them. Using the following observations as evidence, there is a difference:

1. the lower grade of the Poison Canyon ore
2. the more massive occurrence of the Poison Canyon ore
3. the Poison Canyon ore is not as well indurated by calcite cement as the Westwater Canyon ore
4. the Poison Canyon sandstone is significantly lacking in organic detritus such as trees, bones, and trash piles
5. pyrite is more abundant in the Poison Canyon sandstone
6. red iron bands around the ore pods, so common in the Westwater Canyon, are rare in the Poison Canyon ore

Putting these observations together, either:

1. the Poison Canyon ore is primary ore that has travelled a great distance before being deposited. This would account for the lack of organic detritus (humic acid source) in the near vicinity of the ore

or

2. the Poison Canyon ore is secondary ore derived from the remobilization of primary ore. This is not to say secondary ore according to Squyres (1970) (primary ore that has been redistributed by seepage along faults) but primary ore that has moved down the fluid gradient. If several ore bodies were remobilized along the same sandstone horizon they might have these characteristics:
   a. be redeposited as extensive, massive sheets
   b. have a lower U_3O_8 content, due to diffusion
   c. the cement would be more dispersed and less concentrated

   These characteristics fit the Poison Canyon ore well, when compared to the Westwater Canyon ore.

Therefore, the Poison Canyon ore in the Johnny M Mine is a secondary ore not associated with seepage along fault planes.

In summary, the factors controlling the time and location of concentration of uranium and other ore elements are the presence of the necessary humic acids derived from decaying plant matter, and the deposition of a uranium-rich air-fall tuff or ash. While humic acids would probably be present during most of the history of the sediment deposition, uranium and associated ore elements would be present in the waters on an irregular basis, due to the sporadic nature of air-fall eruptions. This would explain why there exist barren sand beds located between sands that are ore-bearing; there was no uranium present in the fluvial system when the barren sands were deposited. While no absolute time can be given for the interval between the deposition of the volcanic ash and the ultimate formation of the ore, the author thinks that the processes are geologically rapid.

CHAPTER VI

CONCLUSIONS

The major conclusions of this paper are as follows:

1. The uranium deposits in the Morrison Formation of the Grants Uranium Region formed during deposition of the host rocks.

2. The carbonaceous matter intimately associated with the uranium ore was originally humic material derived from the leaching of plant material occurring in the fluvial environment. The uraniferous humates subsequently flocculated and formed gel-like masses distributed by groundwater into the various shapes we see today in the mine exposures.

3. In the Grants Uranium Region, the uranium and associated ore elements were derived from volcanic ash contemporaneously deposited with the sediments. The ash also helped to maintain an alkaline pH in the water, facilitating the leaching and transport of humic substances.

4. Accumulation of uranium and the other ore elements took place while the humic acids were migrating in the aqueous solution. Uranium was removed from solution by absorption and ultimately fixed by a cation-exchange process and reduction on the organic matter. Vanadium was probably reduced directly by the organic matter and then absorbed onto the humic acids by a cation-exchange process similar to the one used for the uranium ions.

5. Bacterially generated H_2S, which aided precipitation of uranium and vanadium, was instrumental as an effective precipitant of molybdenum, arsenic, and selenium.

6. The uranium occurs chiefly in the form of an uranium-bearing humate complex, and not as the mineral coffinite.

7. Ore formation was completed during Jurassic time. The subsequent deep burial, coalification, and faulting of the ore bodies were later processes unrelated to primary ore deposition.

8. The ore bodies are localized in paleostream channel systems, thus accounting for the linear aspect of the ore bodies.

9. The fluvial environment in which the host sediments were deposited consisted of a network of aggrading braided streams (Westwater Canyon sandstone) and meandering streams (Poison Canyon sandstone) generally flowing in an eastward-southeastward direction.

10. The major factors controlling the location and time of ore deposition are the presence of anomalous amounts of uranium ions in the fluvial system, and the existence of favorable humic acids to trap and concentrate the uranium and other ore elements.

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APPENDIX A

Analytical Methods

Chemical analysis for this paper was done at New Mexico Tech via X-ray fluorescence methods, using a Norelco analyzer and a tungsten tube. All the samples were ground to 200 mesh, using a small ball mill. To attain the required fineness, the samples were ground for at least 30 minutes. The resulting fine powder was then coned and quartered, and approximately one gram of the sample was made into a pellet by the following methods:

1. The sample was pressed into a thin wafer using the pellet-making apparatus.

2. 13 drops of cement (0.01 gms/ml Butvar 76 in dichloroethane) was then added to the sample.

3. When the cement dried, boric acid (solid) was added to form the backing of the pellet.

4. The pellet was then compressed under 7 tons pressure for 5 seconds and released. The pellet was allowed to dry again.

5. The pellet was then compressed under 15 tons pressure for 5 seconds and released. Again the pellet was allowed to dry.

