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SUMMARY OF THE GEOLOGY AND RESOURCES OF URANIUM IN THE SAN JUAN BASIN AND ADJACENT REGION, NEW MEXICO, ARIZONA, UTAH & COLORADO

J.L. Ridgley, et. al.
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By

Jennie L. Ridgley, Morris W. Green, Charles T. Pierson,

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ABSTRACT

The San Juan Basin and adjacent region lie predominantly in the southeastern part of the uranium-rich Colorado Plateau of New Mexico, Arizona, Utah, and Colorado. Underlying the province are rocks of the Precambrian basement complex composed mainly of igneous and metamorphic rocks; a thickness of about 3,600 meters of generally horizontal Paleozoic, Mesozoic, and Cenozoic sedimentary rocks; and a variety of Upper Cretaceous and Cenozoic igneous rocks. Sedimentary rocks of the sequence are commonly eroded and well exposed near the present basin margins where Tertiary tectonic activity has uplifted, folded, and faulted the sequence into its present geologic configuration of basins, platforms, monoclines, and other related structural features.

Sedimentary rocks of Jurassic age in the southern part of the San Juan Basin contain the largest uranium deposits in the United States, and offer the promise of additional uranium deposits. Elsewhere in the basin and the adjacent Colorado Plateau, reserves and resources of uranium are known primarily in Triassic, Jurassic, and Cretaceous strata. Only scattered occurrences of uranium are known in Paleozoic

sedimentary rocks or in Tertiary sedimentary and igneous rocks.

Although uranium occurs in several formations and rock types within the area, the most important uranium deposits are contained in sandstone facies of the sequence, where geochemical and sedimentological conditions were most suitable for concentration of uranium. The distribution of sandstone and other favorable facies is controlled by the special distribution and association of sedimentary depositional environments operative during past geologic periods in the basin and on the Colorado Plateau. These environments of sedimentary deposition included a variety of both marine and continental types, such as deep and shallow marine, marginal marine, evaporite basin, fluvial, lacustrine, and desert eolian and sabkha (small, subsurface recharged, interdune ponds and lakes). Uranium is most commonly associated with ancient continental stream (fluvial) and lake (lacustrine) deposits of Jurassic age and marginal marine deposits of Cretaceous age.

Most of the 120,000 tons of U_3O_8 produced in the area came from the Westwater Canyon and Brushy Basin Members of the Morrison Formation. The largest proportion of the reserves of 465,500 tons of U_3O_8 (at \$50-per-pound forward cost) are in the area between Gallup and Laguna, New Mexico. Potential uranium resources, most of which remain undiscovered, total 826,600 tons U_3O_8 at \$30-per-pound forward cost and are in the southern San Juan basin. The total resource base for the basin is about 1,500,000 tons U_3O_8 at a forward cost of \$50-per-pound.

INTRODUCTION

The following report has been compiled for the purpose of providing a summary of the geology and uranium resources of the San Juan Basin and adjacent region of New Mexico, Arizona, Utah, and Colorado (plates 1 and 2). This report supplements the Interior Department-sponsored San Juan Basin Regional Uranium Study project, which has as its primary objective the gathering of information pertinent to the analysis of the effects and impacts of future uranium developments on the natural and human environments in the region through the year 2000.

Material contained in this report has been synthesized primarily from literature written during the past 10 years on the geology and uranium resources of the region. The report has been composed for the governmental decisionmaker; however, the authors hope that it will also be of value to the explorationist seeking a broad overview of the regional geology and its relationship to mineral occurrence.

The authors express appreciation to the personnel of the Grand Junction, Colorado, and Albuquerque, New Mexico, offices of the U.S. Department of Energy for their cooperation and aid in providing uranium resource data for this report.

GENERAL GEOLOGIC SETTING

The San Juan Basin and vicinity (plate 1) lies mainly within the southeastern part of the Colorado Plateau physiographic province. This province, which comprises an area of approximately 390,000 square kilometers, lies within the states of Arizona, Colorado, New Mexico, and Utah.

Underlying the province are: (1) a Precambrian basement complex composed mainly of igneous and metamorphic rocks; (2) a thickness of about 3,600 m of generally flat-lying Paleozoic, Mesozoic, and Cenozoic sedimentary rocks; and (3) a variety of Upper Cretaceous and Cenozoic igneous rocks. Uplifts and related downwarps and platforms, as well as faults and monoclinal folds are locally present. These structural features and the rocks they disrupt are discussed in later sections of this report. In addition, sedimentary rocks present south of the map area (plate 1) and north of Socorro, New Mexico, are briefly discussed, as many of these rock units represent southern extensions of rock units present in the San Juan Basin. This discussion was included in order to provide a more complete picture of the stratigraphy and depositional environments of the map area.

STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS

Rocks exposed in the San Juan Basin and adjacent areas range in age from Precambrian to Tertiary. Sedimentary rocks, which are dominantly sandstone, siltstone, mudstone, and limestone, were deposited in a variety of continental and marine environments. Basaltic to granitic igneous rocks were formed under various intrusive and extrusive conditions.

Uranium is known in a number of sedimentary formations and is generally associated with rocks of fluvial and lacustrine origin. Many occurrences of uranium in the area are not economic; however, the largest deposits in the United States occur in members of the Morrison Formation of Jurassic age. This section briefly discusses the lithology, distribution, and environments of deposition of the formations present and, where appropriate, comments on uranium.

Rocks of Precambrian age

Precambrian rocks crop out locally around the margins of the San Juan and Chama Basins. They are present on the east side of the Defiance uplift, in the crest of the Zuni Mountains, along the length of the San Pedro-Nacimiento Mountains, in the Tusas Mountains on the eastern margin of the Chama Basin, and in the Needles Mountains along the northern edge of the San Juan Basin (plate 1). These rocks include quartzite, schist, granite, igneous rocks of basic to intermediate composition, and locally, pegmatites and quartz veins (Lance, 1958; Fitzsimmons, 1967; Barker, 1968; Chenoweth, 1974a; Woodward and others, 1974; and Woodward and others, 1977). Precambrian rocks have a complex history involving multicyclic deposition of clastics, deformation, metamorphism, erosion, and intrusion of igneous rocks in the form of plutons, sills, and dikes.

Uranium is known in the Petaca, Ojo Caliente, and Bromide mining districts in the Tusas Mountains (Chenoweth, 1974a). There uranium occurs in uneconomic quantities in quartz-albite pegmatites, quartz-fluorite veins, quartzite, and in the Tres Piedras Granite of Barker (1958).

Rocks of Cambrian age

Cambrian rocks crop out on the southern flank of the San Juan Mountains along the northern margin of the basin and in scattered areas in northwest New Mexico. In the Four Corners area, Cambrian rocks pinch out to the southeast and thicken to the west and northwest into Arizona, Utah, and Colorado. In the Four Corners area, exposed Cambrian rocks are considered to be part of the Ignacio Quartzite. No uranium occurrences are known in these rocks.

Ignacio Quartzite

The Ignacio Quartzite consists of light-gray to grayish-orange-pink sandstone, quartzite, shale, and conglomerate and ranges in thickness from 0 to 130 m. This lithologic sequence is considered to have been deposited by transgressive (advancing) seas in near-shore marine environments (Bass, 1944; Baars and Knight, 1957; Strobell, 1958). Where present the Ignacio rests unconformably on the Precambrian basement and is unconformably overlain by Devonian rocks. The Ignacio Quartzite in the Four Corners area has been correlated with the Tapeats Sandstone of northern Arizona and with the Ignacio Quartzite of southwestern Colorado (Loleit, 1963; Hilpert, 1969).

Rocks of Devonian age

Devonian rocks are exposed in isolated localities in the San Juan Mountains and are present in the subsurface in the northwest part of the area. From the Four Corners area, Devonian rocks pinch out to the southeast and thicken to the northwest into Utah. The Devonian has been divided into three formations which are, in ascending order, the Aneth Formation, Elbert Formation, and Ouray Limestone. Studies by Knight and Baars (1957), Baars (1966), and Stevenson and Baars (1977), indicate that the Ouray may be of Devonian and Mississippian age. No uranium occurrences have been reported in Devonian rocks.

Aneth Formation

The Aneth Formation (Knight and Cooper, 1955) is composed of brown to black bedded limestone, argillaceous dolomite, and minor amounts of black shale and siltstone. It ranges in thickness up to 70 m and rests unconformably on Precambrian or Cambrian rocks. Parker and Roberts (1963) suggest that the Aneth was deposited under euxinic conditions in sags or topographic lows in marine shelf areas.

Elbert Formation

In the Four Corners area the Elbert Formation (Cross, 1904) is generally divided into the McCracken Sandstone Member of Knight and Cooper (1955) and the upper member. The McCracken Member is composed of as much as 50 m of white, light-gray to red, fine- to medium-grained, poorly sorted, glauconitic sandstone. Contact with the underlying Aneth Formation is conformable and with the overlying upper member is gradational. The upper Elbert consists of as much as 80 m of thin-bedded sandy dolomite and limestone and green to red waxy shales. Deposition of the McCracken Sandstone Member and the upper member took place in shallow-marine to intertidal environments (Baars, 1966; Stevenson and Baars, 1977).

Ouray Limestone

The Ouray Limestone (Spencer, 1900; Kirk, 1931) crops out in the San Juan Mountains and is present in the subsurface in the northwest part of the area. It consists of as much as 30 m of siliceous limestone and dolomite and widespread thin green shale near the top and base. The limestone is oolitic and fossiliferous. The fossil assemblage and lithologies indicate deposition in relatively low-energy marine environments (Stevenson and Baars, 1977).

Rocks of Mississippian age

Rocks of Mississippian age crop out in isolated areas in the San Juan, San Pedro, Nacimiento, and Ladron Mountains and are present in the subsurface in northwest New Mexico. From the Four Corners area, Mississippian rocks pinch out southward and are absent over most of the San Juan Basin. They thicken to the northwest into Arizona and Utah. Mississippian rocks consist of the Redwall Limestone, Leadville Limestone, Kelly Limestone, Arroyo Penasco Group, and Log Springs Formation. Uranium occurrences have not been reported in Mississippian rocks.

Redwall Limestone

The Redwall Limestone has been traced from the Grand Canyon area, through the subsurface, to the Four Corners area. In this area Parker and Roberts (1963) consider the upper part of the Redwall Limestone to be correlative with the Leadville Limestone in the San Juan Mountains. In the Four Corners area the Redwall is composed of gray to grayish-orange, fossiliferous limestone; gray to pale-red, finely crystalline dolomite; and white to light-gray, irregularly bedded chert. It rests unconformably on rocks of Precambrian or Devonian age and reaches a maximum thickness of 100 m. According to McKee (1958), the Redwall Limestone was deposited during two principal marine transgressions and regressions.

Leadville Limestone

The Leadville Limestone (Emmons and others, 1894; Kirk, 1931) crops out in the San Juan Mountains and is present in the subsurface in the northern part of the San Juan Basin. It overlies the Ouray Limestone. It is difficult to differentiate the Ouray from the Leadville since they are lithologically similar (Strobell, 1958; Armstrong and Mamet, 1977). The Leadville Limestone is composed of a thin basal dolomite and a thick, light-gray, massive upper limestone. The formation is as much as 115 m thick. The limestone is locally oolitic and near the base contains abundant crinoid and foraminifera remains. Armstrong and Mamet (1977) suggest that the dolomite was deposited in intertidal to subtidal marine environments and the limestone in shallow marine environments.

Kelly Limestone

Outcrops of the Kelly Limestone are restricted to the Ladron Mountains in the southeast part of the report area. In this area the Kelly Limestone is divided into the Caloso Member and the overlying Ladron Member (Armstrong, 1958, 1959, Armstrong and Mamet, 1976).

In the Ladron Mountains the Caloso Member rests unconformably on the Precambrian basement and is disconformably overlain by the Ladron Member (Armstrong and Mamet, 1977). Here it is approximately 12 m thick and consists of a lower arkosic sandstone and shale unit and an upper stromatolitic limestone and limy, fossiliferous mudstone. The lithologic sequence suggests deposition during marine transgression in subtidal environments.

The overlying Ladron Member ranges from 0 to 15 m in thickness and is composed of a thin basal limy mudstone and sandstone sequence overlain by a thick medium-bedded cherty limestone. It was deposited during continued transgression of marine waters in high-energy shoaling environments (Armstrong and Mamet, 1977).

Arroyo Penasco Group

Rocks of Mississippian Age along the western flanks of the San Pedro and Nacimiento Mountains, compose the Arroyo Penasco Group. The Arroyo Penasco Group is divided into two formations: the Espiritu Santo Formation and the overlying Tererro Formation (Armstrong, 1955, 1967).

The Espiritu Santo Formation is composed of a lower sequence of conglomerate, sandstone, siltstone, and shale, which is overlain by a thick upper sequence of dolomite, dedolomite (dolomite which has been altered in part to calcite), and coarse-grained calcite. The lower clastic sequence interfingers with the upper carbonate sequence and is considered by Armstrong and Mamet (1974) to represent the basal unit deposited during marine transgression. The presence of stromatolitic algal mats and other sedimentary structures in the upper carbonate unit suggests deposition in shallow-marine and intertidal environments. In this area the Espiritu Santo Formation is about 30 m thick and rests unconformably on Precambrian rocks.

The Tererro Formation unconformably overlies the Espiritu Santo Formation. It ranges in thickness from 6 to 12 m and consists of thick-bedded oolitic limestone and silty, pelletoid, fine grained limestone. The oolitic limestone contains abundant remains of fossil foraminifera and algae. The Tererro was deposited during continued marine transgression in shallow-water environments.

Log Springs Formation

The Log Springs Formation (Armstrong, 1955) is present in the San Pedro and Nacimiento Mountains, where it rests unconformably on the Arroyo Penasco Group. It consists of 2 to 25 m of continental clastic red beds composed of arkosic sandstone, conglomerate, and oolitic, hematitic shale.

Rocks of Pennsylvanian age

Pennsylvanian rocks are exposed along the flanks of the San Pedro, Nacimiento, San Juan, Zuni, and Ladron Mountains; near Lucero Mesa; and at isolated localities in the Chama Basin. They are present in the subsurface over most of the area. From the Four Corners area Pennsylvanian rocks thin to the south and thicken to the north into Colorado and Utah.

In the western part of the area, Pennsylvanian rocks comprise the Molas, Hermosa, and Rico Formations; in the eastern and southern parts they comprise the Sandia Formation and Madera Limestone of the Magdalena Group. Isolated sequences of unnamed Pennsylvanian rocks occur in the southern part of the Nacimiento Mountains, in the southeast part of the Chama Basin, and at Chaves Box near Chama, New Mexico.

Several uranium occurrences are known in the Madera Limestone of the Magdalena Group. The occurrences are located east and northeast of Cuba, New Mexico (Chenoweth, 1974b), and northeast of Socorro, New Mexico (Hilpert, 1969, p. 145),. The uranium is associated with carbonized plant debris and copper minerals in arkosic sandstones that are interbedded with limestone and siltstone in the lower part of the sequence, or it is concentrated along faults.

Molas Formation

The Molas Formation (Cross and others, 1905) is present in the northwest part of the report area, where it is as much as 60 m thick and consists of clastic red beds and gray to buff limestone. The red beds consist of red-brown to variegated silstone red shale, and calcareous sandstone. The Molas rests unconformably on the Leadville Limestone and was deposited in environments transitional from continental to marine. The basal sequence of limestone rubble cemented with red silt and red siltstone is interpreted as a residual and reworked soil horizon, and the upper sequence of fossiliferous siltstone and limestone indicates deposition in marine environments (Peterson and Ohlen, 1963).

