National Uranium Resource Evaluation

GEOLOGY AND RECOGNITION CRITERIA FOR URANIFEROUS HUMATE DEPOSITS GRANTS URANIUM REGION, NEW MEXICO

FINAL REPORT

MASTER

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SUMMARY

This report summarizes the geology of the uraniferous humate uranium deposits of the Grants Uranium Region, northwestern New Mexico. The deposits are, in terms of their important geologic characteristics, unique in the world, although possibly similar deposits may exist. We are aware of the risks in drawing general conclusions and interpretations about deposits for which there is only one known example. In this case we have no alternative, and given the enormous importance of these deposits within the United States and the remaining potential of portions of northwestern New Mexico for new discoveries, we offer the accompanying interpretations and guides for the evaluation of new areas.

More than 330 publications were reviewed for this report. Based on this literature review the essential geologic features of the region may be summarized as follows. The host sedimentary sequence is a fluvial sandstone-shale sediment which originally contained an appreciable admixture of acid volcaniclastic material, particularly in the interbedded mudstone units. This volcanic material was altered during transport and after deposition and appears to be the most likely source of the uranium in the ore deposits. Humic acids, derived from buried vegetal matter, were transported, along with the uranium, in the early alkaline ground water system to sites where a change in pH from alkaline to acid caused precipitation of humate. The tabular humate deposits scavenged uranium from the ground water, and those located along the most transmissive zones eventually became ore deposits. The formation of the uranium deposits was a diagenetic process which probably began soon after the sediment was deposited, and continued until the humate was no longer chemically active. The uranium minerals are co-extensive with the humate and thus the geometry and habits of the ore are those of the humate. The primary humate deposits are relatively thin, tabular or sheet-like bodies suspended in the sandstones sub-parallel to the stratification of the host rock. This geometry is believed to have been caused by the precipitation of the humate along a sub-horizontal interface between two chemically different ground waters.

These tabular orebodies generally occur at several stratigraphic levels along narrow linear trends that are miles in length. These ore trends appear to be structurally controlled sedimentary trends within the host sandstone. The trends are characterized by above-average sandstone thicknesses, in straight, sub-parallel belts that have a fairly regular spacing normal to the trend direction. The host rock along these trends has been strongly reduced with the result that detrital magnetite and ilmenite have been destroyed and authigenic pyrite locally deposited. A petrographic study done for this report has shown that albite replacement rims on detrital feldspars and feldspar dissolution also distinguish the reduced, prospective sandstone facies. An overprint of late Tertiary oxidation has destroyed the pyrite and redistributed some of the primary ore in a large portion of the district; however, the prospective trends can still be distinguished by the feldspar and magnetite-ilmenite alteration patterns. This alteration not only makes it possible to recognize the limits of this mineral district but should also serve as a valuable guide in the exploration for similar deposits in other basins where uranium and humic material are known to have been present during sedimentation. In an unexplored basin, a very widespaced grid pattern of holes

for gamma ray, resistivity, and magnetic susceptibility logs should furnish sufficient information to identify ore trends. Isopachous maps have proved to be the most useful method of determining the paleostructural trends and have aided in projecting the established ore trends. What we considered to be the most important conclusions of this study are enumerated briefly below.

(1) Although the geologic characteristics of the uraniferous humate deposits of the Grants Uranium Region are obviously not common in the world, neither are they bizarre or coincidental. On the contrary, they resulted from a particularly fertile ore-forming system involving thick sedimentary sequences rich in organic material and volcanoclastic detritus and uncommonly well-developed aquifers. These characteristics are all very much a part of the source rock and depositional system that produced the sediment pile.

(2) The source of the uranium in the deposits of the Grants Uranium Region is not known with certainty. The district occurs within the general uraniferous province of the Colorado Plateau, as defined by uraniferous basement rocks, and the ore-bearing stratigraphic sequence contains abundant tuff-derived bentonitic clays. There is no unequivocal evidence as to the precise source of the uranium, but it appears to have come from Jurassic acid volcanic intrusives.

Circumstantial evidence suggests that the volcanic material of the sedimentary sequence was the probable source of the uranium. This is based upon circumstantial evidence for the frequent association of uranium deposits with tuffaceous or bentonite-bearing sedimentary sequences has been widely noted. Although not completely satisfying, this is such a pronounced, recurring theme in sandstone uranium deposits that we suspect it indeed reflects the source. However, it is not at all clear whether the uranium was derived from tuffaceous material within the host sands themselves, from the adjacent Brushy Basin Shale, or at some distance up hydrologic gradient from where the deposits are presently located. Evidence is presented which favors some combination of all three alternatives.

(3) The depositional environment of the host sediments was apparently the mid and distal portions of a wet alluvial fan system (fan is used here in the sense of Galloway, 1978 and 1980, rather than in the more limited geomorphologic sense). This environment provided not only the medium-grained host sandstones, but several intimately related geologic characteristics which subsequently determined all the characteristics of uranium deposits including their position, size and grade. The early recognition of a favorable depositional environment is perhaps the single most useful guide for establishing a regional context for resource evaluation and exploration.

(4) The influence of structural control on the location and accumulation of the host sediments is now supported by considerable data. It appears that zones of subsidence related to the fracturing and displacement of basement blocks accumulated the thicker sandstones with which the major mineral trends are associated. It is suspected that the fractures along which displacement occurred may be fundamental, ancient structures that could have suffered considerable alteration, hence may be detected with magnetic surveys. The effect of these structures on the formation and location of the mineral trends is believed to have been of fundamental importance.

(5) The host sediments possess numerous important characteristics which influenced the formation of uraniferous humate deposits. Many of these characteristics are similar to those seen in host rocks which contain other types of sandstone uranium deposits. One important characteristic of the Morrison Formation in the Grants Uranium Region may be the non-oxidized nature of the Brushy Basin shale which is in continuous depositional continuity with the two principal host sands, the underlying Westwater Canyon and the overlying Jackpile sandstone. Where such shales are oxidized, different ore habits seem to result, such as those found in the deposits of the Uravan Mineral Belt or the Chinle Formation.

(6) Ilmenite-magnetite distribution within potential host sandstones is believed to be the simplest and most useful regional alteration pattern related to this type of uranium deposit. The alteration occurs in broad, systematic patterns which should be useful in appraising the remaining potential of northwestern New Mexico as well as other areas.

(7) A method is presented for organizing geologic observations into what is referred to as recognition criteria. The use of such observations to draw subjective inferences about geologic favorability has been used for decades. There is merit, however, in attempting to establish a somewhat more formal system for identifying, and establishing the relative importance of, guides to uraniferous humate-type deposits. As the recognition criteria are based on geologic observations, they should be useful in resource studies and exploration and as a basis for improving current concepts and methods.

(8) The potential of the United States for new districts similar to the Grants Uranium Region is judged to be low based upon presently available geologic information. The geologic characteristics of this type of ore deposit are so well-developed and the district so large, that were others present within the conterminous United States it is likely that they would have been identified. Within northwestern New Mexico it is likely that discoveries will be made within existing trends, within oxidized ground along the projections of known trends, and even within entirely new mineral trends.

(9) Continuing studies on uraniferous humate deposits are desirable in three particular areas. (a) First, topics are suggested which will improve our ability to recognize and evaluate potentially favorable areas for the occurrence of uraniferous humate deposits with the lowest possible effort and expenditure. It is believed that these types of studies are now well along, but certain areas deserve additional attention. (b) Techniques need to be developed from the existing data for evaluating important characteristics of undiscovered deposits such as their abundance, size, grade, and continuity. (c) Geologic and geochemical studies should further investigate the formation and control of this important type of deposit, and test the hypotheses presented in this report. Such research projects will ultimately yield useful information for exploration, deposit evaluation and resource studies.

INTRODUCTION

Background

This report reviews the geology, genesis, and controls of uraniferous humate-type sandstone uranium deposits for the purpose of describing those geologic recognition criteria which seem most useful for evaluating areas with potential for new deposits. The review on which the report is based is part of the National Uranium Resource Evaluation (NURE) program of the United States Department of Energy.

Uraniferous humate deposits occur only in northwest New Mexico within the United States and no well-described deposits are yet known outside the United States. They constitute, nonetheless, about 50 percent of domestic reserves and more than 35 percent of current estimated U.S.\$50 resources (DOE, 1979). The value of these large, relatively high grade deposits has led to intensive exploration over the past 30 years, which has resulted in numerous additional discoveries. Therefore, much has been learned about the characteristics and distribution of these deposits.

The uranium district of northwest New Mexico has been called the Southern San Juan Basin Mineral Belt, the Grants Mineral Belt, and the Grants Uranium Region. Since it is losing its belt-like character due to the discovery of deposits deeper into the basin, the last name is now more applicable. The region is bounded approximately by 106°45' west longitude on the east, and 109° west longitude on the west. To the south and north it is bounded arbitrarily by the parallels 35° and 36° north latitude, respectively. This rectangular area encloses roughly 10,000 square miles (23,500 km²) and encompasses portions of McKinley, Sandoval, Valencia, and Bernalillo Counties (Plate 1). The main mineralized trend extends diagonally across this area for 100 miles between the towns of Gallup and Albuquerque, New Mexico. The town of Grants is centrally located on U. S. Interstate Highway 40, which parallels the south side of the mineral belt.

The Grants Uranium Region is physiographically a land of mesas and canyons typical of the Colorado Plateau of which it is a part. Surface elevations range from 5,500 to 8,000 feet. The highest point, 11,389 feet, is the crest of Mount Taylor which is an extinct volcano straddling the mineral belt northeast of Grants. The climate is semi-arid with an annual rainfall of about 10 inches. Vegetation is sparse and consists of grasses in the valleys and pinon pine and juniper on the mesas and cuestas. Pines and oaks are found above 8,000 foot elevations. There are no large perennial streams. The Rio Puerco Rivers of the east and west and the Rio San Jose are the principal drainages for the area.

A Navajo shepherd, Paddy Martinez, brought the uranium occurrences to public attention in the Spring of 1950. The first shipment of limestone ore was made in December, 1950, and of sandstone ore in the Summer of 1951. Between 1950 and 1958 approximately one billion dollars worth of ore was discovered by drilling (Hilpert and Moench, 1960, p. 430), and by 1967 uranium concentrates of this value had been produced (Kittel et al, 1967, p. 174).

Production from the Grants Uranium Region as of 1979 has been 73 million tons of ore containing 144,220 tons of U_3O_8 .

The Jurassic host rocks of this area were poorly known at the time uranium was discovered. The first comprehensive geologic investigation of the district was made by members of the U.S. Atomic Energy Commission in 1951. This report was published the following year (Rapaport et al, 1952). Both the U.S. Geological Survey and the Atomic Energy Commission have continued with studies on the geology and uranium deposits of the region. Some excellent summary reports are: Craig et al, 1955; Hilpert and Moench, 1960; Granger et al, 1961; Moench and Schlee, 1967; Hilpert, 1969; and Santos, 1970. The most detailed descriptions of the uranium deposits will be found in the New Mexico Bureau of Mines and Mineral Resources Memoir 15 (Kelley, 1963), which is a collection of 38 papers prepared as a guidebook for the Society of Economic Geologists Field Conference in Grants. The most recent volume on the geology and geochemistry of the uranium deposits is the Bureau of Mines Memoir 38, which contains 47 papers (Rautman, 1980). Special acknowledgement must be given to Professors Clay T. Smith at the New Mexico Institute of Mining and Technology in Socorro, who was one of the earliest to work on the Jurassic stratigraphic problems, and Paul F. Kerr at Columbia University, who was directly or indirectly responsible for more than ten theses and papers on the Grants Uranium Region.

A surge in activity by the U. S. Geological Survey in recent years has resulted in geologic quadrangle maps covering much of the mineral belt. The best overview is presented on a generalized geologic and orebody map of the entire district compiled by Chapman, Wood and Griswold (revised, 1979), and published by the New Mexico Bureau of Mines.

The project leading to this report was originally proposed in 1978 by Adams as part of a project to review the geology of the six major types of uranium deposits considered to have significant potential for discovery in the United States. The work plan provided for retaining six geologic experts, each intimately familiar with one of the deposit types. The contract was awarded in November, 1979, and much of the descriptive and interpretative material was prepared over the next several months by Saucier. Hundreds of thin sections were studied for region-wide alteration by Adams. A system was developed for estimating the favorability for uraniferous humate deposits and the authors selected the recognition criteria based on geologic data and the plausible genetic models.

Objectives

The objective of this study is to contribute to the NURE program by providing a more comprehensive synthesis of the geology of uraniferous humate deposits and a more systematic methodology for handling geologic information. The mission of the NURE program is to prepare more reliable and comprehensive uranium reserve and resource estimates for the United States. Preliminary reports have presented interim estimates of reserves in a series of cost categories, and estimates of resources in certain categories (probable, possible, and speculative). Reserve estimates are based almost entirely on

company data supplied to the Department of Energy. By comparison, estimates of undiscovered resources are based upon geologic judgment, which compares the geologic characteristics of known uranium districts with areas perceived to have uranium potential, and assigns to the latter resource potential estimates based upon the general geologic similarities, the comparative areas involved, and the grade and tonnage characteristics of the known district.

The uncertainties associated with resource estimation are considerable and generally accepted procedures for preparing such estimates have not been available. One major uncertainty is the selection, collection and interpretation of geologic information. It seemed that the process of comparing geologic characteristics of known deposits with those of untested areas might be improved by identifying the most critical geologic observations (recognition criteria) and then estimating and accumulating the degree of geologic similarity. This possibility became an important part of the objectives of this study which may be summarized as follows:

- (1) Review the geology of the uraniferous humate region of northwestern New Mexico and identify the important geologic characteristics.
- (2) Determine if significantly different types of deposits occur within the region and if new variants are likely to be discovered.
- (3) Identify geologic characteristics which can be expressed as recognition criteria, the presence or absence of which most strongly affects the favorability or potential of an area for the occurrence of uraniferous humate deposits.
- (4) Develop a simple method for ranking the relative importance of the recognition criteria.
- (5) Develop a method for accumulating the favorabilities derived from individual recognition criteria so as to estimate the favorability for uraniferous humate deposits in a reasonably systematic but practical fashion.

Sources of Information

The descriptive and interpretative material in this report has been accumulated from published and unpublished reports on the Grants Uranium Region and through discussions with geologists possessing first-hand knowledge of these deposits. This material has then been reviewed and interpreted in the context of the writers' own investigations within the Region.

Through numerous discussions with both exploration and research geologists, we have attempted to accumulate as much information and informed opinion as possible. In some cases, previously unpublished data was made available to us and is included in the text. In numerous other cases, we found that data simply does not exist, even for seemingly basic questions such as uranium mineralogy.

We have attempted to be thorough in our coverage of the Grants Uranium Region and have included references to other districts, and technical studies where

they contributed descriptive material or information pertinent to processes and methods of ore formation. Our emphasis has been on the collection and review of well-documented data and observations so as to present a reliable data base for the interpretation of ore genesis and controls and for the preparation of broadly useful recognition criteria. Attempts to develop more specific and refined criteria have not met with great success, due both to the range of conditions favorable for ore occurrence and the continued lack of data in some important areas.

Less attention is paid to discussions of inorganic uranium solution chemistry and ore precipitation than some readers might prefer. This reflects our bias, that humic organic matter so dominates the chemical processes which form these deposits that relations in inorganic systems are merely permissive and tell little about actual ore formation.

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GENERAL GEOLOGY

Regional Setting

The Grants Uranium Region is located on the south flank of the San Juan Basin in the southern part of the Colorado Plateau physiographic province, as shown in Figure 1. The eastern edge of the region extends off the plateau into the Basin and Range province. It is bordered to the south by a northwesterly trending arch which is separated into two segments, called the Lucero Uplift and the Zuni Uplift, by the Acoma sag of Kelley (1963, p. 19). To the east of the San Juan Basin is the Nacimiento Uplift, and to the west is the Defiance Uplift. Sedimentary strata dip steeply off the flanks of the Nacimiento and Defiance Uplifts into the basin. Dips off the north flank of the Zuni Uplift are gentle, and the strata form a broad dip slope into the basin called the Chaco slope (Kelley, 1951, p. 124).

As much as 11,000 feet of sedimentary rocks are estimated to overlie the basement in this area (Moench and Schlee, 1967, p. 5). The beds in the uranium region range in age from Pennsylvanian to Late Cretaceous. Tertiary sediments may have once covered this part of the basin but are no longer present. All the Tertiary rocks present in the area now are Late Tertiary volcanics. The colorful Triassic and Jurassic strata are almost exclusively continental red beds which were deposited in broad floodplains by eolian, lacustrine, and fluvial processes. The Cretaceous beds are mainly of shallow marine origin with interbedded littoral and continental deposits.

North of Interstate 40 these beds dip 3 to 5 degrees northward into the basin. Resistant beds of Cretaceous sandstone form cuesta ridges and the shales erode to form long strike valleys. The sandstones throughout the area tend to be massive and cliff-forming, and exposures are generally excellent. Outcrops may exhibit 500 feet to more than 1,000 feet of strata. Dips are much steeper on the east and west sides of the basin where the beds form north-trending hogbacks. Steep dips on the Chaco slope are generally associated with monoclinial flexures or normal faults.

Stratigraphy

Emphasis in this study will be on the Jurassic rocks, particularly the Morrison Formation. The Jurassic stratigraphic section in the Grants Uranium Region is divided into the San Rafael Group and the Morrison Formation as shown in the stratigraphic column (Table 1). The San Rafael Group includes the Entrada Sandstone, the Todilto Limestone, the Summerville Formation, and the Bluff (Cow Springs) Sandstone. This group ranges from 600 to 1,000 feet in thickness and is composed of a succession of eolian dunes which interfinger with minor lacustrine siltstone and one relatively thin limestone. The Morrison Formation is composed mainly of fluvial deposits which mark the end of a long arid climatic period. The portion of the Morrison Formation of economic interest in New Mexico is preserved only in the San Juan Basin. The formation ranges from 0 to perhaps 700 feet and averages about 500 feet thick

Table 1. Sequence of stratigraphic units containing uranium deposits in the Ambrosia Lake-Laguna area, New Mexico (from Hilpert, 1963).

Age	Gr.	Formation	Thickness (feet)	Character and Distribution	Uranium Deposits
CRETACEOUS		Dakota Sandstone	< 5-125	Tan to gray, medium-grained quartz sandstone, some interbedded carbonaceous shale and local coal lenses. Local conglomerate-filled scours at base as much as 25 feet deep.	Scattered small deposits, generally near base and closely related to carbonaceous material. A few in Ambrosia Lake and Gallup districts have yielded ore.
		Unconformity			
LATE JURASSIC		Morrison Formation	0-700	Brushy Basin Member: mostly greenish-gray mudstone and local thick arkosic sandstone units. Contains the Jackpile sandstone of economic usage at top in Laguna district. Member is 20-300 feet thick and generally thickens eastward and northward from Ambrosia Lake district.	Sandstone lenses contain many deposits. Very large deposits occur in Jackpile sandstone in Laguna district and large ones occur in sandstone units in Ambrosia Lake district.
				Westwater Canyon Member: light-brown to gray, poorly sorted, arkosic sandstone and some interbedded green mudstone. Intertongues with Brushy Basin and thins from maximum of about 300 feet in Ambrosia Lake district to less than 50 feet in the Laguna district where locally absent.	Contains many large deposits in the Grants Uranium Region.
				Recapture Member: distinctive alternating beds of gray sandstone and grayish-red siltstone or mudstone. Beds are a foot to several feet thick. Contact with Bluff Sandstone generally sharp, but intertongues with Westwater Canyon Member. Recapture is less than 50 to more than 200 feet thick.	Contains insignificant uranium mineralization.
	SAN RAFAEL GROUP	Bluff Sandstone	150-400	Pale-red to pale-brown, fine- to medium-grained sandstone. Forms massive cliffs. Upper part marked by thick sets of large-scale crossbeds; lower part grades down into smaller-scale sets of crossbeds and some flat beds.	Contains no known uranium deposits.
		Summerville Formation	90-200	Alternate beds of pale-brown, thin-bedded sandstone and reddish-brown mudstone or siltstone. Sandstone beds thicken in upper part and grade into overlying Bluff Sandstone; at base grades and intertongues with Todilto.	Contains scattered deposits at base, generally where underlying Todilto Limestone is mineralized. No significant production.
		Todilto Limestone	0-85	Consists of upper gypsum-anhydrite member, exposed only in Laguna district, 0-75 feet thick; and lower limestone member, gray, laminated in lower part and more massive, contains interbedded siltstone in upper part, 5-35 feet thick.	Contains (mostly in Ambrosia Lake district) many small and some fairly large deposits in the limestone member.
		Entrada Sandstone	150-250	Consists of upper unit, 80-250 feet thick, of reddish-orange, fine-grained sandstone with thick sets of large-scale crossbeds and a medial unit, 10-85 feet thick, of red and gray siltstone. In the Laguna district, a lower sandstone unit, 0-30 feet thick, may belong in the Entrada or may be the Wingate Sandstone. Medial unit probably unconformable on Wingate Sandstone in Ambrosia Lake district; lower sandstone unit unconformable on Chinle Formation in Laguna district.	Contains scattered small deposits at top of formation, generally where overlying Todilto Limestone is mineralized. Some have yielded ore.
		Unconformity			
		Wingate Sandstone and Chinle Formation		Not described.	
LATE TRIASSIC					

in exposures around the edges of the basin. The preservation of such a thick sequence of Jurassic continental sandstones is unique and distinctive of the Colorado Plateau. An excellent discussion of these rocks can be found in Harshbarger et al (1957).

The Jurassic strata were tilted to the northeast in Lower Cretaceous time and eroded (Silver, 1948; Rapaport et al, 1952; Maxwell, 1976). The Dakota Sandstone of earliest Late Cretaceous age rests unconformably on these beds. Because of the regional angular unconformity, the Dakota overlies older strata to the southwest and eventually overlaps all the sediments about 155 miles (250 km) south of the mineral belt where the Dakota Sandstone lies directly on basement (Green, 1980). The following discussion will be limited to the Morrison Formation and the overlying Cretaceous rocks.

Morrison Formation

West of the Rocky Mountains, strata believed to be equivalent to the Morrison Formation of Late Jurassic age have been divided, on lithologic grounds, into four members (Gregory, 1938). In ascending order, the members are: The Salt Wash Member, the Recapture Member, the Westwater Canyon Member, and the Brushy Basin Member. In the Grants Uranium Region all the members except the Salt Wash are represented, as shown in Figure 2. The two lower members, the Recapture and Westwater Canyon, are predominantly sandstone with associated thin conglomerates and mudstone beds (Table 1). They have been interpreted as being alluvial fan deposits (Craig et al, 1955). The Brushy Basin Member is predominantly mudstone with minor sandstone lenses, also dominantly of fluvial origin. The Morrison Formation overlies the San Rafael Group conformably but is unconformable with the overlying Dakota Sandstone.

Prior to the discovery of uranium in the Grants area, the Morrison Formation in New Mexico included all the Jurassic beds except the Entrada (Wingate) Sandstone (Kelley and Wood, 1946; Wood and Northrop, 1946), and no formal names had yet been proposed. Rapaport et al (1952) were the first to extend the Utah terminology of Gregory (1938) to the Grants area where it was already in use by uranium exploration people. Smith (1954) attempted to introduce some new names for the lower two members of the Morrison Formation near Thoreau, but these names were never used by workers in the area. Historically, a large part of the Morrison problem has been the complicated stratigraphic nomenclature associated with these continental beds. Chenoweth (1953) gives an excellent historical review of this stratigraphic nomenclature. Fortunately, in New Mexico, the Morrison Formation is fairly distinctive, and supposedly well-defined, but even here problems remain.

In order to help visualize the Morrison stratigraphy in three-dimension, a panel diagram has been constructed from measured sections and scattered subsurface data (Plate 2). The datum is the top of the Morrison Formation and the sections extend down to the Recapture Member, or to the top of the Bluff Sandstone. The vertical scale is highly exaggerated. The panel diagram also shows the approximate stratigraphic position of ore-grade mineralization.

Figure 2. Columnar section for the Jurassic rocks in the Grants Uranium Region.

Recapture Member

The Recapture Member is the oldest member of the Morrison Formation that is present in the Grants Uranium Region. This member is the most lithologically inconsistent rock unit in the Morrison. This lithologic variability may even serve as the distinguishing characteristic of the member. Three gross facies can be distinguished which appear to represent clastic deposition in eolian, lacustrine, and fluvial environments.

The Recapture, although a soft and friable unit, is fairly well exposed around the southern San Juan Basin. In general, it is thicker, up to 350 feet, and sandier on the west side of the basin, and thinner and more silty on the east side. It disappears a few miles south of Grants (Thaden and Santos, 1956, p. 73), due to a probable combination of depositional thinning and erosional truncation. Maxwell (1976, p. 98) did not recognize this member on the Acoma Reservation and Freeman and Hilpert (1956, p. 318) found a minimum of 20 feet that could still be recognized as Recapture in the Laguna area.

It is generally agreed that the Recapture Member is truncated by pre-Dakota erosion south of Gallup (Rapaport et al, 1952; Smith, 1957; Edmonds, 1961; and Saucier, 1967), but the precise point of disappearance is in question. Most of these workers think it disappears between Nutria and Ramah, New Mexico. The Recapture Member is recognized along the New Mexico-Arizona state line north to the Four Corners area where it intertongues with the Salt Wash Member. As much as 500 feet of Recapture has been measured west of Sanostee by Craig (1955, p. 139) and Blagbrough et al (1959, p. 14). According to Lease (1967, p. 9), only the upper 200 feet should be considered Recapture in Sanostee Wash. The lower 300 feet is a distinctly different sandstone unit which overlies the Summerville to the south, and intertongues with the upper two-thirds of the Salt Wash to the north. This questionable lower Recapture was mapped as Cow Springs Sandstone near Crystal, New Mexico, on the west side of the Chuska Mountains by Harshbarger and Repenning (1954), and O'Sullivan and Beaumont (1957). Farther south in the Twin Buttes Wash area, Allen and Balk (1954, p. 80), measured up to 550 feet of Recapture, but this may be another instance where the Cow Springs was included in the Recapture. The problem is defining the base of the member in areas where the distinctive red-brown siltstone beds are missing. Since the Recapture Member is conformable, and often gradational, with the Cow Springs, or Bluff Sandstone, selection of the contact is a matter of personal choice. From regional considerations, the Recapture Member is believed to reach its maximum outcrop thickness of 350 feet at Twin Buttes Wash, north of Window Rock.

Even in areas where the member should be well defined, there are problems. For instance, the following Recapture thicknesses have been reported by the U.S. Geological Survey at Haystack Butte: 189 feet by Mullens and Craig (1950); 96 feet by Rapaport et al (1952); and 133 feet by Freeman and Hilpert (1956). Since the overlying Westwater Canyon Member is a distinctive unit, most of the problem has to do with the basal contact of the Morrison Formation.

On the east side of the basin, the problem is even more acute although more obvious. Here the Bluff sandstone is absent and the Recapture Member is either expanded to include the Bluff interval (Santos, 1975, p. 8), or the

member is not differentiated. Woodward and Schumacher (1973, p. 2) defined the "lower member" of the Morrison as the entire section of reddish-brown and maroon mudstones and very fine sandstones between the base of the Westwater Canyon Member and the Todilto Limestone. In essence, the Recapture, which is probably less than 200 feet thick, cannot be differentiated along the east side of the basin, or northward into the Chama Basin. As shown on the panel diagram (Plate 2), the Recapture Member thins gradually eastward from 300 feet at Gallup, to around 200 feet north of Thoreau, to 150 feet in Ambrosia Lake, to less than 100 feet north of Laguna.

The first of the three facies recognized in the Recapture Member is well displayed in Sanostee Wash where it is composed of alternating beds of pink to red-brown, fine-grained, lenticular sandstones 10 to 30 feet thick. The sandstones are trough cross-bedded in the lower two-thirds of a lens and often grade up into small-scale ripple cross-bedding. The cross sectional geometry and sedimentary structures indicate that the sandstones were deposited by small meandering streams which flowed generally due east across broad flood plains composed of red silts. Sears et al (1974, p. 88) concluded from their subsurface study that this interval is mostly claystone in the central part of the basin. This fluvial facies of fine sandstones, silts and clays is essentially all that is exposed in outcrops on the east side of the basin (Ridgley, 1977; Woodward and Schumacher, 1973; Flesch, 1974). Santos (1975, p. 8) describes the most conspicuous feature of the Recapture south of Cuba as parallel red and white banding in layers 3 to 40 feet thick of alternating siltstones and very fine- to fine-grained flat-bedded sandstones. To the south in the Laguna area the Recapture contains a few minor freshwater limestone lenses. Ruetschilling (1973, p. 42) noted a limestone west of San Ysidro that could be followed for 2.5 miles.

The second distinct facies in the Recapture is well displayed at Window Rock, Arizona, and at the northwest apex of the Zuni Uplift northeast of Gallup. It consists of interstratified, very fine-grained, flaggy sandstones and thin lenticular siltstones and mudstones. Beds may be less than one foot thick through intervals of 20 to 30 feet. The red-brown and maroon siltstones and mudstones are somewhat fissile and the greenish-gray and yellow-brown laminated sandstones display primary lineations, rib-and-furrow structures, fossil mudcracks, and some horizons are extensively burrowed by large worms, or some other animal. Gray-green mudstones contain calcareous concretions and the whole section is carbonate-rich. These beds appear to have been deposited in small playa lakes. The lake beds frequently alternate with fine-grained, pink, well-sorted sandstones with large scale trough cross-bedding in sets 10 to 15 feet thick. These sandstones appear to be small eolian dunes which migrated across the salt pans. An occasional sandstone indicates periodic sheet floods.

The eolian facies is the third facies type and is spectacularly displayed at Pyramid Mountain where giant sets of cross-strata are as much as 80 feet thick. The dip directions of the cross-laminations indicate a consistent wind direction to the east. The eolian Bluff Sandstone at Laguna, and the Cow Springs along the east side of the Defiance Uplift also confirm a wind direction from the west (Hilpert, 1963; Harshbarger et al, 1957). The dune field at Pyramid Mountain extends north under the Church Rock mining area and to the south it can be seen in the Nutria Monocline (Plate 2). At Pyramid Mountain, almost the entire Recapture interval is occupied by the eolian facies, and it

extends eastward with diminishing thickness to Thoreau, New Mexico. Harshbarger et al (1957, p. 53) considered this to be a tongue of the Cow Springs, and it apparently does merge with the Cow Springs, or Zuni Sandstone, to the south of Gallup.

This eolian facies has been encountered by drilling between Crownpoint and Chaco Canyon (Clark, 1980), and elsewhere. It appears likely that scattered dune fields occur in the Recapture over much of the southwestern part of the basin. The most diagnostic lithologic character of the Recapture, when the distinctive red-brown siltstones are absent, is the clean, fine, well-sorted sand in this member.

The Recapture is clearly related to the San Rafael Group as pointed out by Green (1975; 1980). The climate was arid and deposition was in mixed fluvial, lacustrine, and eolian environment. Interdune lacustrine deposition appears to have been more prevalent between Gallup and Window Rock which was also the site of a lake or playa in Bluff time. Fluvial conditions are dominant at Sanostee, and between Thoreau and Grants as noted by Smith (1954, p. 16), and the streams flowed generally northeast to east into the basin. This paleogeographical interpretation is in sharp contrast to the one presented for the Recapture Member by Craig and others (1955, p. 140).

Westwater Canyon Member

The Westwater Canyon Member of the Morrison Formation was proposed by Gregory (1938, p. 59), for exposures in Westwater Canyon, 15 miles southwest of Blanding, Utah. This member was subsequently recognized over parts of northeastern Arizona and northwestern New Mexico (Harshbarger et al, 1951, p. 98). Unlike the underlying Recapture Member, the Westwater Canyon is a lithologically consistent unit which represents the first thick, entirely fluvial Jurassic beds of regional extent in the southern San Juan Basin. It is essentially a medium- to fine-grained (Saucier, 1967, p. 47; Santos, 1970, p. 13; Reimer, 1969, p. 19; Martinez, 1979, p. 19), poorly-sorted, feldspathic sandstone with subordinate interbeds of green bentonitic mudstone. Grain size ranges from very fine to very coarse sand and locally the member contains pebble and cobble conglomerate. It is almost universally cross-bedded. The Westwater Canyon is coarser-grained in the vicinity of Gallup and Window Rock and becomes finer-grained to the northeast and east. It is more resistant than the Recapture Member, and it forms near-vertical cliffs, especially between Gallup and Grants. In surface exposures, it is usually colored shades of red or yellow but locally may be white, gray, brown, green, or violet. In the subsurface it ranges from white to dark gray where reduced.

A maximum of 287 feet of the Westwater Canyon Member was measured in Section 11, T 18 N, R 21 W, between Todilto Park and Window Rock, Arizona (Saucier, 1967, p. 49). As much as 400 feet has been penetrated by drilling to the east of this locality. A thickness of approximately 400 feet was also encountered near Borrego Pass (Continental Oil Company, 1978, p. 41). This is probably a maximum figure for this member and occurs only in small areas; however, thicknesses of 300 to 350 feet are not uncommon in the subsurface, even in the Laguna area (Livingston, 1980; Kozusko and Saucier, 1980).

In outcrops, the Westwater Canyon thickens from less than 50 feet, seven miles northeast of Grants to 170 feet at Haystack Butte, 200 feet north of Thoreau,

to 270 feet north of Fort Wingate, as shown on Plate 2. East and southeast of Grants the Westwater Canyon cannot be distinguished on the outcrop from the thin lenticular sandstones of the Brushy Basin Member. The pre-Dakota erosional edge of the Brushy Basin occurs north of Fort Wingate (Plate 3), and from this point the Westwater Canyon thins rapidly to the southwest to where it is completely removed four miles due west of McGaffey, New Mexico (Rapaport et al, 1952; Saucier, 1967). The same erosional thinning occurs south from Window Rock, Arizona, to Hunter's Point where the member disappears.

Harshbarger et al (1957, p. 50) reported that the Westwater Canyon Member intertongues with the Cow Springs along the New Mexico-Arizona state line north of Lupton, Arizona. This interpretation was probably based on a measured section by Craig and Freeman (Cooley et al, 1964, p. 150), who described 94.4 feet of Westwater Canyon below the Dakota at Lupton. However, they placed a question mark on this part of the section to emphasize the doubtful status of this fine-grained, well sorted sandstone unit. It now appears that the Westwater Canyon is not present this far to the southwest, and the sandstone beneath the Dakota at Manuelito and Lupton is part of the eolian facies of the Recapture Member (Saucier, 1967, p. 49). This interpretation is supported by the fact that no fine-grained, eolian beds have ever been described elsewhere in the Westwater Canyon, and the area between Gallup and Window Rock appears to be the coarsest, most proximal portion of the ancient Westwater Canyon alluvial fan.

The base of the Westwater Canyon Member can be readily distinguished in the Gallup area because of the abrupt change in grain size and sorting between the Recapture and Westwater Canyon. This contact is especially prominent where the fluvial Westwater Canyon overlies the eolian facies of the Recapture northeast of Gallup. The striking change in depositional environments led Saucier (1967b, p. 143) to propose the existence of a disconformity separating the two members. This disconformity has also been recognized by Green (1975b, p. 11), and Martinez (1979, p. 7). In the Grants area no disconformity is apparent, and the contact has been described as conformable and transitional by all previous workers. In the Thoreau area, Smith (1954, p. 17) described scours with a relief of 4 to 5 feet at the contact, but in other places he found the two members intertonguing. Green (1980), however, recognizes the disconformity all along the south side of the basin. In the eastern half of the mineral belt, the disconformity is often marked by a thin basal lag conglomerate composed of variegated chert pebbles and reworked sandstone locally containing abundant fossil bone fragments (Green, 1980). Apparently this disconformity occurs below the traditional member boundary, for he would apparently include the upper one-third of the Recapture with the Westwater Canyon on the basis of depositional environment. The distinction is based on an abrupt change from a very arid paleodepositional environment to a more humid one (Green, 1975). The sediments above the disconformity also contain first-cycle arkosic sediment not found below it. This criterion is difficult to apply in subsurface exploration, so the basal contact of Westwater Canyon will most likely continue to be placed at the base of the last medium- to coarse-grained arkosic sandstone above red siltstones or clean quartzose, fine-grained sandstone. In the eastern part of the basin, the Westwater Canyon and Recapture members do intertongue and the contact is arbitrary (Woodward and Schumacher, 1973; Flesch, 1974; Santos, 1975; Green and Pierson, 1977, p. 152).

The top of the Westwater Canyon is usually placed at the top of the uppermost massive sandstone unit, but this varies among geologists. In the Gallup area, the Brushy Basin has been removed, and the Westwater Canyon is directly overlain by the Cretaceous Dakota Sandstone (Rapaport et al, 1952, p. 16). In this area the lower half of the Westwater Canyon is finer-grained than the upper half. This same feature was noted by Smith (1954, p. 17) north of Thoreau, Santos (1970) p. 13) in Ambrosia Lake, and by Livingston (1980) at Marquez, New Mexico. This upward coarsening trend in the Westwater Canyon is primarily due to the reworking of fine-grained sand derived from the underlying Recapture and from older fine-grained sandstones farther to the southwest. The continued rise of the source area also contributed more coarse material in upper Westwater Canyon time, for the upper half northeast of Gallup and in the Window Rock area is markedly more conglomeratic.

Although the upper half is coarser-grained, it is also more broken by mudstone lenses (Sharp, 1955, p. 12; MacRae, 1963, p. 47; Santos, 1963, p. 54). The mudstone interbeds first appear stratigraphically below the erosional edge of the overlying Brushy Basin Member northeast of Gallup, and they extend eastward and northeastward into the basin where some, especially in the upper-most Westwater Canyon, thicken and eventually connect with the main body of Brushy Basin mudstone. This intertonguing of the two members occurs on a regional scale, so the Brushy Basin Member, for the most part, may be considered the fine-grained floodplain facies of the Westwater Canyon Member.

One of the Westwater Canyon sandstone tongues north of Grants has been given an informal name. The term Poison Canyon Sandstone was applied to the upper mineralized part of the Westwater Canyon Member at Poison Canyon in Section 19, T 13 N, R 9 W, by Zitting et al (1957, p. 57). It is separated from the main body of Westwater Canyon by a 30- to 40-foot mudstone called the K shale. In 1954 the only known sandstone deposits in the Grants area were in this upper sandstone in Poison Canyon and in a massive sandstone north of Laguna which was then believed to be equivalent to the Westwater Canyon Member. Freeman and Hilpert (1956, p. 318) discovered that the sandstone north of Laguna was actually a lens in the top of the Brushy Basin Member. Therefore, in order to emphasize the apparent economic importance of the Brushy Basin Member, they decided to include the Poison Canyon sandstone in the Brushy Basin member by placing the contact at the base of the K shale (Hilpert and Freeman, 1956, p. 299). The K shale disappears two miles to the west of the Poison Canyon Mine, and the Poison Canyon tongue cannot be separated from the Westwater Canyon sandstone. To the north and west, the Westwater Canyon thickens by the addition of sandstone lenses to the top of the member. Nevertheless, at any given locality, the youngest, or upper-most, sandstone separated by shale from the top of the more massive Westwater Canyon has been designated the Poison Canyon Sandstone and is usually included in the Brushy Basin Member. In the Smith Lake area, the sandstone called Poison Canyon is more than 200 feet above the base of the Westwater Canyon, whereas in Poison Canyon it is only 100 feet above the base. The sandstone at Smith Lake is clearly stratigraphically higher than the lens at Poison Canyon (Plate 2). Therefore, at best the name is meaningless, and at worst it is misleading and should be abandoned as recommended by Santos (1963, p. 53). According to Smith (1954, p. 16), Rapaport intended the Westwater Canyon Member to include all the sandy facies in the Upper Morrison Formation. A rule of thumb is to include all sandstones in the top of the Westwater Canyon that are thicker

than the intervening mudstone, otherwise label it a Brushy Basin sandstone. The term Poison Canyon should be used only in reference to the southern-most mineral trend in the Ambrosia Lake subdistrict.

Isopachous maps of the Westwater Canyon Member constructed using the above rule of thumb will result in a clearer definition of thick sandstone trends. The more massive lower half of the Westwater Canyon maintains a fairly even thickness except for occasional minor additions of sandstone at the base. The upper half of the Westwater Canyon is much more variable in thickness in a north-south direction caused by the alternate buildup and shaling out of the upper-most sandstones. The regularity and length of these alternating thicks and thins in a southeast trend parallel to the Zuni Uplift are suggestive of structural control. Indeed, Wentworth et al (1980) believe minor basement faults may have influenced Morrison paleotopography sufficiently to have caused the upper Westwater Canyon streams to be localized in parallel, linear belts. These linear thicks in the Crownpoint area are up to 2 miles wide, north to south. Ambrosia Lake appears to be a compound depocenter about 4 miles wide split in the west by a southeast-trending anticline, which was the ancestor to Ambrosia Dome.

This hypothesis is not new. Hilpert and Corey (1957, p. 376) documented pre-Dakota folds in the mineral belt and suggested synclinal control of sandstone thicks. Young (1960, p. 11) further elaborated on the structural control of Westwater Canyon deposition and even produced a regional map showing the postulated folds. Subsequent workers have repeated the idea but have shown no conclusive evidence for structure as a regional control of Westwater Canyon deposition (Thaden and Santos, 1959, p. 36; Squyres, 1970, p. 201; Saucier, 1976, p. 155; Kozusko and Saucier, 1980). However, because of the documented existence of pre-Dakota folds, this idea appears to have merit. It is the best explanation for a long narrow, anomalously thick Westwater Canyon trend extending from the village of San Mateo to the Rio Puerco of the east, shown in Plate 2. Locally, east of Mount Taylor, this thick trend is bordered on the south by a parallel thin or anticline, as illustrated on Plate 3.

The fluvial origin of the Westwater Canyon Member has never been contested; however, there is a spectrum of opinion concerning a fluvial model for this member. Most workers have considered the Westwater Canyon to be a product of braided streams (Craig et al, 1955; Rapaport, 1952, 1963; Kendall, 1971; Flesch, 1974; Martinez, 1979; Jenkins and Cunningham, 1980; Turner-Peterson and others, 1980). However, the Westwater Canyon does not appear to readily fit into any single published fluvial model; therefore, some workers interpret the depositional pattern as passing from braided in the southwest part of the basin to meandering in the northeast (Campbell, 1976; Rackley, 1976; Galloway, 1978, 1980).

Galloway (1978) has recognized four major sandstone facies within the Westwater Canyon Member based on Schumm's (1971) classification of streams according to the ratio of bed-load to suspended load. The facies are: (1) proximal braided bed-load, (2) straight bed-load, (3) sinuous mixed-load, and (4) distributary mixed-load. A fifth facies would be the suspended-load or mudstone-dominated facies represented by the Brushy Basin Member.

The proximal braided facies was recognized only in the upper half of the Westwater Canyon in the vicinity of Window Rock in exposures on the nose of the Zuni Uplift northeast of Gallup. This facies consists of thick, tabular bodies of medium to very coarse pebbly sandstone with little or no mudstone. Longitudinal, gravel bars could be recognized which indicated that stream depths were 10 feet or less (Galloway, 1978, p. 1). Cobbles up to 13 centimeters in diameter occur in the top of this member (Saucier, 1967, p. 61). Other sedimentary structures recognized include elongate conglomerate lenses with flat bottoms and low angle accretionary foreset bedding, abundant planar stratification and medium-scale, low-angle trough and tabular cross-bedding. Basal scours are relatively flat. Deposition was by broad and shallow, fast-flowing water in laterally migrating braided stream channels. The direction of stream flow, as indicated by cross-bedding, was easterly at Window Rock and in the Church Rock area and more northeasterly north of Window Rock (Galloway and Saucier, 1972, per. comm.).

The straight bed-load facies is well displayed in exposures between Gallup and Grants. Sedimentary structures are dominated by broad, low-angle sweeping trough cross-bedding composed mostly of fine- to medium-grained sandstone. A special type of cross-bed called "festoon" is common in this facies. Cross-bedding sets range from 5 inches to 5 feet in thickness and from 3 to 60 feet in length and 2 to 60 feet in width. The dip of foresets averages about 19 degrees, and they are concave upward and wedge-shaped (Saucier, 1967, p. 57; Martinez, 1979, p. 17). The basal channel scour surface is nearly flat and laterally extensive. A thin basal conglomerate composed of well-rounded rock fragments and clay clasts ranging in size from small flakes to masses over 2 feet in diameter commonly rests above the scour surfaces for a few inches to a foot. The conglomerate grades upward into a thick, trough cross-bedded sandstone which in turn is capped by a thin zone of low angle or flat, parallel-bedded sandstone. There is a general fining upwards, but there is never a transition into overlying siltstones and mudstones. The tops of the channel deposits are relatively flat except where, as is usually the case, they are scoured by subsequent channeling. The individual channel deposits range from 3 to as much as 50 feet thick but generally average about 12 feet thick (Campbell, 1976, p. 1013). The original channel was probably hundreds to thousands of feet wide at flood stage and several hundred feet wide at stages of low flow. Because of lateral erosion and superposition of channels through time, only portions of the original stream deposits are preserved. These range from 100 to 1,200 feet wide and average about 600 feet in width (Campbell, 1976, p. 1013).

The coalescing of the individual channel deposits both laterally and vertically form what Campbell (1976) describes as channel systems, which may be miles in width and several hundred feet in thickness. The Westwater Canyon sandstone sequence is broken at intervals of 30 to 50 feet by mudstone lenses. These natural divisions may bound individual channel systems. The mudstone beds get up to 40 feet thick but are locally scoured out completely. The clay galls are derived from these eroded portions. Some of these lenses are fairly extensive and can be correlated up to several miles, especially along the depositional trend. One or two of these shale breaks in the middle of the member may actually be of semi-regional extent. These mudstones generally constitute less than 20 percent of the straight bed-load facies although this percentage may double in the areas of thinner gross sandstone. The mudstone

breaks serve as dividers in the otherwise massive sandstones, and they undoubtedly compartmentalized ground water flow.

Paleocurrent directions have been measured over the years by many different workers using cross-bedding, primary lineations, log orientations, and by following scours in underground mines. All are in general agreement that the transport directions between Gallup and Ambrosia Lake varied locally from east to southeast (Rapaport et al, 1952; Mathewson, 1953; Konigsmark, 1955; Sharp, 1955; Young, 1960; Granger et al, 1961; Clary et al, 1963; Cronk, 1963; Harmon and Taylor, 1963; MacRae, 1963; Rapaport, 1963; Santos, 1963; Granger, 1968; Santos, 1970; Martinez, 1979; Jenkins and Cunningham, 1980; Ristorcelli, 1980; Tessendorf, 1980). The only dissenting opinions are presented by Campbell (1976, p. 1,017) and Turner-Peterson et al (1980) who state that the average bearing of paleocurrents between Gallup and Grants is northeast with a range from northwest to southeast. Saucier (1976, p. 154) noted a change from a more southeasterly cross-bedding orientation in the lower half of the Westwater to a more northeasterly orientation in the upper half. The resultant direction would be east. Thaden and Santos (1959, p. 42) and Santos (1970, p. 17) also found northeast-trending channels more prevalent in the Upper Westwater Canyon and Brushy Basin Members. This may indicate minor basin tilting or rise of the Zuni Uplift in Late Morrison time.

The third facies defined by Galloway (1978) is the sinuous mixed-load facies characterized by an increase in interbedded mudstone and more clay gall zones. Grain size still ranges from fine to coarse, but pebbles are less and the fining upward sequence is better developed, although it still does not match the model for point-bars in a meandering system. The lateral continuity of sandstones and interbedded mudstone units is much less, due to the increase in stream sinuosity. The sedimentary structures are similar to those found in the straight bed-load facies with perhaps a decrease in scale of both cross-bedding sets and the channel deposit itself. Channel fills are several hundred feet to several thousand feet wide and thicknesses increase to 20 or 30 feet. Transmissivity is much reduced due to the cross-cutting of channels, greater clay content, and increased lenticularity of the sandstones.

This facies is believed to be present over large areas in the southeast part of the basin and is exposed in some outcrops on the west side of the Naciminto Uplift. In this area, the Westwater Canyon Member varies from 40 to 240 feet in thickness over short distances (Santos, 1975, p. 9). The upper and lower contacts are transitional with the adjacent members although a middle unit of sandstone can be followed for miles (Flesch, 1974, p. 189). Cross-bedding is much more variable in this facies, but it appears to average ENE according to Flesch (1974, p. 189) and Ridgley (1980, p. 4).

The fourth sandstone facies, the distributary mixed-load, is found along the distal margins of the fan system and is exposed at the surface in the Laguna area. The sandstone units are lenticular and interspersed in a section composed of subequal amounts of mudstone and sandstone. Sandstones in this facies are difficult to distinguish from those in the Brushy Basin Member. Channel widths are typically less than 1,000 feet, and may be less than 100 feet with thickness ranging up to 40 or 50 feet. Grain size is fine to medium sand with some coarse material at the base of scour fills. Sedimentary structures are trough cross-bedding which decreases in size upward to parallel

laminations, and in some instances the fining upward sequence is completed with zones of ripple or wavy laminations at the top. This facies was observed at White Mesa located southwest of San Ysidro, New Mexico, and it is probably present east of Cuba, according to descriptions by Woodward and Schumacher (1973, p. 3).

