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STRUCTURAL CONTROL OF SEDIMENTATION PATTERNS AND URANIUM DEPOSITS OF THE WESTWATER CANYON AND BRUSHY BASIN MEMBERS OF THE MORRISON FORMATION, SAN JUAN BASIN, NEW MEXICO

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INTRODUCTION

The maps in this report were constructed to show (1) regional sedimentation patterns displayed by the Westwater Canyon and Brushy Basin Members of the Upper Jurassic Morrison Formation, (2) structural control of the sedimentation patterns of those members, and (3) structural and (or) sedimentary controls on the distribution of uranium deposits in the Westwater Canyon Member. Maps A-1, A-2, and A-3 are isopach maps of the separate and combined Westwater Canyon and Brushy Basin Members. Maps B-1, B-2, and B-3 show the percent of sandstone in the Westwater Canyon Member and the total thickness, or net amount, of sandstone in the two members. Maps C-1 and C-2 show the ratio of sandstone to mudstone and the number of mudstone interbeds per 100 ft (30 m) of section in the Westwater Canyon Member, respectively. Map D-1 shows the structure at the base of the Dakota Sandstone, map D-2 shows the paleotopography at the base of the Westwater Canyon Member, and map D-3 shows the structures that are inferred to have been active during deposition of the Westwater Canyon.

The study area is the southern part of the San Juan Basin, northwest New Mexico and southwest Colorado (fig. 1). Variously known as the Grants mineral belt (Kelley, 1963), the San Juan mineral belt, or the Grants uranium region (Chenoweth and Holan, 1980), it is the largest uranium-producing area in the United States and has accounted for 40 percent of the total domestic production (Chenoweth, 1976). The study is focused on the Westwater Canyon and Brushy Basin Members because most of the uranium production from the region has been from the Westwater Canyon Member (Adams and Saucier, 1981), and the Brushy Basin Member probably played an important role in the ore-forming process (Bell, 1983; Turner-Peterson, 1985). Brief overviews of the tectonic setting, stratigraphic framework, and types of uranium ore deposits are presented below; see Kirk and Condon (1986) for more complete background material and discussion.

ACKNOWLEDGMENTS

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TECTONIC SETTING

The San Juan Basin is a large structural and topographic basin that assumed its present shape during the Late Cretaceous and early Tertiary Laramide orogeny (Kelley, 1951). The basin is bounded by the Nacimiento uplift and Archuleta arch on the east, the Zuni uplift on the south, the Defiance uplift on the west, and the Uncompahgre uplift and San Juan dome on the north (fig. 1). Permian, Triassic, Jurassic, and Cretaceous rocks are present throughout the basin and are exposed at the margins of the bounding uplifts; rocks of Cambrian, Devonian, Mississippian, and Pennsylvanian age only occur in the northern part of the basin (Stevenson and Baars, 1977). The

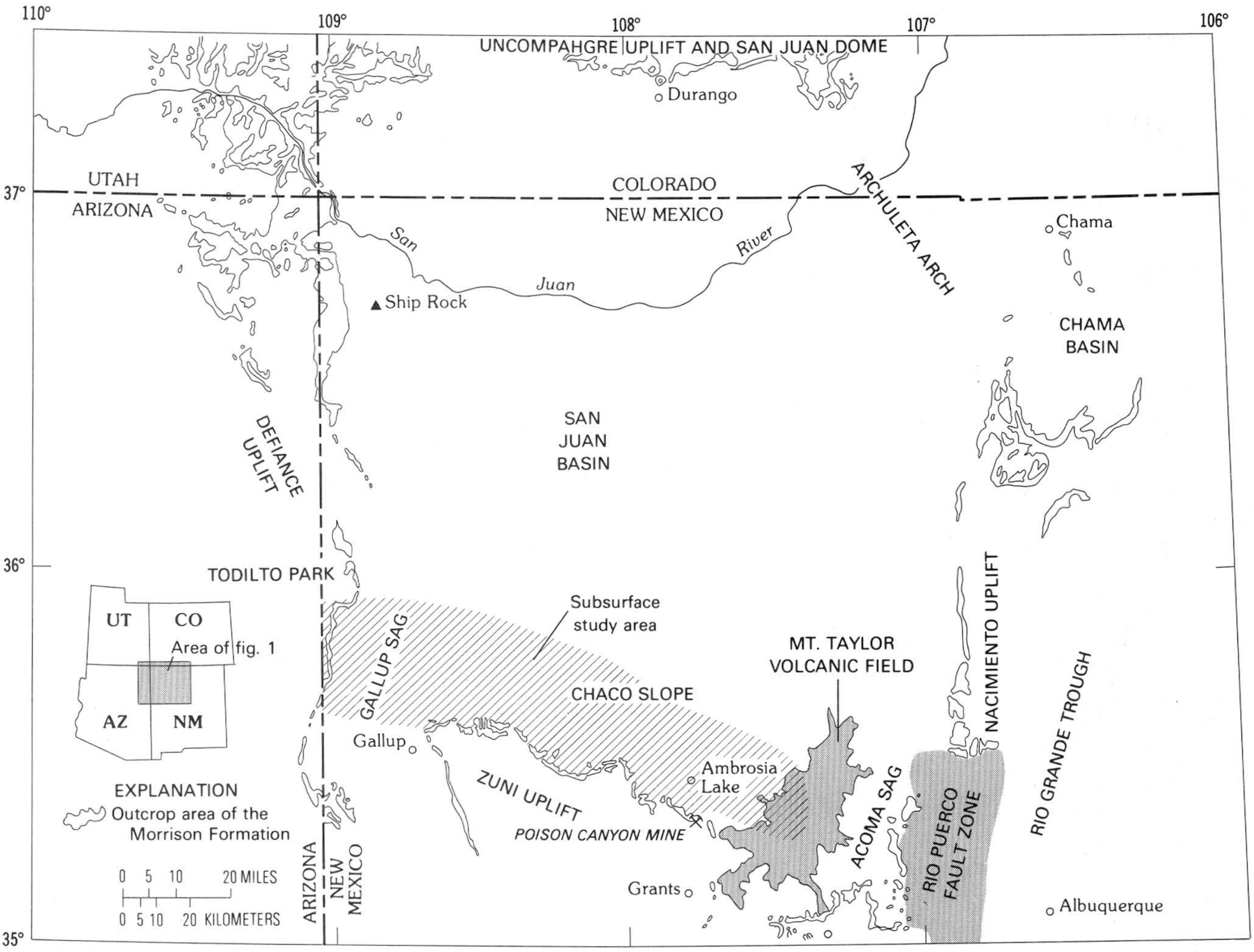

Figure 1.—Map showing subsurface study area (Grants uranium region, hachured) and outcrop area of the Morrison Formation.

presence of this fairly complete suite of rocks indicates that the region has been a site of sedimentary deposition through much of the Phanerozoic.