Hermosa Formation

The Hermosa Formation (Cross and Spencer, 1900) is present in the western part of the report area, where it has been divided into three members. These are, in ascending order, the lower member, Paradox Member, and upper member. Wengerd and Matheny (1958) proposed raising the Hermosa to group status and dividing it into the Pinkerton Trail, Paradox, and Honaker Trail Formations. This latter terminology has not been fully accepted and will not be used in this report. Thickness of the Hermosa Formation is quite variable; it attains a maximum thickness of over 900 m in the report area.

The lower member consists of gray fossiliferous limestone, gray to gray-green shale, and lesser amounts of sandstone and siltstone. Clastic sediment dominates the lower part of the member and carbonate sediment the upper part. Contact with the underlying Molas Formation is transitional. The lower member was deposited during marine transgression in shallow water environments.

The Paradox Member is composed of a complex sequence of interbedded evaporite, black shale, dolomite, limestone, and siltstone. Toward the tern margin of the depositional area, the carbonate sequence grades laterally into a clastic sequence of siltstone and arkosic sandstone (Peterson and Ohlen, 1963; Jentgen, 1977). The Paradox Member was deposited under normal and restricted marine conditions.

The upper member consists of numerous cycles of thin-bedded to massive limestone and dolomite overlain by gray calcareous shale and buff to gray siltstone and arkosic sandstone. The proportion of clastic sediment increases upward in the member. The sequence of lithologies represents deposition during initial stages of marine regression.

Rico Formation

The Rico Formation (Cross and Spencer, 1900) consists of a lower marine carbonate sequence overlain by a dominantly continental clastic sequence of variegated shale and siltstone. It ranges in thickness from 110 to 160 m and is of Pennsylvanian and Permian age.

Sandia Formation

The Sandia Formation of the Magdalena Group (Herrick, 1900; Wood and others, 1946) is exposed in the southern part of the Nacimiento Mountains, in the Ladron Mountains, and in the vicinity of Lucero Mesa and rests on rocks of Precambrian or Mississippian age. It ranges in thickness from 0 to 200 m. The Sandia as defined by Wood and others (1946) consists of a basal sequence of interbedded gray, fossiliferous limestone and shale overlain by purple shale and an upper sequence of dark-brown to brown-green sandstone, siltstone, and thin-bedded argillaceous limestone. The current definition of the Sandia restricts the formation by raising the lower contact, therefore including the lower limestone member in the Espiritu Santo, Tererro, and Log Springs Formations (Baltz and Read, 1960; Armstrong, 1967; Armstrong and Mamet, 1974). The lower part of the Sandia Formation is absent in the Lucero Mesa and Ladron Mountain areas (Wilpolt and others, 1946). The Sandia Formation was deposited in shallow marine environments during early stages of marine transgression.

Madera Limestone

The Madera Limestone of the Magdalena Group (Keyes, 1903; Gordon, 1907) crops out along the flanks of the San Pedro, Nacimiento, and Ladron Mountains and in the Lucero Mesa area. It ranges in thickness from 160 to 330 m, but is nearly 610 m thick in the Lucero Mesa area (Kelley and Wood, 1946). The Madera Limestone has been divided into two members: a lower member composed of gray, fossiliferous, cherty limestone interbedded with thin beds of arkosic sandstone, siltstone and fossiliferous shale and an upper member composed of interbedded arkosic sandstone, fossiliferous shale, and some cherty limestone (Hilpert, 1969; DuChene, 1974; Jentgen, 1977). The lithologic sequence of the Madera Limestone indicates deposition in marine environments during marine transgression and regression. The Madera Limestone rests unconformably on the Sandia Formation, except in the San Pedro Mountains and the northern part of the Nacimiento Mountains, where it rests on Precambrian rocks. In these areas the lower member and the Sandia Formation are absent, owing to the presence of the Penasco uplift at the time of deposition.

Unnamed Pennsylvanian rocks

Northrop and Wood (1945) recognized a sequence of unnamed Lower Pennsylvanian (Morrowan) rocks resting unconformably on the Log Springs Formation and overlain unconformably by the Sandia Formation in the southern part of the Nacimiento Mountains. This sequence consists of 0 to 19 m of interbedded marine, fossiliferous, light-gray to white, arenaceous limestone and fossiliferous, calcareous shale capped by white-gray to purple-gray shale. DuChene (1974) has called this sequence the Osha Canyon Formation.

Two separate unnamed sequences of Pennsylvanian rocks are found in the Chama Basin. Muehlberger (1957) described a sequence of intertonguing red arkosic sandstone, siltstone, and fossiliferous limestone at Chaves Box near Chama, New Mexico. In this area the Pennsylvanian rocks are nearly 80 m thick and thin eastward over the Precambrian basement. The lithologic sequence suggests deposition in intertonguing continental and marine environments.

In the southeast part of the Chama basin, at Arroyo del Cobre, Smith and others (1961) reported the presence of 13 m of thin-bedded, carbonaceous, micaceous siltstone. The stratigraphic section is not completely exposed and correlation with other Pennsylvanian rocks has not been made. Fossil flora obtained from this sequence indicate a Middle Pennsylvanian age.

Rocks of Permian age

Rocks of Permian age are exposed along the flanks of the Chuska, San Pedro, Nacimiento, and Zuni Mountains; in the Lucero Mesa area; and in the southern part of the Chama Basin. They range in thickness up to

830 m and are thickest along the northern and southern parts of the report area (Hilpert, 1963; Rascoe and Baars, 1972). South of latitude 36° N., Permian rocks comprise the Bursum, Abo, and Yeso Formations, the Glorieta Sandstone, and the San Andres Limestone; north of latitude 36° N., Permian rocks comprise the upper part of the Rico Formation, previously discussed, and the Cutler Formation.

Uranium occurrences are known in the Cutler Formation, Abo Formation, and San Andres Limestone (Hilpert, 1969; Chenoweth, 1974b). In the Cutler and Abo Formations uranium occurs in arkosic carbonaceous sandstones; in the San Andres Limestone uranium is associated with faults.

Bursum Formation

The Bursum Formation (upper formation of Magdalena Group) is present only in the vicinity of Lucero Mesa, where it rests on the Madera Limestone and is 30 to 80 m thick. It consists of thick beds of dark-purple, red, and green shale interbedded with thin beds of arkosic conglomerate, arkose, and gray, fossilferous limestone (Wilpolt and others, 1946). The Bursum was deposited in near-shore marine and continental environments.

Abo Formation

The Abo Formation (Lee and Girty, 1909; Needham and Bates, 1943) is exposed in the Lucero Mesa area and along the flanks of the Chuska, Nacimiento, and Zuni Mountains. It is 300 m thick in the Lucero Mesa area, but is only 70 to 200 m thick in the southern part of the San Juan Basin. The Abo consists of reddish-brown shale, siltstone, and arkosic sandstone. The sandstones are lenticular, crossbedded, and carbonaceous. Vertebrate fossils and sedimentary structures indicate deposition under continental fluvial conditions.

The Abo Formation coarsens from south to north and north of latitude 36^{0} N., grades into the Cutler Formation. In the Lucero Mesa area it overlies the Bursum Formation or Madera Limestone; in the Chuska, Zuni, and Nacimiento Mountains it rests on Precambrian rocks (Hilpert, 1969).

Cutler Formation

The Cutler Formation (Cross and others, 1905) is exposed in the southern part of the Chama Basin and along the flanks of the San Pedro and Chuska Mountains, where it rests on Precambrian rocks. Thickness of the Cutler is variable; it is nearly 500 m thick in the Chama Basin but only 330 m thick in the San Pedro and Chuska Mountains. The southward thinning is a result of a facies change into the Abo and Yeso Formations. In the northeast part of the area and in the Chama Basin, the Cutler Formation is composed of an alternating sequence of fluvially deposited, crossbedded, purple arkosic sandstone, which is locally conglomeratic, and purple to orange mudstones (Smith and others, 1961). This stratigraphic sequence becomes finer grained to the west and south. The source area for much of the Cutler Formation was the Uncompaghre Uplift in southwest Colorado.

In the Four Corners area the Cutler Formation has been divided into four distinct units (Baker and Reeside, 1929; Stewart, 1959). These are, in ascending order, the Halgaito Tongue, Cedar Mesa Sandstone Member, Organ Rock Tongue, and De Chelly Sandstone Member. The Halgaito

Tongue consists of 50 to 150 m of red-brown shale, siltstone, and sandstone. Based on observed sedimentary structures, Baars (1973) concluded that the Halgaito was deposited in ancient streams or intertidal channels.

The Cedar Mesa Sandstone Member consists of red and green sandstone and of siltstone and shale, and it ranges in thickness from 225 to 305 m. At its eastern extent, gypsiferous shale and sandstone and bedded gypsum are present. North and east of the Four Corners area the Cedar Mesa interfingers with the lower part of the Cutler Formation. Baars (1962, 1973) suggests that the Cedar Mesa Sandstone Member was deposited in nearshore marine environments, while Baker (1946) considers it to be part eolian.

The Organ Rock Tongue consists of 115 to 270 m of red-brown siltstone, mudstone, shale, and, locally, limestone lenses. It is considered to represent tidal flat deposits (Baars, 1973).

The De Chelly Sandstone Member is composed of fine grained, reddish sandstone and is from 115 to 130 m thick. Large-scale, high-angle cross-stratification and a high ripple index indicate it is of eolian origin (Gregory, 1917; Allen and Balk, 1954; Baars, 1973). On the De Chelly Upwarp, the De Chelly Sandstone has formation rank.

Yeso Formation

The Yeso Formation (Lee and Girty, 1909; Needham and Bates, 1943) crops out in the Nacimiento and Zuni Mountains and in the Lucero Mesa area, where it rests unconformably on the Abo Formation. It thickens from nearly 30 m in the Nacimiento Mountains to over 200 m in the Lucero Mesa area (Baars, 1961). Interbedded red-orange, crossbedded sandstone, gray dolomitic limestone, gypsum, and siltstone compose the Yeso Formation. From south to north the Yeso becomes coarser grained, increasingly arkosic, contains less evaporite, and grades laterally into the Cutler Formation. Baars (1962) suggests that the Yeso Formation was deposited in shallow and locally restricted marine environments.

Glorieta Sandstone

The Glorieta Sandstone (Keyes, 1915; Needham and Bates, 1943) has the same outcrop distribution as the Yeso Formation, which it conformably overlies. It is composed of 90 to 100 m of white, cliff-forming, medium- to fine grained, crossbedded sandstone. In the Nacimiento Mountains and along the southern and southwestern margins of the San Juan Basin, the Glorieta Sandstone is truncated by pre-Triassic erosion. Sedimentary structures suggest deposition in shallow marine environments with local development of offshore bars or eolian deposits (Baars, 1961).

San Andres Limestone

The San Andres Limestone (Lee and Girty, 1909; Needham and Bates, 1943) crops out in the southern part of the area and in the Nacimiento Mountains. It ranges in thickness from 15 m in the Nacimiento Mountains to 130 m in the Lucero Mesa area. In the Lucero Mesa area the San Andres consists of a basal sequence of dolomite and interbedded shale, siltstone, and sandstone overlain by massive, fossiliferous limestone. In the Zuni Mountains the San Andres is essentially all fossiliferous, dolomitic limestone. North of the Zuni Mountains a facies change occurs and the carbonate sequence grades laterally into red beds. In the

Nacimiento Mountains a thin basal dolomite overlain by red-orange siltstone compose the San Andres. The San Andres Limestone was deposited in a series of environments, which are represented by shallow marine facies in the south and shoreward lagoonal and intertidal facies in the north (Baars, 1961).

Rocks of Triassic age

Rocks of Triassic age crop out along the margins of the San Juan Basin, in the southern part of the Chama Basin, and in the vicinity of Lucero Mesa. These rocks reach a maximum thickness of 520 m (O'Sullivan, 1977) in the San Juan Basin and thin to the north, east and south. Fossil fauna and flora indicate that the Triassic rocks are of fluvial and lacustrine origin. Triassic rocks comprise the Moenkopi(?) Formation, Chinle Formation, Wingate Sandstone, and Dolores Formation. The Moenkopi(?) Formation and Wingate Sandstone are present only in the southwest part of the San Juan Basin. The Dolores Formation occurs in the northern part of the basin.

Several small, uneconomic deposits of uranium are found in the Chinle Formation in the San Juan and Chama Basins (Hilpert, 1969; Chenoweth, 1974b). They occur in the Shinarump Member, Poleo Sandstone Lentil, and Agua Zarca Sandstone. The uranium occurs in arkosic, carbonaceous sandstone and, in the Agua Zarca and Poleo deposits, is associated with copper carbonates. Because the Chinle Formation is host for major uranium deposits west and northwest of the San Juan Basin and because its potential for uranium deposits in the report area is good, its various members will be described in some detail.

Moenkopi(?) Formation

In the Zuni Mountains and to the east and southeast, a red siltstone, sandstone, and locally, conglomeratic sandstone sequence, which overlies the San Andres Limestone, has been called the Moenkopi(?) Formation (McKee, 1954). It may be a correlative of the Moenkopi Formation that crops out in Arizona. This lithologic sequence thickens from the Fort Wingate area to the southeast and ranges in thickness from 0 to 65 m (Hilpert, 1969; O'Sullivan, 1977).

Chinle Formation

The Chinle Formation is present throughout the San Juan and Chama Basins. Changes in nomenclature of members occur from west to the east across the area. These nomenclature changes reflect the pinchout of recognizable members across the area and changes in source areas and directions of transport for members. Because of these changes in nomenclature, discussion of the Chinle will be divided into two parts: one covering the western and southern parts of the area, and the other covering the eastern parts.

On the west side of the San Juan Basin, the Chinle Formation unconformably overlies the De Chelly Sandstone Member of the Cutler Formation, and in the southern part of the basin rests unconformably on the Moenkopi(?) Formation. In this area the Chinle comprises several members which are, in ascending order, the Shinarump, Monitor Butte, Petrified Forest and Owl Rock Members.

<u>Shinarump Member</u>.--The areal distribution of the Shinarump Member of the Chinle Formation (Longwell, 1952) is limited to the western and southern part of the San Juan Basin and vicinity (Stewart and others,

1972; O'Sullivan, 1977). East of Fort Wingate the Shinarump thins and occurs as discontinuous lenses. This area may represent the eastern depositional limit of this unit. To the south, Stewart and others (1972, p. 19) indicate that the Shinarump may be present in the vicinity of Lucero Mesa.

The Shinarump consists of as much as 65 m of light-gray, tan, and pale-yellow-orange, coarse-grained sandstone, conglomeratic sandstone, and, locally, conglomerate deposited in high-energy fluvial environments. The sandstones are crossbedded and locally contain concentrations of silicified and carbonized wood. The basal contact is an erosion surface.

In the Monument Valley area, Arizona, the Shinarump Member is host for major uranium deposits, localized in conglomeratic sandstones that fill stream channels cut into the underlying Moenkopi Formation. In the San Juan Basin, only a few small deposits have been found in similar lithologies in the Shinarump (Hilpert, 1969, p. 147).

<u>Monitor Butte Member</u>.--The Monitor Butte Member (Stewart, 1957) is about 100 m thick west of the Chuska Mountains and thins eastward toward the Zuni Mountains. It is composed of red mudstone and siltstone and lighter colored sandstone and conglomerate.