Petrified wood and dinosaur bones are relatively common in the Westwater Canyon Member. The trees have been identified as conifers according to Corbett (1964, p. 39) and Jenkins and Cunningham (1980). Logs up to 5 feet in diameter and over 100 feet in length were found in the Section 30 Mine in Ambrosia Lake (A. Glover, 1980, personal communication). Most of the fossil wood appears to be associated with the coarser, unsorted material in the mid-portion of paleochannels. No limbs are preserved and the logs are generally aligned along the paleocurrent directions which indicates they were transported to the burial sites. No fossil stumps in growth position, or root casts, have been found to indicate a local origin. The larger specimens are usually silicified whereas smaller woody pieces are often carbonized.

Dinosaur bones are more uncommon than wood, but like the logs, show evidence of transport. Most fossil bones are isolated pieces which were abraded during transport. Only one complete skeleton has been found in the Grants region to date, which is extremely unusual considering how well exposed the Morrison Formation is, and how thoroughly it has been examined by prospectors. This indicates either that the animals were rare in this part of the Colorado Plateau, or that the skeletons were all reworked by fluvial processes. Both situations probably existed; however, the lack of evidence for abundant indigenous vegetation suggests that animal life was rare in this area. The absence of coaly beds, carbonaceous shales, or even leaf impressions in overbank mudstones indicates that the climate was still semi-arid and the vegetation was sparse except for trees along the stream courses. Animal and plant life were probably more abundant in the highland areas where the rivers originated. The Westwater Canyon Member appears to have been deposited during torrential floods which may have occurred during a short wet season. The idea of an arid to semi-arid environment in Morrison time was postulated as far back as 1932 according to Baker et al (1936, p. 55), and appears more valid today.

The original concept by Craig et al (1955), of a broad subaerial fan covering most of northwestern New Mexico, has been substantiated by the work to date. The most proximal portion of the fan that is preserved is in the Gallup-Window Rock area, and distributary fingers apparently branch out from this distribution center much as Galloway (1978, p. x-7) mapped them. This fan probably covered more than 20,000 square miles (Campbell, 1976, p. 1013); therefore, it is unlikely that the Westwater Canyon Member was spread across this vast area contemporaneously. The linear variations in gross thickness of the member suggests that deposition was influenced by subtle shifts in basement blocks and by even small structures as proposed by Huffman and Lupe (1977).

Earliest Westwater Canyon deposition may have followed a trough trending east and southeast adjacent to the north side of the Zuni Uplift. The fact that the member lenses out depositionally rather rapidly to the south indicates that the Zuni Uplift was a low positive area. North to northeast tilting during Westwater time caused the major streams to migrate northward across the basin. An old and persistent northwesterly-trending structural hinge northeast of Gallup seems to have controlled where braided deposition ended and

preservation of overbank mudstones began. The Westwater Canyon streams appear to have entered this old basinal area from the west-southwest in Arizona, rather than from south of Gallup as originally proposed.

Brushy Basin Member

The Brushy Basin Member is the most regionally extensive and lithologically consistent member of the Morrison Formation. In most places, it consists of a monotonous section of dominantly gray-green, bentonitic mudstone (Weeks, 1953, p. 1) broken by thin scattered lenticular sandstones. It is this member which represents the Morrison Formation at the type locality at Morrison, Colorado, as described by Eldridge (1896, p. 60). The Brushy Basin Member was deposited across the entire San Juan Basin and is, therefore, exposed on all sides except in the southwest corner of the basin between Todilto Park and Gallup where the member was removed by erosion in Lower Cretaceous time. Where present in the southwest portion of the basin, the typical mudstone section is overlain unconformably by the Dakota Sandstone. In the northeast two-thirds of the basin, the Brushy Basin mudstones grade upward into massive, locally kaolinite-rich sandstone units informally called the Jackpile sandstone in the Laguna area and the Burro Canyon Formation in the north half of the basin. The Burro Canyon Formation has been dated as Lower Cretaceous in southwest Colorado (Stokes, 1952, p. 1,766). The Brushy Basin Member is considered the latest Upper Jurassic unit, but it may transgress the period boundary.

In the Grants Uranium Region, the top of the Brushy Basin has been truncated by the unconformity, so none of the preserved thicknesses is the true thickness. On the west side of the basin about 150 feet of Brushy Basin is reported from Sanostee Wash (Lease, 1967, p. 50), 50 feet is present at Crystal, New Mexico, and perhaps 20 feet is locally preserved at Todilto Park. On the south side, the Brushy Basin ranges in thickness from zero at Pyramid Mountain, to 70 to 100 feet north of Thoreau, 100 to 150 feet at Ambrosia Lake, and over 400 feet north of Laguna. A maximum thickness of 475 feet of Brushy Basin was encountered in a hole drilled at the south end of the Jackpile open pit. This member is 300 to 400 feet thick along the Rio Puerco River on the Bernabe Montano Grant (Kozusko and Saucier, 1980), and it thins slightly northward to less than 300 feet in the Chama Basin (Smith et al, 1961, p. 15; Ridgley, 1977, p. 155). Where this member is 400 feet thick, it is due primarily to preservation in structurally low areas that existed before the Dakota Sandstone was deposited.

South of Interstate 40, on the Laguna Reservation, the Brushy Basin rests directly on the Recapture Member, but as the Morrison section thins to extinction to the south, both members are variegated in color and cannot be distinguished lithologically (Moench and Schlee, 1967, p. 17; Maxwell, 1976, p. 98). In the basin subsurface, the member commonly varies in thickness from 100 to 350 feet with a general thickening in a northeast direction. The variability in thickness is caused by intertonguing with the underlying Westwater Canyon Member, pre-Dakota structural movements, and by relief on the unconformity at the top of the member.

The Brushy Basin Member is typically a silty and sandy mudstone composed mostly of montmorillonite clay (Weeks, 1953, p. 1; Waters and Granger, 1953, p. 5; Granger, 1962, p. 18). According to Cadigan (1967, p. 73), it is primarily a siltstone although locally it may be a nearly pure clay. Thin sections

of the claystone reveal up to 10 percent angular silt-sized quartz and feldspar grains sometimes concentrated in layers (Squyres, 1969, p. 28). Stratification is poorly developed and there is no fissility. Brushy Basin core, however, if left to weather, will separate along ill-defined bedding planes. In some thin sections, the mudstone is composed of angular to rounded, fine- to silt-size particles of quartz, feldspar, and rock fragments, with sparse ragged plates of biotite and muscovite in a dense structureless clay matrix (Moench and Schlee, 1967, p. 18). In core, the mudstones are uniformly greenish where the adjacent sandstones are reduced, and there is no evidence of organic material or pyrite except along thin edges on mudstone lenses. The green color is believed to be due to the presence of ferric iron in the clay lattice (Squyres, 1969, p. 43; Lee, 1976, p. 88). Adjacent to porous oxidized sandstones, the mudstones are reddish-brown. On the outcrop, the silty mudstones are generally pink to red in color or mottled green and red. These colors are probably secondary. The more massive units are generally a uniform grayish-green to light green color.

Volcanic material has been reported in the Brushy Basin mudstones by many workers, namely, Rapaport et al, 1952; Craig et al, 1955; Keller, 1962; Kittel, 1963; Moench and Schlee, 1967; Reimer, 1969; and Santos, 1975. Generally the tuffaceous material is highly altered and reworked, but evidence of some distinct ash-fall tuffs has been found. Moench and Schlee (1967, p. 19) discovered a bed of red volcanic tuff about 5 feet thick which is fairly continuously exposed about 100 feet above the base of the Brushy Basin in the east and northeast part of the Laguna area. South of Cuba, New Mexico, Santos (1975, p. 11) recognized a number of thin zeolite beds in which the replaced glass shards were well preserved by clinoptilolite. These beds were generally less than 6 inches thick. Adjacent clayey material contained no zeolites which suggests that the beds are thin air-fall tuffs. Both analcime and clinoptilolite were identified.

It is unlikely that thick tuffs of regional extent are preserved in this member, for no distinctive marker beds have ever been found, that can be correlated more than a few thousand feet, either on the surface (Keller, 1962, p. 6), or in close-spaced drilling. Even the freshwater limestones that occur in the Brushy Basin, that are locally up to 15 feet thick, are erratic and of small areal extent. Charophytes have been found in some of the limestones (Martinez, 1979, p. 11) which indicated deposition in freshwater lakes. The lakes were small and ephemeral pans which did not exist long enough on the floodplain to sustain a vegetated border. In fact, the lack of carbonaceous shales, lignitic horizons, or even leaf and root impressions in the clays is remarkable. This absence of euxinic sediments in the Brushy Basin led Kittleman (1957, p. 9) to suggest that no true paludal conditions existed in the southern San Juan Basin.

The prevalence of thin channel sandstones throughout this muddy section indicates that most of the member is probably a product of fluvial floodplain sedimentation. Much of the clay component appears to have been transported and deposited as clay, as indicated by contemporaneous clay galls, and soft-sediment deformation described by Squyres (1970, p. 21). Very fine to silt-size glass shards could have been carried long distances suspended in flood waters without destruction. This glassy component of the sediment was probably altered soon after deposition and released silica to the environment.

Sandstones less than 5 feet thick are generally silicified to dense orthoquartzites, and limestone beds 1 or 2 feet thick commonly display thin reticulate veinlets of bright red and orange chert, as noted by Maxwell (1976, p. 98). Many of these chert pans were ripped apart by later floods and produced a coarse autogenous sediment which is unique to this member. The floods deposited sheets of thin, coarse conglomerates composed of carbonate clasts in a granular matrix of unsorted, brightly colored, highly angular chips of chert. Many of these beds are cemented by poikilitic calcite. Fragments of petrified wood and silicified dinosaur bones are common constituents of these conglomerate beds.

Distinct channel sandstones ranging from 5 to 50 feet in thickness are generally similar in composition and internal structures to the Westwater Canyon sandstones. These streams were meandering and display highly variable cross-bedding inclinations. Directional measurement taken from exposures of these lenticular channels probably cannot be projected very far into the subsurface. However, there does seem to be a general tendency for the streams in the upper Brushy Basin to be oriented in a more northeasterly direction.

Jackpile Sandstone

The Jackpile sandstone is an informal name given to a prominent sandstone lens at the top of the Brushy Basin Member. The sandstone unit is a good example of a sandstone lens with a northeast orientation. This massive, yellowish-white sandstone is a body 12 to 18 miles wide, and up to 220 feet thick. It is well-exposed in outcrops north of the village of Laguna. According to Schlee and Moench (1961, p. 148), this large lens of sandstone was deposited by a northeast flowing stream system that was localized by a contemporaneous structural depression. Continued downwarping after deposition followed by erosional truncation left the lower portion preserved in the syncline (Plate 4). This sandstone body was completely removed updip, south of Laguna, but downdip to the north the area of preserved sandstone broadens and the erosional edges of the unit flare outward, as shown in Plate 3.

The Jackpile sandstone is fine- to medium-grained, poorly sorted, and ranges from a subarkose in its lower part to an orthoquartzite in the upper portion (Schlee and Moench, 1961, p. 139; Nash, 1967, p. 76). Locally, pebbles of quartz and chert can be found at the base of some thick exposures (Schlee and Moench, 1961, p. 139). Intense weathering prior to Dakota deposition is believed responsible for the smaller percentage of feldspars in the upper part of the sandstone and for the high content of kaolinite which imparts the white color. This distinctive unit is present in the subsurface to the northeast where it is up to 300 feet thick near the Rio Puerco River (Kozusko and Saucier, 1980), and to the northwest where it ranges from 0 to 200 feet thick in the Torreon area. This unit appears to be present in the Chaco Canyon area in the DOE drill holes where it ranges in thickness from 25 to 145 feet as shown on Plate 2. The white sandstone on the outcrop between White Mesa and La Ventana is correlated with the Jackpile sandstone, and in this area it varies from 25 feet to 180 feet in short distances. Flesch (1974, p. 191) found that the grain size remained fine to medium and the transport direction was still to the northeast north of White Mesa. Somewhere between La Ventana and the Chama Basin the average grain size increases due to the addition of siliceous conglomerate. In the Chama Basin, Saucier (1974, p. 216) correlated

the massive white sandstone below the Dakota with the Burro Canyon Formation of southwest Colorado. The relationship of the Jackpile to the Burro Canyon remains obscure, but the Burro Canyon does appear to be stratigraphically higher, and thus younger, than the Jackpile at Laguna. It is postulated that continued regional tilting of the entire area to the northeast in Lower Cretaceous time caused the erosion of the updip conglomeratic facies of the Westwater and Jackpile fans and this coarse proximal material was deposited farther out into the basin as the Burro Canyon. Deposition in the basin was most likely continuous through Late Jurassic time and into Lower Cretaceous time. The stratigraphic problem has become one of nomenclature. Should the Jackpile sandstone be formalized and extended north into the basin, or should the Burro Canyon Formation be extended to Laguna?

Pre-Cretaceous Unconformity

The intertonguing relations of the lower Brushy Basin Member with the underlying Westwater Canyon Member were discussed in a previous section. The upper contact of the Brushy Basin Member is a major regional unconformity and is an important datum used in mapping structure and constructing cross sections. This unconformable surface formed before the Late Cretaceous Dakota Sandstone was deposited in the San Juan Basin. The epeirogenic tilting to the northeast in Late Jurassic and Early Cretaceous time exposed the updip edges of the Morrison strata to erosion. A broad surface of very low relief developed across these beveled edges. Over most of the region, the unconformable surface is fairly even, but on a local scale, it may have a relief of 30 feet or more caused by channel scours at the base of the Dakota.

Before the Dakota was deposited the underlying rocks were deeply weathered. The arkosic sandstones of the Morrison Formation were kaolinized, especially in areas that may have been topographically low. The Westwater Canyon sandstone in the Gallup area, a Brushy Basin sandstone at the Evelyn mine north of Bluewater, and the Jackpile sandstone were all altered and bleached. The kaolinization is most apparent in the sandstones with little effect noted in the mudstones at the unconformity. In the southeast part of the basin near the confluence of the Rio San Jose and the Rio Puerco, Leopold (1943, p. 59) found small channels on the paleosurface which are filled with as much as one foot of pure kaolin clay. Nash (1968, p. 741) reported similar occurrences in the Jackpile Mine area, and a large kaolin-filled channel on the unconformity was encountered by drilling on the Bernabe Montano Grant northeast of Laguna (Saucier, 1972, per. comm.). The kaolinitic alteration and the reworking and concentration of the kaolin clearly occurred before the Dakota Sandstone was deposited. This suggested to Leopold (1943, p. 63) that the climate became much more humid during Lower Cretaceous time. The water table was apparently higher, and the ground water itself was more acidic.

At Window Rock a thin hematite crust one inch thick caps a 2 to 5 foot zone of hematite staining at the top of the Westwater Canyon Member. Along strike the crust was removed where the Dakota Sandstone scoured down through it, and pebbles of the hematite occur in the conglomerate at the base of the Dakota which dates the crust as pre-Dakota. This would only be a local curiosity except that pebbles of almost pure hematite were also found on the paleosurface at the base of the Dakota several miles south of Gallup. This ferruginous crust, which may have existed on the southwest side of the basin, may be evidence of a humid climate in the interval between Morrison and Dakota deposition.

Dakota Sandstone

The Dakota Sandstone is a transgressive unit of Upper Cretaceous Cenomanian age according to Peterson and Kirk (1977, p. 171), that entered the San Juan Basin from the east. The Dakota Sandstone is a fairly distinct lithologic unit consisting of yellowish-brown fluvial sandstones at the base with interbeds of dark gray carbonaceous shales and locally low-rank coals. The basal sandstone consists of fine- to very coarse-grained, poorly sorted quartz sand with minor conglomerate lenses and stringers at the base. The Dakota Sandstones have a distinctive sparkling, vitreous luster which easily distinguishes them from Jurassic sandstones. The most distinctive feature, however, is the occurrence of carbonaceous shales which do not exist in the Morrison.

The Dakota Sandstone is much more resistant to erosion than the underlying Jurassic formations, and on the outcrop it forms a protective caprock which is responsible for the steepness of the underlying Morrison exposures. Throughout most of the Grants Uranium Region, it is the custom of exploration geologists to call Dakota only those sandstone beds directly overlying the Morrison Formation. In the Gallup-Thoreau area, the Dakota by this definition can be well over 100 feet thick, but eastward the lowermost sandstone thins and passes rapidly up through a transition zone of marginal-marine sandstones and shales and into black marine shales. The lower "Dakota" sandstone is only about 50 feet thick near Grants, and 30 to 40 feet thick in the Laguna area. To the northeast it thins to 20 feet along the Rio Puerco and eventually disappears entirely at Holy Ghost Spring south of La Ventana, where 40 feet of marine shale lies directly on the Morrison Formation. North towards Cuba the basal sandstone reappears and thickens toward the Chama Basin. In general, the marine facies is dominant in the east, and a littoral and deltaic facies is dominant in the west. The best illustration of these stratigraphic relations is given by Marvin (1967, p. 171). More detailed discussions of the Dakota Sandstone along the south side of the basin are given in the following papers: Kirk (1914); Mirsky (1953); Gabelman (1956); Chico (1963); Landis et al (1973); Sears et al (1941).

Igneous Rocks

All the igneous rocks in the district younger than Precambrian are associated with an extrusive complex called the Mt. Taylor volcanic field, located northeast of Grants, New Mexico. The volcanic complex consists of a denuded central stratovolcano built up largely of acidic and intermediate rocks surrounded by broad sheets of basaltic lavas which issued from numerous small cones surrounding the volcano (Baker and Ridley, 1970, p. 107). The earliest volcanic rock is a trachyte lava dome which has been dated 4.37 ± 0.27 m.y. by Lipman and Mehnert (1980, p. 1). Central activity began with voluminous rhyolitic pumice eruptions having a volume of more than 3 cubic miles (Kerr and Wilcox, 1963, p. 209; Baker and Ridley, 1970, p. 107). This activity peaked between 3 and 2.5 m.y. ago, but basaltic to andesitic flows persisted in the area until only a few thousand years ago.

The rocks of the Mt. Taylor volcanic complex have now been fairly well dated by the K-Ar method as Late Pliocene in age or younger (Bassett et al, 1963;

Bachman and Mehnert, 1978; Lipman and Mehnert, 1980). This is in general agreement with the age of fossil fresh water mollusks found at two localities in limestone beds deposited between basalt flows (Moench and Schlee, 1967, p. 27). Some flows capping the lower terraces are Pleistocene in age, and those near the present level of erosion are Recent.

Diabase sills and dikes, one of which is a monchiquite, could pre-date the Mt. Taylor volcanics. The dikes strike in a northerly direction and dip steeply. They may be up to 5 miles long and are rarely more than 10 feet thick. They are most abundant southeast of the village of Laguna. The diabase dikes and sills do not contain olivine, whereas the basalt flows do, which suggests that the two may not be related. The diabasic rocks are, however, clearly related to Late Tertiary tectonic activity bordering the Rio Grande depression (Moench and Schlee, 1967, p. 27; Lipman and Mehnert, 1980, p. 5).

Structure

In Early Mesozoic time, the region was dominated by two northwest-trending positive tectonic elements. These were the Uncompahgre highland in southwest Colorado and the Mogollon highland in central Arizona. As the Mogollon highland was rising in Late Jurassic time, the Uncompahgre highland was becoming more subdued. The result was a general tilting of the whole region to the northeast. This regional homoclinal dip to the northeast was a major controlling feature of Morrison sedimentation (Moench and Schlee, 1967, p. 36). The Morrison was derived from the Mogollon highland and was deposited in the trough between the two highlands as giant alluvial fans or floodplains which drained to the east. Another smaller northwesterly oriented positive feature that existed between the two highlands was the Zuni-Defiance Uplift which was a very low, partially buried topographic feature in Late Jurassic time. All three positive areas appear to have been fault-bounded basement blocks tilted to the northeast. The northwesterly tectonic grain formed by these structures is very prominent on the Colorado Plateau and is the oldest clearly defined post-Precambrian structural trend (Kelley, 1955, p. 65).

The structural history in the Grants Uranium Region can be divided into three periods of deformation. These periods are Late Jurassic to Early Cretaceous, Late Cretaceous to Middle Tertiary, and Middle Tertiary to Quaternary (Hilpert and Moench, 1960, p. 437). Evidence of pre-Jurassic deformation in the area is unclear. For purposes of discussion, these three periods will be referred to as the pre-Dakota, Early Cenozoic, and Late Cenozoic structural periods.

Pre-Dakota Structures

The existence of pre-Dakota structures in the southern San Juan Basin has been well established, especially in the Laguna area, by Moench et al, 1956; Hilpert and Corey, 1957; Hilpert and Moench, 1960; Moench and Schlee, 1967; and Maxwell, 1976; but structures of this age are still poorly known. Structure maps are generally contoured on the base of the Dakota Sandstone which lies on a post-Jurassic unconformable surface. These maps display post-Dakota structures but do not show earlier deformation. The lack of a mappable datum

in the Jurassic section has frustrated efforts to decipher the older structural picture. The Todilto Limestone is a suitable datum, where it is present, but too few holes have penetrated this horizon to be of use. Plate 3 is an attempt to map pre-Dakota structures that have been defined by surface work, or can be inferred by facies or thickness changes in the Morrison Formation. Although this map shows some of the structural patterns of this period, it is highly speculative, and will undoubtedly be subject to changes in the future.

Faults

Pre-Dakota faults that have been observed in outcrops are mostly intraformational faults with minor displacement. Close-spaced drilling for uranium has encountered rapid thickness changes in the Brushy Basin Member, which in some instances indicates the presence of pre-Dakota faults. Santos (1970, p. 24) found the Brushy Basin Member to be thinner on the west side of the San Mateo fault near the Cliffside Mine in Ambrosia Lake. He interpreted this as evidence for strike-slip movement on the fault, but it may well indicate pre-Dakota dip-slip on the San Mateo fault. Kozusko and Saucier (1980) mention possible pre-Dakota movement on some faults in the Rio Puerco fault zone on the Bernabe Montano Grant where the Jackpile sandstone is thicker on the downthrown side of presently recognized normal faults. It is suspected, however, that faults were less common than folds in Jurassic and Lower Cretaceous time.

Folds

Folding appears to have been the dominant mode of structural deformation in Jurassic strata prior to Dakota deposition. Hilpert and Moench (1960, p. 437) recognized two sets of folds in the southern San Juan Basin. The major set consists of broad, gentle warps up to several miles wide that are sinuous in plan view but generally strike east. The largest of these folds (Plate 3) have amplitudes of a few hundred feet. Many, however, may be only a mile or two in width and have amplitudes of 30 feet or less (Young, 1960, p. 18). The second set of folds is well developed in the Laguna district. They trend N 10-30° W, are about a half mile across, and have amplitudes of as much as 100 feet. These northerly-trending folds are mostly flat-bottomed and have abrupt inward dips on either side. They appear to have originated as small, narrow grabens in which the flanking strata are bent inward, but are unbroken (Hilpert and Moench, 1960, p. 437). These folds are clearly pre-Dakota in age, for they have been truncated at the unconformity (Moench and Schlee, 1967, p. 36; Maxwell, 1976, p. 101).

The existence of broad, east and southeast-trending folds along the north side of the Zuni Uplift which may have controlled Morrison depositional patterns has long been suspected (Thaden and Santos, 1959; Young, 1960; Hilpert and Moench, 1960), but it has never been adequately documented. The fact that the Westwater Canyon Member has a thick distributary which parallels the Zuni Uplift in a southeast direction for at least 100 miles strongly suggests structural control on the stream pattern. Santos (1963; 1970) has mapped a broad localized thick trend in the Westwater Canyon across Ambrosia Lake. His north-south cross-sections suggest the existence of an easterly-trending synclinal downwarp. In the panel diagram (Plate 2) prepared for this report,

this thick trend is shown to narrow in the vicinity of San Mateo village and to project eastward to the village of Marquez and then southeastward to the Rio Puerco. This narrow, anomalously thick Westwater Canyon trend is believed to follow a synclinal axis. This belief is strengthened by the fact that on the Bernabe Montano Grant, this thick is on the north side of an anticline with an amplitude of about 200 feet. The anticline was apparently reactivated in Lower Cretaceous time, for the Jackpile sandstone was removed from the crest of the structure. Isopachous trends in the Jackpile suggest that the Jackpile was present over the Westwater Canyon thick at one time but was removed before the Dakota was deposited. This anticline appears to be present on the south side of the main Westwater Canyon trend all the way to Ambrosia Lake. The anticline shown in cross-sections by Hilpert and Corey (1957, p. 375), between Ambrosia Lake and Poison Canyon, is possibly the same structure (Plate 5). Thus, a regular pattern of folding is postulated for the Grants Uranium Region to explain parallel thicks in the Westwater Canyon Member (Plate 3).

The folds are extremely subtle, and are not interpreted to have been caused by regional compression. Wentworth et al (1980) suggested that the folds are a result of vertical movement on minor northwest-striking basement faults during Late Jurassic time. The folding is roughly parallel to the bends in the present outcrop between Gallup and Grants, which itself is structurally controlled. Because of the length and apparent sinuosity of the fold axes across the mineral belt, another idea is postulated. The fold belt, if it in fact exists, may have been caused by slight gravity sliding on the north flank of the Zuni Uplift. The Todilto Limestone and the Summerville were probably still unindurated at the time the Morrison was being deposited, and they could have served as the sole of a decollement. The underlying Todilto Limestone is almost universally crenulated and deformed by intraformational folds on a regional scale. This led Santos (1970, p. 21) to suggest that the folds may be related to gravity sliding in Jurassic time. The sliding would have been caused by the continued tilting of the area down to the northeast with a local accentuation of dip caused by the rising Zuni positive area. A fence of close-spaced drill holes across the mineral belt would be very useful in elucidating the structure, but such data was not available for this report.

According to Young (1960, p. 18), a minor northerly-trending set of folds postdates the major east and southeast set in Ambrosia Lake and the Laguna area. These broad transverse folds of low amplitude were thought to have formed during the second period of deformation in early Tertiary time (Young, 1960, p. 19). However, an isopachous map of the combined Westwater Canyon and Brushy Basin Members in the Grants-Laguna area indicates that some of these north to northeast trending cross folds, or arches, developed in late Morrison time and probably were accentuated in Lower Cretaceous time (Plate 4). The largest and best known fold is the syncline containing the Jackpile sandstone. This structural sag is revealed clearly in the isopachous map. It is flanked by two north-northeast trending arches from which the Jackpile has been removed. The contours suggest that the basement steps down structurally from west to east. The arches are regularly spaced and have a steep east flank which may represent drape over NNE-striking basement faults downthrown to the east. The map also shows interference in the contour pattern caused by the older east-southeast-trending folds. Beyond the mapped area to the north, the combined Westwater Canyon and Brushy Basin averages about 400 feet in thickness, and no clear pattern can be seen with widespaced control points.

Far to the west, drilling has shown that the Torrivio and Gallup anticlines are old structures which were reactivated in the Cenozoic. The Westwater Canyon is thin over these asymmetric structures as shown on Plate 3. They too appear to be folds caused by passive drape of the sediments over tilted basement blocks which have moved at different periods.

Another prominent northeasterly trend occurs north of Crownpoint, New Mexico, and is called the Nose Rock trend. It is defined by a long narrow thick in the Westwater Canyon Member. This anomalously thick zone begins in the Dalton Pass area and continues in a relatively straight line to the northeast. The southeast edge is characterized by abrupt thinning of the Westwater Canyon Member from 300 feet to about 150 feet. This drastic change in thickness along a relatively straight northeasterly line of flexure is shown as a monoclinical flexure on the Morrison tectonic map (Plate 3). Near the southwest corner of T 20 N, R 10 W, the thick northeasterly Westwater Canyon trend appears to join an east to southeast-trending thick. North of this southeast-trending thick an area of relatively thin sandstones are postulated for the Westwater Canyon, which extends from the Chaco Canyon area, southeast to the Holy Ghost Spring area. Facies maps indicate that this was a broad arch in Morrison time which deflected the Westwater Canyon streams. This inferred arch is shown as a dashed anticline of Plate 3. As far as can be reconstructed, the Westwater Canyon depositional pattern is far from random. In fact, the pronounced linear trends along southeast and northeast lines strongly suggest structural control of stream patterns in Morrison time, and such structural control can definitely be documented for the Jackpile sandstone trend near Laguna.

Pipe Structures

Hundreds of chimney-like pipe structures have been found in outcrops between Gallup and Laguna. The pipes are most numerous in the Bluff Sandstone and Summerville Formation but are also common in the Morrison Formation. They range from a few inches to 150 feet in diameter and have never been found to penetrate either the Dakota Sandstone or the Todilto Limestone (Hilpert and Moench, 1960, p. 441; Santos, 1970, p. 25). In the Laguna area, the pipes are commonly concentrated in linear belts which follow the flanks of pre-Dakota folds in the Todilto Limestone (Moench and Schlee, 1959, p. 22). As many as 65 pipes have been found in trends up to 3 miles long (Schlee, 1963, p. 112). High angle normal and reverse faults frequently cut the strata adjacent to the pipes and the pipes may be genetically related to them. The pipes originated during deposition of the uppermost sandstone units that contain them. In the Grants area, the greatest concentration of pipes is found around Haystack Butte where there is no clear relationship to folds or faults.

The pipes are bounded by ring faults and the core is composed of material which has moved down stratigraphically. The core may be a massive sandstone lacking any visible structure, or it may be brecciated siltstone in a clayey matrix. Some pipes have core material which is better cemented than the surrounding host rock, but most show little or no difference in cementation. The pipes tend to flare outward toward the top. Occasionally the sandstones surrounding the pipe sag inward toward the ring faults (Schlee, 1959, p. 120). Evidence of flowage of unconsolidated sand downward is fairly common, as shown in Figure 3.

Figure 3. Sketch of an intraformational slump structure in the Summerville Formation at Pyramid Mountain near Gallup, New Mexico (Saucier, 1967).

It was originally proposed by Gabelman (1957, p. 80) that the pipes represented cryptovolcanic structures which could have served as hydrothermal feeders for the uranium deposits. Megrue and Kerr (1965; 1968) endorsed this concept, and supported it with some data on clay alteration in the pipes. Young (1960, p. 22) proposed earlier that the pipes were due to collapse caused by the dissolution of gypsum in the Todilto. All of these workers ignored the fact that the pipes often bottom out well above the Todilto Limestone, and some are found in areas where the gypsum member of the Todilto was never deposited, such as northeast of Gallup at Pyramid Mountain. In fact, Gabelman (1957, p. 72) mentions that a hole drilled in a pipe at Mesita village showed that the structure did not extend below the Todilto Limestone and could not be volcanic. At the base of Pyramid Mountain, pipes can be seen ending at the top of the limestone (Figure 3). The pipes probably formed by gravitational foundering of sand into underlying water-saturated siltstones as proposed by Schlee (1963, p. 120). The pipes may represent spring vents caused by compaction and dewatering of fine-grained sediment. Penecontemporaneous deformation in the area may have aided in the compaction or dewatering process as suggested by Figure 4. Similar sandstone pipes were described by Phoenix (1958) in the Carmel Formation near Lees Ferry in Arizona. His explanation was that the cylindrical bodies were caused by the release of hydrostatic pressure in the bed at the base of the cylinder contemporaneous with deposition of the sediments. The pressure is due to a combination of lithostatic and artesian pressure. It seems evident that the pipes are simply a form of penecontemporaneous deformation.

Figure 4. Sketch of normal faults and associated slumping in the Zuni sandstone near Pyramid Mountain, New Mexico (Saucier, 1967).

Early Cenozoic Structures

Most of the large structural features on the Colorado Plateau are the result of the Laramide orogeny which occurred in Latest Cretaceous through Early Tertiary time. The Zuni Uplift became prominent at the same time the north side of the San Juan Basin subsided, thus giving the Chaco slope its present northerly dip. The Defiance and Nacimiento Uplifts came into existence and formed the borders of the San Juan Basin as it exists today. Structural trends were dominantly north and northwest. All faults were normal gravitational faults except for a few very small strike-slip faults in the Ambrosia Lake District, and the large upthrust bordering the west side of the Nacimiento Uplift (Fig. 5).

The Zuni Uplift is one of the most complex domal structures on the Colorado Plateau. When it began to rise in Late Eocene time, it was probably covered by 6,000 to 10,000 feet of sedimentary rocks (Kelley, 1967, p. 30). Although various workers have interpreted the Zuni Uplift to be a product of horizontal compression (Kelley, 1955; Gabelman, 1956; Kelley and Clinton, 1960; Young, 1966; Santos, 1970), a very convincing argument for vertical uplift has been made by Rapaport et al (1952), Gilkey (1953), and Bucher and Gilkey (1953). Gilkey (1953) analyzed the fracture pattern in the Zuni Uplift and compared it to folds of known origin. He concluded that the joints of the Zuni Uplift differ radically from those of anticlines produced by lateral compression in which the principal joint set is normal to the axis of the fold. The dominant joint set in the Zuni Uplift is parallel to the axis of the uplift which indicates that it was pushed up from below. This work has been confirmed by Hanshaw and Dahl (1956, p. 2), who also accepted Gilkey's interpretation. Even the outline of the uplift is angular and not oval as would be expected of a compressional fold. Rapaport et al (1952, p. 33) pointed out that the Zuni Uplift is in general form a broad, flat, asymmetrical dome tilted to the northeast. Disturbed strata bordering the uplift are almost universally tensional features. The faults grade laterally into zones of fracturing and monoclines. The northwest end has a block outline, is flat-topped, and is bordered on the northeast and southwest by opposing monoclines. The Precambrian core of the uplift is a horst which has moved upward along deep-seated fractures in the basement. The entire uplift may be pictured as a horst complex draped with sedimentary rocks.

Faults believed to be associated with the uplift of the Zuni block are the San Rafael, the San Mateo, the Ambrosia Lake, the Big Draw and the Bluewater faults. These faults are spaced about 6 miles apart, and they have strikes which vary from due north in the west to northeast in the east, as shown on Plate 1. They appear to radiate out from the core of the Zuni Uplift; however, the displacements on these faults do not increase toward the uplift (Gilkey, 1953, p. 20). Maximum displacements on the faults are generally north of the Interstate highway, and range from about 150 feet on the westernmost fault, to 1,600 feet on the easternmost fault. The Bluewater fault passes northward into a monocline.

A curious feature of all these normal faults is reverse drag (Gabelman et al, 1956, p. 63). The downthrown block has pulled away from the fault plane allowing the hanging wall to bend down toward the fracture surface. This is clear evidence of a tensional tectonic regime. In fact, the entire north

flank of the Zuni Uplift appears to have been stretched in an east and west direction causing the flat-bottomed Gallup sag to drop 4,000 feet along the Nutria Monocline (Woodward and Callender, 1977, p. 211), and the equally flat-bottomed McCartys syncline to drop along part of the San Rafael fault.

The San Ignacio monocline east of Laguna was probably also faulted at this time. Of the three north to northeast trending pre-Dakota arches shown on Plate 3, two of them probably ruptured by faulting in Early Cenozoic time. The Acoma arch did not rupture in the Mt. Taylor area; but, south of Acoma Pueblo, Maxwell (1976, p. 96) has mapped a normal fault along the same trend which could represent a north-trending basement fracture of regional extent.

Santos (1970, p. 22) postulated right-lateral movement on the San Rafael fault of about 4 miles. However, this is believed unlikely due to the fact that there is no apparent off-set in the Westwater Canyon facies across this zone, and the mineralization itself, believed to be Jurassic in age, is continuous across the fault zone. Slack and Campbell (1976, p. 50) proposed a somewhat smaller amount of right-lateral movement along the San Ignacio fault zone to explain the northeast-trending horst and grabens in the Rio Puerco fault zone. Again, no off-set is apparent in the Morrison facies or mineralization. A simple explanation for the Rio Puerco fault zone is that it was an area of apparent wrenching between the south-plunging Nacimiento basement block on the east, and the north-plunging Lucero-San Ignacio basement block on the west. Differential vertical uplift caused the fault zone and this uplifting may have begun as early as Lower Cretaceous time. There does not appear to be any large strike slip faults in the Grants Uranium Region, although a few very small faults with horizontal slickensides have been found in the Ambrosia Lake area (Bucher, 1953, p. 12; Corbett, 1964, p. 57; Moench and Schlee, 1967, p. 47; Santos, 1970, p. 23). These faults generally have only a few feet of displacements and probably represent minor horizontal adjustments related to the Zuni Uplift.

Late Cenozoic Structures

In Late Cenozoic time, the Colorado Plateau was uplifted and the Rio Grande trough to the east was depressed. Subsidence of the Rio Grande depression occurred along north-trending normal faults. On the west margin of the trough, the San Ignacio monocline was strongly faulted and the east limb was downdropped as much as 2,000 feet to the east. Prominent joint and fracture patterns were established over the area, and this was accompanied by the emplacement of numerous diabase dikes and sills (Moench and Schlee, 1967, p. 27). In Late Pliocene time, the Mt. Taylor volcanic field developed in the broad fracture zone associated with the McCartys syncline. Numerous basalt necks dot the countryside in a northeast-trending belt. The Plio-Pleistocene lava flows are off-set by a few north-trending normal faults, but they have not been tilted tectonically. In summary, the Late Cenozoic deformation was a continuation and accentuation of the east-west extensional tectonic regime that may have been established as far back as Late Jurassic time when the Laguna graben, or syncline, formed.

Figure 5. Tectonic map of northwestern New Mexico showing igneous centers and some of the uranium deposits (Kelly, 1955).

Figure 5 (Cont'd). Tectonic map of northwestern New Mexico showing igneous centers and some of the uranium deposits (Kelly, 1955).

Tectonic History

The Grants Uranium Region has experienced differential vertical movements in recurrent episodes since Late Paleozoic time. Three distinct periods of deformation can be recognized in the region. The first period consists mainly of broad shallow folds along east-west and north-south lines that developed during Morrison deposition in Late Jurassic time and continued into Lower Cretaceous time. The second period was the most severe when the San Juan Basin subsided and the surrounding uplifts developed in Early Cenozoic time. Late Cenozoic deformation was mainly fracturing along northerly trends that had developed in earlier periods. In general, the positive areas have become more positive and the negative areas more negative through time. Tectonic movements were vertical along the boundaries of basement blocks. Differential vertical uplifts produced the north and northwest trending monoclinial flexures which are so characteristic of the Colorado Plateau. Folding appears to be due in part to soft sediment deformation, but mostly to passive draping of the strata over basement faults. East-west tension may have begun in Late Jurassic time in the Laguna area, and it appears to have migrated westward through time. According to Gilkey (1953, p. 35), one gains the impression that deep fracture zones in the basement rocks are part of a broad regional pattern and that the Zuni Uplift is only one element which resulted from the formation of horsts along them. One of the problems confronting structural geologists is to develop an hypothesis to account for the dominantly vertical movements on the Colorado Plateau while it was surrounded by a stress field of regional horizontal compression (Woodward, 1976, p. 15).

PETROLOGY OF THE HOST ROCKS

Approximately 98 percent of all the uranium that has been produced in the Grants Uranium Region has come from two Morrison sandstone host rocks. Most of the uranium was mined from the Westwater Canyon Member with the Jackpile sandstone unit of the Brushy Basin Member the second largest producer. These two sandstones are similar lithologically, but they have slightly different post-depositional histories. A considerable amount of work has been done on the petrology of the sandstones, and progress has been made in unraveling their diagenetic history. The Westwater Canyon Member has been studied by Austin (1963), who believed the rock was originally a true arkose, and Corbett (1964), and Livingston (1980) who called it simply a feldspathic sandstone. Cadigan (1967) labeled the Westwater Canyon a feldspathic orthoquartzite, and Flesch and Wilson (1974) and Martinez (1979) call it an arkosic to subarkosic arenite. The Jackpile sandstone has been called everything from a graywacke (Schlee, 1957), because of its high clay content, to an arkose (Nash, 1967), subarkose, and orthoquartzite (Moench and Schlee, 1967). The present composition of these sandstones is somewhat different than their original composition as will be shown.

Allogenic Components

Framework Grains

The sandstones consist mainly of quartz and feldspar which make up 67 to 77 percent of the framework with a clay matrix ranging from 9 to 30 percent and a porosity of 10 to 25 percent. The mineral grains average fine to medium in size are subrounded and moderately sorted. This generalization masks the fact that both the Westwater Canyon and Jackpile sandstones have been recognized to consist, in part, of finer-grained, well-rounded and sorted quartz representing reworked sedimentary rocks, and medium to coarse-grained subangular, poorly sorted grains of quartz, feldspar, igneous rocks, and chert representing first cycle detrital material (Nash, 1967, p. 77; Martinez, 1979, p. 36; Livingston, 1980). In both sandstones fresh, angular, pink, microcline feldspar is most abundant in the coarse to very coarse sand size fraction. Santos (1970, p. 13) analyzed four cores from Section 23, T 14 N, R 10 W, in Ambrosia Lake, and found that the sandstone was 33 percent fine, 58 percent medium, and 9 percent coarse sand which is probably an acceptable average for the Westwater Canyon Member. The Jackpile is fine- to medium-grained, friable, moderately well sorted sandstone with some coarse material up to 2 to 4 mm (Schlee and Moench, 1961, p. 139). The range in mineral composition found by various workers across the district is shown in Table 2.

Quartz

Both strained and unstrained quartz grains are present in the Westwater Canyon and Jackpile sandstones (Corbett, 1964, p. 29; Falkowski, 1980; Hicks et al, 1980). Lee (1976, p. 60) divided the quartz into two types. The first type is of volcanic origin with straight extinction, and the second, subordinate type is plutonic with vacuoles and undulatory extinction. Some polycrystalline quartz derived from metamorphic rocks was observed. Nash (1967, p. 77)

Table 2. The composition of the Westwater Canyon sandstones and the Jackpile sandstone as determined by various workers.

Reference	Quartz	K-Spar	Plagioclase	Total Feldspar	Clays	Rock Fragments	Heavy Minerals	Location
<u>A. Westwater Canyon Sandstones</u>								
Dodd, 1956	48%	39%	7%	46%	Other 6%	-----		Poison Canyon
Knox and Gruner, 1957	30-65%			25%		2-10%		
Konigsmark, 1958	46%	21%	8%			13%		Foutz 1&2 (Jmwc)
Konigsmark, 1958	75%			20%	Other 2.5%	-----		Jmwc
Konigsmark, 1958	48%	39%	7%					Poison Canyon
Konigsmark, 1958	53%	17%	7%		Other 22%	-----		Poison Canyon
Corbett, 1964	66%	15%	< 4%	18.2%	16%		< 1%	Ambrosia Lake
Reimer, 1969				4-10%				Church Rock
Santos, 1970	56-90%			3-33%				Ambrosia Lake
Kendall, 1971	55-75%					5-10%	< 0.5%	Ambrosia Lake
Flesch and Wilson, 1974	55-70%	10-15%	10-15%	20-34%		5-15%		Ojito Spring
Santos, 1975	> 50%			2-30%			< 0.5%	San Ysidro
Martinez, 1979	63-00%	26%	2.9%	27%	< 10%	1-35%		Jmwc
Austin, 1980				25-30%				Jmwc
Falkowski, 1980	35-71%	13-21.5%	14.5%	25-40%		3%		Ambrosia Lake
Hicks et al, 1980	59%	17%	2%	19%	9%		Trace	Chaco Canyon
Livingston, 1980	66.8%	8.8%	3.7%	12.2%		0.8%		Marquez
Ristorcelli, 1980	85%			14%				Ruby Well
Range in Percent	30-99%	9-39%	2-14.5%	2-24%	9-16%	1-35%	Tr->0.5%	
<u>B. Jackpile Sandstones</u>								
Schlee and Moench, 1961	80-95%	Mostly Orthoclase		1-19%		2-3%		
Nash and Kerr, 1966	15.6%	8.2%	0.8%	9%	2.5%			Paguate Ore
Nash, 1967	67%	2%	2%	5%	13.4%			Woodrow Mine
Nash, 1967	56%	14.5%	3.5%	18%	20%	4%		Paguate Ore
Flesch and Wilson, 1974	65-80%			15-26%				Ojito Spring
Santos, 1975	75-95%			1-20%			< 0.2%	San Ysidro
Adams et al, 1978				~ 12%				Jackpile Mine
Beard et al, 1980	86%	5%	5%	10%	2-3%	1%	Trace	St. Anthony Mine
Range in Percent	16-95%	5-14.5%	0.8-5%	1-26%	2-20%	1-4%	Trace	

also found two quartz types in the Jackpile sandstone. The most abundant was well-rounded quartz with wavy extinction in the fine to very fine size range, and a more angular group with sharp extinction in the medium-grained size range. The high temperature beta quartz has been observed on the outcrop in both sandstone units (Saucier, 1972, p. 9). It is relatively common as euhedral grains in the medium- to coarse-grained sandstone, although Kendall (1971, p. 47) reported finding none in the Westwater Canyon Member at the Section 27 Mine, and Nash (1967, p. 77) only observed one grain of this volcanic quartz in thin sections of the Jackpile sandstone. Nevertheless, the two groups of quartz that are recognized support the idea of two sources for the detrital material, one of which is multicycle, mainly plutonic in origin, and the other, first cycle with volcanic quartz common.

Feldspars

Total feldspar content is generally less than 30 percent in the Westwater Canyon Member and less than 20 percent in the Jackpile sandstone. Locally the Westwater Canyon may contain up to 40 percent feldspar (Dodd, 1956, p. 251; Konigsmark, 1958, p. 15; Falkowski, 1980). Pink microcline is the dominant potash feldspar but orthoclase, sanidine, and perthite are common constituents (Hicks et al, 1980). Sodic plagioclase is the second most abundant feldspar and occasionally may constitute one-half the feldspars (Knox and Gruner, 1957, p. 6). It is strongly twinned and largely volcanic in origin (Squyres, 1974, p. 1). It has been estimated that up to one-half of all the feldspars in the upper Morrison Formation are volcanic in origin (Squyres, 1970, p. 173; Austin, 1980). Austin (1980) suggests that dissolution of feldspars originally constituting at least 1 percent of the rock has occurred. As mentioned earlier, the feldspar content is higher in the coarser sand size fractions. Coarse grained microcline is pink, angular, and may be up to 40 percent of bulk samples, but averages 26 percent (Martinez, 1979, p. 29).

Rock Fragments

Rock fragments ranging from sand to cobble size make up about 5 to 10 percent of the host rocks but may get up to 35 percent in places. They consist of igneous rocks, chert, quartzites, clay galls, and fossil woody material. Rock fragments make up the coarsest material in the sandstones, and in the Westwater Canyon Member, these subrounded fragments may be cobbles up to 13 cm in diameter. The maximum pebble size occurs in the upper Westwater Canyon on the nose of the Zuni Uplift, northeast of Gallup.

In this area a relatively soft, yellow-brown, very fine-grained sandstone forms distinctive discoid pebbles and cobbles in the upper Westwater Canyon (Saucier, 1967, p. 62). Martinez (1979, p. 31) found that these sandstone clasts became fewer in number, and smaller in size, to the east from Gallup. In fact, all the pebbles decrease in size rapidly to the north and east, and the composition changes to dominantly chert. This is believed due to a higher survival rate for the chert rather than to any change in source area. Martinez (1979, p. 26) has done the most work on conglomeratic material in the Westwater Canyon Member across the mineral belt. He has found that granite and volcanic clasts average 60 to 75 percent of the pebbles with sandstone, quartzite and chert 25 to 40 percent.

The igneous rock fragments are composed of plutonic and volcanic types. The average composition of bulk pebble samples collected by Martinez (1979, p. 26) is 12.4 percent granite and 9.7 percent volcanic fragments. The granites have a modal composition ranging from granitic to granodiorite, with an average composition of quartz monzonite. Knox and Gruner (1957, p. 10) found some granite pebbles with a myrmekitic texture. A pebble of microcline has been dated at 1.33 b.y. (Lee, 1976, p. 136), which suggests that much of this material is probably from a Precambrian source.

The volcanic material appears to be part of a calcalkaline series of ash-flow tuffs ranging in composition from rhyolite to crystal-rich quartz latite (Martinez, 1979, p. 26). The volcanics are white to grayish-pink pebbles up to 7 cm in diameter. Phenocrysts range in abundance from 2 to 35 percent and consist of subhedral to euhedral, broken, angular grains of plagioclase (oligoclase), sanidine, and quartz. The groundmass is usually intensely altered. These pebbles are well rounded and are more thoroughly altered as the particles approach sand size. Sand-size clay clots common in the Jackpile sandstone may be totally altered volcanic fragments (Adams et al, 1978, p. 1642). The original volcanic content of these sandstones are unknown, but Nash (1967, p. 89) estimates that as much as 30 percent by volume of the Jackpile sandstone may have been derived from a volcanic source.

The most common sedimentary rock fragment in these two sandstones is chert. In the Westwater Canyon sandstone, chert comprises 8 to 30 percent of the pebbles and averages 22 percent (Martinez, 1979, p. 30). The chert pebbles are subrounded, white, brown, gray, to black in color and are composed mostly of microcrystalline quartz. A small percentage of these cherts contain brachiopods, bryozoa, crinoids, corals, and fusulinids, which are Late Paleozoic in age (Chenoweth, 1953, p. 48; Saucier, 1967, p. 62; Martinez, 1979, p. 31). These chert pebbles were derived originally from limestone beds exposed on the Mogollon slope. Knox and Gruner (1957, p. 7) noted the presence of limestone pebbles in the Westwater Canyon Member, and Austin (1963, p. 41) also reported pellets of detrital limestone in some calcite-cemented conglomerate lenses. Austin suggested that detrital limestone clasts may have been more common in the sandstones originally, but were destroyed during diagenesis.