During the Late Jurassic, the San Juan Basin area was part of a back-arc basin, formed inland of an Andean-type magmatic arc that bounded the continent on the west (Burchfield, 1979). This magmatic arc and a landward upland area, termed the Mogollon highlands (Harshbarger and others, 1957, p. 44; Dickinson, 1981, p. 121), provided much of the sediment that now comprises the Morrison Formation (Craig and others, 1955). The area of the present-day San Juan Basin was part of what Saucier (1976, p. 152) called the San Juan trough, a northwest-southeast-oriented depression located between the Uncompahgre highlands to the north and the Mogollon highlands to the south. Eastward- and northeastward-flowing streams carried sediment into this trough and deposited the Recapture, Westwater Canyon, and part of the Brushy Basin Members of the Morrison Formation. The depositional area of the Morrison probably extended southward to the Mogollon highlands; however, the Zuni uplift (fig. 2) appears to have influenced depositional patterns and distribution of some members of the Morrison. There is no outcrop or subsurface evidence that the Defiance uplift (fig. 2) affected deposition of the Morrison. The study area shown in this set of maps lies along the gently northward-dipping (2°-10°) southern flank of the Laramide San Juan Basin.

STRATIGRAPHIC FRAMEWORK

The subject of this study is the Upper Jurassic Morrison Formation. In the southern part of the San Juan Basin the Morrison has three members, from oldest to youngest, the Recapture, the Westwater Canyon, and the Brushy Basin (fig. 3).

The Recapture Member consists of sandstone, siltstone, and mudstone, and has two facies - eolian and fluvial. The eolian facies is greenish-gray to yellowish-gray, fine- to medium-grained, moderately well sorted, quartzose sandstone that is interbedded in places with 1-3 ft (.3-1 m) thick beds of reddish-brown to maroon siltstone and mudstone. Sedimentary structures of this facies include very large to medium-scale

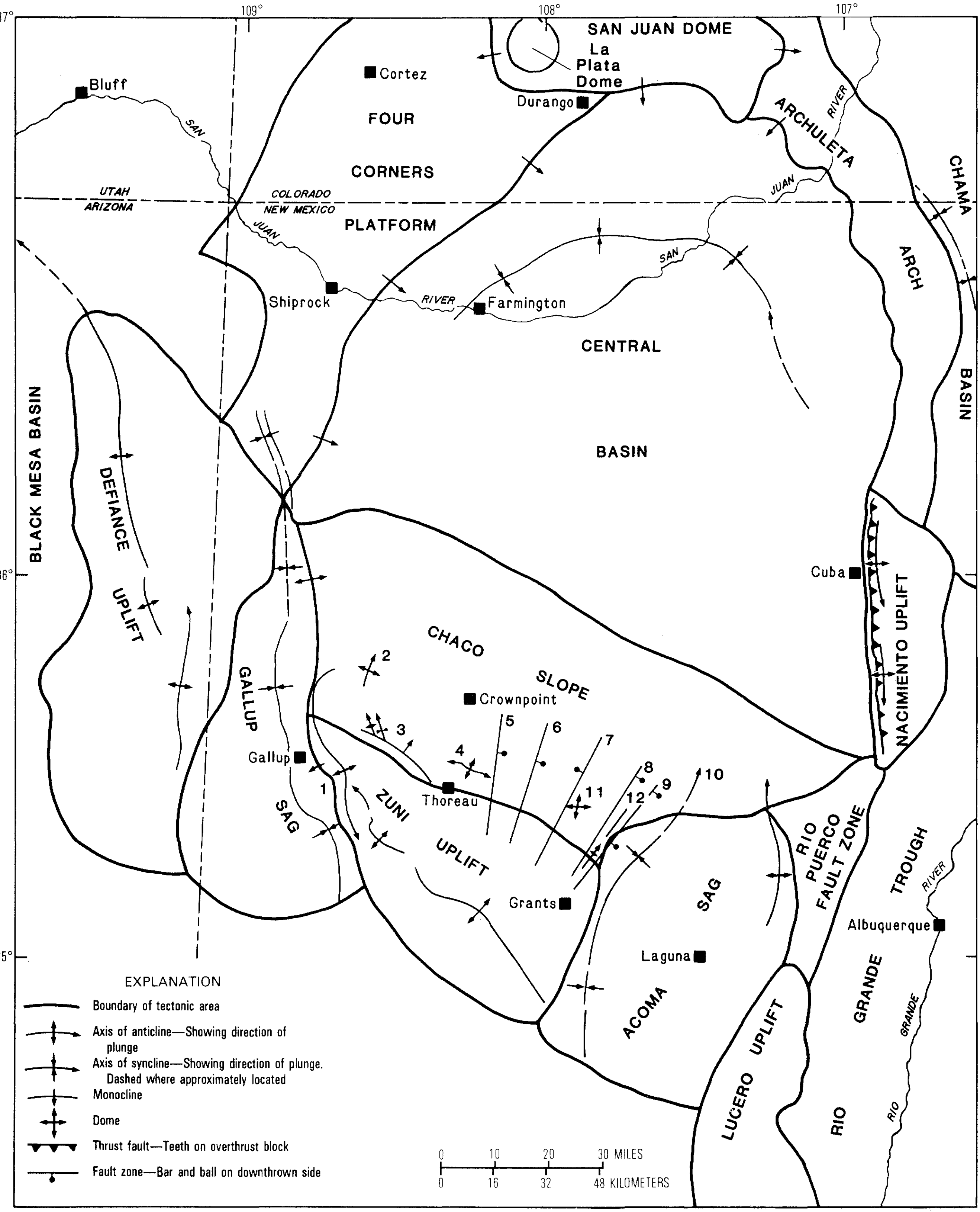

Figure 2.—Map showing structural elements of the San Juan Basin and adjacent areas (modified from Kelley, 1963). Numbers refer to the following structures: (1) Nutria monocline, (2) Coyote Canyon anticline, (3) Pinedale monocline, (4) Mariano Lake-Ruby Wells anticline, (5) Bluewater fault zone, (6) Big Draw fault zone, (7) Ambrosia fault zone, (8) San Mateo fault zone, (9) San Rafael fault zone, (10) McCartys syncline, (11) Ambrosia dome, (12) McCartys arch. All features except McCartys syncline are shown on Map D–1.

