Lithology and Uranium Potential of Jurassic Formations in the San Ysidro–Cuba and Majors Ranch Areas, Northwestern New Mexico

GEOLOGICAL SURVEY BULLETIN 1329

Lithology and Uranium Potential of Jurassic Formations in the San Ysidro–Cuba and Majors Ranch Areas, Northwestern New Mexico

By ELMER S. SANTOS

GEOLOGICAL SURVEY BULLETIN 1329

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1975

UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress Cataloging in Publication Data
Santos, Elmer S.
Lithology and uranium potential of Jurassic formations in the San Ysidro-Cuba and Majors Ranch areas, northwestern New Mexico.
(Geological Survey Bulletin 1329)
Bibliography: p.
Supt. of Docs. no.: I 19.3:1329
1. Petrology—New Mexico—Sandoval Co. 2. Geology, Stratigraphic—Jurassic. 3. Uranium ores—New Mexico—Sandoval Co.
I. Title. II. Series: United States Geological Survey Bulletin 1329.
QE75.B9 no. 1329 [QE445.N6] 557.3'08s [553'.493] 74-22091

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 – Price $1.60 (paper cover)
Stock Number 024-001-02604

CONTENTS

	Page
Abstract	1
Introduction	1
Acknowledgments	4
Previous work	4
Stratigraphy	4
Entrada Sandstone	5
Todilto Formation	6
Summerville Formation	7
Morrison Formation	8
Recapture Member	8
Westwater Canyon Member	9
Brushy Basin Member	11
Mudstone unit	11
Jackpile sandstone of economic usage	12
Dakota Sandstone and Mancos Shale	14
Structure	15
Distribution of minor elements	16
Distribution of heavy minerals	17
Uranium occurrences and exploration	18
Evaluation of uranium ore potential	19
References cited	21

ILLUSTRATIONS

	Page
PLATE 1. Geologic maps of the San Ysidro–Cuba and Majors Ranch areas, Sandoval County, northwestern New Mexico	In pocket
2. Isopach map of the Jackpile sandstone and vertical sections of part of the Morrison Formation, San Ysidro–Cuba and Majors Ranch areas	In pocket
FIGURE 1. Index map of northwestern New Mexico, showing location of quadrangles and line of geologic section shown in figure 2	2
2. Chart showing correlation of Jurassic formations between the Laguna and San Ysidro-Cuba areas	5

LITHOLOGY AND URANIUM POTENTIAL OF JURASSIC FORMATIONS IN THE SAN YSIDRO-CUBA AND MAJORS RANCH AREAS, NORTHWESTERN NEW MEXICO

By ELMER S. SANTOS

ABSTRACT

The aggregate thickness of sedimentary rocks of Jurassic age near the eastern and southeastern margin of the San Juan Basin in Sandoval County, N. Mex., is about 1,150 feet (350 metres). The Entrada Sandstone at the base is overlain successively by the Todilto, Summerville, and Morrison Formations.

The Entrada Sandstone, 97–227 feet (30–69 m) thick, consists of a lower, silty member composed of red and brown siltstone and fine-grained sandstone, and an upper, sandy member composed of brown and white sandstone. The Todilto Formation, 5–125 feet (1.5–38 m) thick, consists of a lower, limestone unit about 5 feet (1.5 m) thick, and an upper, massive white gypsum unit. The Summerville Formation, 0–50 feet (0–15 m) thick, consists of variegated, interstratified mudstone, claystone, siltstone, and sandstone. The Morrison Formation, 750–870 feet (229–265 m) thick, is divided into three members; the Recapture Member at the base, 200-350 feet (61–107 m) thick, is overlain successively by the Westwater Canyon Member, 0–240 feet (0–73 m) thick, and the Brushy Basin Member, 200–350 feet (61–107 m) thick. The Recapture Member consists mainly of red and white color-banded fine-grained sandstone. The Westwater Canyon and Brushy Basin Members consist mainly of red and green mudstone interstratified with grayish-orange arkosic sandstone. The upper unit of the Brushy Basin Member is called the Jackpile sandstone, a name of economic usage. It is 0–165 feet (0–50 m) thick and consists of white and grayish-orange fine-, medium-, and coarse-grained arkosic sandstone.