A violet-colored, fine- to very coarse-grained, poorly sorted quartzite is another common lithology noted in the coarse rock fragments. It has attained a high degree of sphericity and secondary rounding occurs in about 18 percent of the pebbles, indicating transport by turbulent, swift-flowing streams (Saucier, 1967, p. 62). Martinez (1979, p. 31) found that although these metaquartzites were low in abundance, 6 percent or less, they were persistent lithology in the pebble suites.

A very minor amount of other metamorphics has been identified. Knox and Gruner (1957, p. 10) found some biotite schist, and Flesch and Wilson (1974, p. 197) reported quartz-muscovite schist and gneiss (?). Nash (1967, p. 82) estimates that metamorphic clasts make up only 1 or 2 percent of the rock.

Clay Galls

Clay galls are autogenous rock fragments that are abundant in both sandstone host rocks. These clay clasts range in size from fine-grained balls and chips

to masses over 2 feet in diameter. The pebble to boulder size clay galls are usually concentrated at the base of a sandstone channel deposit and they fill scours and other irregularities in the eroded surface. The gall zones are generally a mix of conglomeratic material up to 2 feet thick in places. The weight of the channel fill often flattens the clay balls and squeezes them into a dense mass with little porosity. In other instances, the top of the scoured surface has a single layer of clay galls separated from one another by very coarse sandstone. The line of clay galls can sometimes be followed up the side of a channel to the eroded edge of the clay bed that was the source. Galls of relatively pure clay often come to rest at an angle to their original bedding, and the overburden pressure sometimes causes minute splits through the gall along the old bedding surfaces. It is not unusual to find slicken-sides developed on splits within the gall.

In weakly oxidized sandstone, a series of clay galls along the same diastem which originated most likely from the same bed of mudstone will exhibit various patterns of oxidation. The oxidized clay is usually dark red-brown in color even when the enclosing sandstones are a yellowish-gray color. In some galls the exterior is partially oxidized red, whereas in an adjacent gall the oxidation has penetrated the interior of the clay gall along the bed partings and the exterior remains green in color. In such instances, the exterior is more difficult to oxidize due to adsorbed organic acids, or because of a higher concentration of pyrite around the exterior. In other instances, the exterior is red and the interior is green. In most cases, it appears that the original color of the gall was light green, as was the parent mudstone bed. Occasionally the galls are totally replaced by calcite or amorphous silica and may be mistaken for limestone pebbles or volcanic tuff.

Sand-size clay chips and balls are most commonly found concentrated along coarse laminations in cross-bedding sets. It is often impossible to distinguish original clay particles from altered volcanic material, but undoubtedly most of the chips are pieces of original clay drapes which form during periods of low flow, and are ripped up during the next flood stage.

Organic Detritus

The most common and most prominent fossil material in the Westwater Canyon and Jackpile sandstones is petrified wood. Large silicified logs have been found at many places and usually in association with other logs and organic debris. The most spectacular example of log concentrations is in the top of the Westwater Canyon sandstone in the Section 30 Mine in Ambrosia Lake. In this mine, a large number of logs were buried where the enclosing channels were diverted from an easterly direction to a north-south direction by contemporaneous faulting (Clary et al, 1963, p. 78). According to Glover (1980, personal communication), it was like an entire forest buried. Logs up to 5 feet in diameter and more than 100 feet in length were found in various stages of carbonization and silicification. In one log, some of the wood was so unaltered that it would burn and float on water. Other examples are reported from the Johnny M Mine (Falkowski, 1980) where even trash piles 30 feet wide and 10 feet thick contained mattes of carbonized grass or pine needles, reeds and small branches. The association of ore with fossil logs was especially close in some of the Poison Canyon Mines where mineralized logs and trash accumulations were followed along the base of one channel for a mile and a half (Rappaport, 1980, personal communication). In the Ann Lee Mine, Squyres (1970,

p. 23) found plant remains widespread, but irregularly distributed. Coarse plant detritus was more common in the channels than elsewhere. Small fragments are usually coalified, whereas logs are completely silicified, or else have a silicified interior and a coalified "crust".

Young (1960, p. 9) reported that on the outcrop identifiable woody remains are rare in the main body of the Westwater Canyon Member, but they are quite common and even abundant in the uppermost tongues of the member. Most of the plant remains are coalified. The largest logs rarely exceed a foot in diameter and 10 feet in length. A concentration of large logs was found in the base of the Westwater Canyon in Sections 3 and 10, T 14 N, R 12 W. Another concentration of silicified logs was found in the lower Westwater Canyon on the Nutria monocline immediately southeast of Gallup (Saucier, 1967, p. 56).

In the Jackpile sandstone local concentrations of fossil plant remains have been found. Silicified logs up to 3 feet in diameter and 60 feet long have been observed (Moench and Schlee, 1967, p. 20). In places the logs are so abundant that they seem to have formed log jams (Schlee and Moench, 1961, p. 138). Concentrations of fossil wood have also been noted at the Jackpile Mine in the middle of the sandstone (Gruner, 1956, p. 10; Moench and Schlee, 1967, p. 74).

Plant debris that is more widespread in occurrence, and perhaps volumetrically more important, is the macerated leafy material that settles along foresets in festoon cross-beds. This type of organic accumulation is common in recent stream deposits of the Mississippi River (Frazier and Osanik, 1961, p. 128), and the Rio Grande River in New Mexico (Harms and Fahnestock, 1965, p. 113). Rackley (1976, p. 122) also described this type of organic accumulation in Tertiary arkoses in Wyoming. Carbon flakes or impressions on cross-laminae can often be observed in sandstones of the Westwater Canyon Member. This type of accumulation of light material, especially near the toe of foresets, is a normal consequence of the formation of festoon cross-bedding, as discussed by Jopling (1965, p. 64). Since this sedimentary structure is everywhere present in the Westwater Canyon and Jackpile sandstones, the amount of finely divided vegetal material that could have been buried in the festoons is prodigious.

Heavy Minerals

Detrital heavy minerals in the Morrison Formation range from a trace to about 0.5 percent of the rock (Adams et al, 1974, p. 219). This same figure has been confirmed for the Westwater Canyon and Jackpile sandstones by Cadigan (1967, p. 73), Santos (1975, p. 9), and Hicks et al (1980). At least 12 workers have reported all or some of the following suite of detrital heavy minerals from these two sandstones: zircon, tourmaline, garnet, apatite, staurolite, rutile, magnetite, ilmenite, biotite, muscovite, sillimanite, amphibole, and pyroxene. Sillimanite has only been reported from the Jackpile (Schlee and Moench, 1961, p. 140; Nash, 1968, p. 742), and amphiboles and pyroxenes are conspicuously absent except for a trace found by Sachdev (1980) in a Westwater Canyon sandstone tongue north of Thoreau, New Mexico. According to Martinez (1979, p. 22), zircon is 50 to 88 percent of the translucent heavy minerals, and it occurs in two suites. One suite is well-rounded and the other is euhedral, and both are in the 0.1 to 0.2 mm size range. Colorless, well-rounded zircons are dominant in the Westwater Canyon with only 2 to

13 percent being euhedral. A sample from the Jackpile sandstone that he analyzed showed 38 percent of the total zircons were euhedral. It is suspected that the well-rounded group is Precambrian in age, and most of the euhedral group will prove to be Triassic or Jurassic in age. He also found the tourmaline to average 10 percent of the translucent heavy minerals, the garnets 15 percent, apatite 3.7 percent, and staurolite 0.6 percent. Corbett (1964, p. 36) reported an occurrence of the schorl variety of tourmaline which he believed was derived from veins which may indicate a basement origin for the tourmaline.

Austin (1963, p. 41) reported the total absence of magnetite and ilmenite in the district; however, Corbett (1964, p. 36) found altered grains of magnetite coated with goethite in coarse-grained Westwater Canyon sandstone in the Section 22 Mine in Ambrosia Lake. Allen and Balk (1954, p. 143) found magnetite to be more abundant in the Westwater Canyon Member in the Defiance area than in other stratigraphic units. Saucier (1967, p. 57) also found some magnetite in the Gallup area. Lee (1976, p. 58) and Hicks et al (1980) have found thin laminae of magnetite common in the Westwater Canyon Member deeper in the basin. Lee used instrumental neutron activation analysis on the magnetite and found it to contain significant amounts of Th, Cr, Hf, Sc, Ta, Co, and some rare earth elements. In general, however, Austin's observation about the absence of magnetite and ilmenite in the mineralized areas has been borne out.

Matrix-Cement

According to Nash (1967, p. 89), matrix material is often more than 20 percent by volume in the Jackpile, and Martinez (1979, p. 32) gives a range from 7 to 45 percent for the Westwater Canyon, but the average is probably much less than that of the Jackpile. The detrital matrix material is dominantly montmorillonite clay and volcaniclastics. Detrital montmorillonite is enriched in Ca and Mg and contains little Na (Sachdev, 1980). After a study of possibly unaltered Jackpile sandstone in the Paguate open-pit mine, Nash and Kerr (1966, p. 1285) concluded that volcanic glass and montmorillonite were deposited syngenetically with the feldspathic sand in amounts of up to 50 percent by volume, as determined by modal analyses. The Westwater Canyon sandstones are generally much cleaner. The conglomerate, or gall zone, frequently found at the base of individual channel deposits has a matrix of up to 50 percent coarse sand (Knox and Gruner, 1957, p. 7). The festoon cross-bedded medium-grained sandstone above the conglomerate is generally fairly clean except for sand size clots of reworked clay and particles of volcanic rock which have mostly been altered in place. The finer-grained sand in the upper and lateral portions of the channel deposit probably contained the highest percentage of detrital clays and volcanics, but no estimates are available on the amount. Other detrital components which may have made a small but unknown contribution to the matrix are sericite, kaolinite, and limestone. The detrital clays, dominantly montmorillonite, were the original cement in the sandstones.

Authigenic Minerals

The Westwater Canyon and Jackpile sandstones have undergone diagenetic changes which have altered the clay mineral content, produced secondary cements, and

created a new heavy mineral suite. In addition, the buried vegetal remains were degraded chemically and biologically and produced a soluble fluid product which was transported in the ground water and locally precipitated. This organic precipitate called humate in places constitutes up to 30 or 40 percent of the volume of the rock, and thus locally is an important authigenic component. With the exception of the humate, none of the authigenic minerals discussed in this section are associated specifically with uranium mineralization but are of general occurrence. Some of the authigenic minerals are not diagenetic but were produced during later periods of oxidation. In most examples, this distinction will be obvious.

Clay Minerals

Montmorillonite is the dominant authigenic clay in the Westwater Canyon Member, and it apparently formed early from devitrification of volcanic material in the sandstone (Granger, 1962, p. 20; Lee, 1976, p. 128; Brookins, 1979, p. 11). The montmorillonite occurs as a thin skin, 1 to 10 microns thick, which replaces clasts and in some cases coats the sand grains (Flesch and Wilson, 1974, p. 202; Hicks et al, 1980). It may originally have been a sodium montmorillonite, but if so, the Na has been replaced by Ca and Mg. Mixed-layer illite-montmorillonite is reported to be a minor constituent which occurs sporadically in the Ambrosia Lake area (Lee, 1976, p. 100; Brookins, 1979, p. 11). According to Lee (1976, p. 100), textural relations suggest that the mixed-layer clays are later than the montmorillonite and form from this clay, in places totally replacing the montmorillonite. Santos (1975, p. 9) reported that in the southeast part of the basin the clays are mostly illite-montmorillonite, and more recently Hicks et al (1980) found no montmorillonite in the deeper part of the basin in the Chaco Canyon area. Little or no authigenic montmorillonite has been found in the Jackpile sandstone (Nash, 1967, p. 112; Adams et al, 1978, p. 1645; Baird et al, 1980). The montmorillonite has apparently been replaced by illite-montmorillonite, illite, chlorite, and kaolinite. Chlorite formed by direct precipitation and solid state transformation from montmorillonite. It appears to have formed later than the mixed-layer clays (Lee, 1976, p. 100). Nash (1967, p. 173) distinguished a fine chlorite altered from montmorillonite and a coarse chlorite which was precipitated in the Jackpile sandstone. Small amounts of iron-bearing chlorite are ubiquitous in the Westwater Canyon according to Brookins (1980). It usually is more than 5 percent of the total clay content, but Hicks et al (1980) found up to 30 percent chlorite in samples from core holes in the Westwater Canyon in the Chaco Canyon area. In the Jackpile sandstone, the chlorite content is about equal to the illite-montmorillonite content and ranges from 4 to 10 percent (Brookins, 1980; Baird et al, 1980).

Locally kaolinite is the dominant clay in the Westwater Canyon Member and in the Jackpile sandstone. It has three modes of occurrence and is of at least two different ages (Granger, 1963, p. 27). A minor amount of kaolinite replaces feldspar grains and may be diagenetic in origin, but most of the replacements are probably due to one or more periods of alteration in Cretaceous and Cenozoic time. Some pure kaolin fills small fractures in the sandstones and forms veins in carbonized logs. It may also be concentrated in pockets and channel fills at the Morrison-Dakota unconformity. In the Westwater

Canyon Member, most kaolinite occurs as "nests" of pure kaolinite booklets ranging from 1 mm to 5 mm in diameter which enclose numerous sand grains (Knox and Gruner, 1957, p. 15; Corbett, 1964, p. 43; Granger, 1962, p. 18). The nests are scattered throughout the sandstone and coat all other authigenic minerals except some iron-oxides. The abundance of kaolin nests has no relation to the degree or amount of alteration in adjacent feldspar grains (Kendall, 1971, p. 98). Most often the feldspars are fresh and unaltered, and the kaolinite was undoubtedly precipitated in pore spaces from the ground water. The nests are larger and more numerous in the coarser grained, more porous sandstones. Kaolinite also replaces the small montmorillonite clay pellets and flakes (Squyres, 1970, p. 91). Nash (1967, p. 112) found that kaolinite replacements of montmorillonite usually contain small particles of iron oxide in the Jackpile sandstone. In the Westwater Canyon sandstone, kaolinite makes up 5 to 50 percent of the -2 micron fraction (Brookins, 1980; Hicks et al, 1980). In the Jackpile sandstone, Baird et al (1980) report that kaolinite can be up to 15 percent of the whole rock and is about 80 percent of the clay fraction. The upper part of the sandstone in the Jackpile Mine is clay cemented, and all the clays have been altered to kaolinite (Adams et al, 1978, p. 1,649). In the Jackpile, most of the kaolinite is related to the intense weathering at the unconformity on the top of the sandstone, but the introduced kaolinite found in the Westwater Canyon sandstone may be more related to the Late Tertiary and Recent oxidation, which has altered large volumes of the sandstone around the edges of the basin (Squyres, 1970, p. 91). In summary, the paragenetic sequence for the authigenic clays is: montmorillonite, illite-montmorillonite to illite, Fe-chlorite, and kaolinite.

Calcite

After clay minerals, calcite is the most common cement in the sandstones. It commonly cements the first few inches or feet of sandstone or conglomerate directly overlying a mudstone layer (Granger, 1963, p. 26). This hard "rib" shows up as a strong spike on the single point resistivity logs and has been noted throughout the Grants Uranium Region. Much of this coarse crystalline calcite may have been derived from dissolved limestone clasts which may have originally been present, as proposed by Austin (1963, p. 44). In the Jackpile sandstone, the base of the unit is commonly calcite-cemented, and it appears to be later than the clay grain-coatings (Schlee and Moench, 1961, p. 141). Nash (1968, p. 740) found that well sorted Jackpile sandstone can contain 25 to 40 volume percent calcite which indicates that the calcite is pre-compaction or has replaced detrital clasts. The calcite is generally clear, coarsely crystalline, and often forms poikilitic masses. Occasionally it is found as fracture fillings (Granger, 1963, p. 26). In places the calcite forms concretionary masses within the Westwater Canyon sandstone. Some concretions are equidimensional, but many have a prominent long axis ranging from 5 to 15 feet in length and two minor axes which vary from 0.5 to 10 feet in length (Saucier, 1967, p. 54). A section normal to the principal axis may show a circular, oval, crescent, or even S-shaped outline. The long axes of the concretions on the outcrop near Pyramid Mountain were found to have a narrower range in azimuth than the surrounding cross-beds, which may indicate that they formed shortly after deposition of the sandstone, when the ground water flow was in the direction of stream flow.

Some calcite is late and its relation to kaolinite is unclear (Austin, 1980). Lee (1976, p. 100) found that some kaolinite is being replaced by calcite cement in many samples which is in agreement with Knox and Gruner's (1957, p. 13) findings. Undoubtedly some of the calcite is very early, but it has probably formed at various times in response to changing chemical conditions. It is not uncommon for the calcite content to reach 35 percent in some mines (Knox and Gruner, 1957, p. 14).

Silica

Silica released from the destruction of volcanic material and mafic silicates for the most part became incorporated in authigenic clay minerals and formed quartz overgrowths. Fine-grained silica cement is relatively uncommon except in thin sandstone lenses in the Brushy Basin mudstones. The most common and widespread form of authigenic quartz is as overgrowths on quartz grains. In some places the development of quartz overgrowths was inhibited by the presence of authigenic clay coatings on the grains (Adams et al, 1978, p. 1642). The distribution of the overgrowths is patchy and erratic locally, but its occurrence is widespread in both the Westwater Canyon and Jackpile sandstones. Squyres (1963, p. 97) suggested that authigenic quartz was less than 1 percent of the total volume of the sandstones in the Ann Lee Mine, but Cadigan (1967, p. 73) estimated that the overgrowths may make up 10 to 15 percent of the Westwater Canyon sandstone. Adams et al (1978, p. 1,642) thought that the overgrowths in the Jackpile are broadly related to the zones of feldspar destruction and organic matter. This may also be true for the Westwater Canyon for Austin (1980) estimated that dissolved volcanic feldspars, sanidine and sodic plagioclase may have constituted at least 1 percent of the original whole rock. Where the destruction of feldspars is not so obvious, the overgrowths may be more related to the distribution of mobile organic substances which have the ability to etch quartz and mobilize silica (Evans, 1964, p. 268). More than enough silica was available to account for the overgrowths. In fact, it is surprising that silica cement is not more common, but evidence of the precipitation of opal or chalcedony in the sandstones is rare. Buried logs apparently were silicified early, for they are only slightly compressed by the overburden, whereas the coaly material shows the effect of loading (Corbett, 1964, p. 39).

Some authigenic feldspars have been reported. Corbett (1964, p. 43) found albite that wrapped around detrital grains and included clay and pyrite within its mass. Albite replacement of the outer rims of plagioclase and sanidine grains are widespread in parts of the sandstone units (Adams et al, 1978, p. 1643; and Austin, 1980). Often the centers of these grains have been dissolved out leaving only the resistant albite shell. Authigenic feldspar crystals too small for accurate identification have been found within the hollowed shells of sanidine grains (Austin, 1963, p. 40). Austin also reports (personal communication) that elongated, euhedral, quartz crystals have been found in clay in the Westwater Canyon Member with the scanning electron microscope. These authigenic crystals are relatively common in the Ambrosia Lake area.

Heavy Minerals

Pyrite is the most ubiquitous authigenic heavy mineral in the Grants Uranium Region (Lee, 1976, p. 45). Where present it averages about 1 percent of the

Westwater Canyon sandstone with a range from 0.2 percent to 5 percent (Knox and Gruner, 1957, p. 13; Squyres, 1963, p. 97; Corbett, 1964, p. 42; Ristorelli, 1980; Thompson, 1980). The pyrite most commonly occurs as a dusting of subhedral to euhedral cubes ranging from 0.005 mm to 3 mm in diameter. Austin reports (personal communication) that cubes are most common but elongated cubes, cubes with truncated corners, pyritohedrons and other forms can be found. The average crystal size is probably about 0.1 mm or less (Knox and Gruner, 1957, p. 13; Corbett, 1964, p. 43; Squyres, 1969, p. 81). Pyrite cubes up to 0.5 cm on a side have been found in mudstone lenses in Ambrosia Lake (Granger, 1963, p. 25). In organic-rich sand stones the pyrite may also occur as cement or local interstitial fillings (Rhett, 1980). There are multiple generations of pyrite, but so far no one has noted any systematic differences in the habit or crystal morphology which would distinguish periods of crystallization. Pyrite is relatively uncommon in the Jackpile sandstone, except in proximity to organic accumulations (Adams et al, 1978, p. 1637; Baird et al, 1980), and it was essentially absent from the Westwater Canyon sandstones in the Chaco Canyon core holes (Hicks et al, 1980).

Iron Oxides and Carbonate

Hematite has been found in feldspar cleavage planes and as remnant coatings on grains. These traces of hematite are believed to be early pre-diagenetic oxide stains that have been preserved. Hematite coatings and replacements of magnetite are found on grains in the more distal portions of the Westwater Canyon depositional system indicating some oxidation but little or no post-depositional reduction of the sediments in those areas.

Pervasive hematite staining of the Westwater Canyon Member occurs over a broad area between Gallup and Grants, and in other areas around the edges of the basin as shown in Figure 6. This hematite is derived from the oxidation of the diagenetic pyrite in the sediment and is probably Late Tertiary in age, as will be discussed later. Broad zones of limonitic oxidation usually separate the hematitic sandstones from the pyritic portions, and therefore appears to be a later, intermediate oxidation state of iron.

Adams et al (1978, p. 1,649) found that siderite replaces pyrite where the feldspars are strongly kaolinized in the Jackpile sandstone. Rhett (1980) has reported siderite associated with uranium mineralization in the Nose Rock Area, but Kendall (1971, p. 82) specifically looked for siderite in the Section 27 Mine without success, and it has rarely been reported for heavy mineral suites elsewhere in the region.

Titanium Minerals

The alteration of ilmenite, titaniferous magnetite, and other titanium-bearing minerals in pyritic areas of the Westwater Canyon sandstone has produced leucoxene and anatase (Austin, 1960; 1963, p. 41). The same authigenic heavy minerals are also present in the Jackpile sandstone (Schlee and Moench, 1961, p. 140; Nash, 1967, p. 74; Adams et al, 1978, p. 1645). Anatase octahedra are chiefly found in hollow detrital titano-magnetite grains (Lee, 1976, p. 49), but it also commonly occurs scattered throughout a cubic inch to

Figure 6. Map of the San Juan Basin region showing the extent of strong hematitic oxidation within the Westwater Canyon Member of the Morrison Formation and its association with Laramide uplifts.

perhaps eight cubic inches or more of rock attached to sand grains in much the same manner as pyrite crystals (Austin, personal communication). It can be nearly black, blue, pink, brown, lilac, citron, yellow, or white. The anatase persists in oxidized ground and may be an alteration product of leucoxene. Austin says (personal communication) that much or all of the leucoxene is actually tiny platelets or minute crystals of anatase.

Other Minerals

Other authigenic heavy minerals reported from the Morrison sandstones in minor amounts are: barite, marcasite, ferroselite, native selenium, galena, greenockite, and chalcopyrite (Moench and Schlee, 1967, p. 59; Rhett, 1980). These minerals appear to be closely related to the orebodies and therefore are not widespread accessories of the host rock. Barite has only been reported in areas close to oxidized sandstones. Weeks (1953) reported that spectrographic analyses of the Morrison mudstones revealed the existence of significant quantities of barium. This barium is probably released when the mudstones are oxidized and it is efficiently precipitated down-dip by the sulfates produced during oxidation of pyrite. Much of this barite is radioactive. Marcasite has only been found in traces within or in proximity to the orebodies, especially the stack or redistributed ores.

Humate

Using the definition of Swanson and Palacas (1965, p. 3), "humate" is a collective term for a group of gel-like, solid, humic substances in sediments, coal-like in composition and appearance which fill voids and coat grains in some sandstones. The humic substances form from chemical and biochemical degradation of terrestrial vegetal and animal matter. Humic substances were once believed to be derived principally from lignin, which is one of the most dispersed substances in nature (Manskaya and Drozdova, 1968, p. 115). Lignin is a matrix or cementing substance that firmly binds the cellulose fibers in vegetable tissue (Swain, 1970, p. 341), and it makes up about 30 percent of woody materials. However, algae, lichens, and mosses which do not contain lignin give rise to humic substances (Stevenson and Butler, 1969, p. 537). The contemporary view is a two-stage biosynthetic process in which all plant components are first decomposed into simple monomers and then these are polymerized into high molecular weight polymers. However, a completely satisfactory scheme for the synthesis of humic substances in geologic environments has not yet been developed. Decay of vegetation begins under aerobic conditions as soon as a plant dies, therefore the production of humic substances begins with oxidation aided by bacteria and fungi. The soluble humic substances are brown to black, amorphous, hydrophilic, acidic, organic molecules which range in molecular weights from several hundred to hundreds of thousands (Schnitzer and Khan, 1972, p. 3). These macro-molecules, or organic compounds, are variable in composition but are characterized by a high oxygen content. The molecular structure is poorly understood, but it is partially aromatic in character (Manahan, 1975, p. 3).

The humic substances have traditionally been divided into three groups: 1) acid and base soluble fulvic acid; 2) base soluble, but acid insoluble humic acid; and 3) insoluble humin. It is now believed that these groups of humic substances are part of a system of polymers with no sharp division between

humic and fulvic acids (Stevenson and Butler, 1969, p. 535). Humin may not be a separate group but may simply consist of humic and fulvic acids intimately bound to mineral matter.

The humic and fulvic acids have been shown by X-ray investigations to consist of a flat aromatic condensed ring with functional groups of carboxyl, phenolic, and alcohol groups, as well as simple aromatic ethers and hydrocarbon chains (Swain, 1970, p. 309). Fulvic acids are the earliest degradation product, and they may age or oxidize to humic acids. The humic acids form a colloidal suspension, or sol, in alkaline waters similar to coffee or tea. The humic colloids carry a negative charge. This sol can be flocculated by acidifying the colloidal solution, by adding dissolved cations such as Al^{+++} , Fe^{+++} , and Mg^{++} , or by complexing with clay colloids (Swanson and Palacas, 1965, p. 11). The flocculated humate gel eventually forms a hard, black, brittle solid with a conchoidal fracture, and a specific gravity ranging from one to two. It will not melt if heated, and is insoluble in benzene, or other common organic solvents. In physical appearance, it is similar to coal, but as a stain or grain coating it may resemble dead oil or asphalt. If precipitated by lowering the pH, the humate is easily redissolved in early stages by raising the pH. Maturation of the humate, due to absorption of cations, dehydration, compaction, or radiation renders it more insoluble through time. Therefore, it is an early transitory stage in the process of coalification.

In the Grants Uranium Region, humate often is found impregnating the sandstone surrounding petrified logs from which it was derived. In many cases, the humate halo is asymmetrical or tear shaped with the "tail" pointing down channel (see Fig. 9 later in text) in the direction of sediment transport (Squyres, 1970, p. 62). In places the humate has bled out of the organic trash accumulations and has been attenuated by ground water movement into a long tail extending ten to hundreds of feet away from its source in the paleostream direction (Weege, 1963, p. 121). More often, the humate derived from multiple vegetal sources has formed into broad, elongate pods from 50 to 200 feet wide and several hundred feet long which are oriented parallel to the depositional trends, or which follow the paleochannel scours. It is not uncommon for extensive sheets or blankets of humate to form which are subparallel to the gross stratification. Some of these blankets range from a few inches to more than 8 feet in thickness, are two to three thousand feet wide, and over one mile long. They appear to have precipitated along some nearly horizontal interface such as a paleowater table or the interface between ground waters of different composition.

Swanson and Palacas (1965) described similar extensive humate blankets of Recent age which have formed along the Florida coast in the Choctawhatchee Bay area. In northeastern South Carolina, particularly in Horry County, humate occurs in two geomorphic sites: in pre-Recent barrier islands, and in fluvial terraces of coastal plain streams, such as the Little Pee Dee (Thom, 1967, p. 15). These multiple layers of humate are believed to represent the position of sea level at various times during the Pleistocene.

Swanson and Palacas (1965, p. 11) proposed that the humic substances in Florida were leached from the humus in the sandy sediment above the water table and were carried down to, or below the water table where the organics

were flocculated, either by the adsorption or complexing of dissolved cations, or because of a lowering of the pH which would precipitate the humic fraction. They noted instances where the humate could be readily redissolved by fresh water which would indicate that the flocculation was due more to pH rather than to more permanent compositional changes.

Pods and blankets of humate are probably common occurrences in many recent fluvial channels. In New Mexico, where very recent downcutting has bisected the alluvial deposits in many small streams, pods to sheet-like impregnations of limonite and manganese can be found near the base of the earlier channel deposits. According to Baas Becking and Moore (1959), most of the iron in sediments exists as complexes with organic matter. These bright orange-colored zones a few inches to several feet thick, therefore, probably represent iron-rich humate deposits which precipitated at, or beneath, the water table in the older channel fill. Most of the organic material has now been redissolved or destroyed by oxidation or bacteria, leaving the iron-rich residue.

Humic substances have other properties which affect the mineral constituents of the host rocks. Evans (1964, p. 264) has experimentally shown that various organic substances present in living animal and plant cells can dissolve relatively water-insoluble minerals such as carbonates, phosphates, and silicates at normal surface conditions of temperature and pressure. The humic substances appear to have this capacity, for Nash (1967, p. 166) found that in thin zones in the Jackpile sandstone that are particularly rich in humate, more than 50 percent of the quartz by volume and up to 75 percent of the clay matrix was dissolved by the organics. Huang and Keller (1971, p. 1082) have used humic acids to alter montmorillonite to mixed-layer clays and even to illite. In addition, clays can adsorb up to three or four times their own mass of organic matter as coatings on clay particles (Curtis, 1964, p. 1). Schnitzer and Khan (1972, p. 260) found that 40 mg. of Na-montmorillonite adsorbs 31 mg. of fulvic acid at a pH of 3. The interlayer adsorption increases as the pH is decreased.

Therefore, the buried organic material and its derivatives in the sandstones have been a primary agent of diagenesis. Beside causing the pervasive reducing environment in the main body of the sandstone which destroyed the magnetite and ilmenite and produced pyrite, the humic substances have probably aided in the dissolution of feldspars, and quartz, and have altered the clay minerals. It is even suspected that the organic acids locally improved the porosity of the sandstones by dissolving the matrix material (Baird et al, 1980). Although the humate may exceed 20 percent of the sandstone by volume, it usually is less than 0.5 percent and probably averages about 0.3 percent, within the humate impregnated sandstones. Elsewhere the original dispersed humic substances have been dissolved and removed or destroyed by anaerobic-bacteria and oxidation, so analysis for organic carbon record only traces.

In terms of the paragenetic sequence, the humate is younger than the early montmorillonite and is generally older than the dissolved volcanic feldspars, for the organic matter is seldom found within the hollow albite shells; however, Squyres (1970, p. 103) did report finding organic matter within the feldspar shells. The pyrite, quartz overgrowths, calcite cement, and chlorite are coated by humate and in turn coat the humate which indicate broad overlap

in the times of formation of these minerals. All the limonite and most of the hematite are younger than all other authigenic minerals except for some of the kaolinite in the Westwater Canyon sandstone. Most of the kaolinite in the Jackpile sandstone is older than the patchy areas of hematite which appear to be quite young. In both sandstones, the hematite has been produced by oxidation of the diagenetically reduced sandstones, except in the distal portions of the Westwater Canyon depositional system, where some original hematite may have been preserved.

Oxidation History

It has been proposed that the Westwater Canyon Member was originally deposited as red-beds as seen between Gallup and Grants, and that the "bleached mineralized areas were the result of alteration by mineral-bearing hydrothermal fluids" (Sharp, 1955, p. 16; Konigsmark, 1955, p. 13), or by Cretaceous organic acids (Young, 1960, p. 42). Squyres (1970, p. 121) has presented a strong argument for an original red color of both the Morrison sandstones and mudstones. Preservation of original magnetite in the Westwater Canyon north of Ambrosia Lake rather than hematite replacements is evidence against strong post-depositional reduction or oxidation. It is also difficult to imagine that the thick mudstone section of the Brushy Basin Member was originally all red and was reduced at some later date. Whatever the original color of the sediments, reducing conditions were probably established in this fine-grained material while sedimentation was in progress, as suggested by Granger (1968), Lee (1976) and Saucier (1980). The reduced organic-rich areas can be identified by the absence of magnetite and ilmenite in the sandstones, as proposed by Austin (1960, p. 1758) and Adams et al (1974, p. 220). Magnetite and ilmenite are destroyed in areas of strong reduction, are altered and partially dissolved in weakly reduced areas, and are preserved as fresh mineral grains or hematite pseudomorphs in unreduced areas. Sears et al (1974, plate XXV) attempted to map the distribution of these heavy minerals as a guide to prospective areas. Over much of the southern San Juan Basin, it appears that the Westwater Canyon and Jackpile sandstones were diagenetically strongly reduced. Overprints of oxidation in these areas are later events in the alteration history of the rocks.

Pre-Dakota Oxidation

The first major post-depositional oxidation to affect the Morrison sandstones is related to the pre-Dakota unconformity. This unconformity may represent a time period of up to 30 million years during which the strata were tilted to the northeast and eroded. In the Gallup area, the Brushy Basin Member was stripped away and the Westwater Canyon Member was exposed to weathering and oxidation on the surface. A strong acid environment is indicated by the complete kaolinization of the feldspars and clay minerals within a few tens of feet of the unconformable surface. Humid swampy conditions probably existed which would indicate a high water table and restricted penetration of the alteration effects in the subsurface. Except for the exposed strip of Westwater Canyon sandstone between Gallup and Window Rock, the remainder of the member was probably unaffected and remained in a reduced state.

The Jackpile sandstone was exposed on this unconformable surface throughout Lower Cretaceous time and was pervasively altered. The original unaltered sandstone was preserved only in structurally low areas, well below the water table. Post-depositional structural adjustments placed large areas of the Jackpile in elevated positions where it was leached and eroded. The Laguna syncline became a partially closed basin and a trap for redistributed minerals and organics leached from the flanks of the structure, and from the extensive floodplain that was destroyed updip toward the source area. Ground water not trapped in the Laguna Basin moved downdip toward the axis of the larger San Juan sag to the northeast. This long period of exposure and alteration of the Jackpile sandstones is a fundamental difference between this unit and the bulk of Westwater Canyon sandstones which remained protected throughout this period. However, the deeper portions of the sandstone were not oxidized, and hematite and/or limonite, that may have formed in the shallower sands, were destroyed during later diagenesis.

Tertiary Oxidation

With the onset of Cretaceous deposition, the Morrison Formation was buried and protected from oxidation until after the Laramide deformation, which produced sufficient relief for erosion to once again expose the Morrison on the flanks of uplifts. It probably was not until Middle or Late Tertiary time that meteoric waters gained access to the deeper Morrison sandstones. A regional hydrodynamic flow in the Westwater Canyon sandstone was not established until Miocene time, according to Berry (1959, p. 61), when the San Juan River incised its present course through the Morrison in the Four Corners area. This created an outlet for Westwater Canyon ground waters in the San Juan Basin. Oxidizing surface waters were then able to penetrate the Westwater Canyon exposed high on the flanks of the Defiance, Zuni, and Naciminto Uplifts. These early tongues of oxidation moved toward the San Juan outlet. On the Chaco slope, a broad lobe of oxidation moved more than 15 miles downdip from the outcrop to depths exceeding 2,400 feet (Saucier, 1980). It was limited to the east and west by fractures which apparently hindered the ground water flow. These broad tongues of early oxidation in the Westwater Canyon sandstones around the basin are now colored red. The approximate distribution of these hematitic sandstones is shown in Figure 6. The Jackpile sandstone was exposed only along the Naciminto Uplift during this period of oxidation. The Jackpile in the Laguna area was not exposed until Quaternary time.

Quaternary Oxidation

Since the Late Cenozoic period of deformation, two other ground water outlets from the basin have been created, one in the southeast corner, and one in the southwest corner of the basin (Saucier, 1980). Pleistocene to Recent oxidation patterns in the Westwater Canyon have been somewhat altered by the new outlets, especially by the one in the southeast, which drains to the Rio Grande. This period of oxidation is expressed mainly by limonitic alteration of the diagenetic pyrite which fades out basinward into faintly yellowish-gray rock with little or no destruction of pyrite.

GEOLOGIC HISTORY

The regional geologic setting at the beginning of the Mesozoic Era consisted of a broad northwest-trending trough that existed between the Uncompahgre highland in southwest Colorado and the Mogollon highland in southern Arizona. Prior to Morrison deposition, Mesozoic drainage patterns were generally west and northwest toward the Cordilleran geosyncline. The Morrison Formation represents a shift in the drainage patterns to the northeast and east as the Cordilleran geosyncline and the Mogollon highland were uplifted. Uplift of the Mogollon highland was accentuated structurally and topographically by the development of a volcanic arc farther to the west in Late Triassic and Jurassic time. Acid plutonic and extrusive rocks formed a northwest-trending belt which passed through southwestern Arizona and southern California. As the Mogollon highland was uplifted the Uncompahgre highland became more subdued. The result was a general tilting of the region to the northeast. Concurrently, in Late Jurassic time, the Zuni Uplift, an old positive element, was rejuvenated, and a broad shallow basin and flood plain was formed to the north. The lacustrine Todilto, Summerville, and a local lacustrine facies of the Bluff near Gallup, were deposited in this basin. Coarse clastics of the Morrison Formation were transported down the Mogollon slope to the northeast and deposited in this large basin as described by Craig et al (1955) in their classic paper. There was a southeast migration of fluvial depocenters through Morrison time represented by the Salt Wash fan, the Westwater Canyon fan, and the Jackpile fan, which suggests a continued tilt to the east. The progressive regional tilting of the paleo-depositional slope to the northeast, however, was the major controlling feature of Morrison sedimentation, and it persisted on through Cretaceous time.

Jurassic deposition on the Colorado Plateau was wholly continental and consisted dominantly of sandstones. The climate ranged from extreme aridity in Early Jurassic time to semi-arid in Late Jurassic time. The climate became humid in the Lower Cretaceous and may have been almost sub-tropical in Late Cretaceous time in this area. The lowest member of the Morrison Formation in the Grants Uranium Region is the Recapture Member which represents a continuation of the arid depositional environment of the pre-Morrison stratigraphic units. The Westwater Canyon Member marks a dramatic and abrupt change in depositional environment. The flood of sandy material carried by large streams originating in the Mogollon highland indicates a climatic, or topographic change in the source area. Such changes could be induced in a geologically short period of time by the build-up of large strato-volcanic complexes in southern Arizona. The flood of detrital material with a high content of volcanoclastics lends support to this idea. The clays in the Westwater Canyon and in the partly contemporaneous Brushy Basin Member are dominantly montmorillonites derived from the alteration of a vast amount of volcanic material. Most of the volcanic material is believed to have been altered in the source area, or during transport, with some contribution of air-fall ash in the depositional area.

Both the Westwater Canyon and Brushy Basin Members are fluvial deposits with minor interbedded lake beds more common at the fringes of the depositional system. The preserved portion of the Westwater Canyon Member was deposited by straight to sinuous dominantly bed-load streams, on a wet alluvial fan (Galloway, 1980). The thick depositional trends in the Westwater Canyon

appear to have been determined by minor contemporaneous structural deformation in the basement (Hilpert and Corey, 1957; Young, 1960; Thaden and Santos, 1956, Saucier, 1976; Wentworth et al, 1980), and perhaps by some broad intraformational folds caused by gravitational creep down the flank of the Zuni Uplift. The Westwater Canyon sandstone was reduced contemporaneously with sedimentation, and masses of humate impregnated sandstone formed soon after the alluvial deposits accumulated. The organic material and the areas of strong reduction which it caused, appear to be most abundant adjacent to the Zuni highland which was a low positive area in Late Jurassic time.

The coarse sand and pebbles within the Westwater Canyon Member have been a tremendous aid in determining the provenance of the sediment. The source area consisted of granitic, volcanic, sedimentary, and metamorphic rocks with the igneous rocks making the largest contribution. The finer-grained fraction of the Westwater Canyon sandstones were derived mostly from pre-existing sediments. Quartz sand and chert fragments came mostly from Paleozoic sandstones and limestones with some contribution from Precambrian and Triassic sandstones. The coarser-grained fraction came dominantly from igneous rocks of mixed plutonic and volcanic origin. The plutonic rocks ranged from granites to grano-diorites with an average composition of quartz monzonite (Corbett, 1964, p. 41; Flesch and Wilson, 1974, p. 197; Martinez, 1979, p. 29). Most of the plutonic rocks were Precambrian in age with a minor Mesozoic contribution. The volcanics are represented by clasts of rhyolite to quartz latite ash flow tuffs and are probably all Triassic and Jurassic in age with some minor admixed Precambrian volcanics. Both the Precambrian and Mesozoic igneous rocks represent calcalkaline series in the source area (Martinez, 1979, p. 30). The proportion of volcanic material has probably been underestimated because much of it was destroyed soon after deposition. The combined plutonic and volcanic components probably constituted over 50 percent of the original sediment. The metamorphics make up perhaps less than 2 percent of the material and consists of quartzites, muscovite and biotite schists.

The average Westwater Canyon sandstone is a fine- to medium-grained, moderate to poorly sorted, subrounded to subangular, subarkosic arenite, or more simply, a feldspathic sandstone. The Jackpile was probably derived from the same source area for it is very similar to the Westwater Canyon Member. The present differences are due mostly to the more intense post-depositional alteration experienced by the upper parts of the Jackpile sandstone. Both sandstones have been diagenetically altered with a resulting loss of feldspars, limestones clasts, volcanics, and heavy minerals. The original sands were probably true arkoses (Austin, 1963, p. 41).

Three periods of deformation have been recognized in the Grants Uranium Region. The first was prior to Dakota deposition, the second in the Early Cenozoic, and the third in Late Cenozoic time. The pre-Dakota deformation consisted of broad, low amplitude folds parallel to the axis of the Zuni uplift in Westwater Canyon time, and a set of broader cross-folds trending north to north-northeast during Brushy Basin time. The north-trending arches were more pronounced in the Laguna area during and after deposition of the Jackpile sandstone. The Early Cenozoic or Laramide orogeny had the most profound effect on the region by resurrecting the old Zuni Uplift and outlining the San Juan Basin. The San Ignacio Monocline and the San Mateo Monocline

probably ruptured at this time and evenly spaced, north-trending normal faults disrupted the Chaco slope as far west as Thoreau. Most all of the faults and monoclines were down to the east and the amount of displacement on these structures diminished to the west toward the present Continental Divide. The Colorado Plateau was epeirogenically uplifted in Late Cenozoic time concurrent with rifting in the Rio Grande trough. Older faults were again displaced, but the most notable effects of this period were in the Laguna and Rio Puerco areas where north-striking minor faulting and jointing occurred west of the San Ignacio monocline, and northeast-striking faults and joints formed east of the monocline. Northeasterly fractures in the McCartys syncline localized basaltic vents, and where this fracture zone intersected suspected northwest-trending basement fractures the Mt. Taylor volcanic complex formed. The deformation associated with all three periods has been one of essentially vertical movement. Folds on a regional to local scale are usually asymmetric and appear to have formed by draping of sedimentary strata over tilted basement blocks. Positive tectonic elements have remained positive while negative elements became more negative. There is no convincing evidence of compressional tectonics in any of the three periods. The deformation that has occurred consisted of recurrent movements on old fractures, many of which were evident as far back as Late Jurassic time, and which probably have much older antecedents in the Precambrian basement rocks.

GEOLOGY OF THE URANIUM DEPOSITS

Exploration History

Although Paddy Martinez is credited with the discovery of the Grants Uranium Region, the existence of uranium oxides northwest of Grants was known since the 1920's (Kelley, 1963, p. 1), and may have been examined by federal geologists in the early 1940's. Vanadium Corporation of America is said to have staked claims in the area for vanadium sometime in the 1940's according to Harlen Holen (personal communication, 1980). Smith (1954, p. 23) reported that his students found carnotite on the Todilto outcrop near the Andrews Ranch in 1949. The discovery that started the uranium mining boom of the 1950's was made by the Navajo shepherd Paddy Martinez in limestone at the foot of Haystack Butte on November 15, 1950 (Hilpert, 1969, p. 5). The discovery was made on Santa Fe Railroad land. The railroad sent in a geologist, T. O. Evans, to evaluate the prospect. On January 4, 1951, he discovered the first uranium ore in sandstones in Poison Canyon, so named because of the poisonous selenium-bearing "loco weed" (*Astragalus*) which grew there. By this time, however, numerous uranium occurrences had been found in exposures of the Todilto Limestone east and west of Haystack Butte, and this unusual host rock remained the major prospective unit.

When a Supai Indian, Joy Sinyella, reported Todilto mineralization on the outcrop south of the village of Laguna on the Laguna Reservation in August of 1951, the Anaconda Company was the first to react. They obtained a prospecting and lease agreement on the Laguna Reservation in October, 1951. An airborne reconnaissance program was immediately successful when Woodrow House and D. O. Terry located Jackpile mineralization on the outcrop on November 8, 1951, near the village of Pagate. At this time, the sandstone hosting the Jackpile orebody was thought to be the Westwater Canyon Member of the Morrison Formation. The Westwater Canyon was being prospected between Grants and Gallup with very little success. By 1953, a few small occurrences had been found on the outcrop in the Thoreau and Church Rock areas in upper lenticular sandstones of the Westwater Canyon. In 1953, Anaconda found the large Jackpile orebody by drilling, and in 1954 this company discovered the St. Anthony deposit by pattern drilling to the north. These successful drilling programs in what was believed to be Westwater Canyon may have stimulated Louis Lothman to obtain a lease on Ambrosia Dome from Stella Dysart on February 15, 1955. The driller's log and cuttings from an old oil and gas test hole showed that thick Westwater Canyon sandstones could be intersected at relatively shallow depths on the dome. On March 17, 1955, Lothman intersected ore at 292 feet in his second hole in the south half of Section 11, T 14 N, R 10 W. This discovery became the Dysart No. 1 Mine, the first in the Ambrosia Lake District. Unlike the Jackpile this discovery caused a tremendous amount of excitement and stimulated a large land play. By the summer of 1956, more than 200 drilling rigs were in operation and phenomenal discoveries were being made in the Westwater Canyon Member (Melancon, 1963, p. 4). Zitting et al (1957, p. 54) reported that by early 1957, a total of 33 million tons of ore with an average grade above 0.30 percent U_3O_8 (undiluted) had been found, and there was potential for another 14 million tons. The deepest ore was at 1,500 feet, but the average depth was 700 feet (Birdseye, 1957, p. 26). This was estimated to represent about 50 percent of the known U. S. reserves in Ambrosia

Lake alone, and combined with the giant Anaconda orebodies, New Mexico held perhaps 72 percent of the U. S. uranium reserves. In August, 1957, one mine was producing on a limited basis in Ambrosia Lake, eight shafts were being constructed, and six more were planned (Birdseye, 1957, p. 26). Ambrosia Lake began production in 1958, and soon had six mills in operation with a total capacity of 11,075 tons per day (Hilpert, 1969, p. 9). Anaconda had the largest uranium mill in the U. S. at Bluewater with a rated capacity of 3000 tons per day. The Jackpile orebody was stripped for open pit mining in late 1953, and the Paguate, and L-Bar deposits were found in 1956 (Kittel et al, 1966, p. 10). A summary of more recent discoveries is given by Chenoweth (1977), and Chenoweth and Holen (1980).

According to Chenoweth (personal communication, 1979), ERDA records show that between 1948 and 1978, the entire San Juan Basin produced 66 million tons of ore averaging 0.21 percent U_3O_8 and containing 135,900 tons of U_3O_8 . This was 40 percent of all domestic production through 1978, and over half of this came from Ambrosia Lake. Although the average grade of ore has been falling since 1977, New Mexico still claims 54 percent of the U. S. proven uranium reserves in the \$30 forward cost category. It is estimated that 750 million pounds of U_3O_8 have been delineated in the Grants Uranium Region, and 99 percent of these reserves are in the Morrison Formation (Chapman et al, 1979). All production to date has been from depths less than 2,000 feet, but ore has been found and will be mined to depths of 4,000 feet. There are presently 37 uranium mines and five mills in operation in the region. All but a very minor portion of the present production is from the Westwater Canyon and Brushy Basin Members of the Morrison Formation. Hilpert (1969) gives a comprehensive summary of the uranium occurrences in northwestern New Mexico.