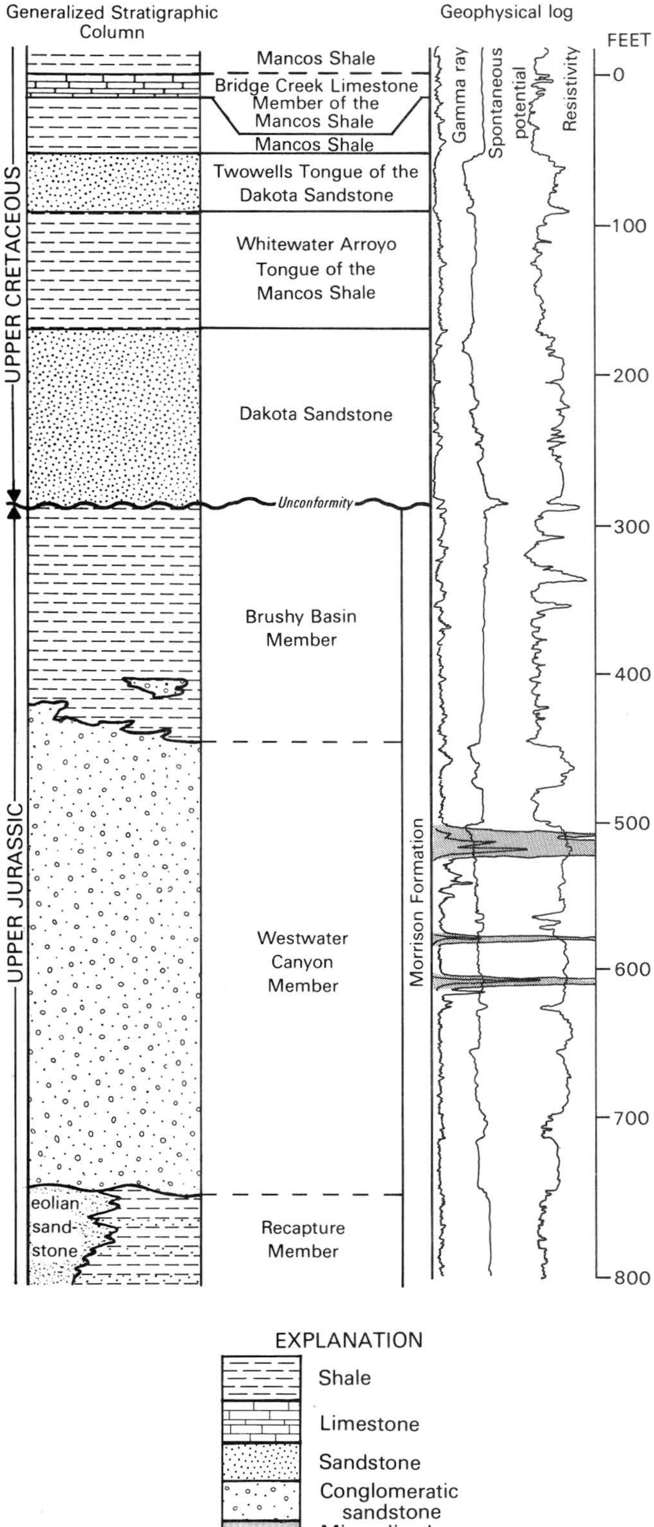

Figure 3.—Representative geophysical log showing the stratigraphic interval from the Recapture Member of the Morrison Formation to the Mancos Shale, and mineralized zones (shown by high gamma-ray readings) in the Westwater Canyon Member.

crossbeds (commonly tabular planar), ripple cross-stratification, flatbeds, burrows, and mudcracks. Crossbedded dunes grade laterally into interdune playa deposits in many places.

The fluvial facies of the Recapture has the same range of lithologies as the eolian facies, with the addition of conglomeratic sandstone and thin beds of sandy limestone. The proportion of fine-grained interbeds is greater in the fluvial facies than in the eolian facies. In many outcrops the lower part of the fluvial facies has thin, lenticular, fine-grained sandstone lenses encased in thick siltstone or mudstone beds. The upper part of the fluvial facies contains proportionately more sandstone and less siltstone or mudstone; the grain size of the sandstone beds commonly increases upward in this facies and includes lags and pockets of pebbles. In the western part of the study area, the fluvial and eolian facies are interbedded; in the central and eastern part of the area, the fluvial facies commonly overlies the eolian facies. Most of the drill holes used in this study only penetrated the upper few feet of the Recapture and, therefore, the Recapture was not studied.

The Westwater Canyon Member overlies the Recapture Member throughout the southern San Juan Basin. In most places the contact is erosional; in some it appears transitional. In the study area, the Westwater Canyon consists of reddish-brown to yellowish-orange, fine- to medium-grained, locally conglomeratic, poorly sorted, feldspathic to arkosic sandstone. The member also contains fine-grained interbeds of greenish-gray to reddish-brown siltstone or mudstone. Sedimentary structures are dominantly trough and tabular-planar crossbeds and horizontal or gently inclined laminations. The Westwater Canyon has been interpreted to be deposits of high-energy braided streams (Craig and others, 1955, p. 157).

A unit informally named the Poison Canyon sandstone is a transitional unit that occurs at the top of the Westwater Canyon Member in the area of the Poison Canyon Mine (fig. 1). The Poison Canyon consists of from one to three Westwater Canyon-type sandstone beds separated from the main body of the Westwater Canyon by a thick claystone or mudstone bed that has a Brushy Basin-type lithology. For purposes of this study, the Poison Canyon sandstone was combined with the Westwater Canyon Member. Although this stratigraphic interval shows a characteristic geophysical-log response throughout the central part of the mapped area, it is believed that the name Poison Canyon sandstone should not be correlated to other areas or used outside of the immediate area of the Poison Canyon mine. On a regional scale, the zone of intertonguing between the Westwater Canyon and the Brushy Basin in one area doesn't necessarily correspond to the zone of intertonguing elsewhere.

The Brushy Basin Member is a heterogeneous unit consisting of light- to dark-greenish-gray and reddish-brown, tuffaceous, bentonitic claystone and mudstone; minor light-gray sandstone and conglomeratic sandstone; and limestone. Zeolite minerals and molds of evaporite crystals are present in the upper part of the member (Bell, 1983). The Brushy Basin has been interpreted to be fluvial and lacustrine, and contains beds of altered volcanic ash (Craig and others, 1955, p. 157; Bell, 1983).

The Jackpile sandstone is a fluvial unit at the top of the Brushy Basin Member that is present east of the study area and was not evaluated in this study. See Nash (1968) or Adams and Saucier (1981) for details concerning the Jackpile.

The Upper Cretaceous Dakota Sandstone unconformably overlies the Morrison Formation in the study area. In the southwest part of the area, pre-Dakota erosion has removed all of the Brushy Basin Member and an unknown thickness of the Westwater Canyon Member. The line of truncation of the Brushy Basin is shown on the maps. Other Upper Cretaceous units above the Dakota Sandstone and their geophysical-log responses are shown in figure 3.

URANIUM ORE DEPOSITS

The ore deposits have been divided into three basic types in the Grants uranium region: primary, remnant, and redistributed (see Kirk and Condon, 1986). Each deposit was classified according to its geometry, its organic content, its postulated origin, and most importantly, its position with respect to a regional oxidation-reduction (redox) interface as recognized by Saucier (1980) (fig. 4). The redox interface (figs. 4 and 5; maps A-1 through D-3) is made up of three components: (1) an area of oxidized, hematitically altered sandstone, (2) an area of reduced sandstone, and (3) an area of oxidized, limonitically altered sandstone between the hematitic and reduced sandstones. The interface isn't a sharp, distinct line; there is a broad zone of lateral and vertical intertonguing between the three components in the area of the redox interface shown on the maps. The position of the interface is adapted from Saucier (1980) and from A.E. Saucier (written commun., 1982).