6. The pellet was then compressed under 20 tons pressure for 5 seconds and removed. Only the pellets that had an absolutely smooth surface were used for analyses.

Each sample was run two times for each element to be determined. Each run consisted of a measurement of the characteristic radiation of the element, and a measurement of the background 1° on either side of the characteristic line. Instrument counting times varied from 10 seconds to 60 seconds, depending on the concentration and sensitivity of the element under investigation. The results were compared to either

U.S.G.S. standards or standards made by the author using a matrix of Ottawa sand. All the data accumulated were analyzed using a data reduction program on a hand-held Hewlett-Packard 25 calculator. All analyses and programming were done by the author.

APPENDIX B

CHEMICAL ANALYSIS

Westwater Canyon sandstones in order of uranium %

Sample	U%	Fe%	Cu (ppm)	Se%	As%	Mo%	V%
1400-2	[illegible]	[illegible]	208	.048	.018	.063	.52
800-3	5.90	.37	109	.056	.023	.073	.35
800-2	5.76	.40	77	.037	.017	.060	.68
800-3	5.71	.86	105	0.000	.022	.063	.44
800-2	5.70	.74	87	.44	.017	.057	1.38
1200-1	5.40	.26	95	.02	.013	.054	.34
800-2	4.97	1.00	77	1.24	.016	.053	1.22
800-3	4.10	.96	220	.013	.011	.052	.36
800-3	4.05	1.19	64	.014	.023	.09	1.04
1400-1	3.90	1.17	95	.008	.01	.031	.32
1200-1	2.60	1.80	141	.058	.006	.027	.54
800-3	2.08	1.82	141	.002	.070	.08	.31
1100-1	1.82	2.70	67	.30	.007	.027	.78
800-3	0.22	8.24	16	.012	.00	.005	.16
1200-1	0.04	1.90	120	.009	.011	.027	.11
800-3	0.01	7.3	65	.00	.00	.00	.07
800-2	0.00	7.0	65	.00	.00	.00	.04
1400-2	0.00	6.5	55	.00	.00	.00	.05

Westwater Canyon claystones

Sample	U%	Fe%	Cu (ppm)	Se%	As%	Mo%	V%
Red Gall	0.00	10.9	1.0	0.00	0.00	0.00	.35
Red Gall	0.00	11.7	1.10	0.00	0.00	0.00	.11
Red Gall	0.00	8.6	1.0	0.00	0.00	0.00	.16
Green Gall	0.10	4.1	1.0	0.06	0.002	0.01	.18
Green Gall	0.00	3.1	1.0	0.02	0.00	0.00	.14

Westwater Canyon sandstone - samples 100' (33 m) from known ore

Sample	U%	Fe%	Cu (ppm)	Se%	As%	Mo%	V%
409 V.D.	0.00	1.6	0.90	0.00	0.00	0.00	.05
409 V.D.	0.00	2.1	1.00	0.00	0.00	0.00	.03

APPENDIX B (cont)

Jordisite ([illegible] gel) samples

Sample	U%	Fe%	Cu (ppm)	Se%	As%	Mo%	V%
1400-2	[illegible]	[illegible]	113	.008	.002	.04	.03
800-3	.00	.90	84	.042	.003	.08	.065

Poison Canyon sandstones in order of uranium %

Sample	U%	Fe%	Cu (ppm)	Se%	As%	Mo%	V%
008-3	3.8	.50	87	.005	.01	.04	.14
016-1	1.3	2.77	25	.013	.005	.013	.23
018-1	1.03	4.61	135	.00	.003	.016	.41
008-1	.97	3.7	35	.00	.003	.013	.32
018-4	.77	3.75	78	.00	.001	.01	.14
016-3	.74	2.81	20	.014	.005	.004	.15
018-2	.68	2.08	32	.00	.00	.009	.14
008-7	.48	.43	27	.00	.001	.008	.08
008-2	.33	2.11	130	.00	.00	.00	.13
008-4	.16	3.00	352	.00	.00	.00	.12
008-6	.05	.15	42	.00	.00	.00	.21
008-9	.00	1.13	53	.00	.00	.00	.06

Claystones bounding the Poison Canyon sandstone

Sample	U%	Fe%	Cu (ppm)	Se%	As%	Mo%	V%
K Shale	0.00	3.66	1.00	0.00	0.00	0.00	.18
K Shale	0.00	3.44	1.00	0.00	0.00	0.00	.11
Brushy	0.00	3.37	1.00	0.001	0.012	0.00	.21
Basin	0.00	3.84	1.00	0.000	0.007	0.00	.19

Ilsemanite (Molybdenum oxide) samples

Samples	U%	Fe%	Cu (ppm)	Se%	As%	Mo%	V%
Blue	.005	.26	1076	.27	.016	.72	.29
Green	.00	.11	2114	.10	.015	.30	.08

APPENDIX C

Methodology of Thin-section Analysis

The thin-sections analysed during this study were prepared at New Mexico Tech. The samples to be cut were first impregnated with epoxy and allowed to dry for 24 hours. The epoxy acted as a binder since the samples were friable. Twenty-seven thin-sections were made; 11 of these were stained with sodiumcobaltnitrate in order to help the writer optically differentiate orthoclase from quartz.