Uranium Deposits

Uranium in the Grants Uranium Region occurs in sandstone, limestone, shale, and coal, representing eolian, lacustrine, fluvial, paludal, and marine depositional environments. Commercial uranium deposits have only been found in rocks of Jurassic and Cretaceous age in the San Juan Basin. These host rocks are dominantly fluvial sandstones. Approximately 98 percent of all the uranium ore produced from the Grants Uranium Region has come from fluvial sandstones of the Morrison Formation. The Todilto limestone has accounted for about 2 percent of the production and a small fraction of a percent came from the Dakota and Entrada sandstones (Hilpert, 1969, p. 60). The Morrison uranium deposits range from several hundred to several million tons in size and contain from less than one million to over 50 million pounds of U_3O_8 in ore averaging about 4 pounds of U_3O_8 per ton (Melvin, 1976, p. 114). The known orebodies were originally clustered in areas which could be considered as isolated districts, such as Laguna, Ambrosia Lake, Smith Lake, and Church Rock. More recent discoveries have made these old district boundaries very indefinite and have added other place names as potential districts, such as Crownpoint, Nose Rock, San Mateo, and Rio Puerco. The deposits in all the districts are similar in that the ores are gray to black and consist of the uranium silicate, coffinite, disseminated in a coal-like organic substance in the sandstone which is believed to be a fossil humate. Oxidized uranium minerals have been of very minor importance in this region. In mineralogy, geometry, and the close association with organic matter, the uranium deposits

are similar to others on the Colorado Plateau, but are much larger in size. The orebodies in the Grants Uranium Region are generally stratiform, and occur as elongate tabular bodies within linear trends. However, as this megadistrict has expanded, the deposits have been found to differ in geometry and in their relation to oxidized host rock. Workers in different areas have observed different types of orebodies, and have tended to generalize about the whole district from experiences in limited areas. Whereas each of these observations may be correct, there is no average, or representative deposit for the entire region. Rather, there appears to be a sequence of orebody types which have evolved through the oxidation and redistribution of early primary ore concentrations.

Granger et al (1961, p. 1188), distinguished two ore types in Ambrosia Lake, pre-fault and post-fault mineralization. More recently, Smith and Peterson (1980) have listed four types: primary (trend), redistributed-fracture controlled (stack), redistributed-geochemical cell controlled, and relict (remnant) deposits. The first type is related to the original and principal mineralizing event whereas all the others resulted from later oxidation of the host rocks and ore. The extent to which oxidation has modified the primary deposits is only beginning to be appreciated. For the purposes of discussion, the deposits will be divided into primary and redistributed ores, either of which may be reduced or partially oxidized. The use of the term "primary" in a genetic sense is intended. The primary ores show no obvious relation to tectonic structures but are controlled in subtle ways on a local scale by sedimentary structures. Redistributed ores appear to be controlled by both sedimentary and tectonic structures. In both types, the mineralogy is relatively simple, and anomalous concentrations of Mo, Se, V, and Fe are associated with uranium. The most distinctive feature of the uranium deposits, whether primary or redistributed, is their intimate association with an amorphous organic substance which impregnates the mineralized rock.

Excellent descriptions of the mineralization are given by Hilpert and Moench (1960), Granger et al (1961), Kelley, (1963), Corbett (1964), Moench and Schlee (1967), Nash (1968), Squyres (1969), Santos (1970), and Kendall (1971). The following descriptions will be largely drawn from these workers. Special acknowledgement should be given to Harry Granger who has contributed very much to our understanding of the geology and geochemistry of the ores in this region.

Primary Uranium Deposits

The primary uranium deposits, as the term implies, are believed to represent the closest approximation to the ore as it was originally formed. The best examples of primary ores are in the Ambrosia Lake District (Plate 5). These deposits have also been called pre-fault and trend ores, but these descriptive terms are not exclusive attributes of primary ore, and therefore are inadequate titles. Both primary and redistributed ores occur in trends, but this feature is particularly characteristic of primary ore in Ambrosia Lake. Three distinct trends have been defined (Santos, 1963, p. 55) in Ambrosia Lake.

Ore Trends

The mineralized trends range from 1,000 to 3,000 feet in width and extend from Ambrosia Dome to the San Mateo fault, a distance of 9 miles. Each trend

consists of multiple ore horizons in the Westwater Canyon sandstone which criss-cross and overlap in a complex fashion within the restricted boundary of each trend. Between trends the sandstones are barren or contain only small, non-economic uranium accumulations. The barren areas between trends vary from one-half to one mile in width. The trends are roughly parallel and strike generally west-northwest. The average strike of ore trends across the entire region is about N 70 W. If examined in 10-mile segments, the gross trends appear to alternate repeatedly from a southeast to an east direction from Church Rock to the Bernabe Montano Grant. There appears to be a close correlation between the trend directions and the belts of Morrison outcrop between Gallup and Grants. In the Laguna area the paleostructure indicated by the Westwater-Brushy Basin isopachous map suggests that the bends in the trend directions are structurally controlled (Plate 4).

The trends in Ambrosia Lake are located in a broad area where the Westwater Canyon Member is more than 200 feet thick (Santos, 1963, p. 55). The Westwater Canyon trend east of Mt. Taylor is definitely located in a zone of anomalously thick sandstone (Livingston, 1980; Kozusko and Saucier, 1980). A similar feature has been documented by Wentworth et al (1980), in the Crownpoint area, and indications are that the Nose Rock trend north of Crownpoint is similarly related to a northeast trending sandstone thick in the Westwater Canyon Member. The Poison Canyon mineral trend located south of Ambrosia Lake is in an area of much thinner total Westwater Canyon sandstone, but the ore is in an upper sandstone unit where this unit is above average in thickness (Konigsmark, 1958, p. 15; Weege, 1963, p. 117). Both the Ambrosia Lake trends and the Poison Canyon trend appear to be located in east-trending synclinal areas separated by a broad, shallow anticline as shown in the cross section on Plate 5, modified from Santos (1970). Individual Ambrosia Lake trends are believed to be localized in even smaller, more subtle synclinal warps containing a slightly greater sandstone buildup at the top of the member.

Shallow folds were active during sedimentation and may have tended to localize the coarser mid-channel facies along the synclinal axes. The sandstones deposited on the flanks of the synclines were finer-grained and may have contained less organic material especially the logs and coarse trash which tended to be concentrated in the central channels as floods waned. Porosity and permeability in the finer-grained sandstones were reduced during diagenesis, and the coarser channel deposits became the zones of maximum transmissivity. As many as six separate mineralized horizons have been found stacked over one another along the main south trend in Ambrosia Lake (Zitting et al, 1957, p. 57). The Westwater Canyon Member in the south trend has scattered mineralization from top to bottom, whereas in the middle trend, ore occurs only in the middle and upper Westwater Canyon and in the north trend, mineralization is restricted to the upper third of the member (Hazlett and Kreek, 1963, p. 87; Santos, 1970, p. 55).

Blanket Ore

The primary uranium ore deposits occur mainly as flat-lying pods, lenses, and blankets which are roughly parallel to the bedding planes in the sandstone (Fig. 7). These blanket-like deposits range from tens of feet, to several thousands of feet in width, and from a few hundred to over five thousand feet in length. Thickness of mineralization is from a few inches to over 15 feet,

Figure 7. Isometric sketch of a primary ore blanket from the south trend in Ambrosia Lake (modified from Roeber, 1972).

but usually is less than 10 feet. The contacts of ore with barren rock are sharp and are usually marked by an abrupt color change from dark gray ore to light gray or yellowish-white country rock. The long dimensions of the deposits almost always parallel the orientation of the sedimentary transport direction, as indicated by channel scours, cross-bedding, log orientations, and other sedimentary structures in the host rock.

Ore pods may be isolated or connected by a thin filament of mineralization which may be too thin to be ore, but is important in understanding the true geometry of the uranium deposits. Such thin sheets of mineralization that extend sub-horizontally through a sandstone unit over several millions of square feet are unique, and this geometry must be considered in any theory on the origin of the deposits. The ore pods are often simply crenulations in the blanket, which the miners call "rolls" (Young and Delicate, 1965, p. 10). These rolls form where the mineral blanket cuts sharply across the sandstone bedding to a different elevation, as shown in Figure 7. In cross section, the step-up resembles a flattened S-shape where the mineralized sandstone is not only thicker but is often higher in grade. The blankets tend to roll up stratigraphically to the north, but in the Homestake Section 23 and 25 Mines, this is not always true. The rolls in these mines, however, have been found to exhibit a periodicity (Roeber, 1972, p. 2; Young and Delicate, 1965, p. 10). That is, the crenulations in the blankets have been found to occur at regular intervals of 50 to 150 feet laterally over widths of up to 3,000 feet (Fig. 7). The regularity of this spacing has been found useful in planning mine development. These rolls are also parallel to the long dimension of the large sheets and also conform to the paleocurrent direction of the host sandstone.

These remarkable sheets of mineralized organic material are well developed in the main south trend of Ambrosia Lake, where they may occur over one another, shingled, or en echelon in multiple horizons scattered throughout the Westwater Canyon Member along trend. They are unconnected, distinct mineralized blankets in sandstone units which are often separated by beds of mudstone (Fig. 8). The middle and north trends have similar mineralization on a smaller scale. Where oxidation has encroached upon the trends, the thin filaments connecting the pods, or extending out from individual pods toward the oxidized sandstone, have been destroyed, and the residual primary ore occurs as isolated, concretionary masses 150 to 250 feet in width, and up to several hundred feet in length as exemplified by the Ann Lee ore shown in Plate 6. In the middle trend, the ore pods, or rolls, have north flanks which step up stratigraphically to the north and the various blankets or pods in the Upper Westwater Canyon do the same thing on a larger scale. The ore layers are at higher stratigraphic levels across the trend from south to north, and at the present time there is no good explanation for either the regular-spaced rolls which climb to the north, or the stratigraphic climb of the various blankets and pods in a north direction. In other places, such as Crownpoint, the mineralization steps down stratigraphically from south to north. This is believed to be due to oxidation in the lower part of the Westwater Canyon which moved the lower ore farther to the north (Wentworth et al, 1980). It may be possible that oxidation has moved down the San Mateo fault and is present north of the Ann Lee and Section 27 Mines. This could explain the staggered ore pattern seen in these mines by Squyres (1963, p. 94) and Kendall (1971, p. 23). Mineralization in the Poison Canyon trend may have been similar to the south Ambrosia Lake trend, but it is much more oxidized and the ore pods are only small scattered remnants of the blanket mineralization which may have once existed. The preserved ore tends to be more closely associated with irregularities in the base of the host sandstone, or to be in proximity to trash piles which apparently supplied much of the carbonaceous material. East of the San Mateo fault the Poison Canyon trend consists of about four separate, parallel sub-trends which are spaced approximately 1,500 feet apart. Each sub-trend is a fairly continuous strand of ore which is only a few tens of feet wide in Section 24, T 13 N, R 9 W. Some of these strings of ore are continuous for over one mile. These are probably partly oxidized remnants of once larger ore pods or rolls.

Figure 8. Idealized cross section showing stack and primary ore as it exists in southwestern Ambrosia Lake (modified from Roeber, 1972).

Trends similar to Ambrosia Lake have been found at Crownpoint and San Mateo, New Mexico, but the ore in both areas has been modified by oxidation. East of Mt. Taylor, one well-defined trend appears to extend from the village of Marquez to the North L-Bar Ranch. It may have once been continuous all the way to the Rio Puerco River, 17 miles to the east, but oxidation has created gaps in the trend. In this eastern area, the trends are up to three-quarters of a mile wide and many miles long. The tabular, concordant mineral lenses or blankets within the trends are 1,500 to 2,000 feet wide with only a central zone about 200 feet in width which is thick enough to be ore. The central ore zone in each blanket is sinuous along trend. Ore zones in the various superimposed blankets weave back and forth along trend in a very complex pattern, as shown by Kozusko and Saucier (1980, Fig. 6). Multiple rolls may be found in each blanket once underground mining begins which would make this eastern extremity of the trend even more similar to Ambrosia Lake.

Jackpile Mineralization

The Jackpile mineralization is a separate trend which is younger and oriented differently than the Westwater Canyon trends. It is composed of a series of tabular ore lenses which are strung out in a northeasterly direction as shown on Plate 4. Mineralization within this trend is also parallel to the sedimentary transport direction of the host sandstone (Schlee and Moench, 1961, p. 134). The mineralized trend is located in the thicker part of the Jackpile sandstone, but it appears to have a closer correlation with the axis of the Laguna syncline, as shown in Plate 4. The mineralization occurs in large, more equidimensional, tabular bodies suspended in the sandstone. In the Jackpile deposit, three principal ore lenses occurred throughout the thickness of the sandstone. The upper lens was about 5,000 feet long, 2,500 feet wide and had a rather uniform thickness of between 10 and 20 feet, except at the edges, where the mineralization abruptly thinned, most likely due to destruction of the mineralization (Adams et al, 1978, p. 1640). The general habit of the lenses is shown in Plate 7. The tops of the ore lenses are sharp and even, whereas the base is gradational. Relief on top of the ore was 40 feet or less over this large area, which is remarkably flat. The Paguate deposit is over 2 miles long and averages 200 feet in width (Kittel et al, 1967, p. 11).

The now isolated ore pods probably were once connected in more continuous blankets but have been disrupted during periods of weathering and oxidation in Cretaceous and Recent times. The two extremities of the trend, one on the L-Bar Ranch and the other between the villages of Paguate and Laguna consist of many ore pods within apparently discontinuous lenses scattered through the Jackpile sandstone (Kittel et al, 1966, p. 12; Forhan, 1977, p. 36). As in Ambrosia Lake, low grade mineralization, in the range of tens to a few hundred ppm U_3O_8 , extends beyond many of the pods contributing to the general blanket form of the deposits.

Ore Controls

Ore controls on a local scale are as difficult to define as those on the regional scale. The distribution of the primary ore in the Westwater Canyon Member is affected by sedimentary features such as minor disconformities or diastems, bedding planes, mudstone conglomerate beds, thin mudstone lenses, filled channels, calcite cement, and the relative thickness of the host

sandstone lens (Granger et al, 1961, p. 1191; Santos, 1963, p. 53; Squyres, 1963, p. 94). Numerous workers have suspected that changes in grain-size control the ore deposits, but there does not appear to be a clear or consistent relationship. Ore appears to be found most often in poorly sorted, medium- to coarse-grained sandstones, but some high-grade deposits are also reported from fine-grained sandstones. It does appear that in most of the orebodies described, ore is associated with the diastems found at the base of each channel deposit. The gall zones and coarse-grained sandstones, if present, occur in the base of these scour fills, and frequently so does early calcite cement. The diastems are also the boundary between fine- to silt-size sandstones in the top of the underlying channel deposit. Much of the primary blanket ore lies above diastems in the coarser, poorly-sorted basal channel deposits, but the ore in a particular blanket commonly crosses and extends beyond a particular channel fill to encompass several diastems. More often the ore passes below the diastem into fine-grained sandstones as shown on Plate 6. Individual blankets tend to follow some common horizon on a larger scale and they seldom move up or down more than 5 or 10 feet from this ghost horizon. However, the change in grain size at the diastems does appear to exert some control on the distribution of the primary mineralization.

For the most part, the primary ore does not occur adjacent to thick beds of mudstone, but it frequently encloses thin discontinuous mudstone lenses and clay gall horizon. It is not unusual to find isolated clay galls in barren ground surrounded by a halo or crust of ore, which suggests that ore was once in this barren sandstone, but has been removed, or at least that ore-forming constituents moved through the sandstone and were precipitated and preserved around the clay. Squyres (1970) and Kendall (1971) have described tear-shaped humate and jordisite halos which have been drawn out in the down stream direction by the movement of ground water. These tails are illustrated in Figure 9 but are projected into the plane of the sketch. Their actual orientation is toward the viewer. The affinity of ore for clays is believed due to the great adsorption capacity clays have for humic substances, as discussed in a previous section.

Accessory Minerals

The orebodies are composed of organic material, believed to be humate, which coats and replaces sand grains and clay. The uranium is disseminated throughout the organic phase possibly as unidentified urano-organic complexes and submicroscopic particles of coffinite. The ore deposits are essentially organic deposits contaminated with uranium, iron, vanadium, molybdenum, and selenium. All of these elements may have originally been concentrated by complexing and absorption in the organic matter, and although a large portion of these accessory elements can now be found in discrete mineral phases, some of the Mo, Se, and V are still present in unidentified forms in the carbonaceous material which some authors believe to be organic complexes (Jacobs et al, 1970, p. 185; Brookins, 1979, p. 10). Hydrogen sulfide, generated by sulfate-reducing bacteria which fed on the organic substrate, caused the precipitation of the iron as pyrite (Jensen, 1963, p. 183). Degradation of the organics would also have released adsorbed selenium which is now mostly present with the iron in the pyrite. The highest selenium concentrations are in the pyrite in the ore although the primary ore often contains more Se than can be accounted for in the pyrite.

Figure 9. Composite sketch of a variety of features associated with ore in the Ann Lee and Section 27 mines (from Squyres, 1970, and Kendall, 1971).

No vanadium mineral species have been identified in the primary ores. The organic substance may have caused the alteration of montmorillonite clay rims and clasts to Mg-Chlorite, and in the process, some of the vanadium was incorporated in the chlorite lattice (Lee, 1976, p. 95). Lee found the V_2O_5 in the ore zone chlorite to range from 1.5 to 3.3 percent. Vanadium concentrations up to 0.50 percent V_2O_5 are found in very high-grade ore, but it usually averages about 0.15 percent (Hilpert and Moench, 1960, p. 446).

Molybdenum occurs in the ore in concentrations up to 200 ppm (Squyres, 1963, p. 94), probably associated with the carbonaceous material, but the highest concentrations of molybdenum are found as separate patchy impregnations of jordisite which occur marginal to the uraniferous ore pods. Black masses of jordisite 1 to 2 feet thick commonly underlie blanket ore and are sometimes found enclosed in the uranium ore as shown in Figure 9. These jordisite masses contain up to 0.36 percent Mo, but seldom more than 100 ppm U_3O_8 . Occasionally the uranium and molybdenum zones overlap to produce a high U-Mo ore (Granger and Ingram, 1966, p. 123).

The uranium content of the primary ores ranges from less than 0.20 percent U_3O_8 to over 15 percent U_3O_8 . The highest-grade ore is commonly associated with humate halos surrounding fossil logs or in carbonaceous clay-rich zones at diastems. The average grade in the Ambrosia Lake primary ores was probably about 0.30 percent U_3O_8 , but assays of at least twice this grade are not uncommon. This is only an estimate and is not to be compared with production grades which are determined by economics. Due to the habits of the ore, oxidation and mining practices, the ore that is delivered to the mill averaged only about 0.22 percent up to 1978, and this has now fallen to 0.15 percent U_3O_8 or less. Some primary ores in places averaged more than 0.50 percent U_3O_8 , and portions of the orebody at San Mateo average 1 percent U_3O_8 . Ores with above average uranium content such as was mined from the Cliffside, Hogan, and Marquez Mines may be due to some enrichment caused by remobilization of uranium and organics along the San Mateo fault during Late Tertiary and Quaternary oxidation.

Trace amounts of such elements as Ta, Sb, Co, As, V, and rare earth elements (REE), have been found to be enriched near ore zones, and thus have been investigated as possible pathfinder elements (Lee, 1976, p. 165; Brookins et al, 1977, p. 266). Enrichments in total REE and thorium have been found near ore and are believed to have been carried by organic complexes, or adsorbed on colloidal species. Ore zone chlorite is especially enriched in REE content. According to Brookins (1980), it appears likely that As and Se were transported as oxyanions and concentrated in sulfides as sulfate reduction occurred. Since all of these trace elements, including uranium, appear to be associated with the organic matter, or in authigenic minerals directly related to the organic matter, their utility as pathfinder elements for uranium is probably limited. Vanadium may prove to be the most useful in this respect, since it remains in oxidized ground, when primary mineralization is oxidized and redistributed, and appears to form a slightly larger halo around the orebodies. However, Brookins (1977, p. 268) and many others have concluded that uranium is probably the best guide to uranium deposits, and this has certainly been true up to the present time.

Age of Primary Mineralization

The primary ore in the form of blanket and pod mineralization is believed to be the earliest form of uranium concentration on the basis of geologic relations, Rb-Sr dating of authigenic clays, organics, and the availability of uranium and accessory elements. It has long been recognized that the primary ores are earlier than the faults and fractures. Almost without exception, the primary ores are offset by faults, and therefore are older than the Laramide deformation. On stratigraphic grounds, an ore pod in the Jackpile sandstone in the Paguate open pit was found to be truncated by the pre-Dakota erosion surface (Nash and Kerr, 1966, p. 1283; Melvin, 1976, p. 146) which makes the ore pre-Late Cretaceous in age. Clark and Havenstrite (1963, p. 108) have illustrated tabular ore layers in the Cliffside Mine in Ambrosia Lake which have been dropped down in the core of a pipe structure. The pipe does not penetrate the Dakota Sandstone and is apparently Morrison (Late Jurassic) in age. The primary ore appears to have been in place before the collapse structure formed sometime in Brushy Basin time. Similar mineralized pipe structures of pre-Dakota age have been found in the Doris Mine in the Poison Canyon trend, and in the Jackpile Mine area. Lee (1976, p. 128) has dated authigenic chlorite in the Westwater Canyon and Jackpile ores and obtained Rb-Sr ages of 139 ± 12 m.y. for the Westwater Canyon, and 115 ± 9 m.y. and 110 ± 10 m.y. for the Jackpile ore. Authigenic montmorillonite was dated 148 ± 9 m.y. and is believed to approximate the age of the host rock. However, as Granger (1962, p. 20) pointed out, it is not known whether the chlorite was formed during the period of uranium mineralization, or whether it represents a slow progressive alteration of montmorillonite under chemical conditions imposed in part by the organic material during a long period subsequent to mineralization. These age dates can be taken as the minimum ages of mineralization. The younger age of the Jackpile ore-stage chlorites is probably real and may date a redistribution event in Lower Cretaceous time.

If the organic material which contains most of the uranium was derived from organic acids released from buried vegetal trash, as appears likely, then it had to have originated very soon after the plant debris was buried and began to rot. Geologic evidence which appears to support an early age for the humate was found in the Dog Mine in the Poison Canyon trend where a distinct sandstone channel with uraniferous humate was mined for thousands of feet. Occasionally a younger cross channel would incise the mineralized trend ore and create a narrow, barren gap, apparently having removed the pre-existing humate (Squyres, 1970, p. 142). A similar type of evidence for the early age of the ore-bearing organics was discovered in the Johnny-M Mine where a small penecontemporaneous graben was found offsetting trend ore a few feet. The faults died out abruptly against an overlying sedimentary unit. Thus, from a consideration of the chemistry and probable origin of the organic material, and geologic relationships, it appears that the humate masses, whether mineralized or not, may have formed very early, while the host rock was being deposited.

The next problem to consider is whether the uranium and accessory elements were available very early or were introduced at some later time. It appears that devitrification of acid volcanic debris in the sandstones occurred almost immediately after burial, for the authigenic montmorillonite clay rims on the

sand grains are the earliest diagenetic changes to be documented. It may, therefore, be assumed that the destruction of the volcanic glasses released uranium, molybdenum, and selenium to the ground water. Coleman and Delevaux (1957, p. 514) found that selenium was present in pyrite in the Morrison Formation on the Colorado Plateau in both barren and mineralized rock. Eighteen samples of pyrite from barren ground averaged 0.14 percent Se, and 20 samples from mineralized rock averaged 0.20 percent. Kendall (1971, p. 85) found the same relations in the Section 27 Mine in Ambrosia Lake. Pyrite in barren sandstone contained 0.10 percent or less Se, whereas pyrite associated with ore contained from 0.10 percent to 1.0 percent selenium. It is assumed that the Se entered the sulfur positions in the sulfide structure during crystallization; therefore, the Se in the ground water during the formation of the early diagenetic pyrite was apparently available in the same relative amounts as during the period of uranium mineralization. This suggests that the two periods may have occurred close in time.

The vanadium may have been derived largely from the magnetite and ilmenite which was destroyed in large portions of the Westwater Canyon and Jackpile sandstones. Lee (1976, p. 63) found that the magnetite also contained significant amounts of Th, Cr, Hf, Sc, Ta, and Co and could have been the source of these trace elements also. The magnetite was probably destroyed shortly after burial when the sandstones were diagenetically reduced (Austin, 1963, p. 39). It therefore appears that all the necessary chemical ingredients to make an ore body were available and mobile in the system shortly after deposition of the host rock.

Redistributed Uranium Deposits

There is evidence that ground water moved and physically shaped the humate after it had flocculated as originally proposed by Squyres (1970, p. 158). With time, however, the uranium-bearing humate matured and became immobilized due to condensation of the humic material and possibly because of alteration induced by radiation (Leventhal and Threlkeld, 1978, p. 431). During much later periods, oxygenated ground waters invaded the host rock and redissolved a portion of the organics and caused a redistribution of the uranium downward along the leading edges of the oxidized sandstones. The redistribution of ore caused by oxidation has been divided into two types: stack ore, which is localized mainly by fracture systems in the host rock, and C-rolls, in which the redistribution is controlled principally by stratigraphy. The C-rolls closely resemble the Wyoming roll-type orebodies in many respects.

Early Redistributed Mineralization

One example of probable early redistribution of primary ore is the mineralized pipe structure in the Cliffside Mine mentioned earlier. Ore within the pipe is thicker and higher grade than correlative ore outside the pipe (Clark and Havenstrite, 1963, p. 113). The ore outside the pipe has apparently been depleted either by dissipation of the humate shortly after the pipe formed or by more recent oxidation which has encroached upon this orebody. In this example, early redistribution is difficult to prove, but Squyres (1970, p. 140) believes that thick, high-grade, organic-rich ore that is definitely controlled by northeast-striking joints in the Cliffside Mine is primary ore that was redistributed in Morrison time. The presence of pipe structures and

the thin Brushy Basin Member on the west side of the adjacent San Mateo fault lend support for Late Jurassic movement along this fault which may have caused the redistribution of the ore. Squyres (1970, p. 57) also cites the existence of jordisite masses within primary trend ore as evidence that the humate gel has moved and engulfed the jordisite which originally occurred outside the ore boundaries. Tear drop-shaped halos of humate around galls and petrified wood fragments suggest that ground water did move the early soft humic gel.

The most famous pipe structure in the Grants Uranium Region is the Woodrow breccia pipe located just east of the Jackpile Mine in the Laguna district. The pipe is 24 to 34 feet in diameter and is circular in plan (Wylie, 1963, p. 177). The pipe crops out near the base of the Jackpile sandstone of the Brushy Basin Member. The Jackpile sandstone appears to have been dropped about 40 feet down into the underlying mudstone. Drilling has shown that the pipe spirals downward at least 230 feet (Hilpert and Moench, 1960, p. 456). Although only a modest amount of ore was produced from this structure, it had the highest average grade in the district. Uranium mineralization which averaged about 1.53 percent U_3O_8 occurred in the ring fracture in the upper 100 feet. From the 100-foot level to the 200-foot level the average grade declined rapidly downward from over 0.50 percent U_3O_8 at the 100-foot level to less than 0.10 percent U_3O_8 at 200 feet (Wylie, 1963, p. 178). Ore in this interval averaged 0.32 percent U_3O_8 and it occurred as disseminations and coatings on brecciated mudstone fragments throughout the core of the pipe.

Because the mineralization became weaker with depth, there is a tendency to think that the uranium was carried down the pipe from the Jackpile sandstone. However, the evidence can also be interpreted to indicate that the mineralization moved up the pipe. The Jackpile is not known to be mineralized near the pipe, or within the pipe. The Upper Jackpile sandstone above the pipe could have been mineralized but it has been destroyed by erosion. Mineralization has been encountered by drilling both in the pipe structure and adjacent to the pipe, in a Brushy Basin sandstone 140 feet below the base of the Jackpile, as shown in Wylie's Figure 1. This sandstone, called the "A" sand, is extremely coarse-grained, unsorted, and porous, and supplied 15 to 20 gallons of water per minute to the shaft. Nash (1967, p. 148) reported that an organic trash pile had been encountered by core holes in the base of the "A" sand adjacent to the pipe structure. Wylie's Figure 1 shows that an ore zone 10 feet thick averaging more than 0.30 percent U_3O_8 was present at the base of this sandstone. The mineralization is assumed to be associated with the trash pile and is probably primary "A" sand mineralization.

If one accepts the origin of the Woodrow and other pipes as related to the dewatering of underlying silty units such as the Summerville Formation, the occurrence of the structure in a syncline, where the water table was presumably near the surface during deposition, it seems most likely that fluid movement would have been up the pipe rather than downward in Jackpile time. The uraniferous humic material was probably leached out of the trash accumulation in the "A" sandstone and was moved up the pipe where adsorption on the clays in the mudstone breccia formed a disseminated lower grade ore, and the concentrated flow along the ring faults in the upper part of the pipe created the rich, sulphidic ore.

This model is supported by the sulfur isotope work of Jensen (1963, p. 186), which shows that the sulfides in the Woodrow pipe have about the highest

enrichments in the heavy isotope (S^{34}) ever found in a sedimentary deposit. This has been accepted by some as proof that the pipe is hydrothermal. However, Jensen's explanation is that the heavy isotope of sulfur was enriched in the underlying Todilto evaporites, and as the lighter isotope was depleted in the pipe, the anaerobes used the Todilto sulfates which migrated up the pipe to generate H_2S . This resulted in a concentration of the heavy isotope in the later sulfides. It appears, therefore, that the mineralization in the Woodrow pipe was remobilized Late Jurassic primary ore from the deeper "A" sandstone. In this respect it is interesting to note that of all the hundreds of pipe structures known in the Grants Uranium Region, only four, the Doris, the Cliffside, Jackpile, and Woodrow, contain uranium mineralization and all apparently intersected pre-existing primary ore deposits.

Stack Ore

Granger et al (1961, p. 1188) were the first to distinguish and describe post-fault or stack ore. Although not widespread in Ambrosia Lake, this type of ore made up a large part of the ore reserves in the Section 23, 24 and 25 Mines located south of Ambrosia Dome. Oxidation has moved downdip from the outcrop through the Westwater Canyon sandstone and encroached upon the west end of the south Ambrosia Lake trend. The primary mineralization was remobilized and moved as much as a few thousand feet to the north where east-west and northwest-trending fracture zones were encountered. The fractures tended to disrupt the ground water flow and caused the mineralization to build up stratigraphically along the fractures. Accumulations of mineralized sandstone 200 feet wide, 700 feet long, and up to 120 feet thick, were the result of the damming effect of thin gouge zones along the fracture surfaces according to Gould et al (1963, p. 66). This type of ore accumulation has been illustrated by Gould et al (1963, p. 68 and 70), Young and Delicate (1965, p. 12 and 31), and Roeber (1972, p. 16). Figure 8 is a composite drawing of this type of ore. The redistributed ore usually has a relatively sharp updip contact against thick oxidized sandstones, and it engulfs the primary ore blankets in the reduced ground by impregnating the sandstone above and below the primary blankets. Where several primary ore horizons existed, the redistributed ore can fill in the intervening barren ground and create thick sections of fairly continuous ore. Both the organics and the uranium are remobilized as the primary ore is destroyed. Uranium is reprecipitated, but available analyses suggest the redistributed ores are depleted in organic material. The ore is darker and richer close to the oxidation front, and it gradually fades out into the reduced ground across the fracture zone. Gould et al (1963, p. 71) found fracture-controlled ore 5 to 15 feet thick which averaged more than 1 percent U_3O_8 , and stack ore up to 110 feet thick averaged 0.20 percent to 0.30 percent U_3O_8 . Since this type of ore fades out into barren ground, the average grade mined is usually just above the cut-off grade of about 0.10 percent U_3O_8 , and therefore the grade of the stack ore that was mined averaged considerably less than the primary ores.

Perhaps the largest example of stack mineralization, whose location is controlled by a fracture zone, is in the Northeast Church Rock Mine near Gallup, New Mexico. Two very large mines are developed on the Pipeline fracture zone which strikes northeast. Oxidation has migrated downdip from the southeast in the Westwater Canyon sandstone which is hematitic along the southeast edge of the fracture zone. Apparently the multiplicity of fractures with off-sets of a few inches each, across a width of about a half mile, has

been sufficient to retard the movement of ground water through this zone. Stack ore occurs in every sandstone unit from the top to bottom of the Westwater Canyon Member as illustrated in Figure 10. The oxidation has moved farther to the northwest in the lower half of the member, and thus the oxidation front is in the shape of a giant "C", concave to the southeast. The individual oxidation fronts in the upper half of the Westwater Canyon are fairly regular in plan and are parallel to the strike of the fracture system. The oxidation fronts in the various sandstone units in the lower half of the Westwater Canyon have a general northeast trend, but each mineralized front is much more sinuous, and the fronts loop in and out in a NW-SE direction, as shown in Figure 11.

In both the Ambrosia Lake and Church Rock districts, the hematitic oxidation in the host rock is separated from the mineralized fronts, or redistributed ore, by a zone of limonitic rock. At Ambrosia Lake the limonite zone is only a few feet wide (Gould et al, 1963, p. 70), but in the Church Rock area the limonitic zone can be hundreds of feet wide. In the lower half of the member the limonitic zone is transitional in color toward the ore. It changes from a strong orange color to a yellowish-white or bleached zone containing scattered pyrite and clay chips with limonite rims. This bleached rock is believed to represent the most recent oxidation in which the organic matter and uranium have been removed, but the pyrite is only beginning to be oxidized. The pyrite is increasingly destroyed toward the limonitic zone. The limonitic zone eventually is transitional into red, hematitic sandstones which represent the oldest oxidized rocks (Saucier, 1980). This sequence of color changes is similar to that described by Adler (1970, p. 333) in some roll-type uranium deposits.

Disequilibrium studies made by company geologists across the oxidation fronts have confirmed the depletion in chemical uranium at the front, and its enrichment in the seepage zone on the reduced side of the stack ore. The remobilization of uranium appears to still be in progress in the Church Rock District, but has stopped, or is extremely slow, on the southwest side of the Ambrosia Lake District as indicated by the narrow width of the limonitic zone.

There is no well developed metal zoning pattern associated with the stack ores, except for selenium, which is usually more concentrated adjacent to oxidized sandstone. Much of the Se occurs as native selenium with lesser amounts present in the mineral ferroselite. Vanadium is present in the stack ore in the minerals montroseite and paramontroseite with the latter more abundant (Granger et al, 1961, p. 1199). Corbett noted a complete suite of oxidized vanadium minerals in the Section 22 Mine. The V:U ratio is higher in the redistributed ore, but the actual vanadium content is usually lower than in the primary ores (Young, 1960, p. 39; Hazlett and Kreek, 1963, p. 89). Both uranium and vanadium are lower in grade in redistributed ore than in the primary ore, but the uranium tends to be lost more easily than vanadium. In the 0.10 percent uranium range, the vanadium content is about equal to the uranium. Above 0.10 percent U_3O_8 , the vanadium content is generally less than uranium, and below 0.10 percent U_3O_8 the vanadium content tends to be higher, as shown in the table from Young (1960, p. 39) and others (see Table 3 below).

A V:U ratio of 1:1 is considered by Harmon and Taylor (1963, p. 106) to indicate redistributed ore. Molybdenum is absent in redistributed ores. Apparently the low Eh and pH required for the precipitation of jordisite was

Figure 10. Schematic map and cross sections of the oxidation front in the Westwater Canyon Member. Roll front uranium mineralization occurs in every sandstone interval from the top to bottom of the member. The line of section is shown in Figure 11.

Figure 11. Map of the sinuous roll fronts in one of the sandstone units of the lower Westwater Canyon Member in the northeast Church Rock area.

not developed in the redistributed ore zones (Lee, 1976, p. 76). Chlorite is found in redistributed mineralization, but its distribution is not as conspicuous as in the primary ores (Lee, 1976, p. 94).

Table 3. Corresponding vanadium values for a given uranium content.

<u>% U₃O₈</u>	<u>% V₂O₅</u>
3.00%	0.50%
1.50%	0.30%
0.25%	0.12%
0.10%	0.09%
0.01%	0.04%

Coffinite remains the principal uranium species that can be identified in the ore. Uraninite was discovered lining a fracture plane in stack ore in the Section 22 Mine (Granger, 1960, p. 54), and it appeared to have been derived from the destruction of coffinite. Granger et al (1961, p. 1198) have also identified uraninite from the Mesa Top and Poison Canyon Mines, and small amounts have been found in the Jackpile Mine and the Woodrow pipe (Nash, 1967, p. 187). As Granger (1960, p. 54) has pointed out, uraninite in the sandstone ores always occurs above the water table or near oxidized ores, and it appears to be a product of the more recent redistribution of uranium.

The age of the stack ores and the redistribution of uranium in general is tied to the age of the broad tongue of hematitic oxidation which migrated down the north flank of the Zuni Uplift. As discussed earlier, this oxidation is believed to be of Miocene age or younger. Indeed, various age dates on the redistributed ores in Ambrosia Lake give an age of around ten million years or less (Dooley et al, 1966, p. 1366; Brookins, 1980). Ore samples from the Northeast Church Rock Mine have recently been dated by the U.S. Geological Survey according to George Hazlett (personal communication). The oldest of six samples was one million years and the youngest ore was less than 500,000 years old.

No redistributed ore has been recognized in the Jackpile sandstone. Primary mineralization occurs close to the outcrop and at the southwest corner of the Jackpile deposit it extended to the outcrop. This unusual situation is due to the fact that, in spite of a northerly dip of the Morrison Formation, the Jackpile sandstone outcrop is a ground water discharge zone due to recharge from the high slope of Mt. Taylor to the northwest. Minor oxidation does occur within and around the orebodies up to several hundred feet back from outcrop and generally above the water table. This type of alteration probably produced some of the uranium-depleted margins of some ore lenses, and there is also evidence for radium migration out from certain ores. In the St. Anthony Mine, uranium has accumulated in fractured Dakota sandstone.

Pseudo-stack ore occurs in the form of multiple overlapping primary ore lenses which can attain thicknesses of 20 to 60 feet, or more, in fortuitous circumstances. Another type of false stack ore is when two or more trash accumulations overlap and create an anomalously thick ore section (Roeber, 1972, p. 5). These types of ore are often called stacks but are not the thick, fracture-controlled redistributed ore that is usually inferred by the term.

C-Roll Mineralization

Primary ore that is redistributed by oxidation, but does not accumulate against fractures will eventually form the C-roll geometry due to ground water drag along the upper and lower contacts of the sandstone unit. If one or both of the contacts are with mudstones, the clays will adsorb the mineralized organic material as the front passes through, and this will appear on gamma logs as the tails or limbs of the roll front. This classic roll-type mineralization is well developed in several areas in the Smith Lake and Crownpoint districts. The origin, mineralogy, and chemistry are the same as with the stack ore, except that the mineralization is stratigraphically rather than structurally controlled.

The C-roll redistribution is well exhibited in the Dalton Pass, Canyon, and Ruby Well orebodies. The Ruby Well orebody is instructive, for it consists in part of primary, trend-type ore, and in part of redistributed ore, and the transition from one to the other is well displayed. The host rocks are tongues of the upper Westwater Canyon Member which project to the east. The sandstone units lens out to the south more rapidly than the main body of the underlying Westwater Canyon, and thus oxidizing surface waters were unable to enter these lenses until erosion had progressed downdip enough to expose them. Oxidation appears to have migrated to the northeast from the Coolidge monocline. The earliest oxidation, which is now hematitic, redistributed some of the primary ore and developed C-rolls in Late Tertiary time. More recent migration of the oxidation front in the lower sandstone tongue has advanced past the earlier C-roll ore and is now up to 1,500 feet beyond the original oxidation front (Ristorcelli, 1980). This more recent oxidation is limonitic and is not always mineralized along its contact with reduced sandstone. The mineralization has mostly remained at the earlier hematite-limonite boundary updip in the west end of the trend, as shown in Figure 12. Farther east along this trend the hematitic oxidation is found beyond the primary ore zone, and it is also unmineralized. The ore has remained as remnants near its original primary trend position and is now totally surrounded by hematitic oxidation. It seems clear that the mineralization is only partly related to the oxidation. The primary ore can be shifted somewhat and modified by oxidation, but it resists any appreciable migration. The barren oxidation fronts which now exist downdip of the trend ore show that new mineralization is not accumulating at oxidation boundaries. This has been found to be true elsewhere in the region. Roll-type mineralization exists only where pre-existing primary ore is available for redistribution, and the redistribution is usually on the order of 1,000 feet or less, and probably no more than about 3,000 feet. If the oxidation persists long enough, the primary ore will be totally destroyed without any reaccumulation at some distant oxidation front. It appears very likely that ore trends once existed, south of Crownpoint between Church Rock and Ambrosia Lake, but have been destroyed by Late Cenozoic oxidation. In the Grants Uranium Region, the oxidation fronts appear to have been destructive, rather than constructive, as was the case in the Wyoming basins.

Figure 12. Schematic map and cross sections of the oxidation front and uranium mineralization in the lower sandstone of the Ruby Well ore trend located in Township 15 North and Range 13 West (modified from Ristorcelli, 1980).

Oxidized Uranium Deposits

Both primary and redistributed uranium deposits can be oxidized to form a third, but relatively minor, ore type in which uranium occurs in U^{6+} rather than in U^{4+} minerals. Oxidized uranium minerals have contributed very little to the total production from the region. Practically all of the ores mined appear to contain uranium in its reduced state, but some deposits at or above the water table are presently undergoing oxidation. A list of the oxidized uranium minerals which have been found in the southern San Juan Basin is given in Table 4. Oxidized minerals can be further divided into pre-mining and post-mining suites.

Oxidized Primary Ore

The primary ores are more resistant to oxidation than the redistributed ores. This is due to the high content of carbonaceous material and the reduced permeability of the ores. The carbonaceous material retards oxidation and the reduced permeability, due to matrix impregnations of carbonaceous material, ore-related silicate minerals, and calcite, restricts the movement of oxidizing ground waters. Primary ore layers that have been partially oxidized show a gradation in color from rich, black rock unaffected by oxidation, through gray, brown, reddish-brown to red oxidized sandstone. Whereas the primary ore layers generally have sharp boundaries between ore and barren rock, oxidized ore boundaries are transitional into barren rock. Oxidation destroys the thin blanket ore between the thicker ore pods and isolates them in oxidized sandstone. In Section 23, T 14 N, R 10 W, numerous black ore pods have been discovered in the south half of the section completely surrounded by hematitic sandstone (Fig. 8). These remnant ore pods, although much reduced in size by the oxidation, maintain the regular spacing of the S-rolls found in the blanket ore in reduced ground (Roeber, 1972, p. 16). Similar remnant primary ore completely surrounded by hematitic sandstones have been found in a number of places. Some ore is occasionally found which is itself red, and contains practically no organic material (Rapaport, 1963, p. 133). Ore pods in less oxidized limonitic or weakly oxidized sandstones are depleted in organic matter and often have gradational boundaries with barren sandstone. The scattered ore pods found in Section 20 in the Poison Canyon trend are believed to represent this stage of oxidation. Ore pods in the very early stages of oxidation may be surrounded by a hematite halo, although the host rock itself still appears a yellowish-gray color (Kendall, 1971, p. 44; Falkowski, 1980).

The Black Jack No. 1 Mine is probably the best known example of remnant primary ore completely surrounded by hematitic host rock. Remnant primary ore is believed to exist in portions of the Northeast Church Rock trend, but it is so engulfed by redistributed ore that it is difficult to identify. There is a gradation from primary ore to barren sandstone where oxidation occurs in the J. J. No. 1 Mine and the southern extension of the Paguate deposit. These mines are located on the two ends of the Jackpile sandstone ore trend, which was apparently destroyed by pre-Dakota oxidation except where preserved in the lowest structural locations in the Laguna syncline.

Oxidized Redistributed Ore

Redistributed ore south of Ambrosia Dome is generally a brownish color and the organic content is very low (Granger et al, 1961, p. 1189). Experiments by

Table 4. Uranium minerals identified in the Grants Uranium Region¹

UNOXIDIZED

<u>Primary</u>	<u>Redistributed</u>
Urano-organic Complexes	Coffinite, $U(SiO_4)_{1-x}(OH)_{4x}$
Coffinite, $U(SiO_4)_{1-x}(OH)_{4x}$	Urano-organic Complexes (?)
	Uraninite, UO_2

OXIDIZED

Pre-Mining

Tyuyamunite, $Ca(UO_2)_2(VO_4)_2 \cdot 5-8H_2O$
 Metatyuyamunite, $Ca(UO_2)_2(VO_4)_2 \cdot 3-5H_2O$
 Carnotite, $K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$
 Autunite, $Ca(UO_2)_2(PO_4)_2 \cdot 10-12H_2O$
 Meta-autunite, $Ca(UO_2)_2(PO_4)_2 \cdot 0-6H_2O$
 Torbernite, $Cu(UO_2)_2(PO_4)_2 \cdot 12H_2O$
 Metatorbernite, $Cu(UO_2)_2(PO_4)_2 \cdot 4-8H_2O$
 Phosphuranylite, $Ca(UO_2)_4(PO_4)_2(OH)_4 \cdot 7H_2O$
 Sabugalite, $HAL(UO_2)_4(PO_4)_4 \cdot 16H_2O$
 Uranophane, $Ca(UO_2)_2(SiO_3)_2(OH)_2 \cdot 5H_2O$
 Beta-uranophane, $Ca(UO_2)_2(SiO_3)_2(OH)_2 \cdot 5H_2O$
 Soddyite, $(UO_2)_5(SiO_4)_2(OH)_2 \cdot 5H_2O$
 Sklodowskite, $Mg(UO_2)_2(SiO_3)_2(OH)_2 \cdot 5H_2O$
 Cuprosklodowskite, $Cu(UO_2)_2(SiO_3)_2(OH)_2 \cdot 5H_2O$
 Schoepite, $UO_3 \cdot 2H_2O$
 Becquerelite, $7UO_3 \cdot 11H_2O$
 Zellerite, $Ca(UO_2)(CO_3)_2 \cdot 5H_2O$

Post-Mining

Andersonite, $Na_2Ca(UO_2)(CO_3)_3 \cdot 6H_2O$
 Liebigite, $Ca_2(UO_2)(CO_3)_3 \cdot 10H_2O$
 Bayleyite, $Mg_2(UO_2)(CO_3)_3 \cdot 18H_2O$
 Zippeite, $K_4(UO_2)_6(SO_4)_3(OH)_{10} \cdot H_2O$
 Uranopilite, $(UO_2)_6(SO_4)(OH)_{10} \cdot 12H_2O$
 Johannite, $Cu(UO_2)_2(SO_4)_2(OH)_2 \cdot 6H_2O$
 Schroeckingerite, $NaCa_3(UO_2)(CO_3)_3(SO_4)F \cdot 10H_2O$

¹From Granger (1963), Kittel et al (1967), and Hounsflow (1976).

Corbett (1964, p. 68) showed that the brown carbonaceous material is more soluble in alkaline solutions. He considered the brown material to be regenerated humic acids which were derived from the primary ore. When these stack ores are subjected to more oxidation, the regenerated humic material is easily destroyed. In such ores, low in organic material, the coffinite can be optically resolved, and Granger (1963, p. 22) was able to concentrate the coffinite sufficiently to obtain strong X-ray diffraction patterns. In one of the separates from the Section 15 Mine, the original ore sample contained 1.03 percent uranium but no detectable organic carbon. A concentrate of brownish-gray coffinite was obtained from this sample and was found to contain 0.4 percent organic carbon in the coffinite. This indicates that organic material is present in the stack ore, and was possibly redistributed from the primary ore but with a uranium/carbon ratio increase from approximately 1 to 2.6. In this part of Ambrosia Lake, the stack ores may have been oxidized sufficiently to remove most or all of the organic material that was probably originally present in these ores.

The Poison Canyon Mine is above the water table and the redistributed ore is being oxidized and re-mobilized once again (Tessendorf, 1980). The oxidized redistributed mineralization has no visible carbonaceous matter except for some humic coatings along fractures. The coffinite grain coatings are partially oxidized to tyuyamunite and metatyuyamunite which forms in the presence of vanadium in an environment high in calcium (Weeks and Thompson, 1954, p. 38). The second generation redistributed ore is a light yellow to medium gray in color and has a positive chemical disequilibrium. A similar occurrence has been described in the Sandstone Mine by Foster and Quintanar (1980). The A-10 orebody in this mine is a light gray ore with a positive disequilibrium. Uranophane obtained in the limonitic zone associated with this mineralization was dated 9 to 10 m.y. The redistribution is undoubtedly still in progress today. According to Granger et al (1961, p. 1,179), oxidation has probably affected every orebody in the region to some extent.

Minor Uranium Occurrences

Uranium occurs in other formations within the Grants Uranium Region, most notably in the Todilto Limestone of Jurassic age, which is stratigraphically below the Morrison Formation, and in the Dakota Sandstone, of Late Cretaceous age, which directly overlies the Morrison Formation. In both formations, the mineralization is associated with deformed areas and the uranium has probably been derived from the Morrison Formation (Gruner, 1958, p. 5; Jobin, 1962, p. 100; Kittel et al, 1966, p. 1). This hypothesis is readily accepted for the Dakota Sandstone but is not so obvious an explanation for the Todilto Limestone. Uraninites from the Todilto have given U-Pb dates ranging from 150 to 175 m.y. (Berglof, 1969, p. 1; Miller and Kulp, 1963, p. 618). The age span 150-175 m.y. is approximately the age of sedimentation which is accepted as Late Jurassic. However, evidence against syngenetic mineralization includes cross cutting relationships, occasional fracture control of ore, and localization of orebodies in intraformational folds which are pre-lithification. The small orebodies in the Dakota Sandstone are more obviously related to fault and fracture systems (Mirsky, 1953, p. 4), but the uranium is specifically localized by carbonaceous material in channel sandstones and by organic-rich, black shales (Gabelman, 1956, p. 306; Pierson and Green, 1980, p. 22). In some Dakota deposits, the uranium has been redistributed as C-rolls adjacent

to faults which served as passageways for uraniferous solutions from the Westwater Canyon sandstone. The Dakota mineralization north of the old Church Rock Mine is the best example of this (Hazlett, 1979, personal communication) and the Diamond No. 2 Mine on the Nutria monocline southeast of Gallup may be another example. A rich uraninite sample from the Hogback No. 4 Mine near Gallup was dated Late Pleistocene by the U-Pb isotope and U-series methods (Ludwig et al, 1977, p. 669), which is in agreement with geologic observations. It should be noted that the Todilto Limestone and Dakota Sandstone formations are the two most organic-rich units in stratigraphic proximity to the Morrison Formation.