Primary ore deposits are intimately associated with kerogen (Leventhal, 1980), or humate (Granger and others, 1961) bodies, and are commonly tabular in cross section and sinuous in plan view. The orebodies occur within sandstone beds of the Westwater Canyon Member and are oriented roughly N. 70° W., are from tens of feet to thousands of feet wide, extend from a few hundred feet to a mile in length, and are from a few inches to over 15 feet thick (Adams and Saucier, 1981). Primary ore occurs in reduced sandstone of the Westwater Canyon at or north of the redox interface (fig. 4). The ore is localized in or adjacent to areas of very thick, very sandy Westwater Canyon where the sandstone-to-mudstone ratio is generally greater than 10, where the number of mudstone interbeds per 100 ft (30 m) of section is less than 3, and where the percent and total thickness of sandstone values are high (table 1). These areas of generally very thick, very sandy Westwater Canyon are oriented east-southeast and are referred to in this report as depocenter axes.

Remnant ore deposits have many of the characteristics of primary ore; however, they are surrounded by barren, oxidized sandstone rather than reduced sandstone, and lie updip from (south of) the redox interface. Remnant deposits seem to be preserved because of some unusual geologic, hydrologic, or structural setting of the host sandstone. Examples of some of these unusual conditions are the following: (1) The organic-rich ore may have been insoluble and impermeable enough to divert oxidizing ground water into adjacent, more permeable rock (Smith and Peterson, 1980); post-ore cementation of orebodies may have had the same effect. (2) The host sandstone may pinch out updip between mudstone beds before reaching the outcrop, preventing the downdip flow of oxidizing ground water. (3) The host sandstone could also pinch out downdip into less permeable mudstone, inhibiting the flow of oxidizing ground water through the host sandstone. (4) Faults may have diverted the flow of oxidizing ground water around an ore zone, thereby helping to preserve the ore.

Remnant ore doesn't seem to be closely associated with areas of isopach thicks, although it does occur in areas that have a high sandstone-to-mudstone ratio, few mudstone interbeds, and a high percentage of sandstone. The amount of total sandstone associated with remnant ore is variable (table 1).

Redistributed ore deposits were formed when oxidizing ground water entered the host sandstone, dissolved the organics from primary ore bodies, and moved the mineralized organic material downdip in solution. Two types of redistributed ore have been described: (1) the fracture-controlled, postfault or stack ore of Granger and others (1961), which has a limited distribution, and (2) the more widely occurring geochemical-cell or roll deposits that have a C-shaped geometry in longitudinal cross section. The geochemical-cell deposits were formed when oxidizing ground water south of the redox interface moved downdip (north) and destroyed or partially destroyed primary deposits. Ground-water flow was directed to the north in transmissive sandstone beds that are commonly bounded above and below by mudstone interbeds. The ore is reprecipitated when the mineralized organics in solution are adsorbed onto clay in the mudstone units that border sandstone beds (Adams and Saucier, 1981, p. 87). The ore is of higher grade where it is adjacent to the updip, oxidized sandstone, and gradually disperses downdip into reduced sandstone. According to Adams and Saucier (1981) this type of deposit only formed where pre-existing primary ore was present updip; movement downdip was normally 1,000 ft (305 m) or less, and no more than about 3,000 ft (914 m). Redistributed ore deposits occur in the thick, sandy depocenter axes, although with more variability than the primary ore deposits (table 1).

METHODS OF STUDY

Approximately 1,800 geophysical logs were examined to produce the contour maps of rock and ore parameters in the subsurface. An additional 2,200 logs were used in the con-