<u>Petrified Forest Member and Sonsela Sandstone Bed</u>.--The Petrified Forest Member (Gregory, 1950) is widespread throughout the San Juan and Chama Basins and vicinity. In the western and southern parts of the San Juan Basin it overlies the Monitor Butte Member, Shinarump Member, or Moenkopi(?) Formation (Hilpert, 1969). The Petrified Forest Member consists of blue, gray, red, brown, and purple mudstone and siltstone

with altered volcanic debris and several sandstone horizons in the middle and upper part. In the western part of the San Juan Basin the Petrified Forest Member is nearly 330 m thick and is divided into a lower and upper part by the Sonsela Sandstone Bed.

The Sonsela Sandstone Bed is present in the southwest part of the San Juan Basin, where it consists of 15 to 50 m of light yellowish-gray, tuffaceous sandstone and lesser amount of siltstone and shale. The sandstone is crossbedded and locally conglomeratic. Pebbles in the conglomerate consist of chert, quartzite, and quartz. Crossbed measurements in the sandstone indicate the Sonsela was deposited by streams flowing to the north (O'Sullivan, 1974).

Owl Rock Member.--The Owl Rock Member (Stewart, 1957) is present in the western and northwestern part of the area shown on plate 1. It is 91 m thick west of the Chuska Mountains; however, in the vicinity of the Zuni Mountains it thins and is truncated by pre-Entrada erosion. The Owl Rock is composed of pale red and red brown coarse siltstone and shale interbedded with sandstone and pale red and light greenish-gray limestone.

The Chinle Formation crops out along the western flanks of the Nacimiento and San Pedro Mountains on the eastern side of the San Juan Basin, and along the southern and eastern margins of the Chama Basin. Along the eastern margin of the San Juan Basin, it rests on the Abo Formation south of latitude 36° N., and on the Cutler Formation north of that latitude. In the southern part of the Chama Basin the Chinle overlies the Cutler Formation, except locally, where it rests on rocks of Pennsylvanian age (Muehlberger, 1957). In the northern part of the

Chama Basin, the Chinle rests unconformably on Precambrian rocks. Thickness of the Chinle varies from nearly 400 m in the southeast part of the San Juan Basin to 130 m in the northern part of the Chama Basin.

The Chinle Formation in this area has been divided into six members, although not all members are recognizable everywhere (Wood and others, 1946; Smith and others, 1961; Stewart and others, 1972). These members are, in ascending order, the Agua Zarca Sandstone Member, the sandstone member, the Salitral Shale Tongue, the Poleo Sandstone Lentil, the Petrified Forest Member, and an unnamed siltstone member.

Agua Zarca Sandstone Member and sandstone member.--The Agua Zarca Sandstone Member crops out along the Nacimiento and San Pedro Mountains and is not recognizable in the Chama Basin. Where present it rests unconformably on Permian rocks and is overlain by the sandstone member or the Salitral Shale Tongue. It pinches out westward into the San Juan Basin. The Agua Zarca is composed of as much as 35 m of red, purple, and gray sandstone, and lesser amounts of conglomerate, siltstone, and shale. The source area for the Agua Zarca was to the north and deposition was by streams flowing to the south and southwest (Hilpert, 1969).

In the southeast part of the San Juan Basin, the sandstone member occurs at the base of the Chinle; however, it rises, stratigraphically, northward, and in the vicinity of the northern Nacimiento Mountains it overlies the Agua Zarca Sitstone Member (Stewart and others, 1972). The sandstone member consists of 50 m of pale-orange, yellow-gray, fine- to medium-grained sandstone that is locally conglomeratic. The sandstone member differs from the Agua Zarca in lithology, color and source.

Paleocurrent measurements indicate this member was deposited by streams flowing to the north and northwest (Stewart and others, 1972; O'Sullivan, 1974).

Salitral Shale Tongue and Poleo Sandstone Lentil.--The Salitral Shale Tongue separates the underlying Agua Zarca Sandstone Member or sandstone member from the overlying Poleo Sandstone Lentil in the northeast part of the San Juan Basin and southern part of the Chama Basin. It has a maximum thickness of 35 m in the Nacimiento Mountains and thins to the north and east. Where the Poleo is absent, the Salitral Shale Tongue cannot be differentiated from the Petrified Forest Member (Stewart and others, 1972; O'Sullivan, 1974), because lithologies of the Salitral are similar to those of the Petrified Forest Member throughout the area. Both units consist of red, brown, purple, and greenish-gray shale and siltstone (Northrop, 1950).

The Poleo Sandstone Lentil crops out around the southern margin of the Chama Basin and in the San Pedro Mountains. It thins southward and pinches out in the vicinity of San Ysidro (Stewart and others, 1972). It is composed of 15 to 54 m of yellow-gray to white-gray, fine to medium grained sandstone, conglomerate, and minor amounts of siltstone and shale. Locally, it contains abundant carbonized plant fragments. The Poleo was deposited by streams flowing to the north and northwest (O'Sullivan, 1974). Cooley (1959) and J. D. Strobell, Jr. (U.S. Geological Survey, 1964, p. 100) suggest that the Poleo Sandstone Lentil may be an eastern equivalent of the Sonsela Sandstone Bed.

The Petrified Forest Member and unnamed siltstone member in the eastern part of the report area are similar in lithology and occurrence to the Petrified Forest Member in the western part of the report area.

Dolores Formation

In the northern part of the San Juan Basin, rocks of Triassic age compose the Dolores Formation (Cross, 1899). The Dolores may be equivalent to the upper part of the Chinle Formation. It has been divided into the lower, middle, and upper members (Stewart and others, 1972) and was deposited under fluvial conditions.

The lower member consists of 10 to 30 m of green-gray, ledge-forming sandstone and conglomerate. The sandstones are fine to very fine grained, horizontally laminated, and thin bedded. This member thins from southwestern Colorado towards the New Mexico state line.

The middle member is composed of 40 to 80 m of grayish-red, brownish-gray, and greenish-gray micaceous siltstone, sandy siltstone, and very fine grained sandstone. Locally, thin lenses of carbonaceous limestone pebble conglomerate are present. Contact with the underlying lower member is gradational to intertonguing. The middle member also thins to the south from southwestern Colorado. Stewart and others (1972) suggested that this member may correlate with the Owl Rock Member of the Chinle Formation; however, O'Sullivan (1977, p. 145) has indicated it may be equivalent to the upper part of the Petrified Forest Member.

The upper member consists of horizontally laminated, light-brown and red-brown siltstone, sandy siltstone, and lesser amounts of sandstone. It is 165 m thick at its northern extent, in southwestern Colorado, and thins southward, where it is truncated by pre-Entrada erosion. This member has been considered by Stewart and others (1972) to be a lateral equivalent of the Rock Point Member of the Wingate Formation and by O'Sullivan (1977) to be a lateral equivalent of the siltstone member and Owl Rock Member interval of the Chinle Formation.

Wingate Sandstone

The Wingate Sandstone (Dutton, 1885; Harshbarger and others, 1957) is the only member of the Glen Canyon Group present in the San Juan Basin. It has been divided into the basal Rock Point Member and the upper Lukachukai Member. The Rock Point Member is restricted to the western part of the basin, where it overlies the Owl Rock Member of the Chinle Formation, and to the areas to the west where it overlies the Petrified Forest Member of the Chinle Formation. It consists of about 100 m of silty sandstone and dark-red-brown, flat-bedded, calcareous sandy siltstone. The origin of the interbedded flat-lying sandy siltstone and silty sandstone has been attributed by Harshbarger and others (1957) to deposition in lagoonal environments and by Stewart and others (1972) to alternating deposition in lacustrine and eolian environments.

In contrast to the Rock Point Member, the Lukachukai Member consists of crossbedded, reddish-brown to orange, fine to medium grained sandstone. The high-angle, crossbedded sandstones of the Lukachukai Member are considered to be of eolian origin. West of the Chuska Mountains, the Lukachukai Member is about 135 m thick. It thins to the east into western New Mexico and pinches out along a northeast-trending line just west of Shiprock (Green and Pierson, 1977).

The age of the Wingate Sandstone is controversial. Originally considered to be Jurassic in age, the Wingate Sandstone was assigned a

Triassic age by Harshbarger and others (1957), based on the presence of Triassic fossils in the Rock Point Member and on observed intertonguing relations between the Rock Point and Lukachukai Members. However, recent work by Witkind and Thaden (1963) and O'Sullivan and Green (1973) indicates that the contact between the Rock Point and Lukachukai is disconformable. Furthermore, a recent study by Peterson and others (1977) suggest that the Lukachukai may be of Jurassic age. Fossil palynomorphs found in the Whitmore Point Member, near the base of the Moenave Formation in southeast Utah, have been assigned an Early Jurassic age (Peterson and others, 1977). In the Four Corners area the Lukachukai and Moenave intertongue; consequently, the Lukachukai may also be of Early Jurassic age. Thus the Wingate may be of Triassic and Jurassic age, and the disconformity between the Rock Point and Lukachukai Members may represent the boundary between the Triassic and Jurassic Systems.

Rocks of Jurassic age

Rocks of Jurassic age are exposed around the margins of the San Juan Basin, in the southern part of the Chama Basin, and in adjacent areas. They reach a maximum thickness of 415 m in the center of the San Juan Basin and thin towards the margins. Locally, Jurassic rocks are absent because of faulting along the west flanks of the Nacimiento and San Pedro Mountains. In the southern part of the San Juan Basin, Jurassic rocks are beveled southward by pre-Dakota erosion and are absent south of a line that extends east-west about 48 km south of Laguna and Gallup.

Jurassic rocks in the area comprise the San Rafael Group, Cow

Springs Sandstone, and Morrison Formation. In the San Juan Basin vicinity, the major uranium deposits are found in the Morrison Formation. The most significant uranium deposits occur in the southern part of the basin in the Westwater Canyon Sandstone Member and in the Jackpile sandstone (economic usage) of the Brushy Basin Member of the Morrison Formation (Hilpert, 1969). Other uranium deposits occur in the Salt Wash Member and Recapture Member of the Morrison Formation, and in the Todilto Limestone (Hilpert, 1969; Chenoweth, 1974b; Green and Pierson, 1977).

San Rafael Group

The San Rafael Group in the San Juan Basin area consists of, in ascending order, the Carmel Formation, Entrada Sandstone, Todilto Limestone, Summerville Formation, and Bluff Sandstone. In the northern part of the San Juan Basin, the Pony Express Limestone Member, unnamed member, and Junction Creek Sandstone Member of the Wanakah Formation are included in the San Rafael Group. In the western part of the basin, the San Rafael Group rests unconformably on members of the Glen Canyon Group; east and south of this area it rests unconformably on the Chinle Formation.

Carmel Formation.--The Carmel Formation (Gregory and Moore, 1931) is present only in the northwest part of the San Juan Basin (Harshbarger and others, 1957), where it rests unconformably on rocks of the Glen Canyon Group. It consists of red siltstone and mudstone of probable inland or coastal sabkha origin (Green and Pierson, 1977) and ranges in thickness from 0 to 85 m. To the northwest, in Utah, the siltstone and mudstone facies grade laterally into marine sandstone and limestone facies.

Entrada Sandstone.--The Entrada Sandstone (Gilluly and Reeside, 1928) is widely distributed throughout the San Juan and Chama Basins and vicinity. In the western part of the area, it rests conformably on the Carmel Formation; elsewhere it rests unconformably on the Rock Point Member of the Wingate Sandstone or on the Chinle Formation. The Entrada is absent at the southern margin of the San Juan Basin, and is nearly 130 m thick in the center of the basin.

In the southern part of the San Juan Basin, the Entrada has been divided into several members (Smith, 1954, 1967; Harshbarger and others, 1957; Green, 1974). Previously the lower part of the formation had been assigned to the Wingate Sandstone or Carmel Formation (Dutton, 1885; Smith, 1954; Harshbarger and others, 1957; O'Sullivan and Craig, 1973). In this area, the Entrada is composed of reddish-orange, fine to medium grained, well-sorted sandstone and an interbedded sequence of dark-red-brown siltstone and mudstone. The sandstone facies represents deposition in eolian environments, and the siltstone-mudstone facies indicates deposition in inland sabkha and interdune environments (Green, 1974; Green and Pierson, 1977).

In the northern and eastern parts of the San Juan Basin and in the Chama Basin, the Entrada Sandstone is undifferentiated. In this area, it consists of medium- to fine grained, well-sorted, crossbedded sandstone of eolian origin. In the southern part of the Chama Basin, the Entrada generally exhibits a three-fold color banding of variable thickness. The basal part is reddish orange, the middle part grayish white, and the upper part yellow tan. The different colors are a result of varying amounts and proportions of ferrous and ferric iron.

Todilto Limestone.--The distribution of the Todilto Limestone (Gregory, 1917) is limited to the San Juan and Chama Basins. West of the Defiance Uplift, in northeast Arizona, the Todilto is absent. In the northern part of the San Juan Basin, the equivalent of the Todilto Limestone is the Pony Express Limestone Member of the Wanakah Formation. The Todilto consists of gray, dense, massive to thin bedded limestone intercalated with sandy shale. In the central and eastern parts of the San Juan Basin and in the Chama Basin, the limestone sequence is overlain by a thick gypsum-anhydrite sequence. Thickness of the Todilto is variable. The limestone facies is as much as 10 m thick; the gypsum-anhydrite facies is as much as 30 m thick. Contact with the underlying Entrada Sandstone is gradational and conformable. The Todilto is considered to have been deposited in a lacustrine environment. Deposition of the gypsum-anhydrite facies was restricted to the deeper part of the lake, centered along the present eastern margin of the San Juan Basin.

Summerville Formation.--The Summerville Formation (Gilully and Reeside, 1928, p. 80) has about the same distribution as the Todilto Limestone along the western and southern margins of the San Juan Basin. Along the east side of the basin, Santos (1975) has mapped the Summerville to an area about 20 km north of San Ysidro. A sequence 3 to 18 m thick of lithologies similar to those mapped as Summerville by Santos (1975) has been recognized in the Chama Basin (Craig and others, 1959; Ridgley, 1977).

In the western and southern parts of the San Juan Basin, the

Summerville consists of massive to flat-bedded, reddish-brown and gray, fine-grained silty sandstone and sandy siltstone and ranges in thickness from 3 to 20 m. Along the eastern margin of the San Juan Basin and in the Chama Basin, the Summerville is composed of fine- to very fine-grained, pinkish-gray, grayish-yellow and pale-reddish-brown siltstone and sandstone interbedded with mudstone. The mudstone near the base of the formation is gray to grayish green; that near the top is reddish brown. A few thin limestone beds are present near the base or top of the formation.

The origin of the Summerville has been variously interpreted. Hilpert (1969) considered it to be a marine deposit; Green and Pierson (1977) consider it to have been deposited in an inland sabkha, which encroached on the margins of the receding Todilto lake. In the Chama Basin the interval equivalent to the Summerville is interpreted as representing deposition in environments transitional between lacustrine and fluvial (Ridgley, 1977, p. 157).

Bluff Sandstone.--The Bluff Sandstone (Gregory, 1938, p. 58-59) is the uppermost formation of the San Rafael Group. It crops out along the western and southern margins of the San Juan Basin, where it conformably overlies the Summerville Formation. In the area of the Grants Mineral Belt the Bluff grades laterally into the Cow Springs Sandstone (Harshbarger and others, 1957, p. 48-51). In areas where the Cow Springs Sandstone and Bluff Sandstone can be separated, the contact is considered to be intertonguing and arbitrary (Green and Pierson, 1977). Harshbarger and others (1957) consider the Bluff to be a lower tongue of the Cow Springs. In the northern part of the basin, the Junction Creek

Sandstone is considered to be an equivalent of the Bluff Sandstone.