Small uranium occurrences have been found on the east side of the San Juan Basin in the Morrison Formation, the Dakota Sandstone, the Upper Cretaceous Mesaverde Group, and the Ojo Alamo and San Jose Formations of Early Tertiary age. Kittleman and Chenoweth (1957) described a number of prospects in the Brushy Basin and Westwater Canyon Members of the Morrison Formation in Sections 11, 24, 25 and 31, T 17 N, R 1 W in Sandoval County. This area is called the Goodner Lease and the uranium occurs in small C-rolls associated with hematitic sandstones. A total of 395 tons of ore averaging 0.13 percent U_3O_8 was produced from two small pits in Sections 23 and 25 (Chenoweth, 1974, p. 311). Farther north in Section 11, T 19 N, R 1 W, uranium is found associated with a tongue of oxidation in the Westwater Canyon sandstone on the Dennison-Bunn claims (Ridgley, 1980). The zone of mineralization is less than 3 feet wide on the outcrop, and the uranium content is less than 0.07 percent. Organic carbon in the rolls ranges from 0.07 to 0.12 percent.

Uranium is found in the Dakota Sandstone in several locations along the hogback in this same area. The Butler deposit 6 miles northeast of La Ventana has mineralization which terminates downdip against a diagonal fault which suggested to Gabelman (1956, p. 312) that the fault acted as a dam to ground water. At La Ventana mesa a thin bituminous coal bed in the Menefee Formation below the sandstone cap rock is mineralized with uranium. Cannon and Starrett (1956, p. 391) believed that the uranium was derived from the Pleistocene Bandelier Tuff which once overlay this area. Chenoweth (1974, p. 313), in reviewing all these small uranium occurrences in rock ranging in age from Jurassic to Early Tertiary in the Cuba and Gallina, New Mexico areas, also concluded that the Bandelier Tuff was the source of the uranium. Grab samples of the tuff have been found which carry up to 30 ppm uranium, and this tuff probably covered this whole area at one time.

In the Spring of 1955, 74 tons of ore that averaged 0.05 percent U_3O_8 were shipped from a prospect, called the Boyd claims (Chenowith, 1958, p. 4) in Fruitland Formation northwest of Farmington in the San Juan Basin. This uranium is believed to have been leached from some other unit and concentrated in the base of this fluvial sandstone.

On the west side of the basin production has come from the Salt Wash and Recapture Members of the Morrison Formation in the Shiprock and Sanostee areas. Minor uranium occurrences were found in the Todilto Limestone in Sanostee Wash, but none of it was ore grade (Blagbrough et al, 1959, p. 16).

In summary, uranium occurrences in units other than the upper Morrison Formation in the southern San Juan Basin have been small and have contributed

very little to the total production of the area. This is expected to remain true in the future. Anomalous uranium occurrences on the east side of the basin are scattered through a broad stratigraphic range and were probably derived from the Bandelier Tuff of Pleistocene age. These deposits are small, surficial, and low grade, and there appears to be little prospect for the discovery of anything larger in the future. Small deposits of Morrison age exist on the Navajo Reservation in the northwest corner of the basin, but they are presently uneconomic, even where found on the outcrop. Future discoveries of significance are expected to be limited to the Grants Uranium Region, as in the past.

ORGANIC MATTER

The association of anomalously high uranium values with organic carbon compounds in sedimentary rocks has long been recognized (Coffin, 1921, p. 183). This organic matter has been called by a variety of names such as thucolite, asphaltite, pyrobitumen, dead oil, carbonaceous matter, kerogen, and humate. The diversity of names in the literature for various forms of mineralized organic material is an indication of the lack of understanding that has existed about these substances. The chemistry of metal-organic compound is fairly well known, but much of this literature is not generally seen by geologists because it has been published in geochemical, organic chemistry, soil science, and biochemical journals. Although much remains to be learned about metal-organic relations, enough is known to outline the general relations which are included here because of the importance of organic material in the Grants deposits.

Types of Organic Matter

There are basically two types of indigenous carbonaceous matter in sediments (Vine et al, 1958, p. 187). One type is derived predominantly from vascular (woody) oxygen-rich plant tissues and is called humic. The other is derived from hydrogen-rich material such as spores, pollen, proteins, and lipids, and is called sapropelic. Sapropel is rich in bituminous materials and yields petroleum, whereas the humic material will yield water-soluble (colloidal sols) humic and fulvic acids. Naturally occurring organic matter is frequently a mixture of these two types. When the fossil organic material is structured, it can be identified as wood, leaves, or algae, and there is little problem distinguishing the two types. The problem arises when the preserved organic material is a black, amorphous substance which stains the sand grains or fills the pore spaces. Visual examination cannot distinguish the redeposited humic extracts from sapropelic bitumens. Although similar in appearance, they differ greatly in chemical structure and composition. The sapropelic carbon compounds generally have an aliphatic, or chain, molecular structure, whereas the humic compounds are more aromatic, or ring structured. In respect to uranium, the most important chemical difference is in the hydrogen and oxygen contents as shown in Table 5 below.

Petroleum initially may contain no oxygen, whereas asphalt contains some oxygen which is probably derived in part from the oxidation of the petroleum residue. If the humic substance is not too coalified, it may be distinguished from the bitumens by two simple tests. First, the humic compounds are insoluble in common organic solvents. The second test is simply to heat the sample. Dead oil and asphalts will usually soften and melt, but humic derivatives are infusible like coal. If the above tests fail, then more sophisticated laboratory tests will be required, and in some cases, such as with the organic material in the Morrison uranium ores, even these tests fail to give unequivocal results. This difficulty in identifying some unstructured organic matter in sediments has been the root of serious misunderstandings concerning the origin of the associated mineralization. This has been unfortunate because the two types of carbonaceous material differ tremendously

in their respective abilities to concentrate metals. For the most part, the pure hydrocarbons do not collect significant amounts of metals, except in instances where there is a significant aromatic component (Erickson et al, 1954, p. 2200; Breger, 1955, p. 15; Leventhal, 1980).

Table 5. Comparison of the average compositions of humic substances and hydrocarbons.

A. HUMATE¹

	C	H	N	O
Fulvic Acid	44-48	4.0-5.5	1.5-2.5	44-48%
Humic Acid	52-62	3.0-4.5	3.5-4.5	32-39%
Humin	55-56	5.5-6.0	4.6-5.1	32-34%

B. HYDROCARBONS²

Crude Oil	82-87	11-15	0.1-1.5%	---
Asphalt	80-85	8.5-11	0-2	0.1-4.5%

¹Manskaya and Drosdova, 1968

²Levorsen, 1954

Metal-Organic Compounds

The aromatic or ring structured molecule is the more important type when considering metal concentrations. Aromatic or humic substances usually have various oxygen and nitrogen-bearing functional groups substituting for hydrogen atoms. Such functional groups as -NH₂, -OH, -COOH, -CO, and -OCH₃, contribute to the building of a great variety of large molecules. These complex molecules have the ability to accumulate and incorporate metal ions by the following methods, as outlined by Mortensen (1963):

1. Adsorption
2. Ion-exchange
3. Chemical reduction
4. Peptization
5. Complexing
6. Chelation

Kochenov et al (1965, p. 68) explain that in a weakly acid medium the role of uranium carbonate complexes decreases sharply and the positively charged ions UO₂(OH)⁺ and UO₂²⁺ become predominant. These positive ions are easily adsorbed by the negative organic colloids. According to Lisitsin et al (1967,

p. 361), the uranyl carbonate complexes decompose at a pH of approximately six. Kochenov et al (1977, p. 86) believe that the mechanism of near-surface concentration of uranium is a combination of sorption and reduction on organic matter. Andreyev and Chumachenko (1964, p. 3) have investigated the oxidation reduction process on solid insoluble organic phases. They found that reduction of U^{+6} to U^{+4} occurs at the surface of the solid organic material, and not in the solution. The reduction takes place within the uranium-organic complexes with the participation of alcohol carbonyl and carboxyl groups. The efficiency of reduction increases with increases in molecular weight of the organic substance. As the uranium is reduced, the organic substance is oxidized and may disappear completely leaving only pitchblende pseudomorphs. The degree of extraction of uranium from solution by solid peat was 98 percent, wood 95 percent, and for kerogen, 100 percent.

In earlier experiments, Szalay and Szilagyi (1968, p. 570) had also found that lignite powder and peat samples sorbed uranium. The process was so rapid, even from very dilute aqueous solutions, that the uranium ions virtually disappeared from the water within one minute. They concluded that the process was a pure cation exchange phenomenon. More importantly, Szalay (1958, p. 183) found that the peat could fix uranium to such an extent that one gram of peat will contain 10,000 times more uranium than the water in which it is in equilibrium. He called this the geochemical enrichment factor or GEF. Kochenov et al (1965) have found uranium being concentrated in peat bogs from groundwaters little more concentration in uranium than background. The effective enrichment factor for the peat-water adsorptive exchange may be as high as 2×10^6 . This has been confirmed by Jennings and Leventhal (Leventhal, 1980), who found uranium concentration factors as high as 10^7 for fulvic acids.

The active ingredient in the peats, lignites, and coals appears to be the fulvic and humic acids. When these substances are removed, the remaining carbon-rich material will still extract some uranium from solution, but the uranium is easily removed by leaching the carbon with distilled water. This indicates that the metal is held by physical rather than by chemical adsorption (Vine, 1962, p. 155). This may explain some of the barren carbonized wood and trash that is frequently found in the Westwater Canyon sandstones. The inert structured carbon itself is not an effective accumulator of uranium. Moench and Schlee (1967, p. 92) found non-uraniferous coaly material in a collapse pipe in the Jackpile open-pit. An unsuccessful attempt was made to extract humic acid from this low-rank coal by using a 5 percent alkali at 100°C . Apparently the soluble humic compound had been pre-extracted from these samples by natural processes (Moench and Schlee, 1967, p. 80).

Schmidt-Collerus (1979, p. 5) has outlined the relation between uranium and the organic matter in considerable detail. His working theory is as follows. Almost immediately after vegetal material is buried, microbiological and chemical activities degrade the lignin-type material to produce soluble fulvic and humic acids. Fulvic acid is probably the earliest soluble fraction to form, and it converts to humic acid by condensation of the molecular structure. The fulvic acids are larger, more oxygen-rich molecules, and they have more complexing sites for metals. A metal-organic complex is a molecule in which the metal is held by simple ionic or covalent bonding. The fulvic acid can pick up metals during migration in the ground water and can carry these

metals over large distances without precipitation. Bacterial degradation slowly changes the fulvic acid to humic acids which retain most of the uranium and any other metals that were collected. The humic acid is precipitated in an acid environment, and a change to only weakly acid conditions is sufficient to precipitate it when uranyl complexes are present. Experiments show that the threshold of precipitation is displaced to pH 6.5 or more, and weak precipitation may even occur at a pH of 8. As anaerobic bacteria continue to feed upon the humic acids, the less stable complexing sites such as the carboxyl and hydroxyl groups are lost, and the uranium is released to convert to uraninite or coffinite. Hydrogen sulfide gas generated by the bacteria may also assist in the reduction and precipitation of additional uranium. The H_2S and CO_2 generated in the humate lowers the pH, causing more humic acids to flocculate, and breaks down the uranyl-carbonate complexes in the ground water. Some of the uranium forms stable chelates with the nitrogen-rich chemical groups and remains dispersed and firmly bound in the organic material. The chelates are chemical compounds or units in which a central metal atom is joined to other atoms in the molecule by both ionic and covalent bonds. Such linkages usually result in the formation of one or more heterocyclic rings in which the metal atom is part of the ring. This type of compound is very stable, and often the metals are not even detectable by ordinary qualitative tests. As the humic material matures, the uranium is present both as a very dispersed mineral phase, and as a urano-organic compound. Thus, Schmidt-Collerus (1969, p. 123) believes that complexing and chelation are the two major chemical processes responsible for the initial accumulation and preservation of uranium in ore deposits.

The Coffinite Problem

Very little is actually known about the mineral coffinite, which is believed to be the primary uranium mineral species in the Grants Uranium Region. Coffinite was first identified in August, 1951, by Stern and Stieff (1954) in high-grade ore from the Arrowhead Mine in Colorado. The X-ray powder diffraction studies indicate that coffinite is tetragonal and isostructural with zircon. The cell dimensions of the Arrowhead material are $a_0 = 6.94$ Å, $c_0 = 6.31$ Å, and $a:c_0$ equals 1:0.909. Chemical analysis on impure coffinite indicated 46.4 percent to 68 percent UO_2 and from 5.2 percent to 8.5 percent silica. Theoretical coffinite has 81.8 percent UO_2 and 18.2 percent SiO_2 , according to Fuchs and Hoekstra (1959, p. 1060). The low silica content was interpreted as evidence that coffinite did not have the simple formula $USiO_4$, but instead had substitution of $(OH)_4^{-4}$ for $(SiO_4)^{-4}$. They therefore proposed the formula for coffinite as $U(SiO_4)_{1-x}(OH)_{4x}$ (Stieff et al, 1955, p. 5). The presence of bonded hydroxyl groups in the structure of coffinite could not be established by chemical analyses of the natural material, for the individual crystallites are approximately 10^{-5} to 10^{-6} cm in diameter.

Gruner and Smith (1955, p. 19) found just the opposite in coffinite from the Jackpile Mine. The Jackpile sample contained 75 percent more silica than required for stoichiometric coffinite. Cell dimensions for this sample were $a_0 = 6.92$, $c_0 = 6.22$, and $a:c_0$ of 1:0.899. Heating experiments showed that the Jackpile coffinite had a higher stability than would be expected if (OH) ions were present in any great quantity in the crystal structure. Gruner and Smith (1955, p. 21) concluded that the composition of the coffinite cannot

deviate appreciably from the formula USiO_4 . This conclusion was supported by Abdel-Gawad and Kerr (1961, p. 415), who observed that coffinite free of organic matter showed no thermal reactions up to 1000°C in vacuum, which indicates the absence of the (OH) group from the mineral lattice. They too proposed that the natural coffinite was similar in composition to synthetic coffinite which is USiO_4 . The reason for the higher UO_2 content of the sample investigated by Stieff et al (1955) was possibly the presence of uncrystallized uranium oxide in the sample.

To date, coffinite has only been synthesized at temperatures above 200°C (Fuchs and Hoekstra, 1959, p. 1058). Both synthetic and natural coffinite decompose in air in the temperature range of 500 to 600°C . All natural coffinite probably contains admixed organic material which burns off between 480°C and 500°C , with the evolution of CO_2 and H_2O (Abdel-Gawad and Kerr, 1961, p. 412; Granger, 1963, p. 22). This is accompanied by color changes in the crystalline material and a sharp drop in weight, which can be as much as 33.3 percent less than the sample weight at 110°C . The organics undoubtedly have something to do with the formation of low-temperature coffinite, but so far the process has not been duplicated in the laboratory. The coffinite forms in preference to uraninite when there is excess silica available (Hostetler and Garrels, 1962, p. 158; Nash, 1968, p. 746; Brookins, 1975, p. 905). Kendall (1971, p. 69) found evidence of apparent colloform texture in coffinite from the Section 27 Mine, and botryoidal coatings on grains found by Nash (1968, p. 746), also suggests slow, low temperature crystallization and possibly nucleation from a colloidal precursor.

Coarser-grained coffinite from partially oxidized redistributed ores in Ambrosia Lake was optically separated and concentrated (Granger, 1963, p. 22). The only coffinite sample discovered so far that was coarse enough to determine its optical properties was a well-crystallized botryoidal specimen found in a vug in the Woodrow Mine. There is much uncertainty about this important ore mineral of the Grants deposits. In fact, it is so poorly described and its formation and paragenesis so obscure that apart from reflecting formation in a uraniferous, silicious reduced environment, it thus far tells us nothing about the precipitation of uranium.

Summary on Organic Material

It appears well established that fulvic and humic acids can efficiently concentrate uranium in a variety of ways, but it has never been clearly established that the organic material in the uranium deposits in the Grants Uranium Region is indeed humic matter. The humic origin of this material has been generally accepted by workers in the area since about 1956. Only recently has this assumption been called into question (Leventhal, 1979; 1980). The following investigations have attempted to establish its identity.

Knox and Gruner (1957, p. 15) believed the organic material was a hydrocarbon residue, but they found that it was insoluble in an organic solvent consisting of 70 percent benzene, 15 percent methanol, and 15 percent acetone.

Granger et al (1961, p. 1196) stated that infrared absorption spectrographs of the ore-bearing carbonaceous matter more nearly resembled low-rank coals than

aliphatic materials. The C, H, N, and O contents were also similar to low-rank coals.

Corbett (1964, p. 68 and 71) found that the brown carbonaceous material in redistributed ores was soluble in alkaline solutions. Infrared absorption spectrograms of organic matter from Ambrosia Lake showed curves similar to those of coalified wood and both these curves matched the curves for uraniferous lignites from South Dakota.

Schmidt-Collerus (1969, p. 112) claimed that the key pyrolysis fragments identified in the Grants uranium ores essentially eliminated the possibility that the organic material was a hydrocarbon.

Jacobs et al (1970, p. 184) tested the organic material and found it to be virtually insoluble in 15 diverse solvents. Up to 30 percent of the carbonaceous material from Ambrosia Lake was extracted by dimethyl sulfoxide. Infrared absorption spectra on the extracted material indicated that it contained carboxyl functional groups. Data obtained from chemical studies and from the mass spectrometer, in addition to the infrared spectra indicated that the extract contained an aromatic component. The extracted organic material had the following composition: 55.3% C, 3.3% H, 28.5% O, 0.01% N, 10.3% S.

Haji-Vassiliou and Kerr (1973, p. 1291) studied the organic material from several major uranium deposits including samples from Ambrosia Lake. Data from infrared spectroscopy and organic elemental analysis were compared with similar data on reference samples of coal and petroleum derivatives. The comparative analysis indicated that decayed vegetation is the main source of the organic matter in all the major uranium deposits sampled.

Adams et al (1974, p. 243) have published the following two analyses of carbonaceous material from the Jackpile Mine:

	C	H	O	N	S
(1)	81.68	4.59	13.46	0.27%	
(2)	72.2	4.7	16.7	0.25	1.4%

The high oxygen and low hydrogen content more closely resembles humic substances than hydrocarbon.

Squyres (1980) was able to dissolve some of the organic matter in Ambrosia Lake ore by using sodium hydroxide with a little hydrogen peroxide added. Such regenerated humic acids can be produced from the oxidation of coals and carbonaceous shales (Granger et al, 1961, p. 1196; Vine, 1962, p. 155; Leventhal, 1980).

Even Leventhal (1980) states that chemically the organic material associated with the ore is most like a high-rank coal, and physically it is most like an amorphous humic or asphaltic resin. Although the foregoing references prove little, we feel the balance of evidence is in favor of a humic affinity for the organic material.

Geologic criteria also indicate a humic origin for this material. It appears to have collected beneath the water table in contrast to hydrophobic petroleum which float and seek out the highest structural locations. Hydrocarbons are not known to corrode quartz or alter clays or even to collect uranium as does the humic material. Convincing evidence is that in many mines some of the organic material can be traced back to the fossil vegetal material from which it was derived. Although it would be more satisfying to have conclusive analytical or structural proof of the humic origin of this material, but it appears to be a prudent assumption.

The importance of recognizing the humic origin of these uraniferous organic substances cannot be overemphasized. As pointed out by Schmidt-Collerus (1967, p. 76) and Kochenov et al (1977, p. 82), there is no convincing data that uranium can be precipitated from weakly concentrated solutions, such as natural waters, by purely inorganic chemical processes. Some type of sorbent or collector is necessary to concentrate the uranium from the weak solution. No more effective natural concentrator of uranium, especially from extremely dilute concentration is known than the humic materials. Recognition of the importance of this material, and the essential role it plays in most uranium deposits in sediments, permits the development of relatively simple models for both primary and redistributed mineralization.

ORE-RELATED ALTERATION

Uraniferous organic lenses are spatially related to zones within the sandstones in which certain detrital minerals have been altered or destroyed and other zones in which certain authigenic minerals have formed within the matrix of the sandstones. These zones, herein referred to as alteration zones, have different distributions but most seem spatially related to the primary ore. Several authors have described aspects of the sandstone mineralogy and alterations (Granger, 1961, 1962, 1963; Keller, 1962; Austin, 1963, 1980; Moench and Schlee, 1967; Nash, 1968; Squyres, 1970; Kendall, 1971; Adams et al, 1974, 1978; Flesch and Wilson, 1974; Hafen et al, 1976; Lee, 1976; Brookins, 1976, 1978, 1979). Some have discussed the geometric relations between the alteration minerals and the uraniferous carbonaceous material suggesting that they formed prior to, subsequent to, or intermittently with ore. It appears that the processes which formed these alteration zones commenced soon after the deposition of the sediments and continued as an evolving diagenetic process of which the formation of the uraniferous organic lenses was only one, albeit important, part. It is our concept of ore-related alteration, therefore, that it is a customary effect of diagenesis, not separated in any way from the normal diagenetic processes but very much a part of them. The alterations and their patterns, described in the following paragraphs, are emphasized because of their spatial relations to the uraniferous organic lenses and their contributions to understanding the origin and controls of the deposits and evaluating unexplored areas for new deposits.

Ilmenite-Magnetite Alteration and Destruction

During this study thin sections from widely-spaced core holes located within and marginal to the Grants Uranium Region were studied. The cores were provided by the Department of Energy and through the kindness of several mining companies. Although samples were commonly not available for the entire thickness of the Westwater Canyon sandstone, a sufficient number of samples from strategically located holes has permitted the identification of alteration patterns for ilmenite and magnetite, as well as for feldspar and authigenic clays. These patterns place strong constraints on the distribution of areas favorable for ore deposits and on the ore-forming processes which produced them. The distribution of ilmenite and magnetite, the most easily detected and the most diagnostic of these patterns, is described in this section. As mineral identifications were not made routinely on the detrital phases, they are referred to collectively as ilmenite-magnetite. Descriptions of the related feldspar alteration patterns and the more complex authigenic clay zones are presented in subsequent sections.

Ilmenite and titaniferous magnetite alteration and destruction are easily recognized in thin sections of the Morrison sands. Adams et al (1974) have described the progressive stages of this alteration with accompanying photographs demonstrating the ease with which stages of alteration may be observed in oblique reflected light using the petrographic microscope. The ilmenite-magnetite alteration associated with the uranium deposits of the Grants Uranium Region is one of iron dissolution and removal rather than the simple

oxidative alteration common in so many red beds. As will be discussed subsequently, evidence suggests that this iron-leaching alteration was effected under reducing conditions which permit the solubilization and removal of iron while leaving behind essentially all the titanium that was present in the iron oxide phases. The remaining titanium is present as very fine-grained white leucoxene and coarser anatase.

Unaltered ilmenite and magnetite within the Morrison sands are characteristically lustrous black color and may be surrounded by an irregular coating of hematite which developed during transport and early post-deposition oxidation. Incipient leaching of these grains under reducing conditions produces an irregular pitted grain surface, the original boundary of which is indicated by residual white TiO_2 . The abundance of the titanium oxide depends on the amount of titanium oxide in the original phase. Continued alteration progressively diminishes the size of the unaltered grain while increasing the size of the titanium oxide border until the entire ilmenite-magnetite grain has been destroyed. It is within sandstones from which all ilmenite and magnetite have been altered that ore deposits occur.

It has been found that the alteration of ilmenite and magnetite is strongly dependent upon the hydrologic continuity and transmissivity of the sandstones. Ilmenite and magnetite have been quantitatively destroyed, for example, within hydrologically continuous sands of the Jackpile sandstone, indicating a pervasive and strong period of alteration throughout that sandstone unit. Isolated sands within shales of the Jackpile sandstone or within the adjacent Brushy Basin sandstone, however, contain essentially unaltered ilmenite and magnetite, attesting to the importance of ground water flow in affecting the alteration of these minerals. Within the Westwater Canyon sandstone, by contrast, it now appears that ilmenite and magnetite have been destroyed in proximity to all primary uranium deposits, but there are broad areas of the sandstone which contain unaltered or only partly altered ilmenite-magnetite. Furthermore, the distribution and intensity of ilmenite-magnetite alteration have been found to display a particular and persistent geometry.

Simplified alteration logs for the drill holes used in this alteration study are given in Appendix 1. For each log the top and bottom (where known) of the Westwater Canyon sandstone is indicated together with the position of samples collected for thin sections, the observed alterations and their intensities. The drill hole locations and an isopach map of the ilmenite-magnetite alterations are shown in Plate 8.

The reader will note in Appendix 1 that ilmenite-magnetite alteration, where present, is at the top of the Westwater Canyon sandstone and extends variable distances down into the sandstone with the intensity of alteration decreasing downward in many holes. In proximity to known uranium deposits, the alteration extends to greater depths, commonly reaching the base of the sandstone. In all cases, ilmenite and magnetite have been completely destroyed in sandstones containing primary mineralization. In large areas of the basin (see Plate 8) the zone of ilmenite-magnetite destruction is thin to nonexistent, and thus far exploration in these areas has been unsuccessful. A characteristic of the known ore districts and a potential guide to new ones, therefore, is the thickness of the ilmenite-magnetite alteration zone.

The typical alteration pattern for ilmenite-magnetite is shown in Figure 13 (Hafen et al, 1976). The mineralized intervals which occur within the zone of ilmenite-magnetite destruction are in this case redistributed uranium related to roll fronts. The destruction of ilmenite and magnetite appears to be complete from the top of the sandstone down to, and some distance beyond, the positions of mineralization below which the magnetite susceptibility log shows a series of spikes reflecting magnetite-bearing heavy mineral horizons. In the major ore districts, complete destruction of ilmenite and magnetite extends to the base of the Westwater Canyon sandstone, but where the ore lenses are high in the sandstone oxidized ilmenite-magnetite may be found in the basal sands. Where alteration has been incomplete, the intensity of ilmenite and magnetite destruction decreases downward within the Westwater Canyon Member, such that partly altered grains may be observed at some distance below the base of the Brushy Basin Member with unaltered grains encountered at greater depths.

In the Jackpile sandstone, ilmenite and magnetite have been quantitatively destroyed from all sands which are not hydrologically isolated. In contrast to the Westwater Canyon, therefore, there is no indication of zoning in the alteration pattern suggesting that the intensity of alteration was high throughout the sandstone. It is a characteristic of the Grants Uranium Region, therefore, that uraniferous organic lenses occur within alteration zones of ilmenite and magnetite destruction.

Studies of mineral paragenesis indicate that ilmenite and magnetite destruction occurred early in the development of alteration assemblages, probably soon after the commencement of alteration of the volcaniclasts (see, Fig. 14). In the Jackpile sandstone, residual TiO_2 from ilmenite and titaniferous magnetite is occasionally found as grain coatings under clay rims and quartz overgrowths but rarely, if ever, occurs within hollow feldspars. These observations suggest it formed early in the sequence of alteration assemblages. Of historic note, Granger (1961, p. 1201) observed that anatase occurs as octohedrons on sand grains near ore in the Bucky No. 1 Mine and was recognized in many drill cores from parts of the district during early exploration leading P. F. Kerr to suggest it might serve as an ore guide. Evidence for a later alteration of ilmenite-magnetite was found by Flesch and Wilson (1974, p. 207) who noted that anatase often is found within partially dissolved feldspars. This paragenetic sequence is presented in Figure 15. Kendall (1971, p. 94), also noted anatase within etched sanidine clasts. Whereas ilmenite-magnetite alteration appears to have preceded feldspar alteration in the Jackpile sandstone, in the Westwater Canyon sandstone feldspar and ilmenite-magnetite alteration may have proceeded simultaneously as indicated by the distribution of their alteration products and patterns.

Feldspar Alteration

Alteration of feldspars by dissolution, replacement and overgrowths has been noted at numerous locations in the sandstones of the Morrison Formation by several authors. Our studies and reviews of other studies suggest that minor amounts of plagioclase and potash feldspar overgrowths are widespread but unrelated to the distribution of uranium deposits. There is some indication they are more abundant in the Westwater Canyon than in the Jackpile sandstone,

Figure 13. Logs for a core hole through the Westwater Canyon Member, Church Rock District, New Mexico. Ilmenite-magnetite distribution indicated by spikes on magnetic susceptibility log and visual estimates from thin sections (modified from Hafen et al, 1967).

Figure 14. Paragenetic relations for the detrital and authigenic minerals of the Jackpile sandstone. Shading represents the clastic deposition or authigenic formation of minerals, dashed lines indicate the destruction of minerals (from Adams et al, 1978).

particularly in the more distal parts of the depositional system in the deeper parts of the basin. We make little reference to overgrowths in this study but they are clearly a part of the alteration system and deserve more careful and thorough research. Feldspar replacement and dissolution, however, particularly among sanidine and plagioclase feldspars, appears to be spatially related to the distribution of other alteration effects, and in some cases to the distribution of primary uranium mineralization.

Feldspar alteration by replacement and dissolution is one of the most notable alteration patterns in the ore-bearing sands of the Grants Uranium Region. Austin (1963) described the altered grains as resembling hollow shells or miniature ping pong balls. The grains he studied were mostly, if not all, produced by the partial solution of detrital sanidine. Whereas some were

completely empty, others contained authigenic pyrite, anatase, calcite or secondary uranium minerals. Most contained sliver-like remnants of the original sanidine identified, optically, spectrographically and by x-ray methods, to contain about 30 percent soda feldspar and 70 percent potash feldspar. Many of these remnants were previously misidentified as authigenic adularia.

Referring to the same features in the Section 27 Mine of Ambrosia Lake, Kendall (1971, p. 53) noted that the sanidine clasts had been etched and dissolved, producing spherical shells with only sliver-like remnants of sanidine remaining in the center. The altered grains are most evident and seem to be more abundant in hand specimen than in thin section. Kendall noted the presence of anatase and pyrite in altered grains. Plagioclase grains displayed similar alteration in only a few isolated cases.

In subsequent studies, Austin (1980) investigated the composition of the feldspar shells or rims, and determined that the x-ray diffraction patterns most closely resemble patterns for microcline. Energy dispersive x-ray spectrography indicated the presence of considerable sodium in the sliver-like

Figure 15. Paragenetic relations for diagenetic alterations in the Morrison Formation, Ojito Spring Quadrangle, New Mexico (from Flesch and Wilson, 1974).

remnants, but little if any in the shell. This replacement of the feldspar rims in Ambrosia Lake by potassium-rich feldspar is in marked contrast to sodium replacement noted elsewhere in the Westwater Canyon sandstones and in the Jackpile sandstone as discussed subsequently.

In the Ojito Spring area on the eastern flank of the basin, Flesch and Wilson (1974, p. 202) found that sanidine and plagioclase feldspars are partially dissolved, while microcline and orthoclase are generally unaltered. Occasional overgrowths on potash and plagioclase feldspars were also noted.

The genesis of the hollow grains was postulated by Austin (1980) to have occurred either during weathering and transport or during early diagenesis through the replacement of sodium by potassium in the outer portions of the detrital sanidine clasts. He favors the weathering process because he considers chemical conditions would have contrasted more strongly than during diagenesis. This interpretation is difficult to reconcile with alteration patterns described subsequently.

Similar feldspar alteration is present in the Jackpile sandstone. As determined by Adams et al (1978, p. 1642), in portions of the sandstone, the outer part of plagioclase and sanidine grains are altered to bright authigenic rims of albite. The albite was identified by x-ray and optical methods and microprobe analyses. Albite replacement was found to be absent or weak in the upper part of the sandstone but with depth begins to develop as thin discontinuous replacement rims on the surface of the feldspar grains. Deeper in the sandstone the rims become more continuous and thicker and the inner boundaries of the rims become increasingly irregular as spike-like zones of replaced feldspar project progressively farther into the grains. The rims range, therefore, from uniform to irregular in thickness. Locally the replacement takes an even more irregular, web-like habit. Wavy optical extinction indicates the boundary between the original and albitized grains is gradational. In the lower part of the sandstone, albitization is accompanied by the dissolution of part or all of the central portion of the original grain that had not been replaced by albite. This dissolution has been referred to as skeletalization and first appears as small holes in the detrital feldspar inside the rim, the size increasing with depth until the original grain has been removed and only the albitic rim remains. The fragile shell could not have been transported in a fluvial system. They are rarely cracked or collapsed and generally do not contain other phases. Furthermore, the alteration was observed only in the vertical zoning pattern which suggests it formed under conditions of increasing sodium relative to calcium with depth (Adams et al, 1978).

The presence of skeletalized feldspars only within albitized rims suggested to Adams et al (1978, p. 1647) that the albitization commenced prior to the skeletalization. Had skeletalization preceded albitization, the outer portion of the grains would be corroded and destroyed. The persistent occurrence of albitized and skeletalized feldspathic sandstone below only albitized feldspathic sandstone suggests the alteration process proceeded up through the sandstone. Furthermore, the zones of albitized and skeletalized feldspars are always present below ore but rarely present away from uranium deposits.

In contrast to the systematic relations described above for the Jackpile deposit, Lee (1976) concluded that alteration patterns for feldspars probably

represent several cycles of depositional history in the Westwater Canyon Member which he found difficult to relate to uranium mineralization. Flesh and Wilson (1974) report minor feldspar dissolution but no feldspar replacement in the Ojito Spring Quadrangle.

Observations made during this study, using thin sections of core samples distributed throughout the Grants Uranium Region, suggest that broad systematic patterns of feldspar alteration are present within the Westwater Canyon sandstone, as they are within the Jackpile sandstone. However, the boundaries of the alteration zones appear to be more diffuse and difficult to define, but feldspar replacement and dissolution are nonetheless present. In general, the pattern of alteration is opposite that observed in the Jackpile sandstone, i.e. the intensities of both replacement and dissolution are greatest at the top of the Westwater Canyon sandstone and decrease downwards. The alteration patterns for the core holes studied are presented in Appendix 1. Although neither crystallographic nor chemical studies of the original feldspar grains or their alteration products were conducted in this study, thin section investigations indicate that untwinned sanidine and, to a lesser extent, plagioclase are the dominant altered grains. Furthermore, x-ray and chemical analyses of the replacement rims from the Chaco Canyon area indicate that the detrital grains have been replaced by essentially pure albite feldspar (Hicks, 1980, personal communication).

Also in contrast to observations in the Jackpile sandstone, the replacement rims in the Westwater Canyon sandstone are commonly thinner and the grains broken and collapsed, such that the fragments of the rims are now floating in the heterogeneous matrix of clay minerals, titanium oxide and other phases. This undoubtedly explains, in part, the greater abundance of other phases observed "within" the hollow grains of the Westwater Canyon sandstone.

The reader will note that the general form of the intensity of feldspar alteration (Appendix 1) is similar to that previously presented for ilmenite-magnetite alteration. This is most likely not coincidental, but rather the systematic response of detrital minerals to a single hydrochemical process which produced the simple vertical alteration zoning within the Westwater Canyon and Jackpile sandstones, with the intensity of alteration increasing toward the Brushy Basin Member.

Clay Minerals

General Distribution

Early studies of the clay mineralogy of the Morrison sandstones in northwestern New Mexico identified the principal clay components. Montmorillonite was recognized by Keller (1962) as the dominant clay mineral in the Westwater Canyon and Brushy Basin sediments, both regionally and locally. He noted the local occurrence of illite and mixed-layer illite-montmorillonite but found no distribution patterns of these phases with respect to the uranium deposits. Granger (1962) made similar observations, noting that montmorillonite is ordinarily the dominant clay mineral in the sandstones of the Westwater Canyon Member where the sandstone is not altered in proximity to the overlying Cretaceous unconformity. Based on microscopic studies of thin sections of

sandstones from the Westwater Canyon he observed that the montmorillonite formed early and predominantly as thin skins on sand grains. As will be discussed subsequently, authigenic clay rims on detrital clasts are common within and close to the ore deposits, suggesting that the "thin skin" referred to by Granger should not have the broad importance he inferred as 11 of his 17 samples were obtained from uranium mines.

Later studies expanded on the earlier observations. Lee (1976, p. 87) confirmed that montmorillonite and kaolinite are the predominant clay minerals in the Westwater Canyon Member. He found magnesium-montmorillonite in all samples except one from near Laguna that contained Na-montmorillonite in the middle part of the Westwater Canyon Member. In all sections he studied, minor amounts of chloritic clay minerals are present in the middle part of the Westwater Canyon Member. Minor amounts of illitic minerals are erratically present but show no persistent pattern and the Laguna section contains expandable mixed-layer chlorite-montmorillonite. In the wide-spaced holes northeast of Ambrosia Lake, Lee (1976, p. 103) found that montmorillonite and kaolinite are widespread but show non-diagnostic features except that in a few thin sections possible alteration of montmorillonite to kaolinite and chlorite to kaolinite were noted.

Brookins (1979) summarized the mineralogy and distribution of clay minerals based on outcrops and subsurface samples. Oxidized outcrop samples from the Westwater Canyon Member appear to contain uniform contents of montmorillonite and kaolinite as the dominant clays. Lesser amounts of chlorite are pervasive whereas the distribution of illitic minerals is erratic. In bleached sandstone remote from ore Lee (1976, p. 100) found well-crystalline chlorite and regularly interstratified illite-montmorillonite in contrast to the assemblages in outcrop. He found chlorite in all sandstone samples studied, whereas the mixed-layer illite-montmorillonite is irregularly distributed. In thin section, the chlorite was observed as worm-like patches on volcanic fragments, or interstitial montmorillonite, or as thin light-green films around clastic grains. He interpreted this as indicative of both direct precipitation and alteration of detrital grains. The mixed-layer clay is of the one-to-one type with regular interstratification, and the textural relation suggested that it formed later than montmorillonite but earlier than most chlorite. Similar observations by Flesch and Wilson (1974, p. 205) for the Westwater Canyon Member within the eastern part of the basin in the Ojito Spring Quadrangle noted that chlorite rather than a swelling clay is the common grain-coating clay. The chlorite forms pseudo-hexagonal flakes aligned at high angles to detrital grain surfaces, whereas the montmorillonite and mixed-layer illite-montmorillonite clays form coatings that wrap around the grains.

Ore-Related Clays

The presence of clay rims surrounding detrital clasts was noted by some of the earliest studies (see, for example, Granger, 1962). Only in recent years, however, as samples well away from known mineralization have become available, has it become evident that to a very large extent this feature is limited to the proximity of uranium deposits. In fact, the development of authigenic clay rims ranks with the precipitation of carbonaceous material and the systematic alteration of feldspars as an important manifestation of the ore-forming process. It is, with the exception of the type of chlorite described

in the preceding paragraph, generally a guide to the proximity of uranium mineralization.

In the Section 23 Mine in Ambrosia Lake, authigenic chlorite is associated with the trend orebodies, occurring as thin films on clasts and admixed with humate (Kendall, 1971, p. 100). The chlorite is difficult to detect optically due to the opaque humate material, but x-ray studies (see also Granger, 1962) show it to be present in minor amounts in much of the trend ore and generally absent outside of ore. Qualitative microprobe wavelength and beam scans suggest that chlorite is an intermediate to high iron phase with low to moderate concentrations of magnesium. The chlorite may be interlayered with illite or montmorillonite, but evidence of clay paragenesis or replacement is lacking. The chlorite-bearing sands do not appear to extend beyond ore in any direction except in rare instances (Squyres, 1970). If the deposits migrated during formation, it appears that the chlorite must have migrated also or precipitated late in the sequence of ore formation. In a few places near ore all of the sand grains are rimmed with coatings of montmorillonite-illite-kaolinite (?) which Kendall (1971, p. 98) interprets as having precipitated from solutions or grown from a colloidal gel.

In studies of the Westwater Canyon ore, Lee (1976, p. 94) also noted the enrichment of chlorite minerals relative to montmorillonite. Chlorite was also found in the redistributed deposits, although less conspicuous than in primary ores. Lee noted the chlorite occurs as well-developed films on clasts and intimately mixed with the organic carbonaceous material (Lee, 1976, p. 94).

A similar association of authigenic clay with the uranium ores was noted in the Jackpile sandstone. Moench and Schlee (1967, p. 57) described probable mixed-layer mica-montmorillonite occurring as plates wrapped around sand grains. Nash (1968, p. 744) described the conversion of montmorillonitic matrix to chlorite or chlorite-montmorillonite mixed-layer clay in the ore zones. X-ray determinations indicated the chloritic mixed-layer clays are variable interstratified in the range of 30 to 70 percent chlorite.

Recent studies by Adams et al (1978, p. 1648) further defined the relations between ore and authigenic clay, noting that zones with illite-montmorillonite rims on detrital clasts, located just above or within the ore zones, are more closely associated with the distribution of uranium-bearing carbonaceous lenses than any other authigenic mineral zones. Zones of illite-montmorillonite clay rims marginal to the orebodies suggest that the ore lenses may at one time have been more extensive. Microprobe analyses of mixed-layer clay indicate high concentrations of both potassium and iron although the latter may be present as admixed phases. The paragenesis of the clay rims relative to other phases suggest that the illite-montmorillonite rims developed after the quartz-kaolin-montmorillonite replacement of certain clasts (volcanic glass?) and the alteration of ilmenite-magnetite to anatase and leucosene (Fig. 14). Quartz overgrowths formed prior to and later than the illite-montmorillonite rims, as evidence by thin wisps of illite-montmorillonite clay both beneath and on overgrowths in portions of the sandstone.

Studies currently underway on samples from deep within the basin suggest that fine chlorite on detrital clasts is widely distributed within the Westwater

Canyon sandstone (Hicks, 1980, personal communication). Pervasive illite-montmorillonite and chlorite rims, on the other hand, occur only in proximity to known uranium deposits, or in poorly-sorted sandstones with high proportions of matrix clay which lead to the preferential concentration of mixed-layered illite-montmorillonite adjacent to the clasts boundaries. Even the unmineralized sandstone within the general region of the Ambrosia Lake district commonly has higher concentrations of illite-montmorillonite rims. Authigenic clay rims, therefore, in contrast to clay assemblage replacements of detrital clasts, seem strongly related to the distribution of uranium deposits.

Some confusion regarding the distribution of clay minerals and their relations to the ore deposits has been introduced by the recent work of Brookins (1979). Referring to studies in the general area of the Mt. Taylor deposit he reports that (1979, p. 6), "Montmorillonite is the dominant clay mineral in the reduced ground downdip of the ore body; chlorite is enriched in the ore zones; kaolinite and altered montmorillonite in the 'oxidized' ground updip of the ore." The reference to "oxidized" ground updip of the ore is not supported by field observations but is used to draw an analogy with the roll-type deposits of Wyoming. Brookins (1979, p. 7) continues,

It should be pointed out at this time that we are using the terms 'oxidized' and 'reduced' for reference purposes and for uniform terminology. Since most of the Wyoming deposits are described in this fashion, and since many of the Grants Mineral Belt deposits reside at an iron redox interface and show trace element zonation patterns comparable to those found in the Wyoming deposits, we do not feel that the use of these terms will cause problems. We must emphasize, however, that the Mt. Taylor deposit from which much of our data has been obtained does not reside at an iron redox interface, although the other transition metals which usually zone across deposits, formed by lateral secretion, zone here as well. Here, use of the terms 'oxidized' and 'reduced' is intended to be used for local reference only.

The use of "oxidized" and "reduced" in this context, unsupported by field observations, fails to recognize the differences between the primary humate associated deposits and the later redistributed deposits and should, in our opinion, be abandoned.

Kaolinite

Kaolin occurs in three distinct habits within the sandstones of the Morrison Formation. First, it occurs with quartz, montmorillonite, and illite-montmorillonite, as an early alteration product of what probably were volcanic glass-bearing clasts. This kaolinite occurs as a fine intergrowth with the other phases and is probably present throughout the sands of the Morrison Formation. A second habit is as replacements of feldspars and other clays in zones of pervasive alteration spatially related to the overlying Cretaceous unconformity. This alteration has been discussed in earlier sections and seems clearly related to altering solutions derived from the organic-rich basal sediments of the Dakota Sandstone. The alteration has overprinted diagenetic and ore-related alteration patterns where deposits are close to the Cretaceous unconformity, as for example, in the Laguna district. A third mode of occurrence is as discrete clots or nests of commonly coarse, intergrown,

kaolin crystals within the matrix of both barren sandstone and ore. It is only the latter which may possibly bear some relation to the ore deposit, but this has yet to be convincingly demonstrated.

Kendall (1971, p. 95) noted that kaolin nests are found throughout the Westwater Canyon in western New Mexico, and are known to occur from the outcrop northwards to beyond the orebodies. Within the nests, kaolin fills available pore space and encloses several to tens of clastic grains but is not stained by the ore-bearing humate. The kaolinite is well-crystallized, and the individual tightly-packed booklets are commonly 10 to 15 microns in their maximum dimension. The crystal size and degree of crystallinity show no consistent variation between samples from ore, barren black material or barren sandstone. On the contrary, kaolin nests in the ore enclosed sand grains coated with ore material. This suggests, as noted earlier by Granger (1963), that the kaolin nests are post-trend ore in age. Kendall also found, however, that some kaolin nests occur within buckshot calcite which he interprets as pre-ore. Some kaolin nests, therefore, may be older than some primary ore.

In the Westwater Canyon sandstone, Flesch and Wilson (1974) noted in the eastern portion of the San Juan Basin that irregular kaolinite clots up to several centimeters in diameter contained well-formed books. The kaolinite is often abundant, but no systematic pattern of distribution was noted.

Lee (1976, p. 88) studied samples from uranium deposits as well as from remote core holes and observed that kaolinite in the Westwater Canyon Member typically occurs as nests, that fill pore space and commonly enclose several clasts. The size of the nests appears to be proportional to grain size and permeability. He concluded that the nests are less abundant in the Jackpile sandstone where the kaolinite assumes a finer-grained more evenly distributed habit in the matrix. Our studies suggest that kaolin nests are at least as abundant in the vicinity of ore deposits in the Jackpile sandstone as they are in the Westwater Canyon, and that the fine-grained kaolin referred to by Lee is probably related to Cretaceous alteration. Lee (1976, p. 95) also recognized the more complex clay mineralogy of the ore zones involving chlorite, kaolinite, montmorillonite, and illitic clay minerals. He concluded that the illitic clay minerals occur in and near the ore zones but only as minor constituents that bear no apparent relation to the uranium deposits. As for the kaolinite, it is not coated with organic carbonaceous material or hematite and Lee concluded that it is unrelated to mineralization.

Those who have studied clay distribution in thin section rather than through x-ray studies of clay concentrates, which tell little about the habit and paragenesis of the clays, consistently observe the presence of kaolin nests in the vicinity of uranium deposits. Furthermore, the kaolin in the nests apparently formed by precipitation in the matrix rather than by the replacement of other material. The formation of the kaolin seems clearly post-ore. The later age of the kaolinite has led some observers to conclude that the kaolinite is unrelated to the formation of the ore deposits. As will be discussed in a later section, it seems likely that the kaolinite forms through the release of aluminum previously complexed with organic material, hence, much is probably related to the organic material of the ore zones. The occurrence of kaolin nests remote from known mineralization suggests that it is not restricted to the proximity of known ore deposits, but nonetheless may

be related to transient organic material. Together with other observations, the distribution of kaolin nests may be a useful guide.

Pyrite

The distribution of pyrite in the vicinity of ore deposits has been described by numerous observers and discussed in an earlier section of this paper. Far less information, unfortunately, is available on the pyrite distribution within the sands above, below, and lateral to the ore deposits and ore trends. Observations collected during this study suggest that, on a regional scale, pyrite and ilmenite-magnetite distributions are antithetic. This is not at all surprising insofar as the destruction of ilmenite and magnetite is believed related to strongly reducing ground waters which could have produced pyrite, in part at the expense of detrital ilmenite and magnetite. Within the zone of ilmenite and magnetite destruction, however, pyrite may or may not be present. Significant concentrations, similar to those seen in the vicinity of known deposits, occur only with total ilmenite and magnetite destruction, but even then the distribution seems more restrictive. More systematic studies are required but it appears that a progressive zoning exists in which a broad pyrite-rich envelope, from a few tenths to a percent pyrite by weight of the sandstone, occurs around deposits and districts and may extend several miles beyond the mineralization. At some distance beyond this zone only partly altered ilmenite and magnetite begin to reappear with the intensity of alteration decreasing until completely undissolved ilmenite and magnetite are present throughout the sand. The systematic study of a series of core holes completely through the Westwater Canyon and extending across the Ambrosia district well into unmineralized ground to the south and north, would identify the limits of the alteration zones and the abundance of the alteration phases with the possible significant refinement of the alteration guides proposed herein.