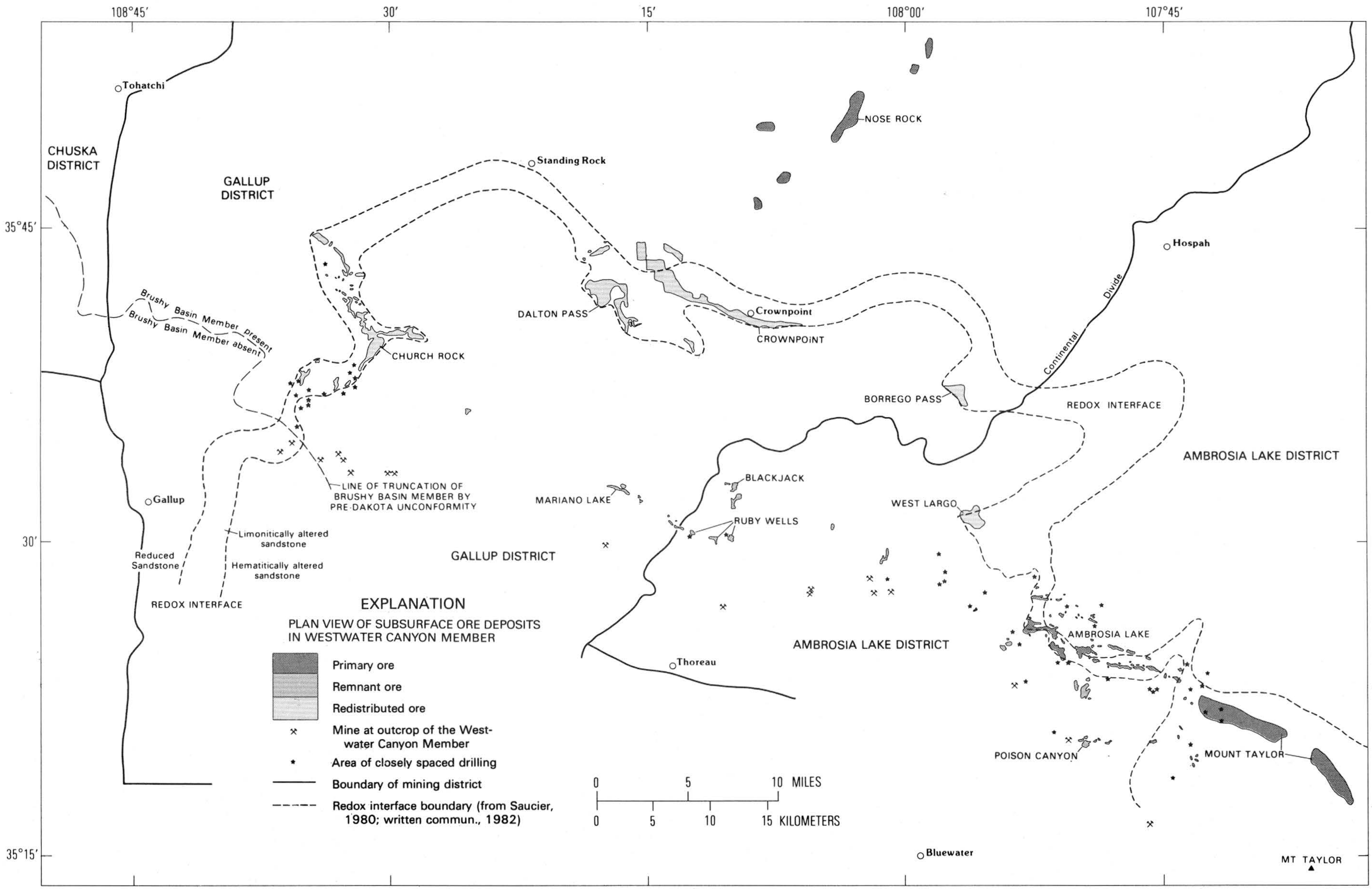

Figure 4.—Map showing ore deposits and deposit types, mining districts, and the regional oxidation reduction (redox) interface.

Table 1.--*Relation of types of ore deposits to contoured subsurface parameters of the Westwater Canyon Member of the Morrison Formation*

[<, less than; >, greater than; leaders (--) indicate no correlation of contoured parameter to ore type]

ORE TYPE	Contoured subsurface parameters					
	Isopach	Sandstone-to-mudstone ratio	Thickness of sandstone	Mudstone interbeds per 100 ft (30 m)	Percent sandstone	Depocenters
PRIMARY	Thick	Mostly >10	High	<3	>80	On thick axes
REMNANT	--	Mostly >10	Variable	<3	>85	On axes
REDISTRIBUTED	Thick	Low but variable	Variable	Mostly <3	Low but variable	On thick axes

struction of the structure contour map. Some of the structure contours were adapted from previous USGS maps (see Thaden and Zech, 1984 for a list of these maps). Data from about 100 surface sections were also used. Figure 3 is an example of a typical geophysical log from the study area that shows picks of the formation and member tops. All of the pertinent information from each log (location, elevation, depth to formation and member tops) was stored on a computer for easy retrieval and manipulation.

In the example log used for figure 3, the boundary between the Dakota Sandstone and the Brushy Basin Member of the Morrison is straightforward. The gamma ray and resistivity curves both show a marked change at the lithologic break between sandstone of the Dakota and mudstone of the Brushy Basin. Locally the contact is shale on mudstone, which may result in small errors in picking the boundary when no lithologic or core descriptions are available.

Picking the boundary between the Brushy Basin and the Westwater Canyon was somewhat more arbitrary, although an effort was made to be consistent throughout the study area. As a general rule, when a sandstone (or sandstones) in the zone of intertonguing between the members was thicker than the underlying mudstone bed, that sandstone was included with the Westwater Canyon. Conversely, an isolated Westwater Canyon-type sandstone bed in the Brushy Basin, overlying a thicker Brushy Basin-type mudstone bed, would have been included with the Brushy Basin.

In some cases, the shape of the spontaneous potential and resistivity curves also aided in deciding with which unit to include a sandstone bed that occurred in the zone of intertonguing. Sandstone beds exhibiting a Westwater Canyon-type lithology commonly have a squared-off, blocky shape or show a coarsening-upward or funnel shape. Sandstone beds having a lithology more commonly associated with the Brushy Basin have flat, sharp bases and show a fining-upward (inverted funnel) grain-size trend.

The contact between the Westwater Canyon and Recapture Members was usually straightforward. Thick sandstone beds of the Westwater Canyon commonly rest erosionally on interbedded mudstone and sandstone intervals of the Recapture (fig. 3). When available, lithologic logs of the Recapture also aided greatly in picking the contact, because the Recapture commonly consists of thick intervals of distinctive maroon mudstone that contrast with the thick arkosic sandstone beds of the Westwater Canyon.

Figure 5 is a map showing the data density in the study area (not including the additional logs used to make the structure contour map). The location of individual drill holes is proprietary information; however, the contoured values give an indication of where control is good and where the drill holes are more widely spaced. Outcrop data are also contoured in the figure. This map was constructed by first overlaying a 1 mi^2 grid on a drill-hole base map. Then the total number of drill holes in four adjacent squares was plotted at the grid intersections and these values were contoured. The manner in which this figure was constructed is somewhat unique, in that the contour lines do not connect control points that represent equal numbers of drill holes. Instead, the lines separate areas of drilling that have the same values. For example, the grid intersection points with 3 drill holes per 4 mi^2 fall between lines 2.5 and 3.5; the grid intersection points with values of 5 fall between lines 4.5 and 5.5, and so on. It was necessary to contour the map in this manner because some fairly extensive areas had grid intersection points with exactly the same values, and thus those areas could not be contoured because they are flat.

Data points for all the maps were hand-contoured by interpolating values between all adjacent drill holes (Condon, 1980). All of the maps in this study were compiled and contoured at a scale of 1:50,000; final publication scale is 1:100,000.