The Bluff is composed of pale-orange or buff, fine- to medium-grained, crossbedded sandstone of eolian and interdune origin. It is nearly 115 m thick at Bluff, Utah, and thins southward to the Grant Mineral Belt, where it grades into the Cow Springs Sandstone.

Cow Springs Sandstone

The Cow Springs Sandstone (Harshbarger and others, 1951) is recognized in the southwest part of the San Juan Basin. According to Harshbarger and others (1957, p. 48), the Cow Springs intertongues with the Summerville Formation, Bluff Sandstone, and lower members of the Morrison Formation. Its thickness varies to a maximum of about 135 m thick near Fort Wingate (Harshbarger and others, 1957), and from this area it thins to the north and east.

Greenish-gray and orange, medium- to fine-grained, well-sorted sandstone makes up the Cow Springs. The sandstones are generally crossbedded, although locally, they may be evenly bedded and flat lying. Sedimentary structures and lithofacies relationships indicate deposition in eolian and interdune environments.

Morrison Formation

The Morrison Formation (Cross, 1894) is exposed along the margins of the San Juan and Chama Basins and is present in the subsurface throughout the area. South of U.S. Highway 66, in the southern part of the area, the Morrison is absent, owing to erosion prior to deposition of the Dakota Sandstone. It ranges in thickness from 0 m at its erosional edge to about 300 m near the center of the San Juan Basin.

The Morrison Formation is composed of arkosic to subarkosic sandstone, which is locally conglomeratic, and variegated gray, maroon, and orange claystone. Deposition took place in a variety of fluvial and lacustrine environments. The Morrison Formation is unconformably overlain by the Dakota Sandstone, except in the northern part of the San Juan Basin and in the Chama Basin, where it is overlain by the Burro Canyon Formation. In the San Juan Basin and northwest areas, the Morrison has been divided into four members, which are, in ascending order, the Salt Wash Member, Recapture Member, Westwater Canyon Sandstone Member, and Brushy Basin Member. Owing to northward facies changes in the Recapture and Westwater Canyon Sandstone Members, which result in differentation problems, the Morrison is usually divided into a lower member and an overlying Brushy Basin Member in the Chama Basin. In the San Juan Basin and vicinity all four members of the Morrison Formation contain uranium deposits.

Salt Wash Member.--The Salt Wash Member (Lupton, 1914) of the Morrison Formation is present only in the northwest part of the San Juan Basin and vicinity, where it rests on the Bluff Sandstone and grades into the overlying Recapture Member. South of the Four Corners area the Salt Wash intertongues with the Recapture and pinches out below the Recapture in the vicinity of Toadlena, New Mexico, near the north end of the Chuska Mountains (Craig and others, 1955). In this area the Salt Wash reaches a maximum thickness of 100 m and consists of interbedded reddish-brown to greenish-gray, medium- to very fine grained sandstone and greenish-gray and reddish-brown claystone and siltstone. The sandstones are crossbedded and locally contain silicified and carbonized plant debris. Deposition of the Salt Wash was primarily by streams traversing an alluvial fan, which extended from northeast Arizona into northwest New Mexico (Craig and others, 1955). Some deposition also took place in lacustrine environments (Chenoweth, 1967, p. 81).

Uranium deposits in the Salt Wash Member are clustered in an area near the Arizona-New Mexico state line in the Shiprock and Chuska mining districts. In these areas the uranium occurs in gray sandstone associated with gray mudstone.

Recapture Shale Member.--The Recapture Shale Member (Gregory, 1938) of the Morrison Formation is exposed along the western, southern, and eastern margins of the San Juan Basin. In the Chama Basin it is included in the lower member of the Morrison Formation (Smith and others, 1961; Ridgley, 1977). In the southwest part of the basin it rests conformably on the Cow Springs Sandstone or conformably on the Summerville Formation; in the northwest part of the basin it overlies the Salt Wash Member; and in the eastern part of the basin it rests conformably on the Summerville Formation. South of U.S. I-40, the Recapture thins and wedges out below the pre-Dakota erosion surface.

The Recapture ranges in thickness generally from 70 to 100 m, but attains a maximum thickness of 200 m locally in the northwest part of the basin. It changes facies south to north across the basin. In the Gallup-Toadlena area, in the western part of the basin, the Recapture consists of pale-reddish-brown to pinkish-gray, medium- to fine-grained sandstone interbedded with greenish-gray and reddish-brown mudstone (Harshbarger and others, 1957; Huffman and Lupe, 1977). The sandstones are lenticular and exhibit low-angle wedge and tabular type cross stratification typical of fluvial processes. Some of the sandstones, however, are considered to be eolian in origin (Harshbarger and others, 1957, p. 53; Huffman and Lupe, 1977). Deposition of this facies is considered to have taken place at the toe of an alluvial fan that extended northward from west-central New Mexico (Craig and others, 1955; Saucier, 1967).

North and east of this coarser facies, the Recapture consists predominantly of fine grained sandstone (Craig and others, 1955). This sandstone facies has a limited distribution. Elsewhere in the report area, the Recapture consists of a thin-bedded, maroon, gray, dark- and light-red-brown, fine- to very fine-grained sandstone, lenticular siltstone, and mudstone facies. Geometry and sedimentary structures of the sandstones and mudstones indicate a fluvial and lacustrine origin for this facies.

Uranium deposits in the Recapture occur in the Chuska mining district in northwest New Mexico. The uranium is found in gray sandstone and occurs as fracture fillings in calcified logs, as impregnations in sandstones, and as halos around mudstone galls (Hilpert, 1969, p. 87). It is often associated with carbonized plant debris. In the Ambrosia Lake and Laguna areas, sandstones in the Recapture are host for minor uranium in deposits (Chenoweth, 1977).

Westwater Canyon Sandstone Member.--The Westwater Canyon Sandstone Member (Gregory, 1938) of the Morrison Formation has about the same areal distribution in the San Juan Basin as the Recapture Member. It has been questionably identified in the Chama Basin (Craig and others, 1959), where it is mapped as part of the lower member (Smith and others, 1961). South of U.S. I-40 the Westwater Canyon thins under the Dakota. Thinning of the Westwater Canyon Member in this area is a result of nondeposition and pre-Dakota erosion (Hilpert, 1969, p. 20). In the western part of the basin the Westwater Canyon rests disconformably on the Recapture Member and is unconformably overlain by the Dakota Sandstone. To the north and east, the Westwater Canyon intertongues with the overlying Brushy Basin Member (Freeman and Hilpert, 1956; Santos, 1975); contact with the underlying Recapture Member is locally scoured, gradational or intertonguing. South of Cuba, the Westwater Canyon changes facies from sandstone interbedded with minor amounts of mudstone to interbedded sandstone and mudstone. This latter facies is present in the northern part of the San Juan Basin and in the Chama Basin.

Thickness of the Westwater Canyon ranges from 130 m in the southwest part of the basin to 30 to 70 m along the east side of the basin. In the southwest part of the basin, the Westwater Canyon consists of arkosic to subarkosic conglomeratic sandstone, poorly-sorted sandstone, and thin beds of light greenish-gray or grayish-red siltstone and claystone. Laterally to the north and east the conglomerate disappears, and the Westwater Canyon Member consists of varying proportions of sandstone, siltstone, and claystone. The ratio of sandstone to claystone and the grain size decrease from south to north. These changes suggest that the source area was to the south and southwest of Gallup (Craig and others, 1955). Sandstones in Westwater Canyon are generally lenticular, crossbedded, and exhibit scour surfaces at their bases. Sedimentary structures and facies relationships indicate (Green, 1975) that the Westwater Canyon Sandstone Member was deposited by high- to low-energy fluvial and associated low-energy overbank and lacustrine depositional systems.

Uranium is found in sandstones of the Westwater Canyon Member at various localities in the southern part of the San Juan Basin area. In the Grants Mineral Belt, the uranium is associated with fine grained, black or brownish-gray material (Granger, 1968), which is probably a humate substance derived from the decay of plant material. The decayed material may have originated within the Westwater Canyon or may have come from the overlying Dakota Sandstone.

Brushy Basin Member.--The Brushy Basin Member (Gregory, 1938) of the Morrison Formation is present throughout most of the San Juan and Chama Basins, except in the extreme southwest part of the San Juan Basin, where it is absent owing to pre-Dakota erosion. Throughout most of the area the Brushy Basin is unconformably overlain by the Dakota Sandstone, except in the Chama Basin and northern part of the San Juan Basin and vicinity, where it is overlain by the Burro Canyon Formation.

The thickness of the Brushy Basin is variable, owing to intertonguing with the underlying Westwater Canyon Sandstone Member and to pre-Dakota erosion. The Brushy Basin ranges in thickness from 70 to 130 m but locally may be thicker or thinner. Greenish-gray and red-orange, montmorillonitic, silty claystone interbedded with hard, dense, greenish-gray, very fine grained sandstone and lenticular, buff to tan channel sandstone make up the Brushy Basin. A few thin limestone beds are locally present. This lithologic sequence suggests deposition in low-energy fluvial and lacustrine environments.

In the eastern part of the San Juan Basin, the upper 8 to 70 m consists of interbedded white to orange, medium- to fine-grained sandstone and greenish-gray claystone of fluvial origin. Locally, this sandstone is coarser grained or conglomeratic. This sandstone-claystone sequence is called the Jackpile sandstone in economic usage. The Jackpile sandstone is host for the major uranium deposits in the southeast part of the San Juan Basin, near Laguna, New Mexico. In the Jackpile, uranium occurs in sandstones and is associated with carbonaceous or humate material.

Rocks of Cretaceous age

Rocks of Cretaceous age are present throughout the report area and consist of shale, sandstone, and interbedded carbonaceous shale and coal beds. These rocks were deposited in a variety of fluvial, near-shore marine, and marine environments. Vertical and lateral facies changes reflect numerous marine transgressions and regressions (Weimer, 1960; Peterson and Ryder, 1975; Peterson and Kirk, 1977). Total thickness of Cretaceous rocks averages about 1,000 m in the southern part of the report area (Dane and others, 1957) and about 2,300 m in the northern part of the area (Reeside, 1924). In the southern part of the area, the complete Cretaceous section is not present, owing to erosion. Cretaceous rocks comprise, in ascending order, the Burro Canyon Formation, Dakota Sandstone, Mancos Shale, Mesaverde Group, Lewis Shale, Pictured Cliffs Sandstone, Fruitland Formation, Kirtland Shale, and Animas Formation. The Animas Formation is Late Cretaceous and early Tertiary (Paleocene) in age.

Uranium anomalies and deposits occur in a number of Cretaceous formations. Uranium mineralization has been found in sandstones of the Burro Canyon Formation on the east side of the Chama Basin (Saucier, 1974). On the east side of the San Juan Basin, uranium occurs in the Dakota Sandstone, Point Lookout Sandstone, and Menefee Formation, and in the La Ventana Tongue of the Cliff House Sandstone (Chenoweth, 1974b, 1977). In these formations, the uranium occurs in carbonaceous shale, carbonaceous sandstone, and coal. In the Gallup and Ambrosia Lake areas, a number of mines have produced uranium from the Dakota Sandstone (Hilpert, 1969; Chenoweth, 1977; Pierson and Green, 1977). Other minor uranium occurrences are in the Fruitland Formation near Farmington, New Mexico, (Clinton and Carithers, 1956), in the Gallup Sandstone near the Chuska Mountains, and at the contact of the Point Lookout Sandstone and Crevasse Canyon Formation north of the Datil Mountains (Hilpert, 1969).

Burro Canyon Formation

The Burro Canyon Formation (Stokes and Phoenix, 1948) is present only in the northern part of the San Juan Basin and has been tentatively identified in the Chama Basin (McPeek, 1965; Grant and Owen, 1974; Saucier, 1974; Ridgley, 1977; Owen and Siemers, 1977). It is absent in the central and southern part of the report area, owing to truncation by pre-Dakota erosion (Young, 1960). Contact between the Burro Canyon and the underlying Brushy Basin Member of the Morrison Formation is generally sharp and locally scoured. Craig and others (1961) indicate that in the northern part of the San Juan Basin the contact between the two formations may be gradational, while Saucier (1974) states that in the southern part of the Chama Basin the contact is disconformable.

The Burro Canyon ranges in thickness from 0 to 65 m and is composed of white, tan, or orange conglomerate, conglomeratic sandstone, and sandstone and red and green mudstone or shale. Pebbles in the conglomerate are chert and cherty limestone fragments. Many of the limestone pebbles contain crinoid stems of probable Paleozoic age. The sandstones are coarse to fine grained and are crossbedded to parallel bedded. Sedimentary structures and lithofacies relationships indicate that the Burro Canyon Formation was deposited by braided to meandering streams (Ridgley, 1977).

Dakota Sandstone

The Dakota Sandstone (Meek and Hayden, 1862) crops out around the margins of the San Juan and Chama Basins. Throughout the area a regional unconformity separates the Dakota from underlying formations. The Dakota overlies progressively older formations from north to south. Thickness of the Dakota varies, but is generally not more than 65 m. Throughout most of the area the Dakota can be divided into continental and marine lithologic sequences (Dane and Bachman, 1957; Grant and Owen, 1974; Ridgley, 1977). The basal sequence generally consists of fluvial sandstone and conglomeratic sandstone, paludal carbonaceous shale and siltstone, and thin coal beds. The upper sequence is primarily medium- to fine-grained sandstone, which is locally crossbedded and burrowed. The upper sequence represents deposition in coastal and near-shore marine distributary channel environments during transgression of the Cretaceous sea from the north and southeast.

Mancos Shale

The Mancos Shale (Cross, 1899) is present throughout the San Juan and Chama Basins. It conformably overlies and intertongues with the Dakota Sandstone, and it also intertongues with the overlying Point Lookout Sandstone. In the southern part of the San Juan Basin, the Mancos intertongues with the Gallup Sandstone and Crevasse Canyon Formation (Molenaar, 1977, fig. 1). In the San Juan Basin and adjacent areas, the Mancos has been divided into several members and tongues. O'Sullivan and others (1972), Landis and others (1973b, 1974), Fassett (1974), and Molenaar (1977) discuss the various divisions of the Mancos and their intertonguing relationships with other formations.

Thickness of the Mancos varies because of these intertonguing relationships; it reaches a maximum thickness of about 660 m in the northern part of the basin and thins to the south. Gray shale, siltstone, and lesser amounts of limestone, sandstone, and bentonite characterize the Mancos. Invertebrate fossils indicate that the Mancos was deposited in shallow to deep marine environments. Deposition took place during several marine transgressive-regressive cycles from the north.

Mesaverde Group

The Mesaverde Group (Holmes, 1877) consists of a sequence of sandstone, shale, and coal. In the San Juan Basin and adjacent areas, the Mesaverde has been divided into five formations. These are, in ascending order, the Gallup Sandstone, Crevasse Canyon Formation, Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone.

<u>Gallup Sandstone</u>.--The Gallup Sandstone (Sears, 1925) is exposed along the western and southern margins of the San Juan Basin. It is conformably overlain by the Crevasse Canyon Formation and intertongues

with the underlying Mancos Shale (Molenaar, 1977). The Gallup Sandstone is a complex regressive sequence consisting of coastal barrier and offshore marine sandstones, estuarine and distributary channel sandstones, fluvial sandstones, and coastal swamp and marsh sandstones, carbonaceous shales, and coal beds (Molenaar, 1973). It was deposited from southwest to northeast as the Cretaceous sea withdrew to the north. It is about 80 m thick near Gallup and thins to the northeast, where it pinches out into the Mancos.