Calcite

Calcite is widely distributed though not pervasive in the sands of the Morrison Formation. It commonly occurs in coarser more permeable sands adjacent to interbedded shale and siltstone horizons and in ill-defined and less predictable positions within the sandstones. Few investigators have noted any relations between these distribution patterns and mineralization. In his studies of the Section 27 Mine, however, Kendall (1971, p. 81) identified a habit of calcite which he interprets as related to the ore-forming process:

Buckshot calcite, an opaque to translucent milky white phase, is closely associated with ore and appears to have been deposited at the same time. . . . Each ovoid may be a large single crystal or a fine-grained aggregate. The enclosed clastic grains are no more corroded or altered than those in the adjacent ore . . . areas enclosed within buckshot calcite appear to contain less authigenic pyrite and kaolin as well as no ore, whereas relic buckshot sites contain more pyrite and kaolin than the buckshot calcite, but less than the surrounding ore. . . . In the Section 27 Mine, and the adjacent Ann Lee Mine (Squyres, 1970), the early buckshot calcite is concentrated at the north edge of the ore trend.

These observations suggest a type of calcite and an asymmetry of mineral zoning not generally described for the orebodies in this district. This may reflect a lack of comparably detailed observations elsewhere or a somewhat restricted phenomena, but the genetic significance of these relations warrants further study.

Other Alterations

Numerous other types of mineral alterations have been noted within the Morrison sandstones, but none seem convincingly related to ore distribution. Two additional types of alteration, however, warrant mention as their regional distribution may ultimately prove to be spatially related to primary uranium mineralization.

As discussed in previous paragraphs, much conjecture and interest surrounds the original oxidation state of the Morrison sandstones. Squyres (1970) has made a convincing case for the original red nature of some of the shales. Most authors, however, (see Lee, 1976, for example) assume that the sediments were never intensely oxidized. The perseverance of ilmenite and magnetite over broad areas and the "reduced" nature of much of the Westwater Canyon and Jackpile sandstones supports this position. It seems likely, therefore, that the Westwater Canyon sands were locally mildly oxidized at the time of deposition, subsequently to be weakly or intensely reduced during diagenesis.

Studies of the Jackpile sandstone in the vicinity of the Jackpile deposit (Adams et al, 1978) have identified portions of the sandstone in which a high percentage of the detrital grains contain minute hematite crystals along cleavages, in twin plane and within fractures within quartz. The matrix of these sands are free of hematite and may even contain pyrite and uraniferous carbonaceous material. These portions of the sandstone were apparently oxidized at the time of deposition or shortly thereafter but were subsequently reduced by processes related to ore formation. Whether this early oxidation was essentially a depositional phenomenon or a post-depositional roll-type phenomenon is not known. The distribution of this early hematite-bearing sandstone appears erratic and does not yet seem to correlate with the distribution of other alteration zones.

The study of thin sections during this project from barren Morrison Sandstone and from the vicinity of ore, suggests that hematite is more abundant within grains in the immediate vicinity of uranium occurrences. This relation has not been firmly established but is reminiscent of the hematite-uranium association in other types of uranium deposits and warrants further study.

Studies of widely-spaced samples within the Westwater Canyon Member, conducted as part of this study, confirm a reasonably pervasive, early hematite alteration throughout the basin. This is observed as locally (a) abundant hematite inclusion within detrital clasts where the matrix has been reduced and heavy minerals are absent and (b) pervasive coatings of hematite around residual ilmenite and magnetite where the latter has not been entirely destroyed. This early oxidative alteration may have mobilized considerable uranium some of which concentrated in the epigenetic carbonaceous zones, hence, it may have been an important part of the ore-forming process. However, because of the

necessity of observing this alteration pattern in thin section, and the remaining uncertainty as to the precise distribution of this alteration zone, it probably will not be as useful in reconnaissance work as other alteration features and therefore will not be further considered in this report.

Recent studies (Brookins, 1979) have emphasized the distribution of rare earth elements (REE) within the Morrison ore-bearing sands in northwestern New Mexico. In particular, enrichments of rare earth elements in many ore samples, particularly in the clay-sized fraction (minus 2 microns) has been noted by Brookins (1976), Lee (1976), and Brookins et al (1978). Also noted is a positive europium anomaly within such samples. There is much speculation as to the significance of these observations and mechanisms whereby rare earth elements have moved and concentrated within the ore.

Similar associations of rare earth elements with uranium mineralization have been reported by McLennan and Taylor (1979) for deposits in the Northern Territory, Australia. Transport by carbonate or organic complexes has been offered as the most plausible concentrating mechanisms. Based on data for the Grants Uranium Region, the rare earth elements appear to be concentrated within ore as is typical of chromium, copper, cobalt, vanadium, selenium, and numerous other elements. On that basis, they would not seem to have much direct application to exploration or resource studies.

Recent studies by Della Valle (1980, personal communication) indicate that rare earth element concentrations increase from the Recapture Member up through the Lower Westwater to the Upper Westwater and then decrease abruptly in concentration within the Brushy Basin Member. These distributions are all based on studies of the -2 micron clay fraction. The significance of these tentative patterns will be discussed in subsequent paragraphs as they may contribute to developing models for the formation and controls of these deposits. As the distributions have not yet been systematically related to proximity to mineralization, they do not seem at this time to constitute a regional reconnaissance criteria.

Paragenesis of Alteration Minerals

Recognizing the numerous types of alteration, the repetitive nature of some alteration processes, and the local distribution of some alteration assemblages, there is essentially an endless variety of paragenetic sequences that might be developed for the sandstones depending upon the experience of the observer. In fact, there are many perfectly correct but quite different paragenetic sequences which are appropriate for different portions of the sandstones. It is unnecessary to address all the variations but subsequent discussions will benefit from the identification of the most general paragenesis for the sandstones.

Lee (1976) presented a simple general paragenetic sequence for post-depositional alteration:

- (1) Smectite (montmorillonite) formation

- (2) Bleaching of host sandstone and alteration of detrital heavy minerals to pyrite and Ti-oxides
- (3) Formation of clay-organo complexes and the enrichment of uranium
- (4) Chlorite formation concomitant with humate coagulation and coffinite precipitation
- (5) Oxidation of pyrite, development of roll-type and other redistributed deposits and the formation of nest kaolinite

This sequence reflects the results of most studies of the ore-bearing sands, particularly the numerous studies of the Westwater Canyon Member. It is also compatible with the detailed studies of Adams et al (1978) conducted in the Jackpile sandstone and represented in Figure 4. Flesch and Wilson (1974) presented a similar sequence (Fig. 15) for the eastern portion of the San Juan Basin although it differs in some important respects (i.e., early chlorite formation and late feldspar dissolution) from the generalized sequences above.

To summarize, an early period of alteration of volcanic clastic material produced montmorillonite, smectite, illite, and mixed-layer clay within the sands. This was in part contemporaneous with the reduction of portions of the host and the alteration of ilmenite and magnetite, locally to pyrite. Locally within the sands humic material then precipitated in the interstices of the sand grains together with, and subsequently enriched by, uranium. The replacement and dissolution of feldspars developed locally within the Jackpile sandstone, but more broadly and roughly coincidentally with ilmenite and magnetite destruction within the Westwater Canyon sandstone. Clay rims of various compositions formed within the sandstones in proximity to the uraniumiferous carbonaceous material and at approximately the same time. Subsequent to the formation of the ore lenses, kaolinite nests formed within the sands followed at a much later time by the introduction of oxidizing solutions which partly oxidized and redistributed the primary deposits.

Alteration Zoning

The distribution of mineral alterations, commonly referred to as alteration zoning, is important to studies of ore formation and control and to exploration and resource studies. Because of the variety of alterations and their different patterns and scales, previous studies of this important aspect of the deposits have predictably come to sometimes conflicting conclusions. Some of these conclusions are briefly reviewed in an attempt to establish relations between them.

Based on studies of the Jackpile sandstone, Nash (1968, p. 742) concluded that petrographic studies and clay mineral analyses of over 150 samples taken away from ore failed to identify distinctive mineral assemblages or texture which could be related to ore solutions. No regional alteration zones based on clays, heavy minerals or textures were identified leading Nash to conclude, "that there were no local conduits for altering fluids at any time and that when ore fluids did go through the sandstones they were buffered and diluted so that probably no distinctive traces were left." Subsequent studies (for

example, Adams et al, 1978) identified zoning patterns which are spatially and specifically related to the distribution of ore lenses. Figure 16 shows the position of, for example, feldspar replacement and dissolution zones and authigenic illite-montmorillonite zones with respect to the ore lenses.

In the Section 27 Mine in the Ambrosia Lake district, Kendall (1971, p. 114) observed,

In an east-west direction, no change in amount or number of minerals present was detected, either within an individual ore pod or along the ore trend. However, in a north-south direction several consistent variations were seen, i.e., greater amounts of coffinite, humate, and jordisite to the north, and buckshot calcite present only at the north edge of the ore trend). This general distribution is strongly suggestive of predominant precipitation to the north and dissolution to the south. Thus, during ore formation it appears that the predominant direction of movement of ions (and probably also the ground water) was from south to north across the ore trend (i.e., downdip).

In an attempt to demonstrate clay mineral zoning, Brookins (1979, p. 32) studied samples from the Mt. Taylor deposit and observed that, "clay minerals show a variation in composition from montmorillonite in front of the ore to chlorite in ore zones and finally to kaolinite behind." As discussed earlier in this report, the use of "in front of" and "behind", implying that the mineralization is related to roll fronts as in the Wyoming deposits, is not, in our opinion, appropriate. The zoning referred to has yet to be shown to be related to specific types or stages of mineralization. Moreover, Brookins has failed to distinguish primary carbonaceous-rich mineralization from later roll-type mineralization which indeed has the characteristics of Wyoming roll-type deposits. Study of the Grants Uranium Region must first focus on the primary ores and their genesis and controls as they place great constraints on the later redistributed mineralization.

Figure 16. Cross sections of part of the Jackpile Mine area showing the distribution of uraniferous humate lenses and mineral alteration zones (from Adams et al, 1978).

ISOTOPE STUDIES

Isotope studies of various elements associated with the uranium deposits in the Grants Uranium Region have been used to investigate ore formation, the age of the mineralization, and the migration history of the associated ore elements. Most of these studies have raised more questions than they have answered, but the important types of studies are briefly reviewed below.

Sulfur Isotopes

A compilation of the sulfur isotope values for pyrite associated with the ores of the Ambrosia Lake and Laguna districts prompted Jensen (1958), and Adler (1963), to propose that hydrogen sulfide gas derived from sulfate-reducing bacteria provided the reducing environment in which the uranium deposits formed. The sulfate source was presumably the connate formation waters and the energy source for the bacteria was provided by the organic matter in the sediment.

Isotopes of the Uranium-Decay Series

Radiochemical analyses of uranium deposits at Ambrosia Lake indicate that migration of various isotopes of the uranium-decay series has occurred (Granger, 1963, p. 60). Whereas uranium is known to be relatively mobile in solutions, protactinium (Pa^{231}) is considered a relatively immobile daughter product. Therefore, Pa^{231} was used as the standard against which the concentrations of other members of the U^{235} series were measured. Although the isotopes Pa^{231} and Th^{230} should be present in constant proportions, they are not at Ambrosia Lake and it is assumed that Th^{230} has migrated along with uranium in both primary and redistributed ore bodies. Five suites of samples collected across primary ore layers indicated that the ore itself is about 20 percent deficient in uranium relative to Pa^{231} . Barren sandstone in the first few feet on either side of the ore layer is 47 percent deficient in uranium. These same samples show Ra^{226} to be nearly 41 percent deficient in the ore layer and about 220 percent in excess relative to Pa^{231} in the adjacent barren sandstones. The radium (Ra^{226}), which is believed to have migrated out of the uranium ores, has been partly reconcentrated in barite and cryptomelane along the surfaces of mudstone layers. The loss of Ra^{226} , which ultimately decays to Pb^{206} , produces large apparent $\text{Pb}^{207}/\text{Pb}^{206}$ age dates and young $\text{Pb}^{206}/\text{U}^{238}$ ages in the ore. The geologically recent movement of some of the radioisotopes causes the disequilibrium between the actual uranium content and the equivalent uranium content of both the primary and redistributed ores of the district. Equilibrium studies of 290 samples showed that the daughter products are in excess in low-grade samples and are generally deficient in the high-grade ores (Granger et al, 1961, p. 1205). The data suggests that while the radium has migrated a short distance away from ore, rarely has a significant amount escaped from the immediate vicinity. This is in contrast to uranium and ionium, some of which appears to have migrated completely out of the sampled areas.

Even the isotopes of uranium itself have been fractionated in the Ambrosia Lake ores (Dooley et al, 1966, p. 1362). Isotopic analyses for U^{234} were made on 30 samples from 5 vertical suites of ore-grade material. U^{238} , U^{235} , and U^{234} were measured by mass spectrometry and the U^{234}/U^{238} ratios were verified by alpha spectrometry. U^{234} variations were found to be as great as 58 percent deficient and as much as 36 percent enriched. The pattern of U^{234} fractionation in both the primary and redistributed ore samples generally showed an enrichment just above the ore and a large relative deficiency near the richest ore. Much greater deficiencies of U^{234} were found in the stack ore than in the primary ore. The leaching solutions responsible for the transportation of the uranium appear to have preferentially picked up U^{234} in an oxidized state from a disintegration site in the solid phase rather than U^{238} and U^{235} . The fractionation is inhibited by less permeable units such as mudstone conglomerate and sandstones cemented by calcite. It is possible and even probable that isotopic exchange occurs along with the leaching and redeposition of uranium and may even have been the dominant process. Dooley et al (1966, p. 1381) concluded that migration and redistribution of uranium at Ambrosia Lake have been both complex and relatively recent. The conclusion gained from the various studies is that significant local redistribution of uranium and its daughters has occurred during the last 200,000 years.

Age Dates

Uranium-lead isotopic ages that have been determined for the Morrison uranium ores in the Grants Uranium Region have all been discordant, and this is not surprising in light of the preceding discussion. The radioactive decay of the uranium isotopes U^{238} and U^{235} and the thorium isotope Th^{232} , decay into three different lead isotopes, Pb^{206} , Pb^{207} , and Pb^{208} , respectively. The proportions of the elements provide a means of dating the uranium minerals. For concordant ages, the ages derived from the ratios Pb^{206}/U^{238} , Pb^{207}/U^{235} , and Pb^{207}/Pb^{206} must all agree within the experimental error. No such agreement has been found in samples from the Morrison Formation, although Berglof and Wampler (1965, p. 164) have obtained a concordant age of 150 to 155 m.y. on uraninite from the Todilto Limestone. In an attempt to obtain a reliable date for the Ambrosia Lake ores, Dooley et al (1966) took the average total Pb/U ratios of 75 samples through ore zones and extending out into barren ground on either side. They determined an age of 100 m.y. for the primary ores, and 10 m.y. for the stack ores.

The isotopic ages for the Morrison uranium mineralization range from 87 to 155 m.y. (Lee and Brookins, 1978, p. 1673; Brookins, 1980). In general, the ages calculated from the U-Pb isotope series have been too low. There are four processes which could cause discordant ages: (1) old radiogenic lead contamination, (2) lead loss, (3) ore redistribution, and (4) later primary mineralization. Miller and Kulp (1963, p. 624) believe the low ages are due to the loss of radiogenic lead. Preferential loss of Pb^{206} has been cited as the main reason for the discordant ages (Miller and Kulp, 1963, p. 624; Berglof, 1969). The loss of U^{234} , radon, or radium would all contribute to an ultimate deficiency in Pb^{206} . For a sample to be suitable for age determination by this method it must first have been in a closed system since it formed; second, the amount of the initial daughter isotopes must be known; and third,

the rate of decay of the parent isotope to the stable daughter products must be known (Brookins, 1980). There are essentially no samples in the Morrison Formation that can meet these criteria.

More recently an attempt has been made to date the mineralization indirectly by determining the age of associated authigenic clay minerals in the ore by the rubidium-strontium method. Authigenic chlorite which is enriched in the ore is believed to be an alteration product of the ore-forming process. The chlorite in ore samples from Ambrosia Lake and Smith Lake gave ages of 139 ± 10 m.y. Similar samples from the Laguna district gave ages of 115 ± 9 m.y. and 110 ± 10 m.y. (Lee, 1976, p. 131 and 136). Authigenic montmorillonite clay rims from barren sandstones in the Westwater Canyon Member and the Jackpile sandstone were dated at approximately 148 ± 9 m.y. (Lee and Brookins, 1978, p. 1681). Although the montmorillonite Rb-Sr dates are probably not as reliable as those for chlorites, the 148 ± 9 m.y. is believed to approximate the age of sedimentation. The date of mineralization in the Westwater Canyon Member and the date of sedimentation are essentially indistinguishable due to the overlap in errors (Brookins, 1980b). The mineralization dates in the Jackpile sandstone, however, are younger than the age of the sediment, and support the idea of Adams et al (1978, p. 1649) and earlier workers that the Jackpile ore lenses were partially oxidized, destroyed and perhaps redistributed in Lower Cretaceous time.

SYNTHESIS

In this section some important details not previously covered are discussed and some important points are re-emphasized. Speculations are offered in an attempt to tie together the numerous observations presented in earlier sections. The discussion is organized under various headings which are factors that have influenced the origin, transportation, and precipitation of the uraniferous humates which constitute the ore deposits. The headings are not necessarily listed in the order of importance and many of the topics overlap at one point or another, hopefully reinforcing the conclusions presented.

Stratigraphy

The host rocks are continental fluvial sandstones and many of the characteristics of this type of orebody may be unique to this type of depositional environment. The largest ore deposits in the Grants Uranium Region are in the bed-load dominated straight to sinuous fluvial systems. A high sandstone to mudstone ratio with good continuity of sandstone units appears to be most favorable. The ore trends are best developed where the gross thickness of the host sandstones is above average. Westwater Canyon thicknesses of 300 feet or more are especially favorable as are thicknesses of 200 feet or more for the Jackpile sandstone. Sandstones with poor sorting and a wide range in grain size are probably more favorable than are units of moderate to good sorting in finer-grained material. Primary mineralization is in reduced, light gray, pyritic sandstones, whereas uniformly oxidized sandstones are not considered prospective.

Structure

In the Grants Uranium Region, only the pre-Dakota structures had any influence on primary mineralization. The long, parallel thick host rock trends and the mineral trends themselves are believed to be due to subtle folds which developed contemporaneously with sedimentation, parallel to the north flank of the Zuni Uplift. North trending asymmetric cross folds which appeared in late Westwater Canyon time influenced the depositional pattern. These broad arches were generally steeper on the east flank. Unusually thick sections of Westwater Canyon accumulated at intervals in the southeast trends adjacent to the steep flanks of the north-trending arches, such as at Marquez, and the Bernabe Montano Grant. Well developed channel systems broadened and lost definition in crossing some of the northerly trending anticlines. Domal areas which probably existed in Morrison time, such as the Ambrosia and San Mateo domes are not prospective because the streams avoided these positive areas. The combination of unfavorable facies and higher structural position makes it likely that subsequent ground waters also avoided these structures. Structural lows of Jurassic age are the sites of the largest primary uranium deposits.

These relations changed in Middle Tertiary time when oxidizing waters entered from outcropping areas. Mineralized areas that became structurally high in

Tertiary time escaped oxidation to some extent. Ambrosia Lake is presently a horst bounded on the east by the San Mateo fault and on the west by the Ambrosia fault zone. Late Tertiary oxidation borders it on three sides and may actually surround the horst entirely.

The unusually intense faulting between Gallup and Laguna may also have contributed to the protection of Ambrosia Lake from more extensive oxidation. (Santos, 1970, p. E-22). Contrary to popular belief, the structurally deformed areas appear to hinder or retard ground water circulation and, therefore, prevent the oxidation and destruction of earlier formed ores. The association of ore on the outcrop with fractured areas was noted by Konigsmark (1958, p. 29). Outstanding examples are the Poison Canyon Mine, the Black Jack No. 1, Section 28 (Smith and Peterson, 1980), and on a larger scale, the Northeast Church Rock Mines and the Bernabe Montano Grant, which is preserved within the Rio Puerco fault zone. A lesser known, but outstanding example is Kerr-McGee's Section 22 Mine where primary blanket ore is preserved in a graben, and stack ore occurs around the outside of the bounding faults (Corbett, 1964, p. 104).

Lithology and Diagenesis

The prevalence of sandstone uranium deposits in arkosic sandstones is well known. The presence of feldspars is not as important as the fact that the host rock is a clean sandstone composed of fairly stable constituents. Graywackes and volcanic-rich sandstones are poor host rocks because they lose permeability very soon after deposition. The Morrison sandstones contained felsic volcanic material which was altered almost immediately after deposition, but the amount was insufficient to clog up the rock, except in cases of very thin lenticular sandstones which were silicified or finer-grained sandstones which may have lost considerable permeability because of clay alteration. Mineral constituents contained in the volcanic material were released to the ground water and carried through the sandstones until chemical conditions were encountered which caused precipitation. Much of the uranium and its accessory elements, Mo and Se, were probably derived mostly from the altered igneous material within the sandstone itself, especially the coarse proximal facies that was later removed by erosion. Such an internal source has been proposed by various workers over the years (Rapaport, 1963, p. 133; Nash, 1968, p. 748; Squyres, 1974, p. 6; Clark, 1980; Falkowski, 1980).

Preliminary chemical analyses (Della Valle, 1980, personal communication) suggest an increase in the concentration of the rare earth elements (REE) from the Recapture up through the Lower Westwater Canyon sandstone and then a decrease in the Brushy Basin. This may reflect leaching of REE in the Brushy Basin and in the Lower Westwater Canyon relative to the Upper Westwater Canyon. The Lower Westwater Canyon also contains lower concentration of REE in the -2m fraction suggesting it also has been leached. This may have resulted from the long history of mild oxidation of this part of the sandstone evidenced by the general preservation of ilmenite-magnetite and the presence of hematite. Sodium, on the other hand, increases slightly in the upper part of the Westwater Canyon compatible with the evidence of widespread albitization discussed earlier.

The mudstones of the Brushy Basin Member have also been considered a source rock for the uranium (Squyres, 1970; Lee, 1976; Galloway, 1980; Tessendorf, 1980). The mudstones are generally considered to contain appreciable volcaniclastics and interbedded altered volcanic tuffs which, when they were diagenetically altered, released uranium and other metals to ground waters to the adjacent sandstones. The identification of altered tuffs supports this premise, but it is likely that much of the clay in the Brushy Basin were deposited as such. Nonetheless, the vast amount of volcanic material in the Brushy Basin mudstones undoubtedly contributed uranium to the surface and ground water system in Late Jurassic time.

Brookins (1979, p. 402) and Della Valle (1980, personal communication) have found that the thorium:uranium ratios for the Brushy Basin are about 1.5. This is interpreted as evidence that uranium in the Brushy Basin has not been leached, in contrast to Della Valle's evidence that REE have been removed. These observations would be compatible with a reducing, probably organic-bearing, diagenetic ground water capable of complexing or chelating the REE (Della Valle, 1980, personal communication; McLennan and Taylor, 1979) while depressing the solubility of uranium. This would also explain the pervasive green to gray-green reduced color of the Brushy Basin.

The Brushy Basin is the transgressive distal fine-grained facies of the Westwater Canyon alluvial fan. It is likely that early ground water flow in these sediments was from the head of the fan to the toe, identical to the streams that deposited the sediments. During the early diagenesis and compaction of the basal Brushy Basin sediments, waters of compaction probably moved down into the top of the Westwater Canyon, particularly where the two members are complexly interbedded, thus promoting the flow of fluids from the former into the latter. The alteration of the Upper Westwater Canyon sands is likely related to those waters from the basal Brushy Basin sediments. The uranium of the deposits, however, probably was derived from ground waters moving within the Westwater Canyon which may have associated the uranium from well up the hydrologic system and leached it from the Westwater Canyon sands.

The diagenetic reduction of the upper part of the Westwater Canyon sands and the entire Jackpile sandstone destroyed the detrital magnetite and ilmenite. These heavy minerals can thus be used as guides to favorable areas as suggested by Adams et al (1974). Sandstones with a normal content of these mineral grains, or their hematite pseudomorphs, are probably unfavorable for the discovery of large mineralized humate deposits.

Ground Water

During Morrison time ground water moved down the fan systems, essentially parallel to the surface flow (Squyres, 1970, p. 200). The mineral trends appear to have developed along the most transmissive zones within the host rocks in Late Jurassic time. Ground water flow in the Westwater Canyon Member was probably channeled to the southeast from Gallup by these transmissive zones in the sandstones and because of continued minor structural downwarping along the north side of the Zuni Uplift. Other thick structurally controlled sandstone trends, such as the one through the Nose Rock area, were also major conduits for ground water.

The surface and shallow ground waters in Late Jurassic time were alkaline and oxidizing. The pH was probably about 8, due to the hydrolysis of the volcanic ash in the system. Squyres (1969, p. 152) estimates that the concentration of dissolved substances was in the range of 1,000 ppm or less, with sodium in excess over calcium. It seems probable that uranium and associated elements were also present in these waters and were derived mainly from acid volcanic materials both in the area of provenance, and the volcanic material deposited within the sediment. The uranium content of these waters was probably between 50 and 300 ppb, transported by both uranyl carbonate complexes, as suggested by Gruner (1958, p. 18) and perhaps fulvic acid complexes as suggested by Schmidt-Collerus (1979, p. 6). Granger et al (1961, p. 1197) have hypothesized that organic matter from decaying plant debris in the Westwater Canyon Member was dissolved in the stream and underflow waters during Westwater Canyon deposition but were precipitated along the interface between the underflow and the deeper, slower moving ground waters. According to these workers, this would explain the elongation of deposits parallel to the depositional trends and would also account for multiple layers of organic material as the sands were laid down.

The relationship of the ore to some sort of horizontal water table or ground water effect has been noted repeatedly in the literature (Hilpert and Moench, 1960, p. 448; Young, 1960, p. 32; Granger et al, 1961, p. 1197; Harmon and Taylor, 1963, p. 106; Moench, 1963, p. 162; Granger, 1968, p. 67; Nash, 1968, p. 743; Roeber, 1972, p. 3; Adams et al, 1974, p. 245). The persistence of this idea through the years is remarkable, and it must be given serious consideration. The association of the humic matter with a paleo-water table or chemical interface parallel to, but below it, would more easily explain the extensive tabular orebodies such as found in the Jackpile deposit. Peculiar features, such as the ore rods described by Moench (1963, p. 162) in the Jackpile deposit, suggest destruction or shifting of the humate lenses soon after their formation. Granger (1980, per. comm.) has photographed and sampled narrow gaps in a primary ore layer in Ambrosia Lake which appear to be due to early redissolution of the humate apparently caused by a downward incursion of alkaline waters which removed the humate. There is no break in the sedimentary structures which would indicate an erosional break. The dark humate layer simply ends abruptly in the sandstone along an almost vertical knife-edge. The humic material was apparently still soft and mobile, for it appears to have flowed locally across the knife-edge boundary into the barren gap left by the removal of the humate. There appear to have been two chemically different ground waters involved in producing this phenomenon. The gross geometry of an extensive thin blanket of ore in a 15 to 20 foot sandstone unit between mudstone beds almost demands some sort of early, semi-horizontal, chemical interface for its origin.

Organics

The uranium mineralization is everywhere co-extensive with the humic organic matter in the sandstones. The uranium is much more often associated with the unstructured humate than with the carbonized plant debris. Although unmineralized humic material is said to have been encountered occasionally in the Westwater Canyon Member, no completely barren humate has ever been confirmed

humic matter is approximately equal to the uranium content in weight percent (Hilpert and Moench, 1960, p. 446; Squyres, 1970, p. 192). Because the organic material is so much lighter, it is greatly in excess over uranium in volume, and therefore, it is primarily responsible for the dark gray to black colors of the ores. Because of the high geochemical enrichment factor for uranium, it takes only a small amount of humic material to accumulate uranium to ore grade. This small amount of humic material ranging between 0.05 percent and 0.5 percent of the rock can be destroyed or remobilized without leaving much evidence of its former presence. The labile nature of the humic matter has caused considerable confusion concerning the precipitation of uranium in some deposits.

Humic material is important in uranium geochemistry for the following reasons:

(1) Humic substances such as fulvic acids are believed to be capable of transporting uranium over long distances in natural waters.

(2) No other naturally occurring chemical substances are known which have the ability of concentrating uranium and other cations from extremely dilute solutions as the humic substances can. Metal concentrations can build up very rapidly under the proper chemical conditions, for it is only limited by the amount of humic material present, and the amount of metal-bearing waters that come into contact with it.

(3) Once precipitated, the humic material serves to protect uranium accumulations with and within the organics by becoming more refractory with age, reducing permeability, and maintaining a strong reducing environment in the deposit.

The chemistry of the urano-organic association is poorly known. Phase diagrams involving uranium species in inorganic systems may have little relation to the actual chemistry of uranium in the organic systems found in nature. Even though the chemistry of the humic materials is poorly understood, far more is known about the metal-organic associations than about the geology of the humate deposits themselves. The whole problem of uranium exploration in the Grants Uranium Region, as in many other places, is in trying to predict where the humates were deposited within this large fluvial system.

Climate

One of the characteristic features of uranium deposits in sandstones is their close association with oxidized continental sediments or red beds. Although red beds do not always denote an arid or semi-arid paleo-climate, the uranium deposits on the Colorado Plateau do seem to be closely associated with such climates. The reason for this may be that arid to semi-arid climates do not promote high organic production and that which does exist under these conditions is quickly oxidized when it dies. Waters in such climates tend to be alkaline, which is favorable for the transportation of uranium and humic substances. Conditions favorable for the precipitation of the organic matter

are not very common, and what sites do exist are unique concentrating centers for the metals in solution. Because of the dry climate, the metal content of the waters may be high also, due to evaporation and more thorough oxidation and leaching of the surface sedimentary material. The underflow of streams in arid regions during periods of little or no discharge can be expected to be quite anomalous in metal content. The annual rise and fall of the water table in the stream beds could cause a flushing action which could enrich a shallow humate deposit in a relatively short span of time.

Conversely, humid climates promote lush vegetal growth and any metals released to the sedimentary environment are immediately locked up in the abundant and widely dispersed organic materials. The net effect is to keep the metals dispersed rather than have them concentrated in a few favorable sites.

Oxidation

Oxidation of the host rocks is extensive in the Grants Uranium Region. Hematitic sandstones have been found up to 15 miles downdip from Morrison outcrops and as deep as 2,400 feet in the Crownpoint area. Weak oxidation may extend much more than 15 miles north of Crownpoint for redistribution of uranium mineralization along oxidation fronts has been described in the Nose Rock area by Clark (1980) and Rhett (1980). These workers attribute the redistribution of uranium in this area to Late Jurassic roll fronts which have subsequently been totally reduced, but it is more likely that recent oxidation has effected the redistribution of mineralization. In studying thin sections from core holes through the southern half of the San Juan Basin, we have noted widespread early mild oxidation, particularly in the lower part of the Westwater Canyon, and common but more restricted late oxidation in the matrix of the sands. Furthermore, the abundance of detrital magnetite in the Westwater Canyon Member suggests that the Chaco area was never strongly reduced by either indigenous or introduced organic matter.

The dominant oxidation in the Westwater Canyon Member on the Chaco slope is Late Cenozoic in age. Unlike the oxidation fronts in the Wyoming basins, which concentrate uranium at the leading edge of oxidation, this oxidation has probably removed a large part of the uranium mineralization in the Grants Uranium Region. Locally the oxidation has been retarded in its basinward advance by the organic rich primary trend deposits. Between ore deposits, the oxidation has progressed farther north. There are generally no uranium accumulations along these salients as would be expected on similar oxidation fronts in Wyoming. It is not clear whether the oxidation process ultimately destroys and disperses the primary ore or if these salients merely traversed areas in which no significant uranium deposits existed, and lacking sufficient uranium in the incoming oxidized waters, no deposits resulted. The latter idea is favored because well-developed fronts exist and uranium, if available, should have precipitated.

Mineralogy

The uranium ore in the Grants Uranium Region is dominantly coffinite dispersed in an organic phase which may contain an undetermined amount of uranium in other forms, principally organic compounds. Some primary tabular orebodies in Ambrosia Lake have scattered patches of jordisite surrounding the uraniferous humate. The richest disseminations of jordisite appear to occur below or along the edges of the orebodies. Selenium is dispersed in both the uranium ore and the surrounding jordisite, but it appears to be more often concentrated along the upper surface of the ore layers in unoxidized deposits (Granger, et al, 1961, p. 1205). If, as is discussed below, the humate was precipitated as tabular bodies along a shallow, horizontal chemical interface below the water table, then this distribution of selenium, uranium, and molybdenum may suggest that the humate body was located at an oxidation-reduction interface separating surface oxidizing waters from deeper H_2S -rich, reduced ground waters. The chemical system may have been similar to redox fronts in Wyoming except that in the Wyoming model the oxidation was introduced long after the rocks were deposited, and it migrated laterally downdip in gently tilted sandstone beds. The Morrison redox fronts, in contrast, would have been pene-syngenetic horizontal fronts which move vertically down into the fresh sediment from the depositional surface. It is also plausible that the Se, U, Mo distributions are more related to late oxidation events than to primary ore formation.

Mineralogy may also be used to distinguish redistributed uranium mineralization from primary mineralization. There are no recognizable vanadium minerals in primary ore, whereas montroseite and paramontroseite are common minerals in redistributed ore. Molybdenum is never redistributed, and calcite cement is rare in redistributed ore. Redistributed ores may contain barite, marcasite, and uraninite in minor amounts. These minerals are not generally associated with primary ore and are good evidence for nearby oxidation. Selenium is usually in a more distinct zone associated with the oxidation front in redistributed ore.

GENETIC MODEL

Evolution of Thought

It is worthwhile at this point to review the history and development of concepts concerning the origin of the uranium deposits in the Grants Uranium Region. The earliest uranium mineralization in the area was discovered in a limestone, and it was associated with a minor amount of fluorite (Hilpert, 1969, p. 101). This was immediately interpreted as hydrothermal in origin which was not unreasonable since the mineralization appeared to follow fracture patterns. Furthermore, fluorite mineralization was known to exist in the Precambrian basement rocks in the Zuni Uplift to the south, and the nearby Mount Taylor volcanic field could certainly have supplied the heat to generate a hydrothermal system. Therefore almost all of the field work in the early 1950's emphasized structure, especially the fault and fracture patterns. The discovery of uranium in sandstones along the outcrop reinforced the hydrothermal concept, because this mineralization was also closely associated with fractured areas, and the sandstones were noticeably bleached in the vicinity of the ores. The Westwater Canyon sandstones are red almost everywhere along the outcrop between Gallup and Grants except in the vicinity of mineralization. The red color was believed to be the original color of the sediment, and the bleached or limonitic areas were thought to be the result of alteration caused by hydrothermal fluids (Konigsmark, 1955, p. 13; Sharp, 1955).

This hydrothermal genesis was reinforced with the discovery of the deeper mineralization in Ambrosia Lake. Maps of the color distribution in the Westwater Canyon Member clearly showed that the mineralization was always in bleached rock, and that red, oxidized areas were barren. Therefore, very little drilling was done in the hematitic sandstones because the pyritic ground was considered evidence for the passage of mineralizing hydrothermal solutions. The discovery of uranium on the flanks of Ambrosia Dome, where it appeared closely associated with what was interpreted to be dried oil or asphalt, caused a modification in the hydrothermal theory (Gabelman et al, 1956, p. 63; Gruner, 1956, p. 204; Young and Ealy, 1956, p. 10). It was proposed that the uranium in the hydrothermal solution was precipitated due to reduction by the bitumen in a fossil oil field. Emphasis turned from fracture studies to detailed structure contour maps to define other positive structures.

Exploration soon showed that the uranium was not localized on the positives, but was in fact in the structurally low areas. Zitting et al (1957) explained that this anomaly could be produced by lowering of the water table and allowing the hydrocarbons to flow out of the structure and into the low areas. This was the beginning of the water table concept, for the uranium was believed to have been localized by the various positions of the oil-water contact as the water table dropped. Although Birdseye (1957, p. 29) continued to believe that the uranium was telethermal and precipitated by the asphalt, others began to question the hydrothermal source of the uranium. Knox and Gruner (1957, p. 23) completely ruled out a hydrothermal origin and suggested that the volcanics in the Morrison Formation could be the source of the uranium. Zitting et al (1957, p. 55) also questioned the hydrothermal model, and favored the idea that the uranium was introduced by the Morrison streams

from the source area. Gabelman et al (1957, p. 67), however, persisted in advocating a strictly hydrothermal model, and used the newly discovered Woodrow pipe in the Laguna District as evidence that "cryptovolcanic feeders" could have supplied uranium to the Morrison Formation.

As it became clear that uranium deposits were not limited to the structurally complex Ambrosia Lake area, or the domal areas, the models began to change. Thaden and Santos (1956, p. 75) suggested that the organic material may have originated from fluids derived from plants, which were moved down dip by ground waters, and were precipitated in stratigraphic traps. Hilpert and Corey (1957, p. 379) completely abandoned the idea of the ores being related to a fossil oil field, and they correctly predicted that the ore trends would project to the northwest and southeast because the distribution of favorable sedimentary facies was controlled by tectonics. To this facies concept was added the idea of uranium precipitated at, or near, a paleowater table prior to Dakota burial (Moench and Schlee, 1957, p. 29; Young, 1960, p. 32; Hilpert and Moench, 1960, p. 450). By this time the organics associated with the ores were generally considered to be of humic origin, but Granger (1960, p. 55) proposed that the humate originated from Dakota-age swamps, and was introduced into the Morrison Formation at the unconformable surface. Memoir 15, published in 1963, contained the best documentation of the universal uranium-organic association in the Grants region. The general impression gained from this volume was that both the uranium and organic matter was largely derived from within the host rock itself. All the essential elements of the humic model associated with some sort of ground water-related tabular horizon were developed by 1960. The major remaining questions, of the source of the humic material and the timing of mineralization, were discussed by Granger (1968). Squyres (1970) proposed that the uranium deposits formed very shortly after deposition of the host rocks and that both the metals and humic substances were derived from volcanic and organic detritus buried with the sediment.

By this time the Wyoming roll-type model was well developed and was being used with great success in exploration in the Wyoming basins and in South Texas. There was a growing feeling, mostly among workers from outside the Grants Region, that the roll-type model had universal application and that it should work in New Mexico as well. In 1971, Kendall concluded that the Section 27 orebody in Ambrosia Lake was an Early Cretaceous roll front. According to his model, the uranium had been leached from the host rocks by an oxidation front which moved north from the outcrop prior to Dakota burial. Most of the humic material would have been introduced at this time. This is an interesting conclusion because the Section 27 orebody is essentially an extension of the Ann Lee orebody in Section 28, which Squyres (1970) had studied. Squyres had concluded that the Ann Lee was a mineralized humate deposit. Kendall (1971, p. 141) even suggested that perhaps all the Colorado Plateau uranium deposits may be parts of one large roll front which was produced while the regional ground water drainage was towards the advancing Late Cretaceous sea. The roll front model had arrived, and with a vengeance.

Two papers appeared in 1976 which reiterated earlier models. Melvin (1976) proposed that the orebodies were controlled by a regional chemical ground water interface and that the humate was derived from the pre-Dakota swamps of Lower Cretaceous age. This was a variation on the older model proposed by Granger (1960-1968). Saucier (1976) stated that structure was the primary

control on the facies and humate distribution in the Westwater Canyon sandstones, and that the mineralization formed according to Squyres (1969) model. This was essentially the same model proposed by Young in 1960, but Young's paper was not open-filed until 1979. Rackley (1976) supported Kendall's interpretation and concluded that all the sandstone uranium deposits were of the roll type, and he proposed that they all be called the "western-states" type deposits. Adams et al (1978) suggested that the tabular uraniferous organic lenses and alteration zones in the Jackpile Deposit formed in a fluctuating zone of mixing between ground waters of dissimilar composition. Humic matter dissolved in high pH water produced by the alteration of volcanic material precipitated upon mixing with overlying normal ground waters of intermediate pH.

More recent papers have elaborated on the roll-type model in the Grants Uranium Region (Riese and Brookins, 1977; Clark, 1980; Peterson, 1980), and they have been unanimous in placing the formation of the "roll fronts" in the Late Jurassic to Early Cretaceous periods. The Wyoming roll-type model has been used with great success in locating redistributed mineralization in the western half of the region, but the primary trend model has been equally successful in extending the mineral belt to the east. The question remains as to whether the primary mineralization was essentially roll-type or are there really two models for the sandstone uranium deposits in the western United States.

Genetic Working Models

As a result of the present re-examination of the geologic data that has accumulated over the past 30 years, it appears that many ideas originally proposed in the late 1950's, concerning the relation of uranium mineralization to humic organic matter and its localization in broadly tabular zones related to ground waters, were essentially correct as applied to the primary ores. Although there are continuing uncertainties as to the precise timing and mechanisms of humate precipitation, the general ore-forming processes presented herein provide a framework for the selection of recognition criteria and the evaluation of potential areas. The primary mineralization is believed to be the result of diagenetic processes which took place within the host rock immediately after deposition. The mineralization process was aided at all stages by the mobile organic acids derived from the vegetal material buried with the sediments. The following genetic working models are presented as the most plausible explanations for the origin of the deposits based on the currently available but hardly unequivocal data.

Working Model I

Based on the regional alteration patterns, in particular the ilmenite-magnetite destruction and feldspar alteration, an ore-forming process may be proposed that emphasizes the juxtaposition of the Brushy Basin Member and the overlying and underlying sands of the Jackpile and Westwater Canyon sandstones. The possible elements of this model are presented below.

Sediment Deposition

The thick sands of the Westwater Canyon below and the Jackpile sandstone above were deposited as a continuous sedimentary sequence with the intervening Brushy Basin Member. The thickness of the sands (150 to 300 feet) and the shales (200 to 400 feet) assured a major hydrologic system with high transmissivity and the continuous deposition assured an integrated hydrochemical system from the moment of sedimentation so that important chemical events of early diagenesis were not lost due to a hiatus in deposition.

The sediment pile possessed uncommon "chemical potential" due to the juxtaposition of two inherently unstable components, organic material in the form of plant debris and volcanic glass in the form of tuffaceous sand and muds. The diagenesis and alteration of these components are known to independently produce widespread alteration assemblages. In the Morrison sediments, this potential was enhanced by the hydrologic system which assured their interaction leading to the development of an efficient ore-forming process.

Both the sands and the shales contained substantial organic detrital material at deposition, the sands a larger component of logs and smaller fragments, the shales fine organic debris such as would be expected to accumulate in overbank and lacustrine settings. Silicified logs and occasional carbonized logs, or trash pockets, attest to the organic material deposited with the sands. The fine carbonaceous debris which probably accumulated on cross-beds is essentially absent and must have been destroyed. No debris remains in the shales, hence its former presence is speculative. Three convincing lines of reasoning suggest, however, that it was once present:

(1) Fine-grained sediments such as the shales and siltstones of the Brushy Basin would be expected to contain organic debris at sedimentation, provided plant material was available. The presence of plant debris in the overlying and underlying sands suggest that it was indeed available. Barring oxidation of the debris during and shortly after deposition, as commonly occurs in continental sediments such as the Recapture Member of the Morrison Formation, it would have been available to produce a reducing environment in the shales during diagenesis. Preservation would have been enhanced by rapid sedimentation and burial below the water table or deposition in a lacustrine environment.

(2) The Brushy Basin in the Grants Uranium Region is almost entirely light to dark green in color, i.e., free of hematite staining which would be firm evidence of oxidation. It seems far easier to have produced the apparently non-oxidized state of such sediments during diagenesis, particularly with indigenous reductants, rather than through some extraneous reductant that would have to be introduced and overcome the non-transmissivity of the shale-rich member.

(3) The Brushy Basin Member is known to be rich in volcanoclastic material which, upon devitrification during diagenesis, would produce an alkaline ground water. Humic material is substantially more soluble in alkaline solutions, and it seems possible that the fine macerated organic debris in the Brushy Basin was quantitatively dissolved in the diagenetic pore fluids which, upon subsequent compaction and dewatering, carried the organic material away in alkaline solutions. It must be re-emphasized, however, that the Brushy

Basin now contains very little organic material and its hypothesized higher organic content at burial is based solely on the points mentioned above and a plausible geochemical argument for its destruction.

Thus, as the Brushy Basin sediments accumulated over the Westwater Canyon sandstone, the stage was set. The arenaceous and argillaceous sediments contained all the components required for the formation of the ore deposits, including the uranium in volcanic glasses, the organic material in detrital plant debris, and the shales and sandstones which would provide the hydrologic setting for post-depositional diagenesis, compaction and dewatering of the shales, and the establishment of ground water chemical interfaces for the formation of the ore deposits.

Diagenesis

As the shales of the Brushy Basin Member commenced to accumulate over the Westwater Canyon sandstone, a regime was established for the juxtaposition of two ground waters of distinctly different chemistry. The waters of the Westwater Canyon sandstone, particularly the deeper portions, were locally oxidizing and locally reducing depending upon the distribution of indigenous organic material. Hydrologically, however, the ground water flowing through this mass of sandstone was never strongly reducing, as is evidenced by the widespread presence of ilmenite and magnetite in the deeper portions of the sand, and indeed by the hematite rims almost everywhere present on these grains. Thus, although there was undoubtedly a considerable amount of organic material incorporated in the sand, much of it was silicified, dissolved, altered and oxidized without the complete destruction of ilmenite and magnetite. This strongly suggests that the Westwater Canyon was in hydrologic continuity with a recharge area, and that the introduced oxidizing solutions destroyed most of the organic material in the sands. These ground waters were not strongly oxidizing, however, because ilmenite and magnetite have only thin hematite rims. This model assumes a continuous flow of ground water within the Westwater Canyon from the time of deposition. It is likely that toward the source area Westwater Canyon sands continued to be deposited for some time, whereas in the more distal regions, the Brushy Basin facies had commenced to be deposited. This region would have permitted easy access for ingress waters and continuous flow within the Westwater Canyon aquifer.

With the deposition of the overlying Brushy Basin, which most likely advanced progressively over the Westwater Canyon from the more distal portions of the fan back toward the fan head, the ground waters of the Westwater Canyon Member were confronted with waters of a distinctly different composition. The shales and siltstones of the Brushy Basin were presumably deposited as typical finer-grained sediments with 40 to 60 percent solids by weight. As greater thicknesses of Brushy Basin sediments accumulated the contained water commenced to be expelled. However, the alteration of the volcanic detritus within the Brushy Basin had already begun so that the composition of the expelled fluids was strongly influenced by their contact with altering volcanic glasses. As is well known, this alteration would have produced alkaline ground waters, which in turn would have been capable of dissolving the fine organic debris dispersed within the Brushy Basin Member. These processes produced the broad grayish-green to green reduction typical of the Brushy Basin before the fluids were expelled up through the accumulating Brushy Basin pile, or down into the underlying Westwater Canyon aquifer. Fluids expelled down into Westwater

Canyon would have been in marked chemical contrast to the oxidizing or very mildly reducing neutral ground waters of the Westwater Canyon with which they would have established a chemical interface and gradient. It is this interface or gradient which most likely caused the formation of the uraniferous carbonaceous primary ores of the Grants Uranium Region.

The shape and position of the interface between the two masses of ground water was probably controlled by the rate of flow of the Westwater Canyon ground waters and the volume and lateral changes in flow rates across the Brushy Basin-Westwater Canyon interface. Field relations in the Grants Uranium Region suggest that in the vicinity of ore districts where the Westwater Canyon becomes overthickened, it does so at the expense of the overlying Brushy Basin by developing upper sands which are laterally interbedded with the Brushy Basin sediments. This provides a unique opportunity for dewatering a larger volume of Brushy Basin, hence, concentrating the discharge of greater volumes of reducing solution directly below these zones of upward, overthickened Westwater Canyon. Although in the present study sufficient subsurface data has not been analyzed to demonstrate this stratigraphic contention beyond reasonable doubt, it is suspected to be valid and would be a worthy subject of study for the evaluation of other portions of the San Juan Basin.

Ore Formation

The mixing of the two solutions hypothesized in the preceding paragraphs provides a simple mechanism for the formation of the uranium deposits in the district. This mechanism is compatible with the distribution of alteration assemblages identified in this study. The alkaline organic-rich reducing solutions expelled from the Brushy Basin down into the Westwater Canyon sandstone altered the detrital ilmenite and magnetite and produced the feldspar alteration and dissolution discussed in earlier sections. The greater intensity of these alterations at the top of the Westwater Canyon is compatible with such an interpretation. Where these waters mixed with the Westwater Canyon ground waters, the decrease in pH led to the precipitation, coagulation, and fixing of the organic material which is notably less soluble in more acid solutions. Depending upon the hydrodynamics, the interface between these two bodies of water may have remained stationary for some period of time, may have moved back and forth repeatedly, or may have led to the precipitation of a vertical series of stacked organic-rich lenses. It would be expected that the boundary would fluctuate and move, leading to numerous local complexities in ore distribution, paragenesis, and alteration. The stabilization of the humates in tabular lenses that locally display S-shaped rolls, may have been the simplest hydrologic response to the chemical interface between the two bodies of water. Once precipitated, the humic matter may have permitted the initiation of several other alteration events. Alumina, silica, and alkali and alkali-earth cations complexed on the organic material were slowly released, partly through changes in the chemical environment of the organic material and partly through its degradation, to form truly authigenic silicate phases which are now recognized as authigenic clay rims on detrital clasts. As these clay phases are best developed adjacent to ore, and as the chemical components, particularly alumina, do not customarily travel and concentrate in such a fashion, circumstantial evidence suggests that the dissolved organic material was the medium for dissolution, transport, and ultimate release of these elements. Furthermore, the development of altered and replaced feldspars within the reduced zones, particularly the hollow

grains, require the removal and transport of considerable amounts of alumina and silica. This too was probably effected by the dissolved organic material.