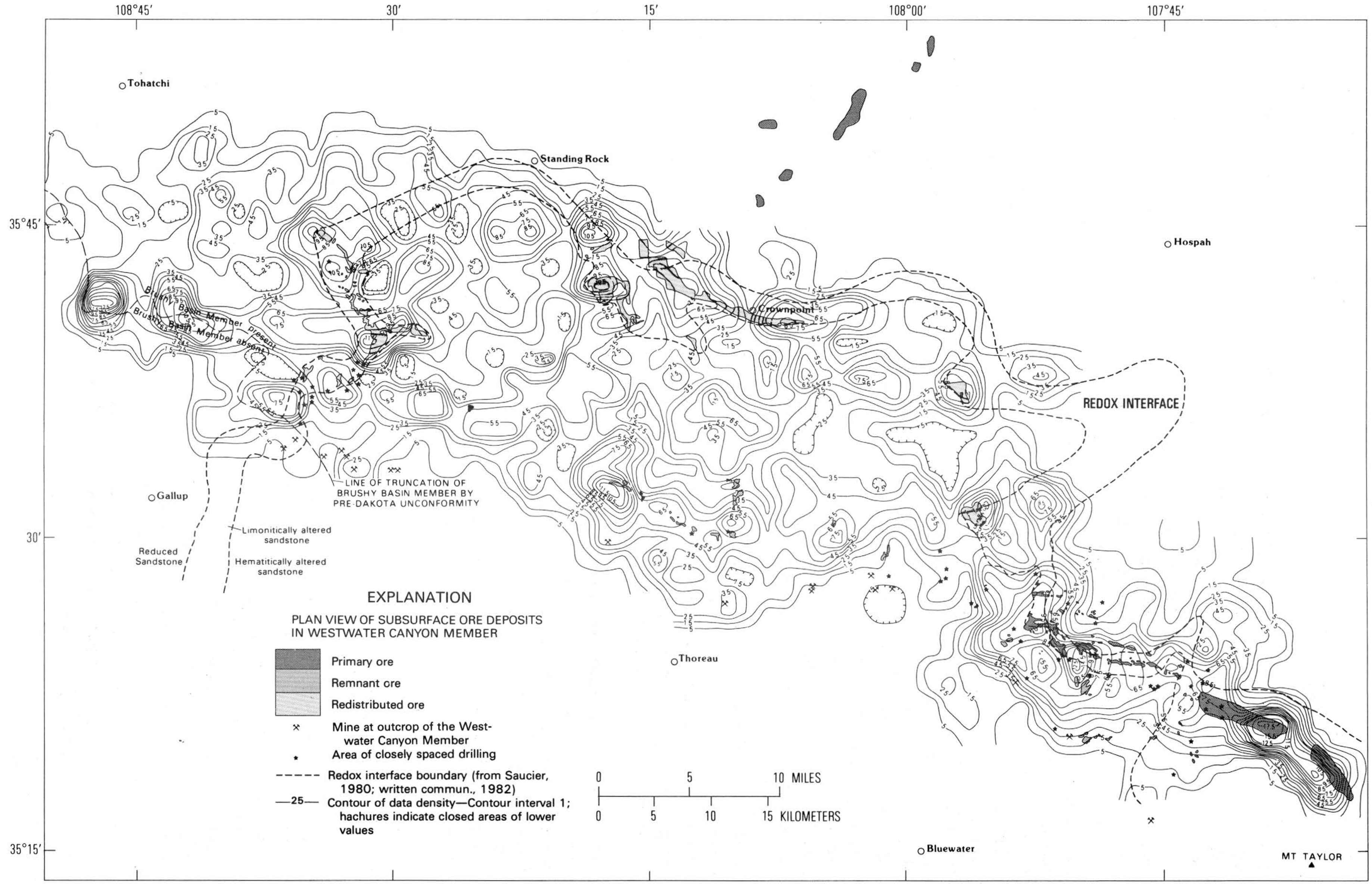

Figure 5.—Map of study area showing density of data used.

MAP A-1

The Westwater Canyon Member ranges in thickness from 440 ft (134 m) northeast of Gallup to less than 80 ft (24 m) northeast of Bluewater (southeast part of mapped area). In general, the Westwater Canyon thins from west to east and from north to south across the mapped area. In both cases the thinning is depositional, although because of different reasons. West-to-east thinning is a result of deposition occurring in areas more distal from the source of the Westwater Canyon, which Craig and others (1955) interpreted to be west-southwest of the study area. North-to-south depositional thinning is believed to have been caused by slight upward movement of the ancestral Zuni uplift in Late Jurassic time. This interpretation is supported by outcrop studies in an area south of Grants, where both the Recapture and Westwater Canyon Members thin depositionally southward on the eastern side of the Zunis (Thaden and others, 1967). The thick area in the central part of the map coincides with the distribution of the zone of intertonguing with the Brushy Basin Member. The thin area of Westwater Canyon west and northwest of Gallup is due to erosion at the pre-Dakota unconformity.

The map shows relatively thick zones of Westwater Canyon that are oriented west-northwest to east-southeast. Because of regional thinning from west to east, the thick zones in the northwest part of the mapped area are thicker than the thick zones in the southeast part of the map. These thick zones, when combined with parameters of sandstone and mudstone in the member, define the depocenter axes that are shown on Map D-3.

Primary and redistributed uranium ore deposits occur within or adjacent to areas of isopach thicks. This relation has been noted elsewhere in mine studies (Wentworth and others, 1980; Fitch, 1980) and in more regional studies (Saucier, 1976; Galloway, 1980). Remnant deposits don't appear to be associated with isopach thicks, although they do occur in depocenter axes that are defined by other parameters of the Westwater Canyon (table 1).

MAP A-2

Map A-2 shows the north to south depositional thinning of the Brushy Basin Member, and the effect of pre-Dakota erosion that truncates the member in the southwest part of the mapped area. Isopach values range from 0 to 260 ft (79 m). The rate of truncation of the Brushy Basin was calculated to be about 10 ft/mi (1.9 m/km), in a northeast to southwest direction. It is difficult to determine any primary depositional patterns in the Brushy Basin because of the amount of material eroded from its top; however, there is a general east-west alignment of the thickest remaining parts of the member. There is no apparent relationship between the isopach values of the Brushy Basin and the location of uranium ore deposits.

MAP A-3

Map A-3 shows the southward depositional thinning of the Morrison Formation and the effect of pre-Dakota erosion in the southwest part of the mapped area. No contours are shown southwest of the line of truncation of the Brushy Basin because the data are so incomplete in that area. East-southeast- and northeast-trending depocenters, evident mainly in the Westwater Canyon Member, can also be seen on this map. The location of uranium ore deposits is more closely related to thick areas in the Westwater Canyon Member than to combined thickness.

MAP B-1

The percentage of sandstone (number of feet of sandstone, divided by total Westwater Canyon Member thickness, multiplied by 100) map shows that the Westwater Canyon has a higher sandstone content in the west two-thirds of the area than in the eastern part of the area. Although some areas in the east have high amounts of sandstone, they are separated by extensive areas having low sandstone content. The range of values also differs from west to east. In the west part of the map, values range from 65 to 95 percent. In the east the values commonly range from 45 to 90 percent. Over much of the map the zones with the highest percent sandstone are oriented east-southeast; however, there are also areas, such as between the Church Rock and Crownpoint deposits and near the West Largo deposit, that show significant northeast-oriented trends. This map was useful in delineating the thick, sandy depocenter axes. The zone of intertonguing with the Brushy Basin Member occurs in the central part of the map, south of Crownpoint, and is indicated by the relatively higher values of percent sandstone in that area.

Primary and remnant uranium ore deposits correspond well with areas of high percentage of sandstone. Redistributed ore is in areas with variable amounts of percentage of sandstone (table 1).

MAP B-2

Map B-2 shows that the total thickness of sandstone in the Westwater Canyon Member decreases markedly from west to east and to a lesser extent from north to south in the study area. This map differs from Map B-1 in that it is a measure of the net amount, or total thickness of the sandstone, not a percentage of the total member thickness. The total sandstone thickness ranges from a high of 320 ft (98 m) to a low of about 40 ft (12 m). A comparison with the percent sandstone map reveals that while the percentage of sandstone is relatively high in the east part of the area, the actual amount of sandstone in that area is low because of the eastward thinning of the Westwater Canyon

(Map A-1). To the east-southeast, and to a lesser extent the northeast, thick zones of sandstone are evident, as is the zone of intertonguing with the Brushy Basin Member south of Crownpoint, where there are broad areas with high net sandstone values.

Primary ore deposits in the Ambrosia Lake district are associated with relatively high cumulative thicknesses of sandstone. The other types of ore deposits do not correlate consistently with total sandstone thickness values (table 1).