Crevasse Canyon Formation.--The Crevasse Canyon Formation crops out around the southern margin of the San Juan Basin. It has been divided into several members, which are, in ascending order, the Dilco Coal Member, Dalton Sandstone Member, Bartlett Barren Member, and the Gibson Coal Member (Beaumont and others, 1956). Beaumont and others (1956), Molenaar (1973), and Kirk and Zech (1977) discuss some of these members in more detail. The Crevasse Canyon Formation is composed of sandstone, clay, and several coal beds and was deposited in fluvial and paludal environments. It is approximately 250 m thick in the southwest part of the basin and thins to the northeast, where it intertongues with the Mancos Shale.

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Point Lookout Sandstone.--The Point Lookout Sandstone (Collier, 1919) is present throughout most of the report area. In the southern part of the area it conformably overlies the Crevasse Canyon Formation; to the north it intertongues with or is gradational with the underlying Mancos Shale. The Point Lookout Sandstone ranges in thickness from 35 m in the southwest part of the San Juan Basin to 115 m in the northeast part of the basin. It is composed of buff, gray, and tan, medium- to fine grained sandstone and lesser amounts of shale and represents marine and coastal barrier deposits. Deposition took place during a major regression of the Cretaceous sea to the northeast (Landis and others, 1974; Molenaar, 1977).

Menefee Formation.--The Menefee Formation (Collier, 1919) is exposed around the margins of the San Juan and Chama Basins and attains a maximum thickness of 500 to 660 m near the center of the basin. It thins from southwest to northeast across the basin. In the extreme southwest part of the basin the Menefee is thin, and it is absent south of the San Juan Basin, owing to pre-Tertiary erosion (Hilpert, 1969; Molenaar, 1977). The contact with the underlying Point Lookout Sandstone is sharp, but conformable, and the contact with the overlying Cliff House Sandstone is gradational to intertonguing (Baltz, 1967). The Menefee consists of a sequence of sandstone, shale, carbonaceous shale, and coal and was deposited in fluvial and paludal environments during continued regression of the Cretaceous sea to the north.

Cliff House Sandstone.--The Cliff House Sandstone (Collier, 1919) crops out locally around the western, southern, and eastern margins of the San Juan Basin; it has not been recognized in the northeast part of the Chama Basin (Landis and Dane, 1967). The Cliff House Sandstone is composed of thick-bedded, gray, buff, and orange-brown, medium- to fine-grained sandstone and minor amounts of gray shale. This lithologic sequence is attributed to deposition in near-shore marine and coastal environments as the Cretaceous sea again transgressed the area. A thick sandstone sequence in the upper part of the formation is known as the La Ventana Tongue. The La Ventana Tongue attains its maximum thickness of

330 m in northwest Sandoval County, New Mexico, and thins to the north. The Cliff House Sandstone, exclusive of the La Ventana Tongue, attains a maximum thickness of 115 m in the southwest part of the basin. It also thins to the northeast where it grades into and intertongues with the overlying Lewis Shale.

Lewis Shale

The Lewis Shale (Cross and Spencer, 1899) is exposed locally in the northern and central parts of the San Juan and Chama Basin. The Lewis is absent in the southwest part of the San Juan Basin, but is nearly 800 m thick in the northeast part (Fassett and Hinds, 1971). Light- to dark-gray and black shale interbedded with light-brown sandstone, sandy to silty limestone, calcareous concretions, and several thin bentonite beds compose the Lewis Shale. In the southwest part of the basin, where the Lewis wedges out between the underlying Cliff House Sandstone and the overlying Pictured Cliffs Sandstone, it is sandier and siltier. Contacts between the Lewis and the Cliff House and Pictured Cliffs Sandstones are gradational to intertonguing. Invertebrate fossils indicate deposition in offshore, relatively deep marine environments. The Lewis Shale was deposited during the final transgression of the Cretaceous sea.

Pictured Cliffs Sandstone

The Pictured Cliffs Sandstone (Holmes, 1877) crops out along the north, west, and south sides of the San Juan Basin. In the northeast part of the basin, it grades into a sandy, silty zone, which is generally considered to be part of the Lewis Shale. Throughout the basin, contacts with the underlying Leware Shale and overlying Fruitland Formation are gradational to intertonguing. The Pictured Cliffs Sandstone ranges in thickness from 25 to 122 m and thins to the northeast. The lower part of the formation consists of interbedded thin sandstones and shales, while the upper part consists of one or more massive sandstones interbedded with thin shale. The sandstones are generally fine to medium grained and are well sorted. The Pictured Cliffs Sandstone is interpreted to represent shallow-marine and beach deposits formed during final regression of the Cretaceous sea (Fassett and Hinds, 1971).

Fruitland Formation

The Fruitland Formation (Bauer, 1917) is present over most of the San Juan Basin except along the eastern margin, where it was truncated prior to deposition of the Ojo Alamo Formation (Molenaar, 1977). Where the overlying Kirtland Shale is present the contact is conformable; where the Kirtland is absent the Fruitland is unconformably overlain by the Ojo Alamo Formation. The Fruitland Formation ranges in thickness from 0 to 152 m and consists of sandstone and siltstone interbedded with carbonaceous shale and coal. In the lower part of the formation a few thin limestone beds are also present. Most of the sandstone units are lenticular. The lower part of the formation is dominated by sandstone and coal and the upper part by siltstone and shale. Sedimentary structures and lithofacies relationships indicate deposition in nonmarine, paludal, fluvial, flood-plain, and lacustrine environments.

Kirtland Shale

The Kirtland Shale (Bauer, 1917) has the same areal distribution as the Fruitland Formation and is also absent along the east side of the San Juan Basin because of erosion. It is generally overlain by the Ojo Alamo Formation; where the Ojo Alamo is absent, though, it is overlain by the Animas, Nacimiento or San Jose Formations. Contact with the underlying Fruitland Formation is conformable and gradational; eastward and northward across the basin the two formations intergrade and are difficult to differentiate. In these areas the two formations are often mapped together. The Kirtland ranges in thickness from 0 to 660 m (Fassett and Hinds, 1971).

In the western and southern parts of the San Juan Basin, the Kirtland is divided into three members: the lower shale member, Farmington Sandstone Member, and upper shale member (Bauer, 1917; Reeside, 1924). The lower member consists of gray shale and a few thin beds of sandstone and siltstone. The Farmington Sandstone Member consists of sandstone interbedded with shale. The upper member is composed of sandstone and shale and is often difficult to differentiate from the Farmington Sandstone Member. The Kirtland was deposited in fluvial and alluvial-plain environments.

Animas Formation

The Animas Formation (Reeside, 1924) of Late Cretaceous and Paleocene (Tertiary) age is present in the northern part of the San Juan Basin, in southwest Colorado and north-central New Mexico. South of this area it thins and grades into the Nacimiento Formation. In the northern part of the basin it unconformably overlies the Fruitland

Formation, except where the Fruitland Formation and Pictured Cliffs Sandstone are absent; in those places it overlies the Lewis Shale. It attains a maximum thickness of 1,000 m in north-central New Mexico, just south of the Colorado state line. The Animas Formation consists of fluvially deposited conglomerate, siltstone, sandstone, and shale that contain abundant volcanic material of andesitic composition. The lower part of the Animas Formation consists of purple to brown sandstone, conglomerate and shale and is known as the McDermott Member (Barnes and others, 1954).

Rocks of Tertiary age

Rocks of Tertiary Age are irregularly distributed throughout the report area and consist of continental sedimentary rocks and of intrusive and extrusive igneous rocks. Because most of the Tertiary formations have limited distribution, discussion of the formations is divided into the following areas: (1) the San Juan Basin, (2) the Chama Basin, and (3) the Southern section.

San Juan Basin

Sedimentary rocks of Tertiary Age comprise the upper part of the Animas Formation (previously discussed); the Ojo Alamo Sandstone, and the Nacimiento and San Jose Formations on the east side of the San Juan Basin; and the Chuska Sandstone on the west side of the basin. Minor amounts of igneous rocks are also present. Several small uranium occurrences are found in the Ojo Alamo Sandstone and the Nacimiento and San Jose Formations in the northeast part of the basin (Hilpert, 1969; Chenoweth, 1974b).

Ojo Alamo Sandstone.--The stratigraphy of the Ojo Alamo was controversial for many years. The original stratigraphic sequence defined by Brown (1910) was redefined by Bauer (1917). Bauer's description was later revised by Baltz, Ash, and Anderson (1966). The age of the Ojo Alamo was considered to be Tertiary by Knowlton (1924) and Cretaceous by Dane (1936). Recent studies by Anderson (1960) and R. H. Tschudy (in Fassett and Hinds, 1971) indicate a Paleocene (Tertiary) age for the Ojo Alamo.

The Ojo Alamo crops out in an irregular pattern from the Cuba, New Mexico, area on the east side of the basin to the Farmington area, and is present in the subsurface in the northeast part of the basin. It has been eroded south of the outcrop belt. The Ojo Alamo is composed of 0 to 130 m of interbedded sandstone, conglomeratic sandstone, and shale. The sandstone is buff to rusty brown, arkosic, and locally conglomeratic near the base (Fassett and Hinds, 1971). Pebbles in the conglomerate consist of jasper, chalcedony, quartzite, granite, and andesite and decrease in size from west to east across the basin. Sedimentary structures indicate that the Ojo Alamo is of fluvial origin. The contact with the overlying Nacimiento Formation is conformable and intertonguing (Fassett, 1966). The nature of the contact with the underlying Kirtland Formation is not clear; however, based on subsurface correlation, Fassett and Hinds (1971) and Fassett (1974) consider the contact to be unconformable.

Nacimiento Formation.--The Nacimiento Formation (Gardner, 1910; Dane, 1946) of Paleocene age crops out in scattered areas in the northeast part of the San Juan Basin. It conformably overlies the Ojo

Alamo Sandstone and ranges in thickness from 300 to 670 m. The Nacimiento coarsens and thickens from south to north, where it grades laterally into the Animas Formation (Dane, 1946; Hilpert, 1969). It is characterized by gray to black, banded shales and clays and lenticular channel sandstones. Deposition took place in fluvial and lacustrine environments (Fassett, 1974).

San Jose Formation.--The San Jose Formation (Simpson, 1948) of early Eocene age crops out in the eastern and northern parts of the San Juan Basin, where it unconformably overlies the Nacimiento or Animas Formation (Hilpert, 1969). It attains a maximum thickness of 1,000 m in the east-central part of the basin. The San Jose consists of interbedded red, purple, and variegated shale or claystone and lenticular, gray, red, and white sandstone. The sandstones are generally arkosic and fine to coarse grained, but locally may be conglomeratic. Mammalian fossils and carbonized and silicified wood are present locally (Simpson, 1948; Hilpert, 1969). Fossil fauna and flora and sedimentary structures indicate that the San Jose is of fluvial origin.

Chuska Sandstone.--The Chuska Sandstone (Gregory, 1917) of early Oligocene to Eocene(?) age crops out only in the area of the Chuska Mountains, along the western margin of the San Juan Basin. In this area the Chuska Sandstone rests on Jurassic or Cretaceous rocks. It ranges in thickness from nearly 230 m at its southern limit to about 600 m at its northern limit. Pinkish-gray to yellow-gray, massive to crossbedded sandstone and interbedded siltstone and shale make up the Chuska. Two types of sandstone are present. One type is coarse to fine grained and is cemented with calcite, opal, or chalcedony. The other type, found primarily in the lower part of the formation, is fine grained and loosely cemented. The second type of sandstone is usually interbedded with siltstone, bentonite, or white ash beds, and minor amounts of gypsum. Sedimentary structures indicate a dominantly eolian origin for most of the Chuska; however, some of the sandstone beds in the lower part of the formation contain cross-stratification that is considered to be fluvial in origin (Allen and Balk, 1954; Repenning and others, 1958).

Igneous Rocks in the San Juan Basin and vicinity.--Tertiary igneous rocks, both plutonic and volcanic, are widespread in the report area (plate 1), where they intrude rocks that range in age from Precambrian to Tertiary. The plutonic rocks exist as stocks, laccoliths, and related dikes and sills. The volcanic rocks exist as extinct volcanoes and volcanic necks, diatremes, dikes and sills, lava flows, and extensive sheets of ash-flow and ash-fall tuffs. Hunt (1956, p. 40) notes that the laccolithic mountains are clustered in the central and east-central part of the Colorado Plateau, and that the volcanic centers are found mostly around the edges of the plateau, especially around the southern edges.

Callaghan (1951, p. 119), in a report on the Tertiary and later igneous rocks of the San Juan Basin, observed that "...the central part of the Basin is nearly free of bodies of igneous rocks. However, the outer margin is ringed by scattered igneous masses. Most of these masses are erosional remnants and many are landmarks that have a prominence out of proportion to their areal extent." In the area covered by plate 1, the San Juan Mountains of southwestern Colorado, the

Jemez Mountains and Mount Taylor in New Mexico, and the Navajo and Hopi Buttes volcanic fields in northeastern Arizona are the most important representatives of volcanic rock accumulations. Ute Mountain, southwest of Cortez, Colorado, is a stock, and the La Plata Mountains, northwest of Durango, Colorado, the Abajo Mountains, southwest of Monticello, Utah, and the Carrizo Mountains of northeastern Arizona are laccoliths. Ship Rock, in New Mexico, is the most prominent example of a volcanic neck in the Colorado Plateau region, but numerous other necks may be found, particularly on the west side of the San Juan Basin. Lava flows are common in the San Juan Mountains, as well as in the Navajo and Hopi Buttes volcanic fields, and ash-flow and ash-fall tuffs are present in the San Juan Mountains and in the Jemez Mountains. Diatremes, which are breccia-filled volcanic pipes formed by gaseous explosions, are common in the Navajo and Hopi Buttes volcanic fields (Hunt, 1956, p. 50; Shoemaker, 1956b). Dikes and sills are associated with most of the major plutonic and volcanic centers.

Callaghan (1951, p. 119) gives the following summary of the types of igneous rocks found in the San Juan Basin and vicinity: "Aside from the San Juan and Jemez volcanics, which are considered as being outside the Basin, the flow rocks and volcanic necks are dominantly of basaltic or basaltic-andesite composition and appearance. Those at the west side of the Basin are abnormal in having the low silica content of basaltic rocks but a high content of potash which is suggested mineralogically in their content of biotite and, in some localities, of leucite. These rocks are therefore classified as trachybasalt and minette. Rhyolite, trachyte, latite, and andesite occur in the core of Mount Taylor and make up the greater proportion of the rocks of the Jemez and San Juan Mountains. The larger intrusive bodies are of dioritic or monzonitic composition." For additional information on the igneous rocks, the reader is referred to Hunt (1956) and Shoemaker (1956a, 1956b).

Chama Basin

In the Chama Basin, rocks of Tertiary Age comprise the El Rito Formation, Abiquiu Tuff of the Santa Fe Group, Los Pinos Formation, and local outcrops of igneous rocks. No uranium occurrences are known in these rocks.

El Rito Formation.--The El Rito Formation (Smith, 1938) of Eocene(?) age unconformably overlies rocks ranging in age from Permian to Cretaceous. Its areal distribution is limited to the southeast part of the Chama Basin (Smith and others, 1961). The El Rito is composed of interbedded boulder conglomerate and micaceous, arkosic sandstone and has a maximum thickness of 130 m. Boulders are principally blue-gray quartzite of probable Precambrian age. Smith and others (1961) consider the El Rito to be a fanglomerate deposit that was derived from highlands to the north and east.