It would also be expected that once the tabular humic zones had been precipitated as gel-like masses in the sandstone, the continued flow of ground water would have produced the hydrodynamic shapes that have been recognized in the deposits of the Ambrosia Lake (Squyres, 1970). The waters moving through and past the humic zones, furthermore, would have been introducing small amounts of uranium in solution, particularly as they were mildly oxidizing solutions from the Westwater Canyon ground waters proper. With time, the expulsion of Brushy Basin waters into the Westwater Canyon probably diminished and ultimately ceased, so that the regime of the deeper more oxidizing waters increasingly encroached upon the shallower reduced ground water facies. This would have permitted continued ground water flow to slowly contribute small amounts of uranium to the deposits, ultimately producing the high grades now characteristic of the ore lenses. The solutions were not sufficiently oxidizing, however, to completely destroy the ore lenses. Once the ground water became more stagnant at the end of the Jurassic depositional cycle, it became mildly reducing due to the influence of the residual detrital and epigenetic carbonaceous material. This last event provided the widespread characteristic drab color of the sands now seen in the subsurface. A similar sequence of events could have operated between the Brushy Basin shales and the Jackpile sandstones following their deposition.

Working Model II

An alternate scenario is also plausible. Whereas the preceding model presented an explanation for the regional alteration patterns based on the derivation of organic-rich reduced solutions from the Brushy Basin, one might presume that all the humic matter, and most of the uranium, was derived from the Westwater Canyon sandstones rather than the Brushy Basin mudstones. If sufficient organic detritus is buried with sediments, an anaerobic environment will develop below the static water table (Love, 1964; Jensen, 1958). Bacterogenic H_2S , and carbon dioxide, methane, and hydrogen gas from fermentation of the vegetal material will cause a drop in pH (Rackley, 1976, p. 112). Iron in the ground water and in iron-bearing detrital grains may react with the H_2S to form monosulfides, and eventually, stable pyrite. This chemical reduction of the sands can occur very early and at shallow depths.

The surface and shallow ground waters in Late Jurassic time are assumed to have been alkaline and oxidizing, due to the arid or semi-arid climate, and the alteration of volcanic debris in the sediment. The surface waters probably had a pH of about 7.5 to 8 due to the hydrolysis of the volcanic ash in the system. Humic acids leached from woody trash and macerated leafy material by the alkaline waters in the upper oxidizing portions of the channel deposits could have moved down to the static water table, and at this point, or some distance below, the pH was sufficiently low to cause flocculation of the humic substances. Granger (1968, p. 67) hypothesized that precipitation occurs along the interface between the stream underflow and the deeper slower moving ground waters. Flocculation of the humate will definitely occur at a pH of 5, but can occur at much higher pH's if the humic acids are somewhat mineralized. Uranyl humate complexes have been found to precipitate at a pH of 6.5 (Schmidt-Collerus, 1969, p. 30). The initial flocculate is a thin gel which can be molded by lateral ground water flow as described by Squyres

(1970, p. 158), or by seasonal fluctuations in the water table. The humate will be in the form of broad, tabular, semi-horizontal masses in the channel sands, perhaps as shallow as 10 to 20 feet below the stream bed. Bacteria which feed upon the precipitated humate contribute to a further lowering of the pH and thus to further flocculation of humic acids. Once the channel deposit is buried, the humate lense is protected by a stratigraphic rise in the acidic reducing environment, and by the continued adsorption of cations. Once the channel deposit is buried, the sequence can be repeated over again at a higher stratigraphic level, if organic material is available in the overlying deposits.

The uranium content of the surface and shallow ground waters could have ranged from 50 to 300 ppb, and it was probably transported by both uranyl carbonate complexes, as proposed by Gruner (1958, p. 18), and organic acid complexes, as suggested by Schmidt-Collerus (1979, p. 6). The uranyl humate complexes could have been precipitated directly as a result of the drop in pH across the sub-horizontal redox front, whereas the carbonate complexes were destroyed by the deeper acid waters, and the uranium released to contribute to the enrichment of the humate. Hydrogen sulfide generated in the humate gel by bacteria caused the precipitation of Fe, Mo, Se, and As as sulfides. The molybdenum apparently precipitated as a negative colloidal sulfide which was repelled by the negative humic colloids. This is why the jordisite masses are almost never in actual contact with humate as pointed out by Squyres (1970, p. 160), and Kendall (1971, p. 39).

Eventually the tabular humate impregnation matured and hardened into a brittle grain-coating or interstitial filling in the sandstone. During maturation, the large organic molecules broke down due to oxidation, microbial attack, aging, and radiation, and much of the complexed uranium and vanadium was released. The uranium formed the silicate coffinite, and the vanadium entered the lattice of authigenic chlorite.

The diagenetic process outlined above takes place early, quickly, and efficiently. The ability of the humate to collect and concentrate uranium, however, diminishes rapidly with time. The factors which limit the size and richness of the deposit are the initial concentrations of humic matter, the uranium content of the waters, and the permeability of the sediment which controls the rate of exposure of the uranium to the organics. All of these factors are at a maximum immediately after the sandstones are deposited. The labile nature of both the volcanic source material and the organic acids also support the idea of a very early age for the ore-forming process. This organic model is simple and lends itself to easy laboratory confirmation (Ethridge et al, 1980).

The real problem is explaining how such large deposits of humate, such as those found in Ambrosia Lake, form. The chemical factors are believed to remain the same whether the deposit is only a few pounds, or a million tons in size. The factors which determine the size of the humate deposits are geologic. Geologic parameters such as the size of the fluvial deposit itself, the amount of buried vegetal material and the porosity and permeability are dependent upon the depositional environment and climate. Assuming the climate remains constant during mineralization, the other geologic variables are mostly determined by structure. The highest concentration of transported organic debris appears to be located adjacent to the Zuni positive area in

sedimentary trends that appear to be structurally controlled down-warps which channeled and superimposed high energy fluvial systems. These shallow "synclines" also funneled subsequent ground waters which were carrying dissolved humic substances and uranium along the same linear trends. The result of these very subtle structural influences was the accumulation of unusually large masses of uraniferous humate concentrated along the axes of these down-warps. The relatively thin, sheet-like geometry of the ore lenses and their elongation in the down-stream direction are unique characteristics of this type of uranium deposit and are best explained by this working model.

Uranium Source

The main source of the uranium was the acid volcanic detritus which may have constituted 20 percent or more of the original Westwater Canyon and Jackpile sandstones and a substantially larger percentage of the intervening Brushy Basin shales and siltstones. Alteration of these volcanoclastics during transport, and very soon after deposition, released uranium and other metal ions to the fluid system which may already have been anomalous in uranium due to the alteration of vast amounts of tuffaceous material in the area of provenance.

The low thorium:uranium ratios in the Brushy Basin sediments and correspondingly higher values in the Westwater Canyon (Delle Valle, 1980, personal communication), particularly in the lower part of the member, suggest that the Westwater Canyon has been leached of its uranium while leaching of the Brushy Basin has contributed little or no uranium. This is compatible with the generally reduced state of the Brushy Basin sediments, i.e. non-oxidation hence low uranium solubility, and the evidence we see for pervasive mild oxidation of the ilmenite-magnetite bearing lower Westwater Canyon sandstone. Precisely from where the uranium in the ore deposits came is unknown, but it is likely that the main source was up hydrologic gradient and from rocks that were oxidized by the time the early post-depositional Westwater Canyon ground waters formed the deposits.

Structural Controls and Ore Trends

The chemical factors discussed above were entirely the result of a prepared sedimentary sequence. The inherently unstable components were combined in a "batch mix", as it were, and promptly began to transform upon deposition. All of this would probably not have occurred but for basement structures that permitted the accumulation of thick organic-rich sands and shales as wet alluvial fans. These structures produced a series of trends, the most productive of which is located parallel to the southeast-trending Zuni Mountains and includes the Ambrosia Lake, Church Rock, Mt. Taylor, Marquez, and Bernabe Montano mineralized areas. A similar trend is reflected by the northeast-trending Jackpile sandstone with its major deposits. Not only did these structures control the location of persistent overthickened sands, it appears that they promoted the development of sands which extended into and were intimately interbedded with the Brushy Basin shales and siltstones, the Westwater Canyon at its top, the Jackpile at its base. This interbedding may

have focused Brushy Basin dewatering into the sands whose thicker trends reflect structural control of sedimentation. Were it not for the structural influence on the trends the uranium mineralization in the Grants region would probably be a much broader scattering of smaller orebodies along shorter, ill-defined trends.

Comparison with Wyoming Roll-Type Deposits

Two principal types of uranium deposits in sandstones have been recognized in the western states. These two types have been called the Colorado Plateau, or trend type, and the Wyoming, or roll-type type (Shawe and Granger, 1965; Fischer, 1970). There are valid distinctions between these two types that have long been recognized. The most obvious distinction is that roll fronts are usually closely associated with the interface between altered and unaltered sandstones, the altered sand of some districts containing dispersed hematite, whereas the trend type is normally found in completely reduced host rock. It had previously appeared that the "reduced host rock" around the deposits was similar in its composition and characteristics, but as shown in this report there are broad and systematic alteration patterns which differ above and below the tabular ore-bearing zones.

A second obvious distinction is the abundance of epigenetic, redistributed humic material in the Grants ores. Although there is evidence of some redistributed humic material in the roll-type deposits, it is far less in absolute amount. The trend deposits parallel the channels or sedimentary transport directions of the host sandstone whereas the roll-type deposits are commonly aligned along redox interfaces almost normal to the paleostream directions. The geometry of the two types also differs. The trend deposits are generally concordant, whereas the roll-type deposits are discordant reflecting the very important difference in time of formation. The uraniferous humate deposits formed soon after deposition, whereas the roll front deposits were superimposed on the sands at a later time. This criterion, however, is not always that distinctive. In spite of the distinctions between these two types of sandstone uranium deposits, their differences have become blurred in recent years in some authors' attempt to place all sandstone uranium deposits under the roll-type classification.

RECOGNITION CRITERIA

Introduction

The geologic characteristics of important uraniferous humate deposits have been reviewed and discussed in the context of ore-forming processes in the preceding sections of this report. We now proceed to identify those geologic characteristics related to these deposits that we feel are most diagnostic for the presence or absence of deposits in unexplored areas. The geologic characteristics selected, including geophysical and geochemical observations, are referred to as recognition criteria, and have been shown to be related in some significant way to this type of deposit. These recognition criteria should be useful in resource studies and exploration for estimating the geologic favorability of an area of study for the occurrence of a uraniferous humate deposit.

The selection, definition, and ranking of recognition criteria are routinely performed by the expert geologist "in his head". The material presented in this section and in Appendix 2, is not intended for the "expert" but for those geologists involved in exploration or resource studies who are still developing their data bases and interpretations. Nor is this material presented as a "cookbook" to be perfunctorily applied to prospective areas. Considerable geologic judgement is required in the use of the recognition criteria, and inexperienced geologists will encounter much difficulty. The criteria are merely guides to be used by trained geologists as they develop their evaluations of unexplored areas for purposes of exploration or resource studies.

To be useful in resource studies or exploration, recognition criteria are chosen so that: (a) when they are present or favorable, the chances of a deposit being present are significantly increased, i.e. they are important "good news"; or (b) when they are absent, or unfavorable, the chances of a deposit being present are significantly decreased, i.e., the negative criteria are important "bad news". Some recognition criteria have both attributes and are thus particularly useful. By using only criteria that significantly affect the likelihood of a deposit being present or absent, one avoids the distraction of including geological observations which are too ubiquitous or undiagnostic to be useful guides to the favorability of an area.

Considerable subjectivity is involved in the selection, definition, and use of the recognition criteria. Because geologic observations do not lend themselves to rigorous numerical treatment, the use of such data unavoidably involves subjective judgement. In our opinion, it is far better to use the data and the judgements, carefully documenting where and how subjectivity has been used, than simply to leave the reader to make the most of geologic information such as was presented in the preceding sections of this report. In the following paragraphs, therefore, we subjectively select and define those criteria which, based upon our experiences and the data contained in the preceding sections of this report, we consider to be most useful for evaluating areas for uraniferous humate deposits. We make no pretense that these are the only criteria and definitions that could have been chosen; they are simply the best ones we were able to devise. The reader may prefer other criteria

and/or other definitions which, if they reflect geologic facts, may improve our list. We acknowledge that such improvements will be needed, and solicit constructive comments and contributions. Only through a consensus of careful observations and informed opinions will the criteria become reliable and useful.

Recognition criteria may be defined so that they are general or specific. For example, permeability might be chosen as a criterion, and defined to incorporate observations on relevant geologic characteristics, such as sorting, rounding, and sphericity. Conversely, each of these could be chosen as a criterion. For simplicity, we prefer to lump criteria, and therefore, have subdivided them only as far as seem necessary to avoid ambiguity and to identify the most important geologic observations. Here again, subjective judgment and personal preference enter the process.

The detail or scale of each recognition criterion deserves special mention. As exploration and resource studies are conducted on areas of vastly different size and degree of geologic definition, it is appropriate to include recognition criteria that range from regional in scale (i.e., "regional tectonic setting", "uranium content of basement rocks", etc.) to local (i.e., "alteration in the sandstone", "color of interbedded shales", etc.). We have attempted to do this in the accompanying criteria, but some readers may consider certain criteria too general or too detailed to be useful, or may wish to include criteria yet more general or more specific. These options, where supported by geologic data, may improve the list of recognition criteria.

In Figure 17 the criteria we have selected for the uraniferous humate deposits are arranged by scale of observation, proceeding from the broadest and most regional on the left to the most local on the right. The reader will note that the criteria also are arranged in a hierarchical format with the more general criteria, located at the top of the diagram, progressively subdivided into more detailed "modifying" criteria toward the bottom of the recognition criteria net. This format, patterned after Hart, Duda and Einaudi (1978), permits the lowest level criteria (terminal criteria), which are based on field observations, to be combined to evaluate the favorability of the higher level criteria above them. In the evaluation of an area this combining process continues up through the recognition criteria net until the favorability of the area of study for a uraniferous humate deposit is determined. A rigorous method for combining information on the criteria has been presented by Hart, Duda and Einaudi (1978) and a specific application developed for roll-type deposits by Rackley (Gaschnig, 1980). In Appendix 2 we present a much-simplified method for combining geologic observations to reach favorability estimates. The reader is cautioned that the individual criteria are used only to establish the favorability of intermediate level criteria. The ultimate favorability estimate for a uraniferous humate deposit is the composite effect of many criteria and it is not necessarily equivalent to the probability of a deposit being present as will be discussed in Appendix 2.

With recognition criteria identified and organized as in Figure 17, it is now possible to geologically define each criteria and establish its relative importance in determining the favorability of the criteria above it in the net.

Figure 22. Recognition criteria net for the uraniferous humate type sandstone uranium deposit. Numerical estimates of relative favorability are not assigned to recognition criteria shown in dashed lines.

Figure 17. Recognition criteria net for the uraniferous humate deposits, Grants Uranium Region. Numerical estimates of relative favorability are not assigned to recognition criteria shown in dashed lines.

The selection and definition of criteria is subjective, as discussed earlier, but the estimation of the relative importance of criteria is even more so. The justification for assigning importance or weight is that intuitively we feel some criteria are more important than others. As with the criteria themselves, we have assigned the best set of weights we could develop, but they are entirely subjective and the reader may be justified in modifying our estimates to reflect his data. Weights assigned are obviously only approximations to indicate the relatively encouraging or discouraging nature of a particular definition of a criterion. An estimate of +65, for example, might as well have been +75 or +50. We are simply attempting to capture the geologist's approximate estimate of the relative importance of geologic observations as an additional aid in the evaluation of unexplored areas. The system is subjective and imprecise and likely to remain so, but the subjective information is useful if we can learn to collect and use it properly. It is toward that end that relative importances are assigned to all criteria in the following section and a simple method for accumulating this information is presented in Appendix 2.

Evaluation of Recognition Criteria

The assignment of importance or weight to recognition criteria may be conveniently explained by referring to the four criteria in Figure 17 which evaluate Host Sandstone Composition (HSC). Each of the four criteria embodies, in the geologist's mind, numerous considerations which relate to geological observations, the processes they reflect and their importances to the presence or absence of a uranium deposit. With respect to evaluating HSC, which in turn will be used with three other criteria to evaluate the favorability of the Host Sandstone, these are presumably the five most important criteria that could have been selected, and we assume no important criteria have been omitted.

In most cases, any five such criteria will have different importances in establishing the intermediate criterion above them. Therefore, importance or weight is assigned to each recognition criterion with the aid of the relation shown in Figure 18. Weights are assigned to each criterion independently of the others based on how sufficient the presence of the criterion by itself is for establishing the presence of favorable HSC or how sufficient the absence of the criterion is by itself to establish the absence of favorable HSC. For example, if one knows something about the organic content of the sands in some area under consideration, but knows nothing about the three other criteria, how favorable is HSC? The range of organic contents one might expect in sandstones includes:

- widely dispersed silicified logs and carbon trash
- very rare silicified logs and carbon trash
- no silicified logs or carbon trash
- abundant carbon trash

The favorability of HSC decreases through this (additional descriptions of possible organic concentrations might have been chosen but, as with all the criteria, no attempt is made to be inclusive, merely to provide enough examples so that the geologist can use his judgement in applying the criteria

Figure 18. Example of the assignment of weights to recognition criteria using the four criteria that determine Host Sandstone Composition.

to other geologic conditions). Therefore, the likelihood of favorable HSC being present is highest if the organic content of the sands is widely dispersed silicified logs and carbon trash, and lowest if the sands contain abundant carbon trash.

Suppose the sands of some area are known to contain widely dispersed silicified logs and carbon trash. Since this is the type of organic content characteristic of the Westwater Canyon and Jackpile sandstones, it is suggestive or "good news" for the presence of the proper HSC, but how suggestive is it? In Figure 18, modifying expressions have been arranged along arbitrary scales from 0 to +100 and 0 to -100 as an aid to the geologist in estimating the importance or weight for a particular criterion. The positive scale is used when geologic observations confirm the presence of a recognition criterion, i.e. it is encouraging or "good news" for the occurrence of the higher level criteria. The negative scale is used when the criterion is absent, i.e. it is discouraging for the presence of favorable HSC. Zero is used when the available data neither increases nor diminishes the favorability of HSC. The scale ranges and modifying expressions might have been chosen quite differently, for example, 0 to 1.0 or 0 to 500 and with different words such as "favorable" and "very favorable" for the positive scale and "unfavorable" and "extremely unfavorable", etc., for the negative scale. The conventions used were arbitrarily chosen but seemed easy to work well as explained below.

To assign weights to a criterion, the geologist asks, "If the criterion is absolutely perfect, i.e., if the sands in the area under evaluation contain the perfect type of organic matter, how suggestive is it that favorable HSC is present?" In the case of organic matter, we feel the presence of widely dispersed silicified logs and carbon trash is very suggestive that the HSC is perfect, i.e., the criterion by itself is sufficiently important that if present with no information on other criteria it provides +55 percent certainty that the HSC is perfect.

If on the other hand, carbonaceous material is abundant, it is very damaging for proper HSC, thus we have designated it very discouraging and assigned it a value of -70. The presence of abundant carbonaceous material essentially destroys the potential for not only a favorable HSC, but for a uraniferous humate deposit. It is up to the geologist using this system to place proper weights on levels of organic content not specifically defined (such as "very rare silicified logs and carbon trash"), using his judgement and the examples provided.

Organic matter is not the only criterion for evaluating HSC. The abundance of volcanic clasts also has significant impact. When considered without any other information, the presence of favorable amounts of volcanic clasts is moderately suggestive (+45) for the presence of favorable HSC. If the sands contain more than 50% volcanic clasts, it is considered very discouraging and we have assigned a value of -65.

The nature of the clastics, on the other hand, is at best only mildly suggestive (+30), i.e. when the host sandstone is an arkose. If the sand is very poorly sorted and/or contains altered or unresistant clasts, we consider it very discouraging and have assigned a value of -70. The fourth criterion, sand-shale proportion, has similarly been assigned suggestivity values for when it is favorable and negative values for when it is discouraging for the

presence of favorable HSC. Values have been assigned for all the lowest level criteria and for the intermediate level criteria for evaluating the yet higher level criteria, and are tabulated in Table 6. The "model" is now ready to use in the evaluation of real data.

The reader will have perhaps made two observations from the foregoing discussion. First, it is assumed that each recognition criterion is independent of all others, i.e. each is used separately to evaluate the criterion above it. In fact many criteria are not independently variable, and would affect the likelihood of the higher criterion differently in combination than they do by their simple sum. However, error or bias due to nonindependence of variables is lost in the accumulated uncertainties of the geologic data and the conclusions we make about them. Secondly, there is a continuous range of decreasing favorability for each criterion starting at the maximum weighting and extending down to the most discouraging, "worst case". In applying the method, the geologist should use his judgement in selecting favorability values for his field observations. For example, he may believe his area is a graben but that it is a very large graben system which would increase its favorability up toward Intracratonic Non-marine Basin (Table 6). He might, for example, assign a value of +50 in contrast to our value of +25 and be justified in doing so. This method is to be used with geologic judgement and good sense and is not a substitute for them.

Description of Recognition Criteria

In order to apply the recognition criteria net (Fig. 17) to the evaluation of field areas, it now remains to (a) describe the recognition criteria so that they can be evaluated with field geologic observations and (b) assign numerical value to various states of the criteria depending upon how suggestive or discouraging the states are for the intermediate criterion above them. In the following pages, the criteria are organized by the major second level criterion shown in Figure 17. The subjective values for the criteria, estimated according to the procedures described in the preceding paragraphs, for the various criteria accompany the definitions. The values for the descriptive criteria are summarized on Table 6.

Regional Tectonic, Structural and Geologic Setting

Tectonic Setting

Of the possible tectonic settings in which a favorable sedimentary sequence might accumulate, the broad intracratonic basin is by far the most favorable because of its size and the associated geologic conditions which promote both the accumulation of the host sediments and a proper diagenetic history. The favorability of some potential environment may be arranged as follows:

(1) Intracratonic non-marine basin	+80
(2) Intermontane basin	+45
(3) Graben	+25

(4) Coastal plain	-10
(5) Miogeosyncline	-80
(6) Eugeosyncline	-95

Structural Setting

In the most favorable settings basement structures, principally fault-bounded tilted blocks and grabens, are believed to have controlled the formation of linear sedimentary trends. These trends, in turn, controlled the distribution of thick sand bodies. These structures were active during sedimentation and are part of the regional tectonics which produced the broad depositional environment. Less favorable basins will be characterized by monotonous, uniform dips around their margins. In more favorable basins the outcrop patterns will be broken by structures which occur within or project into the basin and deflect or break the outcrop pattern and alter dips. Structures such as monoclines, domes, broad plunging folds, and bounding basement uplifts are all evidence of basement instability. Guides to the presence and locations of basement structures may be inferred from fracture sets within younger sediments, alignments of volcanic necks, regional folds, and other features that respond to basement control.

Structural favorability may be generalized as follows:

(1) Numerous structural elements occur within the basin and appear to control the attitudes and habit of the sediments.	+30
(2) The uniform distribution of sediments within the basin and the absence of obvious structure suggests broad basement stability.	-50

Deformation

As uraniferous humate deposits are formed during diagenesis of the sediments, the attitude of the beds is essentially that of deposition. After deposition the sediments may be folded, faulted, and even metamorphosed. Some of the structures may promote destruction of the deposits, whereas others may even help preserve districts as the faults in Ambrosia Lake are believed to have done. The absence of strong deformation, including metamorphism, is somewhat favorable, whereas strong deformation is definitely unfavorable. We have been unable to assign simple weights to various combinations of type and intensities of deformation.

Sediment Provenance

Rocks yielding coarse stable clasts, such as quartz and feldspar, are suitable source rocks for favorable host sandstones. Broad areas of intermediate to acid plutonic or "granitic" rocks and mature coarse clastic sediments are considered favorable. Evidence of hypabyssal intrusives and volcanics are also favorable. In most cases, particularly with broad intracratonic basins, the sediment source areas are not known and may even be multiple. For this reason we have refrained from assigning favorability values to potential source terrains.

Table 6. Estimates of the values (Scale +100 to -100) for recognition criteria for uraniferous humate deposits for establishing the favorability of the criteria above them in the criteria net (see Fig. 17).

<u>Criterion</u>	<u>Estimate of Suggestivity When Present or Favorable</u>	<u>Estimate of Discouragement When Absent or Unfavorable</u>
Uraniferous Humate Deposit		
Tectonic, Structural and Regional Geologic Setting	+30*	-95*
Continental Sedimentary Sequence	+55*	-95*
Host Sandstone	+45*	-95*
Alteration and Mineralization	+65*	-95*
	+195	-380
Tectonic, Structural and Regional Geologic Setting		
Tectonic Setting	+80	-95
Intracratonic, non-marine basin (+80)		
Intermontane basin (+45)		
Graben (+25)		
Coastal plain (+10)		
Miogeosyncline (-80)		
Eugeosyncline (-95)		
Structural Setting	+30	-50
Numerous structures (+30)		
Few structures (-50)		
Deformation	no values assigned	
Sediment Provenance	no values assigned	
Uraniferous Province	<u>no values assigned</u>	
	+110	-145
Continental Sedimentary Sequence		
Age	+30	-80
Mesozoic (+30)		
Devonian to Permian (+20)		
Cenozoic (+10)		
Pre-Devonian (-80)		

Table 6. (continued)

<u>Criterion</u>		<u>Estimate of Suggestivity When Present or Favorable</u>	<u>Estimate of Discouragement When Absent or Unfavorable</u>
Associated Sediments		+30	-90
Thick and widespread	(+30)		
Thin and limited	(-90)		
Host Sediments		+75*	-95*
Thickness			
Area			
Sand-Shale Facies			
Shales		—	—
		+135	-265
Host Sediments			
Thickness		+25	-40
Several hundred feet	(+25)		
Few hundred feet	(-40)		
Area		+25	-50
> 10,000 square miles	(+25)		
< 1,000 square miles	(-50)		
Sand-Shale Facies		+40	-35
Continuous sedimentation	(+40)		
Discontinuous sedimentation	(-35)		
Shales		+60*	-85*
		+150	-210
Shales			
Color		+45	-80
Greenish	(+45)		
Red or dark gray	(-80)		
Bentonite		+75	-75
Abundant	(+75)		
Absent	(-75)		
Carbonate and Silica		+30	-30
Present	(+30)		
Absent	(-30)		
		—	—
		+150	-185

Table 6. (continued)

<u>Criterion</u>		<u>Estimate of Suggestivity When Present or Favorable</u>	<u>Estimate of Discouragement When Absent or Unfavorable</u>
Host Sandstone			
Area		+20	-50
> 700 square miles	(+20)		
< 100 square miles	(-50)		
Thickness		no values assigned	
Depositional Environment		+45	-70
Mid fan	(+45)		
Distal fan	(-60)		
Proximal fan	(-70)		
Permeability		+10	-50
High	(+10)		
Low	(-50)		
Composition		+55*	-95*
Organic matter			
Clastics			
Volcaniclastics			
Sand-shale proportions		_____	_____
		+130	-265
Composition			
Organic Matter		+55	-70
Trash and silicification	(+55)		
None	(-60)		
Abundant	(-70)		
Clastics		+30	-70
Arkose	(+30)		
Argillaceous	(-10)		
Graywacke	(-70)		
Volcaniclastics		+45	-70
Moderate	(+45)		
None	(-30)		
Abundant	(-75)		
Sand-Shale Proportions		+35	-70
60-80% sandstone	(+35)		
40-60% sandstone	(+15)		
> 80% sandstone	(-50)		
< 40% sandstone	(-70)	_____	_____
		+165	-280

Table 6. (continued)

<u>Criterion</u>		<u>Estimate of Suggestivity When Present or Favorable</u>	<u>Estimate of Discouragement When Absent or Unfavorable</u>
Mineralization and Alteration			
Mineralization		+20	-70
Common	(+55)		.
Some	(+20)		.
None	(-70)		
Alteration		+80*	-95*
Ilmenite-magnetite			
Pyrite			
Feldspar		—	—
		+100	-165
Alteration			
Ilmenite-Magnetite		+75	-85
Destroyed	(+75)		
Partly destroyed	(0)		
Unaltered	(-85)		
Pyrite		+60	-35
Significant	(+60)		
Trace	(+10)		
None	(-35)		
Feldspar		+40	-60
Strong alteration	(+40)		
Moderate alteration	(+15)		
Unaltered	(-60)	—	—
		+175	-180

*Values assigned to intermediate level criteria.

Uraniferous Province

There is accumulating evidence that uranium deposits in sandstone occur most frequently in what have been termed "uraniferous provinces." These are areas in which the rocks, particularly the Precambrian granitic rocks (or the refractory minerals in them such as zircons), acid volcanics, continental clastic sediments, pegmatites and even metamorphic rocks, contain (a) more than an average concentration of uranium or (b) an abundance of uranium anomalies. In the case of intracratonic basins, because of the distance of transport, the sediment provenance is commonly not known and the immediately underlying basement may have little to do with potential. For this reason we have not estimated relative favorability values for Uraniferous Province.

Continental Sedimentary Sequence

A sequence of sediments deposited in the same general depositional system is referred to as a Sedimentary Sequence. This Sedimentary Sequence will include the potential Host Sediments and other sediments referred to as Associated Sediments which indicate the general nature of the depositional environment but which are of themselves not necessarily favorable to the occurrence of deposits. The Host Sediments, Associated Sediments, and their Age will be considered separately.

Age

Sediments of certain ages are favorable to the occurrence of deposits because of the evolution of organic material and the dominance of certain tectonic styles. Prolific development of land plants since Silurian time provides the possibility that sediments younger than Silurian may contain plant debris, and hence the reducing environments so critical to the formation of uraniferous humate sandstone deposits. Crustal tectonics leading to the formation of broad intracratonic continental sedimentary basins, characteristic of the Upper Paleozoic and Mesozoic, are more favorable than the Cenozoic tectonism which produced abundant but small basins of deposition.

The age of the continental sedimentary sequence is:

(1) Mesozoic.	+30
(2) Devonian to Permian.	+20
(3) Cenozoic.	+10
(4) Pre-Devonian.	-80

Associated Sediments

Thick sequences of red beds and eolian sandstones with interbedded non-marine chemical sediments (fresh water limestone, playa and lake deposits) indicate continental sedimentation under dry climatic conditions. These general conditions are considered favorable provided suitable host rocks are present, even though, so far as known, these rocks themselves are decidedly unfavorable for the occurrence of uraniferous humate deposits. Favorability increases

somewhat with the thickness of the sedimentary column and its area of distribution (a sedimentary column of several hundred to several thousand feet, and occurrences over tens to hundreds of thousands of square miles in area would be favorable).

The associated sediments are:

- (1) Dominantly continental, thick and widely distributed. +30
- (2) The continental sediments are absent or very thin and restricted in area. -90

Host Sediments

"Host Sediments" refer to a particular part of the Continental Sedimentary Sequence which is composed of sediments that were deposited in related depositional environments and may include one or more sedimentary members, formations or even groups. Host Sediments is a more broad and general criterion than, for example, Host Sandstone which may or may not be known to occur within the Host Sediments. Data on Host Sediments is useful, therefore, in initial regional reconnaissance whereas data on Host Sandstone will be required in more detailed target evaluations. The "host sediments" will generally be part of a Continental Sedimentary Sequence which either contains uranium deposits or anomalies, or is being evaluated for its uranium potential.

Thickness. In general the favorability of host sediments increases with thickness.

- (1) Host sediments are several hundred feet or more in thickness. +25
- (2) Host sediments are a few hundred feet or less in thickness. -40

Area. Favorability increases as the area of the host sediments increases. A very approximate estimate of the importance of area would be:

- (1) Greater than 10,000 square miles. +25
- (2) Less than 1,000 square miles. -50

Sand-Shale Facies. Favorable sedimentary sequences contain sandstones and shales that are interbedded in facies relations without major breaks in sedimentation. In the Grants Uranium Region, both the underlying Westwater Canyon and the overlying Jackpile sandstones were deposited continuously with the intervening Brushy Basin Member.

- (1) Principal sands and shales of the host sediments were deposited without breaks in sedimentation and are interbedded at their boundaries. +40
- (2) The principal sands and shales were deposited with breaks in sedimentation and are not interbedded. -35

Shales. Shales and siltstones associated with the potential host sandstone are believed to be important to the formation of uraniferous humate deposits. Not only do they form hydrologic limits to the ore-bearing aquifers, but they may have provided uranium and organic material in some cases to the deposits. Characteristics of the shales and siltstones considered important are discussed below.

Color indicative of non-oxidized sediments; commonly greenish to gray-green are most favorable. Primary oxidized red sediments are distinctly unfavorable although minor interbeds of oxidized sediments are not discouraging. An abundance of dark organic-rich mudstones and siltstones is also considered unfavorable.

Color of the shales and siltstones are:

- (1) Greenish to gray-green with only minor red interbeds. +45
- (2) Either red or dark gray shales and siltstones. -80

Bentonite, derived from acid tuffs and other volcanic material, is believed to be an important component of the host sediments, particularly the shales. Bentonitic units can be easily recognized by the "popcorn" texture on outcrop.

Shales and siltstones contain:

- (1) Abundant (30-70 percent) bentonitic clays. +75
- (2) Only non-bentonitic clays. -75

Carbonate and Silica in the forms of fresh water limestone and bedded cherts are indicative of lacustrine deposition. Chert indicates movement of silica in the sediments and is often derived from the alteration of volcanics.

- (1) The shales and siltstones contain both carbonate and chert horizons. +30
- (2) Shales and siltstones contain neither chert nor carbonate. -30

Host Sandstone

The host sandstone is a specific, potentially favorable sandstone unit within the host sedimentary sequence. Potential host sandstones contain lithic constituents that could have contributed uranium to the geologic environment, and which are permeable enough to allow the transport of dissolved uranium to the sites where the uranium is precipitated. Permeability of the sandstone is affected by the stability of the clasts, the grain size, sorting, and clay content. The transmissivity of the unit as a whole is affected by the thickness, area, sand-shale ratio, and continuity of permeable units. In general, the larger the area of the sandstone, the greater the potential for the existence of an environment favorable for the development and preservation of uranium deposits. Thick sandstone units are more favorable than thin,

lenticular units. However, the absolute thickness is not as important as local areas which are anomalously thick in comparison with adjacent areas.

The depositional environment is an important criterion, for it determines many of the characteristics of the sediments deposited in a fluvial system. In the Grants Uranium Region it appears that the most favorable portion of the fluvial system was the medial, or mid-fan areas, where bed-load dominated streams deposited a favorable ratio of sandstones and mudstones. The mid-fan environment was also the best place for the accumulation and preservation of organic matter in the sediment. The soluble humic acids derived from the buried organic material was the determining factor in the location, and accumulation of the uranium deposits.

Area

In general, the larger the area of the sandstone, the greater the potential for deposits somewhere within that area.

(1) Sandstone covering more than 700 square miles.	+20
(2) Sandstone covering less than 100 square miles.	-50

Thickness

Local thick accumulations of sand, i.e. areas of sand thicknesses greater than neighboring areas, tend to be more favorable than uniform thickness or uniformly changing thicknesses of sand. Thickness is also important as larger deposits are restricted to thicker sands (i.e., greater than 200 feet) but smaller deposits can occur in thin sands. We do not assign values to thickness so as not to rule out smaller deposits (i.e., < 1 million pounds U_3O_8), but favorability values could be chosen once one selects the minimum target size.

Depositional Environment

The proximal portion of an alluvial fan is the highest energy portion of the fluvial system and is generally unfavorable because of excessive permeability which may result in a low content of preserved carbonaceous material due to rapid oxidation after deposition. The distal portion of the wet alluvial fan is a low energy fluvial system which deposits a dominantly fine suspended load of silt and clay with a minor amount of sand. This environment is generally unfavorable for deposits. The favorable part of the fluvial depositional system is the medial portion of the fan where bed-load to mixed-load streams have deposited a mixture of sandstones and shales and where buried organic matter is not quickly destroyed.

The favorability of depositional environments is approximately as follows:

(1) The sandstone is in the medial or mid-fan and consists of medium- to coarse-grained sandstones with distinct interbeds of shale.	+45
(2) The sandstone was deposited in the distal portion of the fan and is dominantly shale with scattered, thin, lenticular beds of sandstone.	-60

- (3) The sandstone is part of the proximal fan and consists of coarse, conglomeratic sandstones with very little interbedded shales. -70

Permeability

Permeability in a sandstone is governed by grain size and sorting. Most large, high-grade deposits are found in medium- to coarse-grained, moderately to poorly sorted sandstones. In order of decreasing favorability, sandstones may be classified as follows:

- (1) The potential host sandstone is a medium- to coarse-grained, moderately sorted sandstone with good permeability. +10
- (2) The sandstone is a poorly sorted, dominantly very coarse-grained or very fine-grained sandstone with low permeability. -50

Composition

A potential host sandstone may be considered to have a favorable composition if it contains a framework of stable mineral grains, a moderate amount of labile volcanoclastic material, some buried organic matter either in the sandstones or interbedded shales, and a sandstone to shale ratio that does not interrupt the hydrologic continuity of the sandstones.

Organic Matter. The presence of some organic matter in the potential host rock is necessary to supply the humic acids which form the uranium deposits. However, an abundance of organic matter is unfavorable. Field relations in the Grants region suggest that much organic matter has been dissolved from the host sandstones as indicated by silicified logs and the general absence of fine detrital organic debris within the sands. Some pockets of trash and trash interbeds with shale, particularly at the base of channel scours, however, are preserved. These relations suggest that ground waters dissolved the accessible dispersed plant debris while the hydrologically isolated or more concentrated accumulations persevered. Much of the dissolved humic material may subsequently have been deposited in the humate lenses of the ore zones.

- (1) Silicified logs and local trash accumulations are present in the sandstones. (Evidence of organics in the shales may be entirely lacking, as in the Grants Uranium Region). +55
- (2) There is little or no evidence of carbonaceous material in the sedimentary units. -60
- (3) Detrital plant debris is abundant in the sandstones and the shales are gray and pyritic. -70

Clastics. Sandstones ranging from quartz arenites to arkoses are composed of chemically stable clasts which are capable of maintaining the porosity and permeability of the rock. The more arkosic sediments may be somewhat more

favorable because they indicate a granitic source area which could have supplied some uranium to the fluvial system. Poorly sorted sands or those with unstable clasts are less favorable.

(1) The potential host sandstone is an arkose.	+30
(2) The sandstone contains a moderate amount of interstitial clay and silt.	-10
(3) The sandstone is a graywacke with abundant clays and soft lithic fragments.	-70

Volcaniclastics. The presence of moderate amounts of acid volcaniclastic material in a potential host sandstone is considered favorable so long as the destruction of this material has not destroyed the permeability. It is likely that much of the glassy material was altered after deposition and is no longer recognizable. The presence of high temperature beta-quartz crystals, and the volcanic feldspar, sanidine, are evidence for a volcaniclastic component in the original sediment. The favorability of the volcanic clasts may be estimated as follows:

(1) Volcanic clasts comprise 10-30% of the sandstone by volume.	+45
(2) Little or no evidence of volcanic clasts (less than 5%).	-30
(3) Volcanic clasts comprise more than 50% of all the clasts.	-75

Sand-Shale Proportions. A massive sandstone without any shale or siltstone interbeds is unfavorable as is a potential host rock composed predominantly of shale. In the Grants Uranium Region, the percentage of sandstone in the ore trends is 70 percent or more. The 30 percent shale is most favorable if it is confined to several fairly persistent horizons within the sandstone unit, rather than scattered randomly through the section. The percentage of sand is related to favorability as follows:

(1) 60-80% sandstone	+35
(2) 40-60% sandstone	+15
(3) More than 80% sandstone	-50
(4) Less than 40% sandstone	-70

Alteration and Mineralization

We have proceeded from the most general regional recognition criteria to the more detailed and now present those observations most closely related to mineralization. If a host sandstone has been identified, the following criteria can be used, but one should define a specific area of investigation and keep in mind that the descriptions of the criteria will be for that entire area. If the geologic conditions for the criterion are different within parts

of that area of investigation, it may be necessary to subdivide the area. For example, if pyrite is abundant in part of the area, but absent in the other part, it does not make sense to average the two and refer to the entire area; it is far better to divide the area into parts and describe the recognition criteria separately for each. Some of the criteria may seem too detailed for reconnaissance investigation but, as we have discussed in the text, all have been found to have broad patterns.

Mineralization

The magnitude, frequency, and type of uranium anomalies within the host sediments and host sandstones are important indications of the favorability of the sediments. Anomalies would include uraniferous plant trash, high and erratic background in shales and siltstones, and concentrations at shale-sandstone contacts. Actual concentrations may range from two to three times background. In the Grants Uranium Region gamma ray anomalies usually occur only in proximity to ore and are, therefore, the most reliable guides to the uranium deposits within the altered sandstones.

(1) Anomalies in the host sediments and/or host sandstones are common, i.e. significantly more than in comparable sediments.	+55
(2) Anomalies in the host sediments and/or host sandstones are few, but slightly more than comparable sediments.	+20
(3) Anomalies in the host sediments and/or host sandstones are absent to rare, i.e. less than in comparable sediments.	-70

There is much lacking in the foregoing compilation of recognition criteria. Some important criteria have probably been omitted while some of those included are ambiguous and difficult to evaluate. Some definitions are perhaps too abbreviated to provide proper guidance for the selection of criteria weights. Undoubtedly the weights assigned to the various favorable and unfavorable states of some of the criteria are not what the reader would have chosen. We have attempted to address all these problems, but we recognize the criteria will benefit enormously through refinements by experienced geologists. In spite of these shortcomings, we feel the recognition criteria considerably improve the usefulness of the geologic data, that was compiled and interpreted in earlier sections of the report, for resource studies and exploration.

Alteration

Broad patterns of mineral alteration are now recognized within ore-bearing sands of the Grants Uranium Region. The most widespread systematic alterations involve the partial to complete destruction of ilmenite, and magnetite and calcium-bearing plagioclase and sanidine. These alterations are used as recognition criteria. In addition, authigenic clay rims (illite-montmorillonite and Fe-chlorite) and to a lesser extent quartz overgrowths, kaolin nests, calcite and discoloration of TiO_2 clots may also relate to ore distribution. Their patterns, as discussed in the text, are either too specific to

mineralization or have not been defined adequately, hence are not included among the recognition criteria.

Ilmenite-Magnetite. Ilmenite and magnetite are entirely destroyed within host sands in proximity to ore deposits. Where some ilmenite and magnetite remain in the sandstone, alteration intensity increases toward the overlying or underlying shale. Thick zones of total ilmenite-magnetite destruction over broad areas are most favorable.

(1) Ilmenite-magnetite destroyed in more than 70 percent of the sandstone thickness.	+75
(2) Ilmenite-magnetite destroyed in 25-75 percent of the sandstone thickness.	0
(3) Ilmenite-magnetite destroyed by reduction and dissolution in less than 25 percent of the sandstone thickness.	-85

Pyrite. Pyrite concentrations in the host sandstone form broad zones, perhaps up to several miles around ore trends. Outside these pyrite-bearing halos the sands are essentially free of pyrite, whereas within the zones concentrations may reach significant concentrations (0.5% to 3% or more).

(1) Sandstone contains significant concentrations of pyrite.	+60
(2) Sandstone contains trace of pyrite.	+10
(3) Sandstone contains no pyrite.	-35

Feldspar. The distribution of feldspar alteration, principally sodium replacement of the outer portion of feldspar grains and feldspar dissolution, is broadly similar to that of ilmenite-magnetite alteration. The alteration is best developed adjacent to a bounding shale and decreases intensity into the sandstone. This alteration is less useful than the ilmenite-magnetite destruction because it is best observed in thin section, whereas the former can be evaluated with a magnet. It is useful, nonetheless, as a confirmation of perhaps the most useful regional guide to ore trends, the ilmenite-magnetite destruction.

(1) Feldspars displaying both hollow centers and replaced rims are abundant.	+40
(2) Feldspars displaying replaced rims are common, but skeletal or hollow grains are rare or absent.	+15
(3) Feldspars are unaltered.	-60

There is much lacking in the foregoing compilation of recognition criteria. Some important criteria have probably been omitted while some of those included are ambiguous and difficult to evaluate. Some definitions are perhaps too abbreviated to provide proper guidance for the selection of criteria weights. Undoubtedly the weights assigned to the various favorable

and unfavorable states of some of the criteria are not what the reader would have chosen. We have attempted to address all these problems, but we recognize the criteria will benefit enormously through refinements by experienced geologists. In spite of these shortcomings, we feel the recognition criteria considerably improve the usefulness of the geologic data, that was compiled and interpreted in earlier sections of this report, for resource studies and exploration.

REFLECTIONS AND CONTINUING STUDIES

The deposits of the Grants Uranium Region have been known for almost thirty years and yet there has been no generally accepted explanation for the origin and controls of these important deposits. As a result, exploration has been conducted on a pragmatic basis, drilling along the projections of trends and with wide-spaced reconnaissance drilling in previously untested areas. As pointed out in this report, it now seems likely that wide-space reconnaissance holes can provide sufficient information to identify the most favorable areas for intensive exploration. The very early studies in the district identified many of the important relations and had that work continued we are confident it would have materially aided subsequent exploration of the region and provided a basis for resource studies. Even now such work would prove valuable and we make a plea for the establishment of continuing geologic studies for the purpose of compiling and interpreting basic geologic information in support of future industry exploration programs and whatever resource studies are deemed to be necessary. Such work is properly the function of the U. S. Geological Survey which, through cooperation with private companies, can develop geologic analyses of major mining districts that will provide benefit for all concerned.

Below are identified some specific areas for continuing studies which we have arranged more or less in order of importance. We focus first on those which will more immediately aid exploration and resource studies and leaving until last those which are more scientific in nature and therefore have longer range rewards.

(1) Published data for the Grants Uranium Region is reasonably abundant for the ore deposits themselves but is noticeably lacking for the barren sandstones above, below and lateral to the ore deposits. As any explorationist appreciates, it is the wise use of unmineralized samples that can most significantly benefit an exploration program. Through the kindness of numerous companies and the Department of Energy, we were able to amass considerable information which has permitted the development of a preliminary picture of the regional alteration within barren sandstones. This alteration is presumably related to the mineralizing processes. We suspect that future programs, if properly designed and executed, would meet with similar cooperation, and we recommend that they be undertaken without delay. Continuing studies should be designed with specific objectives and for perhaps a five-year program. The objective should be to develop exploration and resource guides by collecting whatever useful samples and information are warranted, particularly through cooperation with companies.

(2) Our review of the literature suggests that much of the best descriptive data is contained in older publications. These were prepared at a time when the emphasis was on description rather than interpretation. In later publications, with some important exceptions, there is more emphasis on interpretation than documentation, sometimes without reference to the previously documented data bases. This is particularly true in the last decade as attempts to interpret the Grants deposits in the context of the roll-type model have received much attention. To understand the Grants Uranium Region, therefore, one needs to faithfully review the older publications.

(3) Throughout the literature we have noted references to the relation between uranium and organic material in the ores of the Grants region. Many authors plead for studies which will help unravel the significance of this association and the mechanisms which produce the tabular habit of the ore deposits. Their pleas have been largely unanswered. We believe we have made some progress in that direction, but it is only a beginning in terms of any fundamental understanding of the organic-uranium association. The continuing studies of the Grants Uranium Region recommended in a previous paragraph should incorporate the results of any new investigations of uranium-humate associations.

(4) We emphasize the role of contemporaneous basement subsidence in the accumulation of a proper sedimentary sequence for the formation of uraniferous humate deposits. Whereas there is now considerable indirect supporting evidence, the basement structures and associated displacements have not been confirmed. Geophysical studies should be conducted to identify whether or not such faults exist and whether displacements explain the stratigraphic relations observed in the Morrison Formation. We suspect that such structures may be detectable with magnetic surveys due to repeated periods of alteration along what are probably very old and fundamental breaks in the Precambrian basement. It is also possible that gravity surveys may be useful.

(5) The importance of interbedding relations between the host sandstones and the Brushy Basin shale is suggested as a possible control for the position of the ore trends. This interpretation is based upon the Ambrosia Lake and Laguna District trends and seems well founded. A regional review of these relationships, however, is warranted because of the extreme importance of the proposed interbedding relations in controlling the position of the ore districts.

(6) Authigenic clay rims precipitated on the detrital clasts are known to be well developed within and immediately adjacent to uraniferous humate lenses. Whereas these clays are dominantly illite-montmorillonite in the Jackpile sandstone, they are dominantly chlorite or some mixed-layered chlorite bearing phase in Ambrosia Lake. There is also evidence now that fine dustings of authigenic chlorite occur over broad areas of the Westwater Canyon, principally in the middle and lower part of the member and in the more distal parts of the depositional system. This latter occurrence is almost certainly not closely related to ore horizons. Limited data and time have prohibited our synthesizing and interpreting these clay patterns. We suspect that the distribution of authigenic clays will be systematic and related in some broad pattern to the ore-forming processes. Whether or not these distributions contribute to resource studies or exploration will only be known after further studies are undertaken, and we recommend that they be pursued.