MAP B-3

Map B-3 shows two main areas of sandstone accumulation in the Brushy Basin Member. One trends mainly east-west, and is located just north of the southern outcrops of the member in the central part of the map. The other trends nearly due north and is located just east of a line connecting Thoreau and Crownpoint. The cumulative thickness of sandstone ranges from a high of about 70 ft (21 m) to a low of less than 10 ft (3 m). The north-trending area of sandstone accumulation follows the trace of the Bluewater fault zone (see Map D-1). The depositional pattern in that area suggests that the Bluewater fault was downthrown on the west during deposition of the Brushy Basin Member, and caused a greater accumulation of sandstone along the west-facing scarp. If this relationship existed, it is interesting that later Laramide movement on the Bluewater fault is reversed—downthrown on the east.

The thickness of sandstone is probably less influenced by the effects of pre-Dakota erosion and truncation. Much of the sandstone in the Brushy Basin is in the lower and middle part of the unit, and thus the primary depositional patterns of sandstone in the member are less affected by erosion at the top of the unit.

The only uranium ore deposits that appear to correlate with thickness of sandstone values of the Brushy Basin are remnant deposits located north of Thoreau. These deposits are in the zone of intertonguing between the Westwater Canyon and Brushy Basin Members.

MAP C-1

Sandstone-to-mudstone ratios of the Westwater Canyon Member, calculated by dividing the total number of feet of sandstone by the total number of feet of mudstone, range from about 1.6 to over 300. (The mudstone thicknesses were read directly from geophysical logs, and were not recalculated to uncompacted thicknesses). Ratios over 30 were assigned a value of 30 for purposes of contouring, and the line representing a ratio of 10 is the highest contour line shown. Across the map there are east-southeast-oriented zones that display high sandstone-to-mudstone ratios, although some northeast trends are also evident. Many of the areas with high sandstone-to-mudstone ratios coincide with areas of greater isopach thickness. The area of variable values through the central part of the map occurs because of the higher amounts of mudstone included in the zone of intertonguing with the Brushy Basin Member.

In general, primary uranium ore deposits are associated with areas of intermediate to high sandstone-to-mudstone ratios, and remnant deposits are almost entirely within areas that have ratio values greater than 10. Redistributed deposits are located in areas that have intermediate to low ratio values (table 1).

MAP C-2

Map C-2 shows the number of mudstone interbeds in the Westwater Canyon Member, normalized to show the number of interbeds per 100 ft (30 m) of section. The actual number of interbeds, compiled from geophysical logs, was divided by the total thickness of the member in each drill hole and multiplied by 100 to eliminate variations caused by the regional thinning of the Westwater Canyon from west to east. The resulting values range from 1 to 8. In general, there are more interbeds through the central part of the map, where the Westwater Canyon and Brushy Basin Members intertongue, than in areas to the north or south.

Comparison of Map C-2 with Maps B-1, B-2, and C-1 can indicate whether there are many thin interbeds or a few thick interbeds in any particular area. For example, if an area has low cumulative thickness of sandstone values, low percent sandstone, low sandstone-to-mudstone ratio, and a high number of interbeds value, this indicates that there are many thin mudstone interbeds. Conversely, a low number of interbeds would indicate the presence of a few relatively thick mudstone interbeds.

Primary and remnant uranium ore deposits are associated with areas having low (fewer than 3) numbers of interbeds per 100 ft (30 m) of section (table 1). The main purpose of constructing this map was to see if the occurrence of redistributed ore deposits could be correlated with areas having a greater number of interbeds. Fitch (1980, p. 43) mentions this relationship as a general exploration guide for ore in the Grants uranium region. On the bias of the map presented here, this did not prove to be the case because, with few exceptions, redistributed deposits are also associated with areas having fewer mudstone interbeds.

MAP D-1

Figure 2 shows the major structural elements of the San Juan Basin and adjacent areas. The structures that are numbered on figure 2 are named on the structure contour map, with the exception of McCartys syncline (McCartys syncline is east of the mapped area). The most noticeable feature of the map is the difference in the amount of faulting from west to east across the mapped area. The west half is relatively unfaulted, whereas the east half is intensely faulted and fractured. This faulting may have been related to the development of the Acoma sag and Rio Grande trough because the fault density and the amount of offset on the faults decreases westward away from the sag.

The most important aspects of Laramide tectonism and Laramide and younger uplift and erosion were in (1) controlling late Tertiary oxidation of the Westwater Canyon Member, and (2) localizing the redistributed, geochemical-cell uranium deposits that are associated with the redox interface.

In the early Eocene, after Laramide deformation rejuvenated the Zuni Mountains, the Westwater Canyon Member was exposed at the surface and formed an aquifer. Oxidizing ground water entered the aquifer and flowed north toward a discharge area along the San Juan River (figs. 1 and 2). The hematitically altered sandstone updip from (south of) the redox interface probably formed in the early Miocene to late Pliocene as the oxidizing ground water moved northward (Saucier, 1980, p. 120). Subsequently, other discharge areas have developed in the topographically and structurally low Rio Puerco fault zone or Rio Grande trough to the east of the study area, and the Gallup sag to the west (fig. 2). The limonitic alteration zone that is adjacent to the hematitically altered sandstone probably formed in the late Pliocene to Holocene along present ground-water flow patterns (Saucier, 1980, p. 120).

The position of the redox interface and some redistributed orebodies may be structurally controlled in places. The redox interface bulges northward at the Bluewater, Big Draw, and San Mateo fault zones. These north- to northeast-trending fault zones may have acted as conduits, along which oxidizing ground water moved northward. East-southeast-oriented depocenter axes in the Westwater Canyon Member also may have acted as secondary ground-water conduits that give the bulges in the redox interface an easterly skew.

MAP D-2

Map D-2 is a derivative, interpretive map that shows what is believed to be the topography at the time of the initial Westwater Canyon deposition. The map was made in several stages by first unfaulting and unfolding the unconformity at the base of the Dakota Sandstone to produce a horizontal plane. This was done by assuming a constant elevation for the base of the Dakota throughout the study area. Then, the combined thickness of the Westwater Canyon and Brushy Basin Members (Map A-3) was subtracted from this plane, and the resultant elevations were contoured to produce a structure contour map of the base of the Westwater Canyon (unpub. data).

The effects of pre-Dakota erosion were removed by constructing an isopach of the interval between the top of the Twowells Tongue of the Dakota (fig. 3) and the base of the main body of the Dakota, making a minor correction for the constant southwestward thinning of the intervening Whitewater Arroyo Tongue of the Mancos Shale (unpub. data). It was assumed that the top of the Twowells is a time line (datum), and that variations of the Twowells-Dakota isopach thickness were due to relief on the pre-Dakota erosion surface. An arbitrary datum (parallel to the top of the Twowells) was then passed through the pre-Dakota surface at the thinnest point of the isopached interval. It was assumed that all of the Dakota below this arbitrary datum represented material that had been eroded from the Brushy Basin Member. This interval below the arbitrary datum was then added to the Brushy Basin, the combined Brushy Basin and Westwater Canyon thickness was again subtracted from the base of the Dakota, and a new structure contour map of the base of the Westwater Canyon was constructed.