Abiquiu Tuff of the Santa Fe Group.--The Abiquiu Tuff (Smith, 1938) of the Santa Fe Group is of Miocene(?) age and is exposed in the southeast part of the Chama Basin. In this area it is nearly 450 m thick and unconformably overlies the El Rito Formation. The Abiquiu Tuff consists of light-gray to pale-orange tuff and micaceous, tuffaceous sandstone. North and east of the type section, near Abiquiu, New Mexico, it coarsens and consists primarily of conglomerate and coarse-grained sandstone. The Abiquiu Tuff was deposited in lacustrine or flood-plain environments.

Los Pinos Formation.--The Los Pinos Formation (Atwood and Mather, 1932) of Oligocene to Pliocene(?) age crops out in the southeast part of the Chama Basin, east of El Rito Creek. It consists of nearly 230 m of fluvially deposited sandstone, siltstone, and conglomerate. Smith and others (1961) consider the Los Pinos to be stream-channel and gravel-fan deposits that developed south and east of the San Juan Mountains. The upper part of the Los Pinos Formation may correlate with the upper part of the Abiquiu Tuff (Smith and others, 1961).

Igneous rocks in the Chama Basin.--In the northeast and southeast parts of the Chama Basin, igneous rocks of Tertiary age consist of basaltic dikes and flows.

Southern section

In the southern section (south of southern limit of plate 1), rocks of Tertiary age include, in ascending order, the Baca Formation, the Datil Formation, and the Santa Fe Group (upper part). Uranium occurs in carbonaceous sandstones of the Baca Formation north of the Datil Mountains and west of the Bear Mountains (south of Lucero Mesa). It also occurs in a shear zone at the base of the Popotosa Formation (basal formation in the Santa Fe Group) just east of the Ladron Mountains.

Baca Formation.--The Baca Formation of Eocene(?) age crops out in the area north of the Datil Mountains and west of the Bear Mountains. It unconformably overlies folded rocks of Cretaceous age and ranges in thickness from nearly 230 m at the Bear Mountains to about 500 m north of the Datil Mountains. In the vicinity of the Bear Mountains, the Baca Formation consists of coarse conglomerate, red and white sandstone, and red clay. Pebbles and boulders in the conglomerate are mainly quartzite and granite of Precambrian age, limestone of Pennsylvanian age, and detritus from the Permian Abo Formation (Wilpolt and others, 1946). North of the Datil Mountains the Baca consists of pink, medium- to coarse-grained, crossbedded sandstone, pink to red shale and siltstone, and minor amounts of gray shale. The Baca Formation was deposited in fluvial environments.

Datil Formation.--The Datil Formation (Winchester, 1920) of Oligocene age is exposed in the vicinity of the Datil and Bear Mountains, where it reaches a maximum thickness of 660 m. It unconformably overlies the Baca Formation in the Datil Mountains, but elsewhere rests unconformably on Cretaceous or older rocks (Wilpolt and others, 1946; Hilpert, 1969). The Datil Formation is primarily volcanic and consists of purple and red latite, rhyolite, and andesite flows, agglomerate, tuff, conglomerate, and sandstone.

Santa Fe Group.--The basal formation of the Santa Fe Group, the Popotosa Formation of early to late Miocene age, crops out in the vicinity of the Ladron Mountains. It consists of 1,000 to 1,660 m (Denny, 1940) of volcanic debris and gray to buff tuffaceous sandstone, siltstone, and conglomerate. The sandstone beds are generally crossbedded and lenticular and were deposited in fluvial environments.

In the southern section, the upper part of the Santa Fe Group (Baldwin, 1956) is present only in the area north and west of Socorro, New Mexico. In this area it unconformably overlies the Popotosa Formation and is several hundred meters thick. The upper part of the group ranges in age from Miocene to late Pliocene (Hilpert, 1969) and is composed of red, brown, and gray unconsolidated fluvial sandstone, siltstone, claystone, and conglomerate, and locally includes tuff, andesite, and other volcanic rocks.

STRUCTURAL GEOLOGY

The following quote from Fischer (1968, p. 739) provides a summary of the structural geology of the Colorado Plateau region:

> "In most of the Colorado Plateau region the Precambrian basement rocks are covered by a veneer of sedimentary beds, 1 to 3 miles thick. Typically, these beds lie nearly flat, but in places they have been disturbed by folds and faults, some of which displace the basement, and in places they have been intruded or covered by magma...
>
> The most conspicuous structural features are uplifts. The largest of these are crustal blocks, as much as 100 miles long, that are tilted like partly raised trap doors, with thousands of feet of structural displacement. These blocks are probably bounded by faults in the basement rocks, but in general the sedimentary cover drapes over the block edges without faulting, forming the prominent monoclinal flexures of the region. Some uplifts are coupled with basins formed by blocks tilted downward; the three largest basins--the San Juan, Piceance, and Uinta--are coupled with uplifts outside the Plateau proper. The "laccolithic" mountains of the central part of the Plateau are domal uplifts of several thousand feet relief and the order of 10 miles across, raised by the invasion of magma into the sedimentary cover. The so-called "salt anticlines," which resulted from arching of beds due to the upward flowage of evaporites along linear structures, have been breached by erosion and now form spectacular valleys a few miles across and 10 to 30 miles long.
>
> Faults are prominent structural features in parts of the Plateau region. High-angle reverse faults occur in places along the eastern margin of the Plateau, but all other exposed faults are of the normal type. Normal faults of large displacement bound large elongate blocks along the west side of the Plateau, and a complex series of normal faults bounds the Rio Grande trough along the southeast edge of the Plateau. Faults of small to moderate displacement occur in places in the surface rocks along the monoclines and the salt anticlines; it is probable that these flexures are associated with faults of larger displacement in the basement rocks. Minor faults are common in many parts of the Plateau region, as are joint systems in the more competent beds that are mainly sandstone.

Collapsed pipes are common in the Laguna area, New Mexico, and near Moab, Utah, and a few occur in the Grand Canyon area, Arizona, and in the San Rafael Swell, Utah. The larger ones are a few hundred feet in diameter, and their cores are displaced downward a hundred feet or more and are rather intensively brecciated. A few of these pipes are uranium-bearing and form deposits having unique characteristics."

Tectonic divisions within the report area (plate 1), taken from Kelley and Clinton (1960, fig. 2), are the Monument Upwarp, Blanding Basin, Paradox fold and fault belt, San Juan dome, San Juan sag, Tyende Saddle, Red Rock bench, Four Corners platform, San Juan Basin, Archuleta arch, Chama Basin, Black Mesa Basin, Defiance Uplift, Gallup sag, Chaco slope, Nacimiento Uplift, Rio Grande trough, Mogollon slope, Zuni Uplift, Acoma sag, and Puerco fault belt. A number of reports (Hunt, 1956; Kelley, 1950; Santos, 1970; and Woodward and Callender, 1977) discuss the structural geology of various parts of or combinations of these tectonic divisions.

These tectonic divisions contain folds and faults of diverse magnitudes. Plate 1 shows the faults that can be depicted conveniently at the scale of the map. Kelley and Clinton (1960, fig. 2) show the larger folds and faults on the Colorado Plateau. These include structures that mark the boundaries between tectonic divisions, such as the Nutria monocline between the Gallup sag and the Zuni Uplift, and the Nacimiento fault between the San Juan Basin and the Nacimiento Uplift.

A description of each fold and fault in the area covered by plate 1 is beyond the scope of the present report. However, the bibliography contains numerous references that will provide detailed information. Of particular use in locating faults and folds are the geological quadrangle and other geological maps at various scales prepared by the

U.S. Geological Survey as well as by state agencies of Arizona, Colorado, New Mexico, and Utah. Map coverage is shown by indices available from appropriate state and federal organizations. Structural geology as related to uranium deposits is discussed by Hilpert (1969), Kelley (1955), Moench and Schlee (1967), and Shoemaker (1956a). Information on structural geology is given by most of the reports on areal geology listed in the bibliography.

GEOLOGIC HISTORY

Although the general geologic history of the San Juan Basin is relatively simple, the detailed depositional history of the basin is quite complex. The following discussion presents a brief review of the depositional and tectonic history of the San Juan Basin and adjacent areas.

Our knowledge of the Precambrian Era is limited because of the lack of outcrops in most of the report area. Outcrops of Precambrian rocks are confined to the margins of the area. A few wells have penetrated the Precambrian in the centers of the San Juan and Chama Basins; however, the data obtained have added little to our knowledge of the geologic history of this time period.

Exposed Precambrian rocks indicate a complex history involving deposition of clastics (mainly quartzose sands, silts, and clays), deformation, metamorphism, erosion, and later intrusion and extrusion of igneous rocks of basaltic to granitic composition (Reiche, 1949; Fitzsimmons, 1961). Each of these events was probably repeated several times, but the sequence may have been different each time.

At the close of the Precambrian Era the rocks were eroded, and according to Kelly (1955), the area remained a stable shelf for much of the Paleozoic Era. Early Paleozoic sedimentation was limited; Cambrian rocks extend only into the northwest part of the San Juan Basin. To the west, Cambrian rocks consist of a thick sequence of marine carbonates and clastics. In the report area, Cambrian rocks, represented by the Ignacio Quartzite, are dominantly clastics deposited on a stable shelf area during marine transgression into the area from the west.

The absence of rocks of Ordovician and Silurian age may be due to nondeposition, but more likely is due to erosion. In many places in the northwest part of the basin, rocks of Devonian age rest on the Precambrian basement.

Deposition of rocks of Devonian and Mississippian age took place under similar conditions. Devonian and Mississippian rocks are dominantly carbonates (limestone and dolomite) but include some clastics (shale, sandstone, and siltstone). Sedimentary structures and fossil assemblages indicate that Devonian and Mississippian rocks were deposited in a variety of shallow to intertidal marine environments during numerous marine transgressions and regressions in the area. Rocks deposited during this time include the Aneth Formation, Elbert Formation, and Ouray Limestone of Devonian age, and the Redwall and Leadville Limestones, Arroyo Penasco Group, and Kelly Limestone of Mississippian age. Between Late Devonian and Early Mississippian time, the sea withdrew and the area was eroded. Subsurface data indicate that rocks of Mississippian age rest on the Precambrian basement in areas where Devonian rocks also rest on Precambrian rocks (Stevenson and Baars, 1977, fig. 2).

During Late Mississippian time the sea withdrew and a karst-like surface developed on the exposed carbonate rocks. Deposition of terrigenous sediments of the Log Springs Formation on the east side of the San Juan Basin marked the change from marine to continental environments of deposition.

A hiatus in deposition continued over much of the area into Early Pennsylvanian time. In the northern part of the San Juan Basin, the Molas Formation was deposited under conditions similar to those for the Log Springs. The upper part of the Molas Formation and lower part of the Hermosa Formation reflect a change back to marine deposition as the sea again transgressed the area.

During Early Pennsylvanian time, tectonic movements, which were to affect Pennsylvanian and Permian sedimentation, were initiated. Structural highs that formed at this time were antecedents of the Zuni and Defiance Uplifts, Penasco Uplift (in the vicinity of the San Pedro and northern Nacimiento Mountains today), and Uncompaghre Uplift of southwestern Colorado and north-central New Mexico. Between the Zuni-Defiance and Uncompaghre Uplifts a trough formed, extending from the Paradox Basin in southeast Utah into northwest New Mexico. This trough was the site of deposition of marine and continental sediments during Pennsylvanian and Permian times.

From Early to Late Pennsylvanian time a thick sequence of marine limestone, dolomite, and locally, evaporite was deposited over the area. These deposits now compose the Hermosa Formation in the northwest part of the area and the Sandia Formation and Madera Limestone in the eastern and southern parts of the area. The lower part of the Madera Limestone is absent in the vicinity of the northern Nacimiento and San Pedro Mountains. It apparently was not deposited there, owing to the presence of the Penasco Uplift.

Towards the close of Pennsylvanian time the sea withdrew and a regressive sequence (Rico Formation) of marine carbonates overlain by continental shales and siltstones was deposited. By Permian time deposition in this trough area had nearly covered the ancient Zuni-Defiance and Penasco Uplifts. Only the Uncompaghre Uplift remained a structural high at this time.

Permian rocks reflect the change back to continental deposition. The Uncompaghre continued to shed clastic debris to the west and south. Coarse fluvial sediments deposited at this time now compose the Cutler Formation. Towards the south the rocks are finer grained and reflect deposition by fluvial systems on a coastal plain. These deposits include the Bursum and Abo Formations. The southern part of the area was then invaded by marine waters and the Yeso Formation, Glorieta Sandstone, and San Andres Limestone were deposited. At the close of Permian time the sea withdrew and Permian and older rocks were deformed and eroded (Hilpert, 1969).

During Late Permian or Early Triassic time the area to the east may have been uplifted or the basin may have sunk, as Triassic rocks bevel Permian rocks towards the east. In Early Triassic time the area was characterized by a vast flood plain, on which the Moenkopi(?) Formation was deposited.

During Middle to early Late Triassic the southern rim of the San Juan Basin was uplifted and the flood plain tilted to the west and northwest (Peterson and Ohlen, 1963). This flood plain is envisioned by Colbert (1950) as a vast lowland traversed by streams and dotted with scattered forests and lakes. During this period volcanism occurred south of the area (Allen, 1930; Stewart and others, 1959), and the Uncompaghre Uplift was rejuvenated. Structural highs to the south and the Uncompaghre Uplift were the sources of sediments that now compose the Chinle Formation in the area. By the Late Triassic, the Uncompaghre had been reduced to an area of low relief, as indicated by the onlap of sediments on the southwest side.

Stable conditions marked the change from Triassic to Jurassic time. Erosion took place over most of the area, as indicated by a widespread unconformity between Triassic and Jurassic age rocks. This erosion surface was then covered by vast dune fields and inland or coastal sabkhas. The Wingate Sandstone, Carmel Formation, and Entrada Sandstone were deposited at this time.

In Late Jurassic time the Zuni Uplift was rejuvenated and the flood plain tilted northward. After deposition of the Entrada Sandstone, the area was covered by a large lake. In this lake was deposited the limestone and gypsum of the Todilto Limestone. As the lake dried up the area was again covered by sediments of dune fields and inland sabkhas, which now compose the Summerville Formation and the Bluff and Cow Springs Sandstones.

Uplift to the southwest, in the Mogollon Highlands, preceded deposition of the Morrison Formation. The Mogollon Highlands are believed to be the source for much of the sediment in the Morrison. The various members of the Morrison Formation were deposited on a vast plain in a variety of fluvial and lacustrine environments. Deposition was accompanied by volcanic activity, as much of the Morrison contains volcanic debris.

During deposition of Jurassic sediments the basin sank and land masses to the west and south rose. These tectonic movements caused folding and flexing in the basin, especially around the southern margin (Hilpert and Moench, 1960). The presence of folds and flexures no doubt influenced the course of sedimentation in the basin (Hilpert and Moench, 1960; Huffman and Lupe, 1977). The effect of these structural features on the localization of uranium deposits in the Morrison Formation is more important in the Laguna District and less so in the Ambrosia Lake District (Hilpert, 1969, p. 68, 75). Although the folds and flexures developed at this time may not be directly related to all uranium deposits, their influence on sedimentation patterns may have permitted accumulation of sediments favorable as sites for subsequent uranium deposition.

Sediments of the transitional period from Jurassic to Cretaceous time are absent over most of the area, owing to erosion. Only in the northern part of the San Juan Basin and in the Chama Basin are rocks of Early Cretaceous age preserved. Here rocks of the Burro Canyon Formation reflect deposition under fluvial and local lacustrine conditions.