The thin-sections were analysed on a Zeiss microscope supplied by the Geoscience Department. To determine the percentage of detrital minerals, a minimum of 650 point counts per slide were taken using an automatic point counter. Pictures of certain textural features in selected thin-sections were taken by the writer using an Olympus camera and optics.

The comparison chart for sorting and sorting classes (Folk, 1968, p. 102) was used to visually estimate the degree of sorting and Phi Standard Deviation in the thin-sections analysed. Degree of roundness was visually estimated using a chart for visual estimation of roundness and sphericity (Krumbein and Sloss, 1955). The size of detrital grains was determined by comparing the long dimension of the grain with the known diameter of the field of view under the magnification being used.

APPENDIX D

Results of Thin-section Analysis (in %)

Upper Westwater Canyon sandstone horizon

Sample	Quartz	Microcline	Orthoclase	Plagioclase	Chert	Lithic Fragment	Miscellaneous	Organic
802-1	61.4	5.2	12.9	18.1	2.0	.4		2
802-5*	61.4	4.5	10.3	21.6	2.2		Biotite	5
802-14	61.5	7.7	5.3	21.7	3.8		Apatite	8
802-17	46.2	15.4	12.3	16.3	5.3	4.5		7
802-18	49.8	8.8	19.4	21.3	0.7			5
802-19*	59.0	9.5	15.0	15.2	1.3			20
1201-4*	55.0	16.7	16.7	10.3	1.3			<1
1401-4	71.9	4.6	13.1	9.5	0.9		Chlorite	4
1402-8*	57.3	15.0	15.8	7.7	4.2			<1
1402-12	62.8	5.5	19.8	8.7	3.2			4
014-1*	46.8	21.1	16.9	9.9	5.3			1

Lower Westwater Canyon sandstone horizon

Sample	Quartz	Microcline	Orthoclase	Plagioclase	Chert	Lithic Fragment	Miscellaneous	Organic
803-3	39.1	23.3	21.8	13.4	2.4		Antiperthite	15
803-4*	53.7	9.7	16.1	17.4	3.1		Biotite	6
803-5	47.3	10.0	24.6	16.9	1.2			10
803-16	55.8	14.4	14.4	12.9	2.5			9
803-17*	59.1	5.1	21.3	11.7	2.8			5

NOTE: * next to sample signifies that thin-section was stained for feldspar
Organic percentage is the amount of humate material in relation to the entire thin-section, but is not counted in the total.

APPENDIX D continued

Poison Canyon sandstone horizon

Sample	Quartz	Microcline	Orthoclase	Plagioclase	Chert	Lithic Fragment	Miscellaneous	Organic
004-1*	71.1	2.8	22.8	3.4				0
004-2	71.6	6.1	14.3	5.8	2.2			5
006-2	72.8	4.8	17.9	3.2	1.3			<1
008-1	75.4	1.8	20.8	1.3	0.7			[illegible]
008-3*	74.1	2.7	21.5	1.7			Biotite	1
008-6	68.6	4.1	25.6	1.1	0.6		Chlorite	<1
012-1	72.6	6.0	17.6	3.0	0.8			2
016-2*	67.5	3.9	20.3	6.5		1.8		3
016-3	63.9	5.4	25.2	5.2		0.3		3
018-1	61.0	6.1	27.5	4.4	1.0		Perthite	2
018-2*	75.3	3.8	16.9	3.7	0.3			1

NOTE: * next to sample signifies that thin-section was stained for feldspar
Organic percentage is the amount of humate material in relation to the entire thin-section, but is not counted in the total.

Terms used in this paper to describe the degree of relative abundance:

1. Typical
2. Extremely common
3. Very common
4. Common
5. Relatively common
6. Uncommon
7. Rare
8. Very rare
9. Atypical

APPENDIX F

Plates located in back pocket:

PLATE I - North Side Ore Bodies - Major Faulting

PLATE II - South Side Ore Bodies - Major Faulting

PLATE III - Johnny M Mine - Major Faulting

PLATE IV - North - South Cross Section

PLATE V - Northwest - Southeast Cross Section

This thesis is accepted on behalf of the faculty of the Institute by the following committee:

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Date 11-22-78