The structure contour map (unpub. data) still had a slight regional slope of about 1/4° to the northeast - either a depositional or a structural slope. A northeastward dip may have reflected regional structural dip to the northeast because cross-bedding studies have indicated that the Westwater Canyon streams entered the basin from the west and southwest (Craig and others, 1955). This 1/4° regional dip masked subtle irregularities on the base of the Westwater Canyon and was also rotated out to produce the paleotopographic reconstruction shown here. The numbers on the contour lines are feet above or below an arbitrary datum within the Westwater Canyon Member.

The paleotopographic map shows a general west-northwest to east-southeast alignment of high and low areas with local northeast-southwest trends. In particular, there are two low areas, one northeast of Gallup and one southeast of Tohatchi, that converge at about the Church Rock deposits and cover most of the central part of the map. There is also an east-southeast-oriented low through the Ambrosia Lake deposits in the southeast part of the map.

MAP D-3

Map D-3 is a derivative, interpretive map that shows (1) actively rising Jurassic structures that affected upper Morrison sedimentation patterns, and (2) depocenter axes, along which sandstone of the Westwater Canyon Member accumulated.

The areas of paleohills and valleys shown on the paleotopographic reconstruction (Map D-2) could have been produced in several ways. (1) If there was any hiatus in deposition between the Recapture and Westwater Canyon Members, the configuration of Map D-2 might represent a pre-Westwater Canyon erosion surface. (2) The streams of the Westwater Canyon may have scoured out some of the underlying Recap-

Table 2.--*Relation of inferred actively rising Jurassic structures to contoured subsurface parameters*

[Leaders (--) indicate no correlation of contoured parameter to Jurassic structure]

	Westwater Canyon Member						Brushy Basin Member			
Positive Jurassic structures	Paleo-topographic feature	Isopach value	Sandstone-to-mudstone ratio	Total thickness of sandstone value	Number of mudstone interbeds per 100 ft (30 m)	Percent sandstone value	Isopach value	Total thickness of sandstone value	Combined thickness of Westwater Canyon and Brushy Basin	Laramide structure
Church Rock	High	Thin	Mostly low (mixed)	Low	3-5	Mostly low	Thin	--	Thin	--
Dalton Pass	High	Thin	--	Low	3	Moderate	Moderate	Low	Thin	--
Bluewater	High	Thin	--	Low	2-3	Low	--	Low	Thin	Flat area
Borrego Pass	High	Thin	Low	Low	3-4	Low	Variable to thick	Low	Thin	Big Draw fault
West Largo	High	Thin	High	Moderate	3-4	Moderate	Variable to thick	Low	Thin	--
Ambrosia Dome	High	Thin	Low	Low	4-5	Low	Thin	--	Thin	Dome
Ambrosia North	High	Thin	Low	Low	4-5	Low to high	Variable	Low	Thin	--
McCartys Arch	High	Thin	Low	Low	6-7	--	Thick	High	Thin	Anticline

ture Member as the high-energy Westwater Canyon stream system prograded over the Recapture from the southwest. (3) The paleotopography could have been mainly structurally controlled. It is felt that this last mechanism was probably most important in producing the observed paleotopography.

If paleotopography was not structurally controlled, the hills at the top of the Recapture should have become buried as sedimentation of the Westwater Canyon proceeded, and the Brushy Basin should show no evidence of the paleohills. Conversely, if the paleohills were structurally controlled and continued to rise during sedimentation, they should have affected depositional patterns in the entire Westwater Canyon and possibly in the Brushy Basin. These hypotheses were tested by superimposing the other subsurface parameter maps on the paleotopographic reconstruction, and noting whether the parameter was affected by the positive paleotopographic features.

Some of the positive structural features do seem to have affected depositional patterns of the Westwater Canyon and Brushy Basin in the following ways (table 2). The isopach values of the Westwater Canyon, and in many cases the Brushy Basin, are low over the positive structures compared to adjacent areas. The sandstone-to-mudstone ratio, thickness of sandstone, and percentage of sandstone in the Westwater Canyon are low over the positive structures; the number of mudstone interbeds per 100 ft (30 m) of section is relatively high over the positive structures. Additionally, the combined thickness of the Westwater Canyon and Brushy Basin is low over all of the positive structures. These patterns indicate that there were actively rising Jurassic structures that affected sedimentation of both the Westwater Canyon and Brushy Basin Members. One Laramide structure, Ambrosia dome, is apparently an old feature that was reactivated during Laramide tectonism. Both the Westwater Canyon and Brushy Basin Members are thinner and less sandy over the dome compared to surrounding areas, which indicates that the dome was a positive topographic feature during the time of their deposition.

After determining that the Westwater Canyon was thinner and less sandy over the actively rising structures, the next step was to define where sandstone accumulation did occur. This was done by placing a clear overlay on each subsurface parameter map and marking the areas that were thick, and that had high values of thickness of sandstone, percentage of sandstone, and sandstone-to-mudstone ratio, and that had few mudstone interbeds. In this manner long, curvilinear areas of the Westwater Canyon having these characteristics were defined. These areas of thick, sandy Westwater Canyon are termed depocenter axes. It was decided not to call these areas stream channels, because without crossbedding studies it is not possible to tell if stream flow was actually down the axes of these depocenters. A recent seismic study over the Church Rock deposits (figs. 1, 4) suggested that a Jurassic-age graben may have controlled the location of a depocenter in that area (Phelps and others, 1986; Kirk and Condon, 1986).

As shown in table 1, primary and redistributed uranium ore deposits occur along thick depocenter axes. Remnant deposits don't appear to be closely related to areas of isopach thicks; however, they are along depocenter axes that are defined by high sandstone-to-mudstone ratios, high percentage of sandstone, and low numbers of mudstone interbeds.

SUMMARY

The maps presented in this report show that the basic sedimentation patterns displayed by the Westwater Canyon and Brushy Basin Members of the Morrison Formation were influenced to a large extent by Jurassic-age structures that were active at the time of deposition of those units. The fluvial architecture of the Westwater Canyon, consisting of sinuous, arcuate depocenters that are thick and sandy and are separated by thinner, more muddy areas, shows a correlation with positive and negative structural features that were active during its deposition. These structural features also controlled deposition of the Brushy Basin to some degree, and in one case a structure was reactivated to produce a Laramide feature.

Uranium ore deposits in the Westwater Canyon Member show a correlation of ore with sedimentological features, and so, were also indirectly controlled by structural features. In particular, primary and redistributed ore deposits are found in conjunction with thick, sandy depocenters of the Westwater Canyon.

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