Sometime in Late Jurassic to Early Cretaceous time the southern part of the basin was uplifted and beveled. Lower Upper Cretaceous rocks of the Dakota Sandstone rest on progressively older rocks from north to south within the basin and basin margin. South of the San Juan

Basin the Dakota Sandstone rests on rocks of Permian age.

The area at this time was a broad, subsiding plain (Hilpert, 1969) traversed by streams and dotted with swamps in which carbonaceous siltstones and coals accumulated. As subsidence continued the area was covered by marine waters entering from the north and southeast. Numerous transgressions and regressions followed (Peterson and Kirk, 1977), depositing intertonguing sequences of shale and sandstone and lesser amounts of limestone and coal. These sediments were deposited in marine, nearshore marine, beach, paludal, and fluvial environments and compose the stratigraphic sequence from the upper part of the Dakota Sandstone through the Pictured Cliffs Sandstone. The Pictured Cliffs Sandstone was deposited as shallow marine and beach sands during the final regression of the sea from the area.

As the sea withdrew, the area was once again dominated by terrestrial sedimentation. The area was a vast alluvial plain traversed by streams and dotted with swamps. The Fruitland Formation and Kirtland Shale were deposited at this time.

During latest Cretaceous or early Tertiary time there was renewed tectonic activity accompanied by volcanism to the north. These tectonic events are referred to as the Laramide orogeny. During this period, the final emergence of the San Juan, Nacimiento, San Pedro, and Zuni Mountains and Lucero, Brazos, and Defiance Uplifts occurred around the margins of the area. The San Juan and Chama Basins formed and were soon separated by the formation of the Gallena-Archuleta Arch. The higher areas began to shed debris into the basins. In the San Juan Basin, fluvial conditions persisted, and the Animas Formation, Ojo Alamo

Sandstone, and Nacimiento Formation were deposited.

During the Tertiary Period, numerous structural features formed, especially along the margins of the San Juan Basin. Monoclinal folds, such as the Defiance and Nutria folds, formed on the basin side of marginal uplifts; depressions or sags, such as the Zuni and Acoma sags and the McCartys syncline, formed between adjacent marginal uplifts; and thrust faults appeared. Rocks along the east and west margins of the basin were steeply turned up.

Deepening of the basin occurred at this time, and its margins were beveled. In Eocene time the San Jose and Baca Formations were deposited over the beveled surface of earlier Tertiary rocks. During the same period in the Chama Basin, the El Rito Formation was deposited as a fanglomerate derived from highlands to the north and east (Smith and others, 1961, p. 37).

At the end of Eocene time the San Juan Basin was tilted to the north. Deposition continued into Oligocene and Miocene time and was accompanied by renewed volcanic activity in the San Juan Mountains, Mogollon Highlands, and Jemez Mountains. Volcanic debris was contributed to fluvial systems, and lava flows of basic composition covered large areas. The Abiquiu Tuff was deposited during this period.

Volcanic activity continued from Miocene into Pliocene time and was marked by lava flows and dioritic intrusives in the Mount Taylor area and Carrizo Mountains. The Chuska Sandstone, Datil Formation, and Santa Fe Group were deposited during this period and reflect the influence of volcanic activity in eolian, lacustrine, and fluvial settings.

During late Miocene or early Pliocene time there was a broad regional uplift, and large areas of the San Juan and Chama Basins were eroded. Large amounts of Tertiary and pre-Tertiary rocks were removed. This period was also accompanied by faulting or rejuvenation of old faults. Mobilization and redeposition of uranium, especially in the Ambrosia Lake area (Hilpert, 1969, p. 69), occurred at this time.

PALEONTOLOGY

Most of the Devonian to Tertiary formations in the San Juan Basin and adjacent areas contain fossils. Important fossiliferous formations include the Ouray Limestone of Devonian age, the Arroyo Penasco Group of Mississippian age, the Sandia Formation and Madera Limestone of Pennsylvanian age; the Abo, Yeso, and Cutler Formations and San Andres Limestone of Permian age, the Chinle of Triassic age, most Upper Cretaceous formations, and the Nacimiento and San Jose Formations of Tertiary age. Numerous paleontologic and geologic reports have described and listed the fossil assemblages. Some of the most comprehensive reports are those by Girty (1900), Kindle (1909), Gilmore (1917, 1919), Knowlton (1917, 1924), Stanton (1917), Reeside (1924), Northrop (1961, 1974), Kirkland (1963), Fassett and Hinds (1971), Armstrong and Mamet (1974), Ash (1974), and Colbert (1974).

The Devonian Ouray Limestone, of marine origin, is characterized by a fossil assemblage of invertebrates that includes brachiopods, pelecypods (clams), and corals (Girty, 1900; Kindle, 1909). The Arroyo Penasco Group contains a variety of marine invertebrate fossils, including algae, foraminifera, echinoderms, crinoids, ostracodes, gastropods (snails), pelecypods, brachiopods, bryozoans, corals, and jellyfish (Northrop, 1961; Armstrong and Mamet, 1974). This varied fossil assemblage indicates that the Arroyo Penasco was deposited in shallow-marine to intertidal environments.

The fossil assemblage of the Sandia Formation and Madera Limestone indicates deposition in a variety of marine environments. The fossils include algae, foraminifera, corals, bryozoans, brachiopods, pelecypods, gastropods, trilobites, crinoids, echinoderms, cephalopods, scaphopods, worm trails, and shark teeth (Northrop, 1974).

Fossiliferious Permian units consist of the Abo, Yeso, and Cutler Formations and San Andres Limestone. The fossil assemblage of the Abo Formation is composed of vertebrates and invertebrates that indicate deposition in continental and marine environments. The assemblage includes amphibians, reptiles, fish, plants, pelecypods, gastropods, scaphopods, and cephalopods (Kirkland, 1963). Marine fossils found in the Yeso Formation and the San Andres Limestone consist of brachiopods, pelecypods, gastropods, scaphopods, cephalopods, and ostracodes (Kirkland, 1963). The presence of fossil plants, fish, amphibians, and reptiles indicates that the Cutler Formation is of continental origin (Kirkland, 1963).

The Chinle Formation contains abundant fossil remains of plants, fish, amphibians, reptiles, and fresh-water pelecypods (Ash, 1974; Colbert, 1974). This fossil assemblage indicates deposition in lacustrine and fluvial continental environments.

The most important fossiliferous Cretaceous units comprise the Mancos Shale, Cliff House Sandstone, Lewis Shale, Pictured Cliffs Sandstone, Fruitland Formation, Kirtland Shale, and Animas Formation. Principal paleontologic studies of these units are those by Gilmore

(1917, 1919), Knowlton (1917, 1924), Stanton (1917), Reeside (1924), and Fassett and Hinds (1971). An invertebrate fossil assemblage of pelecypods, gastropods, and cephalopods indicates the Mancos Shale, Cliff House Sandstone, and Lewis Shale are of marine origin. The presence of fossil pelecypods, gastropods, shark teeth, and reptiles suggests that the Pictured Cliffs Sandstone was deposited in marine and continental environments.

The Fruitland Formation and Kirtland Shale contain a variety of fossil vertebrates, invertebrates, and plants indicative of lacustrine and fluvial environments of deposition. Vertebrate fossils include dinosaurs, reptiles, and fish; invertebrate fossils are fresh- and brackish-water pelecypods and gastropods. Fossil plants in the Animas Formation are of continental origin.

Tertiary fossil assemblages are notable in that they include mammals and lack dinosaurs. The Nacimiento Formation is characterized by a variety of fossil vertebrates, invertebrates, and plants of continental origin. Vertebrate fossils are mammals, reptiles, and fish; invertebrate fossils are primarily pelecypods. The San Jose Formation contains fossils of mammals and plants and is of continental origin.

The effects of uranium development in the San Juan Basin on fossil-bearing formations should be minimal. The principal uranium host rock in the San Juan Basin is the Morrison Formation. Although the Morrison Formation is known for its many fossil localities in Utah, Colorado, and Wyoming, it is not particularly fossiliferous in the San Juan Basin. Consequently, uranium development should have little effect on fossil localities in the Morrison. Many more fossil localities are found in the Cretaceous sequence in this area, but these should not be greatly disturbed by normal exploratory drilling and underground mining. However, if open-pit mining tehniques are employed, uranium development could have a more severe impact on the locally fossiliferous Cretaceous formations.

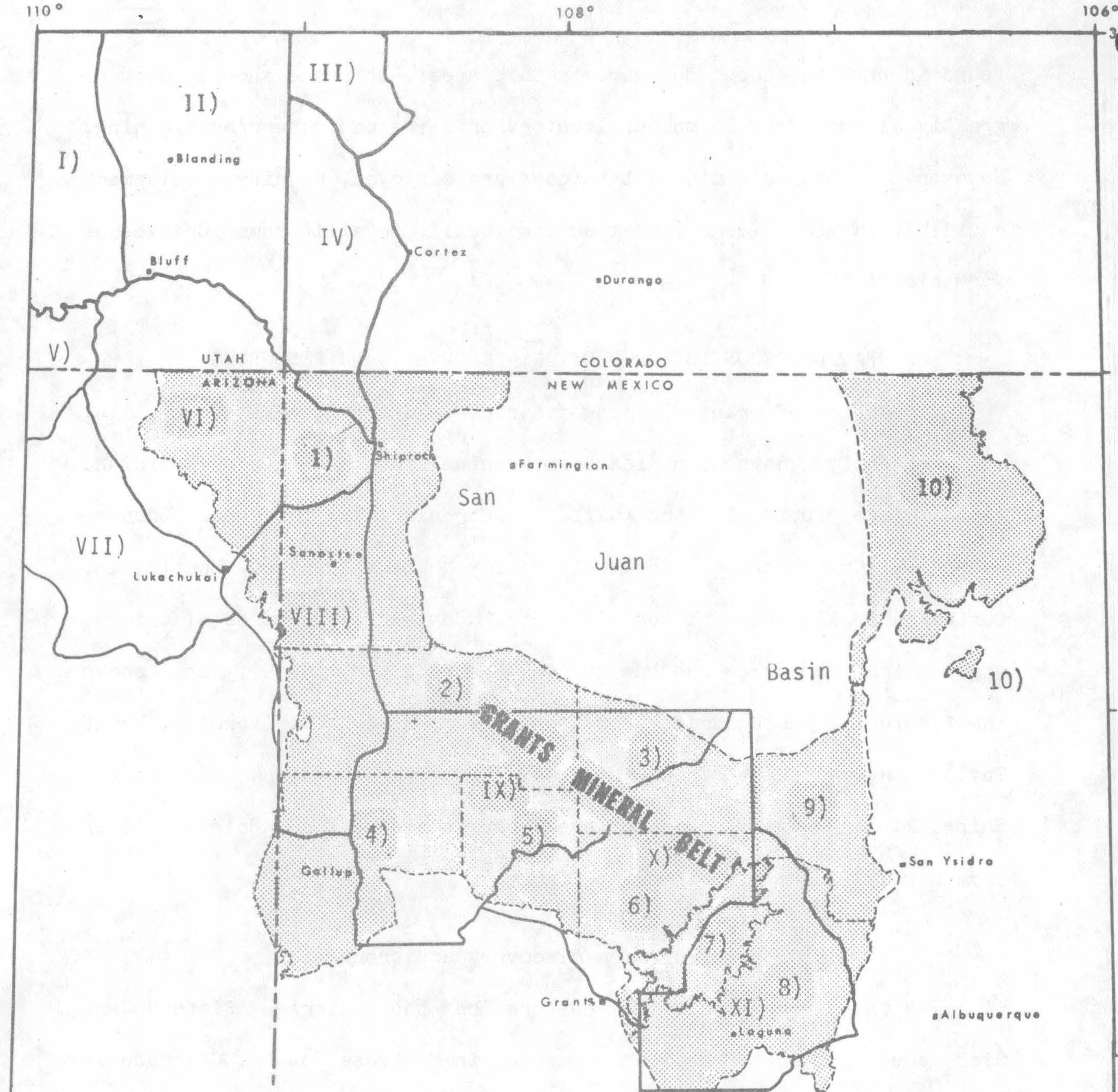
URANIUM DEPOSITS, PRODUCTION, RESERVES, AND RESOURCES

Location of uranium mining districts and ore reserve areas

Presently known deposits of uranium in the San Juan Basin and vicinity are found in the Gallup, Ambrosia Lake, Laguna, Chuska, Shiprock, Chilchinbito, Monument Valley, White Canyon, Monticello, Cortez, and Slick Rock mining districts. Boundaries of these districts, adapted from Shoemaker and Luedke (1952) and Hilpert (1969), are shown in figure 1. Boundaries for the Gallup, Blackjack, Ambrosia, Mount Taylor, Laguna, West Chaco Canyon, East Chaco Canyon, Nacimiento, Shiprock, and Chama uranium ore reserve areas (H. H. Holen, written commun., 1977) are also shown in figure 1.

History of uranium discovery and production

The first uranium ore in sandstone on the Colorado Plateau was discovered in the Morrison Formation in Montrose County, Colorado in 1898, and the first uranium discovery in the study area was near Shiprock, New Mexico, in 1918. Ore produced through 1947 from various areas, including the Shiprock, Chuska, Monument Valley, White Canyon, Monticello, and Slick Rock districts, consisted mainly of vanadium, but some uranium and radium were also recovered (Fischer, 1968, table 1, p. 738). Following the announcement in 1948 of the U.S. Atomic Energy



—— mining district (Hilpert, 1969; Shoemaker and Luedke, 1952.

I) White Canyon
II) Monticello
III) Slick Rock
IV) Cortez
V) Monument Valley
VI) Shiprock
VII) Chilchinbito
VIII) Chuska
IX) Gallup
X) Ambrosia Lake
XI) Laguna

ore reserve area, (H. Holen, written commun., 1977)

1) Shiprock
2) West Chaco Canyon
3) East Chaco Canyon
4) Gallup
5) Blackjack
6) Ambrosia
7) Mt. Taylor
8) Laguna
9) Nacimiento
10) Chama

Figure 1. -- Index map of the San Juan Basin and vicinity, showing locations of uranium mining districts and ore reserve areas.

Commission's ore-buying program, uranium discoveries were made in the Ambrosia Lake district in 1950 and in the Laguna and Gallup districts in 1951. To date, the main production of uranium from the Colorado Plateau has come from Jurassic rocks of the Grants Mineral Belt located in the southern part of the San Juan Basin. This mineral belt includes the Gallup, Ambrosia Lake, and Laguna districts.

Additional information about the history of uranium discovery and production may be found in reports by Fischer (1968), Kelley, Kittel, and Melancon (1968), Hilpert (1969), and Chenoweth (1977).

Uranium occurrences and deposits

General

Much of the following information on uranium occurrences and deposits has been summarized from the following sources: Hilpert (1969), Chenoweth (1974a, 1974b, 1976, 1977), Chenoweth and Malan (1973), Lovering (1956), Finch (1955, 1959, 1967), Fischer (1956, 1968) Gabelman (1956a, 1956b), Granger (1968), Kelley, Kittel, and Melancon (1968), Moench and Schlee (1967), Peirce and others (1970), and Shoemaker (1956a, 1956b). A number of other important papers are also listed in the bibliography.

In the area shown by plate 2, uranium is found mainly as tabular deposits in sedimentary rocks that range in age from Paleozoic through Cenozoic, in pegmatites and veins in igneous and metamorphic rocks of Precambrian age, in veins in volcanic rocks of Tertiary age, in pipe deposits in sedimentary rocks of Jurassic age, and in diatremes in sedimentary rocks of Tertiary age.