(7) The sediment source for the Morrison Formation is probably remote from the present distribution of the sediments. It was previously thought to be exposed south of the Mogollon rim in Arizona, but it may have been much farther west. The recognition of uraniferous provinces is a fundamental criterion for resource studies and exploration. Studies should continue, therefore, in an effort to ascertain not only the precise source of the Morrison sediments but to identify techniques useful in tracking sediment sources and identifying uraniferous provinces.

(8) There is no accurate map showing the extent of oxidation in the Westwater Canyon Member of the Grants Uranium Region. There is no such map even for the Ambrosia Lake District. Recognition of possible recent oxidation far out into the basin has an important bearing on how much of the southern portion of the San Juan Basin is still prospective. We recommend that such a map be prepared.

(9) There has long been considerable interest in the development of pathfinder minerals or elements to guide exploration. We believe that the development of alteration patterns discussed in this report goes a long way to fulfilling that need and provides a basis for testing other pathfinders. It is possible, for example, that the uranium content of the minus 2 micron fraction, or the vanadium content of oxidized sands would be useful. Whatever effort is made to develop such pathfinders should be done within the context of the genetic working models presented in this report.

(10) The ore trends tend to be located on the south side of linear sandstone thicks in the Westwater Canyon Member. This tentative observation should be examined first for its accuracy and, if confirmed, the reason for this relation.

(11) The derivatives of plant debris are somehow involved in the genesis of most sandstone-type deposits. We encourage studies directed toward the maturation, alteration, transport and reprecipitation behavior of such debris in ground water regimes.

(12) The expected characteristics of the ore deposits become extremely important after prospective areas are selected. Factors such as the shape, continuity and grade become more predictable when the geologic controls are better understood. For example, what causes the apparent periodicity in the ore pods in some of the tabular mineralization within Ambrosia Lake? Moderately detailed studies of trends or groups of orebodies are required. The scale of such studies is between the regional considerations discussed herein and the excellent studies that have been performed on specific orebodies.

POTENTIAL FOR URANIFEROUS HUMATE-TYPE DEPOSITS IN THE UNITED STATES

Uraniferous humate deposits of the type found in the Grants Uranium Region are not known with certainty to occur elsewhere in the United States or the world. There has been speculation that some of the deposits in Niger, South Australia, Pakistan or even the deposits of the Franceville Basin of Gabon, are analogs of this important class of uranium deposits. The geologic characteristics presented in the recognition criteria, however, are not even approximately matched in these districts, except possibly Niger. However, the potential for a new district similar to the Grants Uranium Region elsewhere in the world is considered favorable. The Cretaceous of Chubut, southern Argentina, for example, is similar in many respects to the Morrison Formation of northwestern New Mexico.

The prospects for an entirely new uraniferous humate district in the United States are considered to be poor. There are no known geologic settings sufficiently analogous to Grants to be likely targets for the repetition of this major mineral region. The Chinle Formation of the Colorado Plateau might have been a favorable sediment sequence on the basis of organic-rich sands and volcaniclastic-rich shales. However, almost pervasive oxidation within the sediments at deposition, produced a different post-depositional history. This led to the formation of one important district, but it is much smaller than the Grants district and the deposits are different.

Another sedimentary sequence with some potential might have been the Morrison Formation outside of the Grants Uranium Region. The deposits discovered in the Salt Wash Member within the Uraavan and Henry Mountain Mineral Belts, for example, indicate the presence of abundant uranium. Many aspects of the stratigraphy are decidedly favorable for uraniferous humate deposits. However, outside the Grants Uranium Region the thickness and continuity of the sandstones decreases and the oxidation of the shales of the Brushy Basin increases. We consider it unlikely that large uraniferous humate deposits of the Grants type will be found elsewhere in the Morrison sediments, and we do not see other stratigraphic sections within the United States that offer great promise.

Grants Uranium Region

Within the Morrison sediments of the Grants Uranium Region, there are numerous opportunities for further discoveries. First, new deposits, generally small in size, will continue to be discovered and developed by closer-spaced drilling within, and as immediate extensions of, known mineral trends. Discoveries of residual ore bodies will also continue to be made along the projections of known trends but within areas of oxidation. Deposits of these types have been pursued for several years, so large deposits are unlikely. Several five to ten million pound orebodies will probably be discovered.

Some major new discoveries are to be expected within large unexplored segments of known ore trends. Examples would be the continued discovery and delineation of individual orebodies within the Nose Rock trend, and the substantial

likelihood that one or more major orebodies exists along the Grants mineral belt in the Cebolleta Grant area between the Mt. Taylor deposit and the deposits of Marquez. Even here the trend will be discontinuous and may resemble the Marquez Canyon mineralization more than the Mt. Taylor deposit. These discoveries await only favorable land situations and substantial drilling budgets, which will be required by the considerable depths to the favorable Westwater Canyon sands.

New ore trends provide the greatest potential for major new discoveries within the region. In the past, exploration guides for the location of new trends have been based largely on widely scattered oil well control points, broad concepts about regional sedimentary patterns, and some combination of concepts for ore formation and ore control. This report has documented the association of regional alteration patterns with major ore trends, in particular ilmenite-magnetite destruction. Regional information on the distribution of these patterns permits, therefore, evaluation of the potential of the unexplored and poorly explored parts of the basin.

The factors which most strongly affect ore occurrence are combined on Plate 9, so as to delineate the favorable portions of the region, particularly those that remain to be prospected. As discussed earlier in this report, favorability is greatest in ilmenite-magnetite altered sandstones which have not been subsequently oxidized. The original areas of such alteration and reduction are now much diminished in size by the incursion of Late Cenozoic oxidation. The extent of this oxidation north of Standing Rock, New Mexico, is unknown at the present time. Therefore, the favorability of the largest area of essentially untested ground in the southwest part of the Grants Uranium Region is unknown. Over most of the remainder of the region, exploration drilling appears to have reached or exceeded the limits of the prospective areas, as mapped on Plate 9.

In general, favorable areas are found between broad areas free of ilmenite-magnetite destruction to the northeast and areas of pervasive late oxidation to the south and southwest. The area north from the Ambrosia trend and east from the Nose Rock trend has poor potential based upon sparse ilmenite-magnetite alteration. The only area of some interest is the favorable salient of alteration which projects northeast from the Ambrosia Lake area, however, this area has recently been drilled with no success.

South and southwest from the Ambrosia Lake, Crown Point and Church Rock districts, the sands of the Westwater Canyon have been pervasively oxidized. Isolated, residual primary deposits will be found within the zone of oxidation, but they are expected to be small as discussed in an earlier paragraph. Redistributed mineralization along the oxidation front will provide additional exploration targets where the front has not been explored.

The limit of the Nose Rock trend to the northeast has not been defined. It is possible that it extends several miles beyond Chaco Canyon, judging from the persistence of the analogous Grants mineral belt toward the southeast to the Montano Grant. One might expect, pursuing this analogy, that the trend will become progressively more narrow and discontinuous toward the distal part of the sedimentary system, i.e. toward the northeast. This possible deterioration in the quality of the deposits and the increasing depths to the Westwater Canyon farther into the San Juan Basin will cause exploration and discovery to proceed more slowly.

Major new discoveries will probably be made west and northwest of the present line of discoveries in the Nose Rock trend. These deposits may define subsidiary trends within the main belt, as occur in Ambrosia Lake, or may be cleanly separated and form distinct mineral trends. The amount of ore to be expected in such a trend could be comparable to the Ambrosia Lake District.

The potential of the San Juan Basin farther to the northwest is difficult to assess with present data. There is some information that suggests ilmenite-magnetite destruction has occurred within the Westwater Canyon sands, hence they have some favorability. The exposed Westwater Canyon sands along the western margin of the basin, however, are ilmenite- and magnetite-bearing, hence unfavorable, so that if favorable sands exist in the northwestern portion of the basin they are part of a fan system emanating from the Gallup sag area. It is likely that at least one additional trend could be present, but that possibility could only be evaluated with wide-spaced data of the type discussed in this report.

The Poison Canyon trend may continue to the southeast and east under the Mt. Taylor volcanic field, and possibly on east toward the Rio Puerco. The mineralization on this southern-most trend will be of good grade but thin and very narrow, similar to the known portions of the Poison Canyon trend. It will only be practical to prospect for this type of mineralization in areas of shallow drilling, such as in the Laguna district.

Additional significant targets may exist within the Jackpile Sandstone or its equivalents in the deeper parts of the San Juan Basin. We believe there is some chance for northeast-trending sand depositional axes similar to the Jackpile sandstone itself, which might locally blossom into major sandstone trends with associated uraniferous humate deposits. Finally, the possibility exists that the favorable environment of the Morrison Formation may permit economic mineralization to spill over into adjacent formations under special stratigraphic and structural settings. Possibilities might include mineralization related to closely-spaced fractures within the Bluff sandstone or Dakota sandstone. Although such deposits will probably be discovered, they will not be comparable in size or grade to the uraniferous humate deposits and, being only hypothetical at this point, will be difficult exploration targets.

In conclusion, the Grants Uranium Region is in a mature stage of development. Future exploration will be deeper and more expensive. It is expected that another quarter to one-half billion pounds of U_3O_8 remain to be discovered. Therefore it is still an exceptionally good place to explore for large deposits. The Grants Uranium Region should retain its position of pre-eminence among the uranium districts of the United States for a long time to come.

APPENDIX I

SCHEMATIC DRILL HOLE ALTERATION LOGS

The alteration of the Westwater Canyon sandstones was studied in considerable detail as part of this project. Thin sections for several samples from each of 51 holes, supplied by nine companies, provided the basis for the observations. The drill holes are reasonably well distributed throughout the Grants Uranium Region, hence the alteration patterns are regionally representative.

Compiled on the following pages are schematic alteration logs for each of the core holes. The top and bottom of the Westwater Canyon Member is shown where that information is available. The nature and intensity of alteration for ilmenite-magnetite, hematite, and feldspar are indicated by symbols that are explained on the first page of logs.

Hole No.: 0300-0700-22-12-4
 Company: Exxon Minerals U.S.A.
 Location: Sec. 22 Twn. 12 Rnge. 4

Hole No.: M5-3-14.5-3-22
 Company: Exxon Minerals U.S.A.
 Location: Sec. 22 Twn. 12 N Rnge. 4 W

Hole No.: 19-12-32-129
 Company: Phillips Petroleum Co.
 Location: Sec. 32 Twn. 19 Rnge. 12

Hole No.: 19-12-32-224
 Company: Phillips Petroleum Company
 Location: Sec. 32 Twn. 19 Rnge. 12

EXPLANATION

- A Abundant to complete alteration
- M Moderate alteration
- T Minor alteration
- U Unaltered or alteration phase absent
- () Hematite alteration only in grains
- Alteration obscured by clay or calcite matrix cement

Hole No.: AN-4
Company: Anaconda
Location: Sec. 36 Twn. 18N Rnge. 17W

Hole No.: R-1
Company: Anaconda
Location: Sec. 11 Twn. 13 Rnge. 8

Hole No.: R-2
Company: Anaconda
Location: Sec. 11 Twn. 13 Rnge. 8

Hole No.: R-3
Company: Anaconda
Location: Sec. 28 Twn. 15 Rnge. 7

EXPLANATION

- A Abundant to complete alteration
- M Moderate alteration
- T Minor alteration
- U Unaltered or alteration phase absent
- () Hematite alteration only in grains
- Alteration obscured by clay or calcite matrix cement

Hole No.: R-4
Company: Anaconda
Location: Sec.28 Twn.15 Rnge.7

Hole No.: R-6
Company: Anaconda
Location: Sec.28 Twn.16 Rnge.9

Hole No.: R-5
Company: Anaconda
Location: Sec.28 Twn.15 Rnge.8

Hole No.: R-7
Company: Anaconda
Location: Sec.6 Twn.15 Rnge.8

EXPLANATION

- A** Abundant to complete alteration
- M** Moderate alteration
- T** Minor alteration
- U** Unaltered or alteration phase absent
- ()** Hematite alteration only in grains
- Alteration obscured by clay or calcite matrix cement

Hole No R-8
Company Anaconda
Location Sec 30 Twn 15 Rnge 8

Hole No R-9
Company Anaconda
Location Sec 20 Twn 16 Rnge 7

Hole No D-63
Company Ranchers Exploration and Development Corp
Location Sec. 7 Twn 13 Rnge 8

Hole No U-3-C
Company Ranchers Exploration and Development Corp
Location Sec 18 Twn 13 Rnge 8

EXPLANATION

- A Abundant to complete alteration
- M Moderate alteration
- T Minor alteration
- U Unaltered or alteration phase absent
- () Hematite alteration only in grains
- Alteration obscured by clay or calcite matrix cement

Hole No. CC-1

Company: U.S. Department of Energy

Location: Sec. 5 Twn 20 Rnge. 9

Hole No. CC-2

Company: U.S. Department of Energy

Location: Sec 9 Twn 20 Rnge 9

Hole No. CC-3

Company: U.S. Department of Energy

Location: Sec 9 Twn 20 Rnge 8

Hole No. CC-4

Company: U.S. Department of Energy

Location: Sec II Twn 20 Rnge 8

EXPLANATION

- A** Abundant to complete alteration
- M** Moderate alteration
- T** Minor alteration
- U** Unaltered or alteration phase absent
- ()** Hematite alteration only in grains
- Alteration obscured by clay or calcite matrix cement

Hole No. CC-5
Company U S Department of Energy
Location Sec 31 Twn 20 Rnge 7

Hole No. CC-6
Company U S Department of Energy
Location Sec 13 Twn 19 Rnge 8

Hole No. CC-7
Company U S Department of Energy
Location Sec 21 Twn 19 Rnge 7

Hole No. CC-8
Company U S Department of Energy
Location Sec 31 Twn 21 Rnge 9

EXPLANATION

- A** Abundant to complete alteration
M Moderate alteration
T Minor alteration
U Unaltered or alteration phase absent
() Hematite alteration only in grains
- Alteration obscured by clay or calcite matrix cement

Hole No CC-12
Company U S Department of Energy
Location Sec 32 Twn 21 Rnge 10

Hole No CC-15
Company U S Department of Energy
Location Sec 16 Twn 20 Rnge 10

Hole No CC-17
Company U S Department of Energy
Location Sec 23 Twn 19 Rnge 8

Hole No CC-9
Company U S Department of Energy
Location Sec 27 Twn 20 Rnge 8

EXPLANATION

- A** Abundant to complete alteration
- M** Moderate alteration
- T** Minor alteration
- U** Unaltered or alteration phase absent
- ()** Hematite alteration only in grains
- Alteration obscured by clay or calcite matrix cement

Hole No CC-24
Company US Department of Energy
Location Sec 3 Twn 19 Rnge 9

Hole No CC-26
Company US Department of Energy
Location Sec 21 Twn 18 Rnge 6

Hole No WC-1
Company US Department of Energy
Location Twn 16 Rnge 11

Hole No CC-25
Company US Department of Energy
Location Sec 13 Twn 19 Rnge 9

EXPLANATION

- A Abundant to complete alteration
- M Moderate alteration
- T Minor alteration
- U Unaltered or alteration phase absent
- () Hematite alteration only in grains
- Alteration obscured by clay or calcite matrix cement

Hole No WC-3
Company U S Department of Energy
Location Twn 16 Rnge II

Hole No WC-7
Company U S Department of Energy
Location Twn 16 Rnge II

Hole No WC-12
Company U S Department of Energy
Location Twn 16 Rnge IO

Hole No WC-10
Company U S Department of Energy
Location Twn 16 Rnge IO

EXPLANATION

- A** Abundant to complete alteration
M Moderate alteration
T Minor alteration
U Unaltered or alteration phase absent
() Hematite alteration only in grains
- Alteration obscured by clay or calcite matrix cement

Hole No TW-1-15-15-1
Company Tidewater Oil Co
Location Sec 1 Twn 15 Rnge 15

Hole No TW-16-16-16-5
Company Tidewater Oil Co
Location Sec 16 Twn 16 Rnge 16

Hole No TW-13-15-13-2
Company Tidewater Oil Co.
Location Sec 13 Twn 15 Rnge 13

Hole No TW 21-15-13-2
Company Tidewater Oil Co
Location Sec 21 Twn 15 Rnge 13

EXPLANATION

- A Abundant to complete alteration
M Moderate alteration
T Minor alteration
U Unaltered or alteration phase absent
() Hematite alteration only in grains
- Alteration obscured by clay or calcite matrix cement

Hole No 32-P2-23
Company Homestake Mining Co
Location Sec 32 Twn 14 Rnge 8

Hole No. 32-Q-19
Company Homestake Mining Co
Location Sec 32 Twn 14 Rnge 8

Hole No 32-Q5-33
Company Homestake Mining Co
Location Sec 32 Twn 14 Rnge 8

Hole No UN-H-AA-II
Company United Nuclear - Homestake Partners
Location Sec 32 Twn 14 Rnge 9

EXPLANATION

- A Abundant to complete alteration
- M Moderate alteration
- T Minor alteration
- U Unaltered or alteration phase absent
- () Hematite alteration only in grains
- Alteration obscured by clay or calcite matrix cement

Hole No UN-H-13-A-1
 Company United Nuclear - Homestake Partners
 Location Sec 13 Twn 14 Rnge 10

Hole No UN-H-23-A
 Company United Nuclear-Homestake Partners
 Location Sec 25 Twn 14 Rnge 10

Hole No UN-H-25-A
 Company United Nuclear-Homestake Partners
 Location Sec 25 Twn 14 Rnge 10

Hole No UN-H-26-22
 Company United Nuclear-Homestake Partners
 Location Sec 26 Twn 14 Rnge 9

EXPLANATION

- A Abundant to complete alteration
 M Moderate alteration
 T Minor alteration
 U Unaltered or alteration phase absent
 () Hematite alteration only in grains
 - Alteration obscured by clay or calcite matrix cement

Hole No UN-H-46
 Company United Nuclear-Homestake Partners
 Location Sec 15 Twn 14 Rnge 10

Hole No KM-181-C
 Company Kerr McGee Resources Corp
 Location Sec 22 Twn 14 Rnge 10

Hole No KM-421
 Company Kerr McGee Resources Corp
 Location Sec 30 Twn 14 Rnge 9

EXPLANATION

- A Abundant to complete alteration
- M Moderate alteration
- T Minor alteration
- U Unaltered or alteration phase absent
- () Hematite alteration only in grains
- Alteration obscured by clay or calcite matrix cement

APPENDIX 2

ESTIMATION OF GEOLOGIC FAVORABILITY FOR THE OCCURRENCE OF URANIFEROUS HUMATE-TYPE DEPOSITS

Numerous methods have been used for estimating the geologic favorability or expected resource endowment of an area for various types of ore deposits (Cargill and Clark, 1978; Singer and Overshine, 1979; Voelker et al, 1979; Harris and Carrigan, 1980). In this section we present a simplified method for estimating the favorability of an area for the occurrence of uraniferous humate deposits using the recognition criteria net (Fig. 17) and the weights assigned to the recognition criteria (Table 6). It must be emphasized that the favorability estimate reflects only the general geologic similarities between known deposits, as defined by the recognition criteria, and the geologic characteristics of an area in which similar deposits might occur. A higher degree of geologic similarity yields a higher favorability estimate, suggesting a greater likelihood that the type of deposit for which the recognition criteria were developed is present in the untested area. No attempt is made to estimate the number of deposits or their geologic size, grade, and continuity. These characteristics require information about the known deposits which, in many cases, is not yet available.

The use of this method presumes that sufficient geologic information is available for the area of study so that weights can be confidently assigned to the recognition criteria. In most cases, geologic data are incomplete and values cannot be assigned to all criteria. Using the method described below the absence of a value for a criterion is analogous to assigning it a value of zero. This could introduce a significant error in the interpretation of the favorability estimate if the geologist fails to note where data were lacking. If the true favorability of the criterion is significantly higher than zero, the absent data leads to a fallaciously low estimate of the area's favorability. This is a common situation, particularly in resource evaluation of Federal lands where adequate geologic information is customarily unavailable for the systematic evaluation for all types of deposits. Geologic favorability simply cannot be estimated until an adequate data base is available. Where data are lacking, the large negative and positive weights indicate those recognition criteria for which data must be acquired. The assignment of a weight of zero may also significantly overestimate favorability if that criterion is in fact very discouraging. There is no substitute for a sufficient data base.

Calculation of Estimated Favorability

The procedure for calculating an estimated favorability may be conveniently explained by returning to the discussion of Host Sandstone Composition (HSC), considered under Evaluation of Recognition Criteria. Weights were assigned to various favorable and unfavorable states of the four criteria that determine the favorability of HSC. To evaluate the favorability of HSC for field areas, favorability values, based on field observations, are assigned to the four criteria. Table 7 presents hypothetical results for four imaginary field areas. In accumulating the values of the recognition criteria, negative and positive values are accumulated separately, but in like fashion.

Table 7. Hypothetical recognition criteria values from four imaginary field areas for the four criteria that determine Host Sandstone Composition.

	Estimated Favorability Values (Fe)				Maximum and Minimum Favorability Values	
	Area A	Area B	Area C	Area D	(Fm+)	(Fm-)
Organic Matter	+55	+20	+50	-70	+55	-70
Clastics	0	+15	+ 5	+20	+30	-70
Volcaniclastics	0	+ 5	+10	-75	+45	-70
Sand-Shale Proportions	<u>0</u>	<u>+30</u>	<u>+30</u>	<u>+25</u>	<u>+35</u>	<u>-70</u>
	+55	+70	+95	+45 -145	+165	-280

In Test Area B, for example, Organic Matter has been assigned a value of +20. Clastics provide an additional 15, and so forth for the other two criteria, yielding an estimated favorability (Fe) for HSC of +70. However, if all the criteria had been perfect, and the maximum favorability values had been used, the sum of the four criteria would have been +165 (Table 7). It is necessary, therefore, to normalize the estimated favorability (Fe) by dividing it by the maximum favorability (Fm) value to yield a normalized (Fn) value:

$$\frac{Fe}{Fm} = Fn \quad \text{or,} \quad \frac{70}{165} = .42$$

The favorability of HSC for Area B is 42, i.e. moderately suggestive.

For Area D the negative and positive criteria are combined in like manner but separately, then normalized and summed:

Negative values

Organic Matter		Volcaniclastics	
-70	+	(-75)	= -145

$$\frac{Fe}{Fm-} = Fn \quad \text{or,} \quad \frac{145}{280} = -.52$$

Positive Values

Clastics		Sand-Shale Proportions	
20	+	25	= +45

$$\frac{Fe}{Fm+} = Fn \quad \text{or,} \quad \frac{45}{165} = .27$$

Combining the normalized positive and negative values ($-52 + 27 = -25$) one determines that Area D has a relatively large negative number, hence, a discouraging Host Sandstone Composition. This is not a very favorable area in which to prospect for a uraniferous humate deposit. In fact, the large negative values for organic matter would be sufficient in most geologists' minds to all but kill the potential of this area. The explorationist should not waste further time in collecting other detailed geological information from this area. This example shows that the geologist making the evaluation must always inspect individual negative numbers, which, if sufficiently discouraging, can destroy the entire potential for the area, even though the accumulation of numerous positive observations may yield a net positive answer.

It can be seen in Figure 17 and Table 6 that Host Sandstone Composition is merely one of four criterion that define the favorability of the Host Sandstone. From Table 6 it will be seen that HSC can contribute a maximum of 55 points, hence, in our example for Area B, HSC becomes:

$$0.42 \times 55 = 23 = \text{Applied Normalized Favorability (Fna)}$$

This value can now be used with similar values for the three other intermediate criteria in calculating the favorability value for Host Sandstone. In a similar manner, all other terminal criteria are combined to evaluate intermediate criteria until the favorability for a uraniferous humate-type deposit has been evaluated. This favorability is not necessarily equivalent to the probability of a deposit being present as is discussed in a later paragraph.

Completeness of Confidence of Geologic Data

If the field geologist has complete geologic data and is equally and completely confident about all his field observations, he may evaluate the favorability according to the preceding paragraphs. In most cases, however, he will lack data and probably have various levels of confidence regarding the data that does exist. His confidence for different observations may range from completely certain that, for example, a uranium source rock is present, to no confidence (i.e., he does not know) that the age of the prospective basin sediments is Eocene. In such circumstances methods can be devised to modify the favorability estimates, but no calculations can overcome the lack of data or confident observation. Such shortcomings must be carefully documented and the resulting favorability estimate interpreted accordingly.

Interpretation of Results

Favorability estimates prepared by the methods described in the preceding paragraphs should be accepted and used only after review of four important parameters:

- (1) The final favorability estimate itself;
- (2) Favorability estimates for intermediate level criteria;

- (3) Favorability values for individual criteria, particularly large negative values;
- (4) Completeness of data and certainty of observations.

Each of these is briefly discussed with reference to favorability estimates made for three areas in the United States and presented in the next section.

The final favorability estimate reflects the net geologic favorability of an area, when compared with the Grants region, for which the recognition criteria net and maximum and minimum favorability values were selected. A score of 100 indicates a perfect geologic fit, i.e. virtual assurance that at least one deposit is present. A final score of zero indicates a very low level of favorability, provided the geologic data was complete, and the prospects of finding a deposit would be comparable to hitting a deposit with a dart thrown at a map of North America. A favorability of +50, therefore, is only half as favorable as one of +100. If the score is based on high confidence in the observations and complete data (i.e., no zeros assigned to criteria) the area may be said to possess only half the favorable attributes necessary for a deposit. This does not mean the area has a fifty percent chance of a deposit being present. In our judgment the likelihood is less, but how much less is difficult to estimate. At a favorability estimate of zero the chances of a deposit being present are vanishingly small, and at negative favorabilities the chances are even worse. Figure 19 is our subjective attempt to relate estimated favorability of an area to the chances of a deposit being present within that area. The relationship suggests that the chances of a deposit being present decrease more rapidly than the estimated favorability. At 75 percent favorability, for example, we feel there is about a 50 percent chance that a deposit is present.

The estimated favorability values for the second level criteria of the recognition criteria net (Fig. 17) for the three areas considered in the next section are also useful for interpreting the favorability estimates. Inspection of these values, which are tabulated below, permits one to determine the contribution of each intermediate level criterion to the final estimated favorability.

Second Level Criterion	Applied Normalized Favorability Values			Applied Normalized Values	
	Chinle	Denver	Henry	Values	
	NE Ariz.	Basin	Mtns.	Max	Min
Tectonic, Structural and Regional Geologic Setting	+30	+18	+27	+30	-95
Continental Sedimentary Sequence	+48	+17	+52	+55	-95
Host Sandstone	+10	+24	+45	+45	-95
Alteration and Mineralization	+16	-13	+23	+65	-95

Figure 19. Schematic relation between calculated favorability for uraniferous humate-type deposits and the chances of a deposit being present within the area evaluated.

The Chinle of Northeastern Arizona received low scores for Host Sandstone and Alteration and Mineralization. This shows that, although the formation was deposited in a favorable tectonic setting and with a favorable continental sedimentary sequence, the characteristics of the sandstone and its alteration and mineralization are not very similar to the Grants region. The Dawson Arkose of the Denver Basin scored low in all criteria indicating that it is not very prospective for uraniferous humate deposits. It is known, however, to offer potential for roll-type deposits. The Salt Wash Member of the Morrison Formation scored very high for all criteria except alteration and mineralization. This suggests the area has potential for a uraniferous humate deposit but with some deterrent related to either mineralization or alteration. One should pursue this down through the lower levels of the criteria net and establish with what criteria the less favorable observations are originating.

Strongly negative values for individual criteria are, in some cases, sufficient to essentially kill the potential of an area. In the final favorability estimate a single large negative value for a terminal criterion may become lost in generally positive criteria values, hence, the geologist must inspect the values of individual criteria. In the example above, the low score for Alteration and Mineralization results from low scores estimated for the apparently unfavorable feldspar and ilmenite-magnetite alteration.

Finally, the completeness of the data, hence the number of zero values, may produce erroneous estimated favorability values. In exploration, low favorability values due to incomplete and uncertain data are not as unfavorable as low favorability values resulting from negative or low positive criteria values. In resource studies, however, the absence of data could yield an apparent favorability much lower (or higher) than the area warrants. Careful inspection must be made of incomplete and uncertain data and the resulting favorability estimate interpreted accordingly. Where new data or more certain observations are needed, the criteria weights will indicate which observations are most important to obtain.

Example of Favorability Estimates

In the following pages, recognition criteria are used to estimate the geologic favorability for uraniferous humate-type deposits in two continental interior basins in Arizona and Utah and one range front basin in Colorado. These examples are chosen to illustrate one simple method for developing favorability estimates. In each case something was known about favorability of the area based on previous exploration and the discovery of certain types of uranium mineralization.

The following abbreviations are used throughout:

CNA = Chinle Formation, Northeastern Arizona

DDB = Dawson Arkose, Denver Basin, Colorado

SHM = Salt Wash Member of the Morrison Formation, Henry Mountains, Utah

Fe = Estimated favorability value

- Fm+ = Maximum positive favorability value
- Fm- = Maximum negative favorability value
- Fn = Normalized Favorability value
- Fna = Normalized applied favorability value

Estimated Favorability (Fe) is simply the sum of the favorability values assigned to each of a group of criteria that determines the favorability of a higher intermediate level criterion, based upon field data.

Maximum Favorability (Fm+) is the sum of the maximum values that could be assigned to those criteria.

Minimum Favorability (Fm-) is the sum of the minimum values that could be assigned to those criteria.

Normalized Favorability (Fn) is equal to the estimated favorability divided by the maximum (or minimum where appropriate) favorability. It may be interpreted, therefore, as a percentage of the total possible favorability of the criteria.

Normalized Applied Favorability (Fna) is the normalized favorability of a group of criteria which is then multiplied by the weight assigned to the criterion above; the product is the weight for that higher level criterion that is then used with other criteria to calculate the favorability of the next higher level criteria. For example (Fig. 17), four criteria determine the favorability of Host Sandstone Composition. The normalized favorability obtained from these four criteria is not used directly in combination with the three other criteria that establish the favorability of Host Sandstone, but is multiplied by the positive or negative value (+55, -95) assigned to Composition (see Table 6). It is necessary to calculate Fna only where higher level criteria have been assigned separate weight values, generally toward the top of the criteria net, and all are indicated by asterisks in Table 6.

I. Tectonic, Structural and Regional Geologic Setting

The favorability is determined by the geology of two criteria:

(a) Tectonic Setting

- CNA +80 (cratonic basin)
- DDB +45 (a range front basin)
- SHM +80 (cratonic basin)

(b) Structural Setting

- CNA +30 (numerous structures)
- DDB +20 (some structures)
- SHM +20 (as above)

(c) Favorability Score

The favorability estimate (Fe) is the sum of the individual favorability numbers derived from field data:

$$\text{Fe CNA} \quad 80 + 30 = +110$$

$$\text{Fe DDB} \quad 45 + 20 = +65$$

$$\text{Fe SHM} \quad 80 + 20 = +100$$

Reference to Table 6 shows that the maximum favorability for Tectonic, Structural and Regional Geologic Setting that could be derived from the sum of these criteria is

$$F_m = 80 + 30 = +110$$

We now want to know the extent to which the estimated favorabilities achieved the maximum potential favorability, hence we divide the estimate (Fe) by the maximum (Fm). One also notes (Table 6) that the maximum values of Tectonic, Structural and Regional Geologic Setting for evaluating the favorability for a uraniferous humate-type deposit are +30 and -95. We can, therefore, combine two steps and calculate directly the normalized applied favorability which is the contribution to the favorability for a uraniferous humate deposit:

$$F_{na} = \frac{F_e}{F_m} \times 30$$

Thus,

$$F_{na} \text{ CNA} = \frac{110}{110} \times 30 = +30 \quad (\text{a perfect score})$$

$$F_{na} \text{ DDB} = \frac{65}{110} \times 30 = +18 \quad (\text{out of a possible } +30)$$

$$F_{na} \text{ SHM} = \frac{100}{110} \times 30 = +27 \quad (\text{near perfect score})$$

II. Continental Sedimentary Sequence

(a) Age

$$\text{CNA} = +30 \quad (\text{Mesozoic})$$

$$\text{DDB} = +10 \quad (\text{Tertiary})$$

$$\text{SHM} = +30 \quad (\text{Mesozoic})$$

(b) Associated Sediments

CNA = +30 (very favorable)

DDB = +30 (as above)

SHM = +30 (as above)

(c) Host Sediments

(1) Thickness

CNA = +25 (several hundred feet)

DDB = +25 (as above)

SHM = +25 (as above)

(2) Area

CNA = +25 (broad area)

DDB = -30 (limited area)

SHM = +25 (broad area)

(3) Sand-shale facies

CNA = +40 (continuous and interbedded)

DDB = +20 (some interbedding)

SHM = +40 (continuous and interbedded)

(4) Shales

a. Color

CNA = -80 (hematitic)

DDB = +30 (mostly reduced)

SHM = +10 (mixed oxidized-reduced)

b. Bentonite

CNA = +75 (abundant)

DDB = -60 (very minor)

SHM = +75 (abundant)

c. Carbonate and Silica

$$\text{CNA} = +30 \quad (\text{present})$$

$$\text{DDB} = -30 \quad (\text{absent})$$

$$\text{SHM} = +30 \quad (\text{present})$$

d. Shale Score

$$\begin{array}{rclcl} \text{Fe CNA} & = & \text{Pos} + 75 & + 30 & = +105 \\ & & \text{Neg} - 80 & & = -80 \end{array}$$

$$\begin{array}{rclcl} \text{Fe DDB} & = & \text{Pos} + 30 & & = +30 \\ & & \text{Neg} - 60 & + (-30) & = -90 \end{array}$$

$$\text{Fe SHM} = +10 + 75 + 30 = +115$$

The assigned weights to shale are +60 and -85 (Table 6), hence:

$$\text{Fna CNA Pos} = \frac{105}{150} = .7$$

$$\text{Fna CNA Neg} = \frac{80}{185} = .43$$

$$\begin{array}{rclcl} \text{Fna CNA Net} & .7 - .43 & = & .27 \\ \text{Fna CNA} & .27 \times 60 & = & +16 & (\text{out of possible } +60) \end{array}$$

$$\text{Fna DDB Pos} = \frac{30}{150} = .2$$

$$\text{Fna DDB Neg} = \frac{90}{185} = -.49$$

$$\begin{array}{rclcl} \text{Fna DDB Net} & -.49 + .20 & = & -.29 \\ \text{Fna DDB} & .29 \times (85) & = & -25 & (\text{out of possible } -85) \end{array}$$

$$\text{Fna SHM} = \frac{115}{150} \times 60 = +46 \quad (\text{out of possible } +60)$$

$$\text{Fna DDB Neg} = \frac{90}{185} = -.49$$

$$\begin{array}{rclcl} \text{Fna DDB Net} & -.49 + .20 & = & -.29 \\ \text{Fna DDB} & .29 \times (85) & = & -25 & (\text{out of possible } -85) \end{array}$$

$$\text{Fna SHM} = \frac{115}{150} \times 60 = +46 \quad (\text{out of possible } +60)$$

(5) Host Sediment Score

$$\text{Fe CNA} = +25 + 25 + 40 + 16 = +106$$

$$\begin{aligned}\text{Fe DDB} &= \text{Pos} + 25 + 20 = +45 \\ &\text{Neg} - 30 - 25 = -55\end{aligned}$$

$$\text{Fe SHM} = +25 + 25 + 40 + 46 = +136$$

The assigned weights to Host Sediment are +75 and -95 (Table 6), hence:

$$\text{Fna CNA} = \frac{106}{150} \times 75 = +53 \quad (\text{out of possible } +75)$$

$$\text{Fna DDB Pos} = \frac{45}{150} = .3$$

$$\text{Fna DDB Neg} = \frac{55}{210} = .26$$

$$\text{Fna DDB Net} = .3 - .26 = +.04$$

$$\text{Fna DDB} = +.04 \times 75 = +3 \quad (\text{out of possible } 75)$$

$$\text{Fna SHM} = \frac{136}{150} \times 75 = +68 \quad (\text{out of possible } 75)$$

(d) Continental Sedimentary Sequence Score

$$\text{Fe CNA} = +30 + 30 + 53 = +113$$

$$\text{Fe DDB} = +10 + 30 + 3 = +43$$

$$\text{Fe SHM} = +30 + 30 + 68 = +128$$

$$\text{Fna CNA} = \frac{113}{135} \times 55 = +46 \quad (\text{out of possible } +55)$$

$$\text{Fna DDB} = \frac{43}{135} \times 55 = +18 \quad (\text{out of possible } +55)$$

$$\text{Fna SHM} = \frac{128}{135} \times 55 = +52 \quad (\text{out of possible } +55)$$

III. Host Sandstone

(a) Area

$$\text{CNA} = +20 \quad (\text{widespread})$$

$$\text{DDB} = +20 \quad (\text{as above})$$

$$\text{SHM} = +20 \quad (\text{as above})$$

(b) Depositional Environment

CNA = -60 (distal fan)
DDB = +30 (mid-distal fan)
SHM = +45 (mid-fan)

(c) Permeability

CNA +10 (high)
DDB -20 (moderately low)
SHM +10 (high)

(d) Composition

(1) Organic Matter

CNA = +55 (logs and trash)
DDB = +55 (as above)
SHM = +55 (as above)

(2) Clastics

CNA = +30 (arkosic)
DDB = +30 (as above)
SHM = +30 (as above)

(3) Volcaniclastics

CNA = +45
DDB = -30
SHM = +45

(4) Sandstone-Shale Proportions

CNA = -70 (excessive shale)
DDB = +20 (50% sandstone)
SHM = +35 (60-80% sandstone)

(5) Composition Score

Fe CNA = Pos +55 + 30 + 45 = +130
Neg -70 = - 70

$$\begin{array}{rclclcl} \text{Fe DDB} & = & \text{Pos} & +55 & + 30 & + 20 & = & +105 \\ & & \text{Neg} & -30 & & & = & - 30 \end{array}$$

$$\text{Fe SHM} = +55 + 30 + 45 + 35 = +165$$

$$\text{Fna CNA Pos} = \frac{130}{165} = .79$$

$$\text{Fna CNA Neg} = \frac{70}{280} = .25$$

$$\text{Fna CNA Net} = +.79 - .25 = +.54$$

$$\text{Fna CNA} = .54 \times 55 = +30 \quad (\text{out of possible } +55)$$

$$\text{Fna DDB Pos} = \frac{105}{165} = .64$$

$$\text{Fna DDB Neg} = \frac{30}{280} = .11$$

$$\text{Fna DDB Net} = +.64 - .11 = .53$$

$$\text{Fna DDB} = .53 \times 55 = +29 \quad (\text{out of possible } +55)$$

$$\text{Fna SHM} = \frac{165}{165} \times 55 = +55 \quad (\text{perfect score})$$

(e) Host Sandstone Score

$$\begin{array}{rclclcl} \text{Fe CNA} & = & \text{Pos} & +20 & +10 & +30 & = & +60 \\ & & \text{Neg} & -60 & & & = & -60 \end{array}$$

$$\begin{array}{rclclcl} \text{Fe DDB} & = & \text{Pos} & +20 & +30 & +29 & = & +79 \\ & & \text{Neg} & -20 & & & = & -20 \end{array}$$

$$\text{Fe SHM} = +20 + 45 + 10 + 55 = +130$$

$$\text{Fna CNA Pos} = \frac{60}{130} = +.46$$

$$\text{Fna CNA Neg} = \frac{60}{265} = -.23$$

$$\text{Fna CNA Net} = .46 - .23 = +.23$$

$$\text{Fna CNA} = .23 \times 45 = +10 \quad (\text{out of possible } +45)$$

$$\begin{aligned}
 \text{Fna DDB Pos} &= \frac{79}{130} = +.61 \\
 \text{Fna DDB Neg} &= \frac{20}{265} = -.08 \\
 \text{Fna DDB Net} &= .61 - .08 = +.53 \\
 \text{Fna DDB} &= .53 \times 45 = +24 \quad (\text{out of possible } +45) \\
 \text{Fna SHM} &= \frac{130}{130} \times 45 = +45 \quad (\text{perfect score})
 \end{aligned}$$

IV. Alteration and Mineralization

(a) Mineralization

CNA = +55 (abundant anomalies)
 DDB = +20 (some anomalies)
 SHM = +55 (abundant anomalies)

(b) Alteration

(1) Ilmenite-Magnetite

CNA = -50 (minimal data but probably partly to totally oxidized)
 DDB = -75 (oxidized but not dissolved)
 SHM = -50 (minimal data but alteration probably local at best)

(2) Pyrite

CNA = +10 (traces present)
 DDB = +20 (some present)
 SHM = +40 (moderate concentration)

(3) Feldspars

CNA = -55 (minimal alteration)
 DDB = -55 (as above)
 SHM = -55 (as above)

(4) Alteration Score

$$\begin{array}{lcl} \text{Fe CNA} & = & \text{Pos } +10 \\ & = & \text{Neg } -50 \quad -55 \end{array} \quad \begin{array}{l} = +10 \\ = -105 \end{array}$$

$$\begin{array}{lcl} \text{Fe DDB} & = & \text{Pos } +20 \\ & = & \text{Neg } -75 \quad -55 \end{array} \quad \begin{array}{l} = +20 \\ = -130 \end{array}$$

$$\begin{array}{lcl} \text{Fe SHM} & = & \text{Pos } +40 \\ & = & \text{Neg } -50 \quad -55 \end{array} \quad \begin{array}{l} = +40 \\ = -105 \end{array}$$

$$\text{Fna CNA Pos} = \frac{10}{175} = +.06$$

$$\text{Fna CNA Neg} = \frac{105}{180} = -.58$$

$$\text{Fna CNA Net} = .58 - .06 = -.52$$

$$\text{Fna CNA} = -.52 \times 95 = -49 \quad (\text{out of possible } -95)$$

$$\text{Fna DDB Pos} = \frac{20}{175} = +.11$$

$$\text{Fna DDB Neg} = \frac{130}{180} = -.72$$

$$\text{Fna DDB Net} = -.72 + .11 = -.61$$

$$\text{Fna DDB} = -.61 \times 95 = -58 \quad (\text{out of possible } -95)$$

$$\text{Fna SHM Pos} = \frac{40}{175} = +.23$$

$$\text{Fna SHM Neg} = \frac{105}{180} = -.58$$

$$\text{Fna SHM Net} = -.58 + .23 = -.35$$

$$\text{Fna SHM} = -.35 \times 95 = -33 \quad (\text{out of possible } -95)$$

C. Alteration and Mineralization Score

$$\begin{array}{lcl} \text{Fe CNA} & = & \text{Pos } +55 \\ & = & \text{Neg } -49 \end{array} \quad \begin{array}{l} = +55 \\ = -49 \end{array}$$

$$\begin{array}{lcl} \text{Fe DDB} & = & \text{Pos } +20 \\ & = & \text{Neg } -58 \end{array} \quad \begin{array}{l} = +20 \\ = -58 \end{array}$$

$$\begin{array}{lcl} \text{Fe SHM} & = & \text{Pos } +55 \\ & = & \text{Neg } -33 \end{array} \quad \begin{array}{l} = +55 \\ = -33 \end{array}$$

$$\begin{aligned}
\text{Fna CNA Pos} &= \frac{55}{100} = .55 \\
\text{Neg} &= \frac{49}{165} = .30 \\
\text{Net} &= +.55 - .30 = +.25 \\
\text{Fna CNA} &= .25 \times 65 = +16 \quad (\text{out of possible } +65) \\
\text{Fna DDB Pos} &= \frac{20}{100} = +.20 \\
\text{Neg} &= \frac{-58}{165} = -.35 \\
\text{Net} &= -.35 + .20 = -.15 \\
\text{Fna DDB} &= -.15 \times 95 = -14 \quad (\text{out of possible } -95) \\
\text{Fna SHM Pos} &= \frac{55}{100} = +.55 \\
\text{Neg} &= \frac{33}{165} = -.20 \\
\text{Net} &= +.55 - .20 = +.35 \\
\text{Fna SHM} &= .35 \times 65 = +23 \quad (\text{out of possible } 65)
\end{aligned}$$

The second level favorability estimates calculated in the preceding pages can now be tabulated in preparation for calculating the favorability estimates for uraniferous humate deposits in these three areas:

<u>Second Level Criterion</u>	<u>Applied Normalized Favorability Values</u>			<u>Applied Normalized Values</u>	
	<u>Chinle NE Ariz.</u>	<u>Denver Basin</u>	<u>Henry Mtns.</u>	<u>Max.</u>	<u>Min.</u>
Tectonic, Structural and Regional Geologic Setting	+30	+18	+27	+30	-95
Continental Sedimentary Sequence	+48	+18	+52	+55	-95
Host Sandstone	+10	+24	+45	+45	-95
Alteration and Mineralization	+16	-14	+23	+65	-95

The favorability for uraniferous humate-type deposits in these three areas is calculated using the data above and the same procedures used in the preceding calculations:

$$\text{Fe CNA} = 30 + 48 + 10 + 16 = +104$$

$$\text{Fe DDB} = \text{Pos } +18 + 18 + 24 = +60$$

$$\text{Neg } -14 = -14$$

$$\text{Fe SHM} = 27 + 52 + 45 + 23 = +147$$

$$\text{Fn CNA} = \frac{104}{195} \times 100 = 53\%$$

$$\text{Fn DDB Pos} = \frac{59}{195} = +.30$$

$$\text{Neg} = \frac{14}{380} = -.04$$

$$\text{Net} = +.31 - .04 = +.27$$

$$\text{Fn DDB} = .27 \times 100 = 27\%$$

$$\text{Fn SHM} = \frac{147}{195} \times 100 = 75\%$$

These results suggest that, although all three areas bear considerable resemblance to the Grants Uranium Region, their favorabilities for uraniferous humate-type deposits are substantially less. The Salt Wash in the Henry Mountains area, with a favorability of 75 percent, is decidedly the best but there is probably no more than a 50 percent chance that the area contains a uraniferous humate deposit (see Figure 19). The Chinle of Northeast Arizona and the Dawson Arkose of the Denver Basin, Colorado are lower still, with chances for uraniferous humate-type deposits probably in the range of 10 and 20 percent.

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PANEL DIAGRAM OF THE MORRISON FORMATION
SOUTHERN SAN JUAN BASIN, NEW MEXICO

EXPLANATION

- Jackpile Sandstone
- Brushy Basin member
- Westwater Canyon member
- Recapture member
- Measured Section
- Drill Hole
- Uranium Mineralization
- Morrison-Dakota Contact

INDEX MAP
Showing Location of Control Points

	Morrison Outcrop		Erosional edge of Jackpile Sandstone
	Mount Taylor Volcanics		Erosional edge of Brushy Basin Member
	Folds		Erosional edge of Recapture Member
	Monoclines		Erosional edge of Westwater Canyon Member
	Faults		Depositional edge of Westwater Canyon Member

PRE-DAKOTA SUBCROP AND PALEO-STRUCTURE MAP

0 10 20 miles
0 10 20 30 kilometers

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Explanation

●	Drill hole	x	Subsurface anomaly in Jackpile ss.
▲	Measured Section	↕	Fold Axes
■	Uranium Deposit (Jmj)	—	Erosional Edge of Jackpile ss.
▨	Mineralized Area (Jmj)	—200—	Isopach—interval 50 feet

ISOPACHOUS MAP

Combined Brushy Basin and Westwater Canyon Members
of the Morrison Formation in the Laguna Area

STRUCTURE AND MINERALIZATION MAP OF AMBROSIA LAKE DISTRICT

NORTH-SOUTH STRATIGRAPHIC PROFILE ACROSS AMBROSIA LAKE

ANN LEE ORE BODY RIB MAPS

PLATE 6

CONSECUTIVE NORTH-SOUTH DRIFTS SPACED APPROXIMATELY 40 FEET APART

EXPLANATION

- Uranium Ore
- Molybdenum Mineralization
- VC-M Grained Sandstone
- M-VF Grained Sandstone
- Disconformity
- Drill Hole
- Waste

Source : J.B. Squyres

Single-point Resistivity Log

Source: Moench and Schlee, 1967

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ISOPACHOUS MAP FOR THE INTERVAL OF TOTAL ILMENITE-MAGNETITE DESTRUCTION IN THE UPPER WESTWATER CANYON MEMBER, GRANTS URANIUM REGION, NEW MEXICO

- Morrison Outcrop
- Mount Taylor Volcanics
- ILMENITE-MAGNETITE PRESENT
TO TOP OF WESTWATER (on side
of pattern)

CONTOUR INTERVAL 50'

• 242' Drill Hole Location and Thickness of Destruction

0 10 20 miles
0 10 20 30 kilometers

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DISTRIBUTION OF URANIUM DEPOSITS AND PROSPECTIVE AREAS IN THE MORRISON FORMATION GRANTS URANIUM REGION, NEW MEXICO

- Morrison Outcrop
- Mount Taylor Volcanics
- Uranium Deposit
- Mineralized Area
- Limit of Hematitic Oxidation
- Limit of Limonitic Oxidation
- Border of Prospective Westwater Canyon Sandstone (Based on total ilmenite-magnetite destruction and extent of pyrite, feldspar alteration and known mineralization)

0 10 20 miles
0 10 20 30 kilometers

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