Most of the uranium obtained to date from the Colorado Plateau has come from tabular deposits in sedimentary rocks. Production from deposits in the Morrison Formation, Chinle Formation, Todilto Limestone, and Dakota Sandstone account for almost all of the ore mined. Minor occurrences or small deposits are known in sedimentary rocks of other ages (Hilpert, 1969). No significant production has come from veins, pegmatites, or diatremes, and only one of the pipe deposits has been an important producer.

Tabular deposits in sedimentary rocks are generally lenticular bodies which are roughly parallel to the bedding of the host rock. The most important host rocks are fluvial, carbonaceous, arkosic, crossbedded sandstone and conglomeratic sandstone. Lacustrine limestone and marginal-marine carbonaceous sandstone, shale, lignite, and coal contain small- to medium-size tabular deposits in the southern and southeastern parts of the San Juan Basin and vicinity. Eolian sandstones along the northwestern flank of the San Juan Mountains, Colorado, contain uranium-bearing vanadium deposits. Ore minerals (Granger, 1963; Fischer, 1968) found in the sedimentary rocks consist of primary pitchblende, uraninite, or coffinite, as well as various yellow secondary minerals. Uranium often occurs as a urano-organic complex in carbonaceous shale, lignite, and coal. The ages of the primary deposits are often nearly as great as the ages of their respective host rocks; however, subsequent remobilization and reprecipitation of the uranium may produce deposits much younger than the rock in which they are found.

The emplacement of uranium in pegmatites (in igneous and metamorphic rocks), vein deposits (in volcanic rocks), pipes, and diatremes is controlled mainly by faults, igneous intrusions, or collapse structures. Uranium minerals present are often similar to those of the sandstone deposits, except that some higher-temperature primary uranium-bearing minerals, such as euxenite, fergusonite, and samarskite, are found in the pegmatites.

Uranium in Precambrian rocks

Precambrian rocks in the map area consist mainly of metamorphic rocks of various types, although some igneous and sedimentary rocks are present. Uranium (plate 2) is found in pegmatites along the northeastern border of the Chama Basin and in altered granite in the core of the Zuni Uplift (Lovering, 1956). None of the occurrences is of commercial importance.

Uranium in Paleozoic rocks

Rocks of Paleozoic age are present throughout the report area and consist of fluvial, lacustrine, eolian, shallow- and deep-marine, coastal, and evaportie-basin deposits.

A number of occurrences and a few small deposits of uranium are found in Paleozoic rocks in the southeastern part of the report area. The host rocks are mainly carbonaceous, fluvial red beds of the Cutler and Abo Formations of Permian age. The Madera Limestone of Pennsylvanian age contains a few small deposits associated with faults.

Uranium in Mesozoic rocks

Uranium in Triassic rocks.--Minable deposits of uranium in Triassic rocks occur mainly in southeastern Utah and northeastern Arizona in the Monument Upwarp and Defiance Uplift areas. A few minor occurrences are known along the southern and eastern sides of the San Juan Basin. In the report area, the mines in Triassic rocks are more productive than any others except those in Jurassic rocks.

The uranium is found mainly in fluvially deposited channel sandstone and conglomeratic sandstone of the Chinle Formation of Late Triassic age. Carbonized plant material is common in the ore-bearing parts of the rocks.

Uranium in Jurassic rocks.--Minor amounts of uranium are found associated with vanadium in the eolian Entrada Sandstone, and small- to medium-size uranium deposits occur in the lacustrine Todilto Limestone. Medium-size to very large uranium ore bodies are found in fluvial sandstone of the Morrison Formation.

The deposit in Jurassic sandstone shown on plate 2 northwest of Silverton, Colorado is in the Entrada Sandstone. This deposit, which is on the northwestern flank of the San Juan dome, contains mainly vanadium and has only minor amounts of uranium.

Uranium deposits in the Jurassic Todilto Limestone are found mainly along the southern margin of the Grants Mineral Belt where the limestone has been deformed by intraformational folding. Uranium occurrences in limestone are also known in the Sanostee, New Mexico area, as well as near the town of Coyote, New Mexico, on the southern margin of the Chama Basin.

Deposits in the Morrison Formation are found along the southeastern, southern, and western parts of the San Juan Basin. Deposits similar to those on the western side of the San Juan Basin are found to the north in the Blanding Basin and in the Paradox fold and fault belt. One deposit in a collapsed pipe structure, the Woodrow deposit (Hilpert, 1969, p. 106), is found in the Morrison Formation north of Laguna, New Mexico.

Deposits in the southeastern part of the San Juan Basin and vicinity are small, but deposits in the southern part of the area in the Grants Mineral Belt are very large. The deposits in the Grants Mineral Belt are found mainly in high-energy, fluvial, carbonaceous sandstone of the Westwater Canyon and Brushy Basin Members of the Morrison Formation. The belt is roughly coincident with the Chaco slope (plate 1) and extends from Laguna to Gallup, New Mexico, a distance of about 135 km. Results of drilling suggest that the belt may be at least 40 km wide.

Deposits on the western side of the San Juan Basin, as well as in the Blanding Basin and the Paradox fold and fault belt, are found mainly in medium-energy, fluvial, carbonaceous sandstones of the Salt Wash Member of the Morrison Formation. Some deposits are found in the Recapture Member in the Sanostee area, New Mexico. The deposits are generally considerably smaller than deposits in the Grants Mineral Belt.

Uranium in Cretaceous rocks.--Uranium deposits and occurrences are found mainly in the southern and southeastern parts of the San Juan Basin. A few scattered occurrences are known in the western and northwestern parts of the basin as well as in the central part of the Blanding Basin. The deposits are found mainly in carbonaceous, medium-energy, marginal-marine, distributary-channel sandstones, but some are found in lignite and in paludal shale. Most of the deposits are in the Dakota Sandstone, but some are found in the Menefee, Fruitland, and other formations above the Dakota.

Uranium in Cenozoic rocks

Small, noncommerical tabular deposits of uranium are found on the northern and eastern sides of the San Juan Basin in sedimentary rocks of the Nacimiento and San Jose Formations of Tertiary age. One medium-size vein deposit occurs in the Tertiary Espinaso Volcanics of Stearns (1943) on the eastern side of the Los Cerrillos district, south of Santa Fe, New Mexico. Several small uranium occurrences are found in the Baca and Popotosa Formations just south of the map area. Uranium, generally in non commercial grades or quantities, is also found in association with Tertiary diatremes of the Hopi Buttes volcanic field just west of the southwestern part of the map area, and in Tertiary volcanic rocks of the San Juan Mountains, north of Silverton, Colorado.

Origin of the deposits

The tabular deposits in sedimentary rocks of the report area and elsewhere are generally believed to have been derived by precipitation of uranium from ground water caused by the reducing action of either carbonaceous material present in the sediments or anaerobic bacteria. The ground water probably obtained its uranium content by leaching granitic, arkosic, and (or) tuffaceous rocks. Permeable beds of the host rocks allowed passage of the uranium-bearing waters, whereas interbedded claystone and mudstone acted to constrain and thus concentrate flow of the waters.

Uranium in pegmatites was probably deposited at a late stage of igneous activity at temperatures considerably higher than those attained during formation of the tabular deposits in sedimentary rocks. The vein deposits were probably formed at temperatures intermediate to those for the above types. The uranium in the veins may have come entirely from hydrothermal solutions derived at depth from igneous sources, although some of the uranium may have been derived from descending or laterally moving waters that had leached uranium from granitic, arkosic, or tuffaceous rocks or from other uranium deposits. Uranium in the diatremes may have a depositional history somewhat similar to that for the veins, whereas the uranium in the pipes or collapse structures may have an origin related to that of the tabular deposits in the sedimentary rocks in which the pipes are found.

Additional information on the origin of tabular uranium deposits in general, and of the deposits of the San Juan Basin and vicinity in particular may be had from the following reports: Finch (1967), Fischer (1956, 1968, 1970, 1974), Granger (1968), Hilpert (1969), Kittel and others (1967), Moench and Schlee (1967), Nash (1968), and Rackley (1976). Ridge (1972, p. 323-339) provides an excellent annotated bibliography for the mineral deposits on the Colorado Plateau. Other references, including some to vein, pipe, and other types of uranium deposits may be found in the bibliography of this report.

Uranium production, reserves, and resources

Uranium had been known in the Salt Wash Member of the Morrison Formation in the Shiprock district for a long time prior to its discovery in 1951 in the Todilto Limestone, other members of the Morrison, and the Dakota Sandstone in the Grants region. Production from the San Juan Basin 1948-1976 totaled slightly over 121,000 short tons (1) U_3O_8 (table 1). Of this amount, more than 95 percent came from the Westwater Canyon and Brushy Basin Members of the Morrison in the Gallup-Grants-Laguna area, about 2.2 percent from the Todilto Limestone, about 0.2 percent from the Dakota Sandstone, about 2.0 percent from the Salt Wash Member in the Shiprock district, and less than 0.1 percent from the Recapture Member of the Morrison. Since 1963, about 0.9 percent has been recovered from mine waters, mainly from mines in the Westwater Canyon Member. Very minor production is recorded from the Fruitland Formation in the Farmington area. Production is minor from the Colorado and Utah portion of the San Juan Basin.

Production from New Mexico, mostly from the Grants Mineral Belt, ranged from 36 to 50 percent of the total U.S. production between 1968 and 1976. New Mexico's share was 50 percent in 1968, decreased to 36 percent in 1973 and increased steadily to 46 percent in 1976.

Resources of uranium have been categorized and defined in different ways by the Departments of Interior and Energy (Finch, 1976; Masters, 1977). Because the Department of Energy (DOE) has provided the resource data, their system is used here. In general, that system defines reserves as that part of total resources that has been identified and developed to the point that the mineable portion at various forward costs (2) can be calculated within reasonable limits. Potential

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(1) Records kept by the U.S. Department of Energy and private industry report uranium production in short tons only, and this convention will be followed here. For conversion to metric tons, multiply by 0.9072.

(2) Forward cost is part of the cost of producing a pound of U_3O_8 and therefore is not market price. Market price is substantially greater than forward cost. See U.S. Energy Research and Development Administration (1977) for procedure of determining forward cost.

Table 1.--Production from the San Juan Basin, 1948-1976. [After Chenoweth, 1977, and from data supplied by U.S. Department of Energy]

Resource area	Short tons U_3O_8	Years of Production	Host Formation
Grants Mineral Belt	114,862	1951-1976	Morrison Fm.
	2,718	1951-1976	Todilto Ls.
	246	1951-1970	Dakota Ss.
	1,145	1963-1976	Mine water
Carrizo Mountains	263	1948-1968	Morrison Fm.
Lukachukai Mountains	1,742	1950-1968	Morrison Fm.
Sanostee Wash	81	1951-1976	Morrison Fm., and Todilto Ls.
Nacimiento and Farmington	1	1954-1959	Morrison Fm., Dakota Ss., and Fruitland Fm.
Utah portion of figure 1	85		Morrison Fm.
Colorado portion of figure 1	1		Morrison Fm., and Entrada Ss.
Total	121,144		

resources are mostly the undiscovered resources that fall into three categories--probable, possible, and speculative--that are listed in the order of being successively less assured. The probable resources are extensions of known deposits as well as undiscovered deposits along trends near known deposits. Possible resources are projections from areas having known deposits into unexplored areas within a basin. Speculative resources are estimated only for those formations that have little or no known production or reserves and thus are relatively small in the basin. More detailed definitions may be found in the report by the U.S. Energy Research and Development Administration (1977).

As of January 1, 1978, reserves of U_3O_8 at forward costs of $30 per pound or less total 367,600 short tons, and at $50 per pound or less total 465,500 short tons (table 2). Increasing the forward cost increases the reserves about 25 percent. Much of these reserves between the $30- and $50-per-pound forward cost categories cannot be mined profitably without a significant increase in the average concentrate price, which was about $20 per pound in 1977. The largest proportion of these reserves is in the main mining area extending from Gallup on the west, through Grants, to Laguna on the east. Most of these deposits between Gallup and Grants are in the Westwater Canyon Sandstone Member of the Morrison Formation, and those in the Laguna area are in the Jackpile sandstone (of economic usage) of the Brushy Basin Member of the Morrison Formation. Reserves in the Utah and Colorado portion of the San Juan Basin are very small.

Potential uranium resources are summarized in table 3, which gives the probable and possible resources in two forward cost categories of

Table 2.--Uranium reserves for resource areas in the San Juan Basin.

[Except as noted, data supplied by the Resource Division, Grand Junction Operations Office, Department of Energy]

Resource area	$30 reserves (1/1/78) short tons U_3O_8	$50 reserves (1/1/78)[2/] short tons U_3O_8
Ambrosia, Mt. Taylor, and East Chaco Canyon	179,000	216,500
Laguna, Chama, and Nacimiento	73,500	96,000
Blackjack, Gallup, West Chaco Canyon, and Shiprock	114,500	153,000
San Juan County, Utah		
Utah portion of figure 1	85	90
Colorado portion of figure 1	0	0
Tailings at Durango, Colo.	475[1/]	475[1/]
Total	367,560	466,065

1/ From Ranchers Annual Report, 1977, p. 16, which reports 1,460,000 tons of tailings containing 1 lb/ton and 65 percent recoverable.

2/ Includes $30 reserves.

Table 3.--Potential uranium resources in the San Juan Basin. [Data supplied by the Resource Division, Grand Junction Operations Office, Department of Energy]

Resource area	$30 category (1/1/78) short tons U_3O_8		$50 category (1/1/78)[1/] short tons U_3O_8	
	Probable	Possible	Probable	Possible
Shiprock and West				
Chaco Canyon	77,200	263,200	100,100	325,200
Gallup	30,600	17,200	35,700	21,900
Blackjack	29,000	12,300	31,500	15,500
East Chaco Canyon	17,700	71,000	23,700	94,600
Ambrosia	47,500	36,600	61,300	47,800
Mt. Taylor	111,500	24,100	151,800	32,000
Laguna	29,600	5,900	32,600	7,200
Nacimiento and Chama	1,300	45,000	1,600	53,500
Central Basin	0	800	0	1,200
Utah portion of figure 1	0	500	0	700
Colorado portion of figure 1	0	5,600	0	7,600
Totals	344,400	482,200	438,300	607,100

1/ Includes $30 resources.

$30 per pound U_3O_8 or less and $50 per pound U_3O_8 or less. Of the total potential resources of 826,600 short tons U_3O_8 reported in the $30-per-pound-or-less category, about 40 percent are in the Shiprock and West Chaco Canyon resource areas. About 5,800 short tons U_3O_8 at $30 per pound or less are considered to be speculative (not given in table 3) and are located mainly in Montezuma County, Colorado, the Chama resource area, and shallow formations outside the named resource areas in New Mexico. No resources are estimated by DOE for the Morrison Formation below 5,000 foot depth and for rocks of Triassic, Paleozoic, and Precambrian ages.

Vanadium is associated with uranium in the Salt Wash Member of the Morrison Formation in the Shiprock resource area. For the $30-per-pound-or-less U_3O_8 category, probable vanadium resources total 29,400 short tons of V_2O_5, and possible vanadium resources total 22,800 short tons V_2O_5 in these resource areas. Similarly, for the $50-per-pound-or-less category, the vanadium resources total 32,200 short tons V_2O_5 each for probable and possible categories. Small amounts of vanadium resources are estimated in the Utah and Colorado portions of the basin.

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