A comparison of ore-bearing sandstone units in the Ambrosia Lake and Laguna mining districts with equivalent sandstone units in the area studied reveals many similarities, in color, texture, mineral composition, and minor-element distribution. Differences are minor and most of the sandstone in the Morrison Formation above the Recapture Member in the area studied is considered to be a potential host for uranium ore deposits.

INTRODUCTION

This report describes the results of a study made in 1967-69 of the sedimentary rocks of Jurassic age in the San Ysidro–Cuba and Majors Ranch areas on the east side of the San Juan Basin in northwestern New Mexico (fig. 1). The sandstone units which are known to contain uranium ore deposits in Valencia and McKinley Counties to the west were studied in more detail than unproductive units.

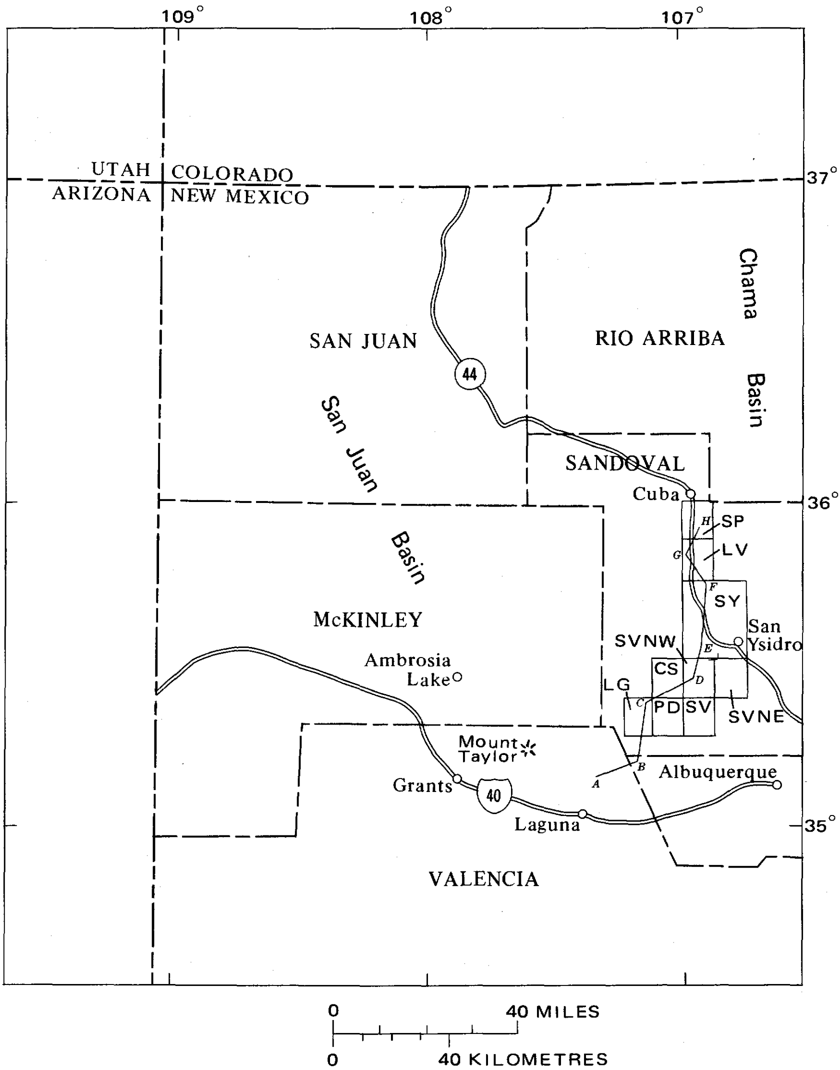

FIGURE 1. — Index map of northwestern New Mexico, showing location of quadrangles and line of geologic section shown in figure 2. See plate 1 for location of mapped areas. Quadrangle names are abbreviated: CS, Casa Salazar; LG, La Gotera; LV, La Ventana; PD, Puerco Dam; SP, San Pablo; SV, Sky Village; SVNE, Sky Village NE; SVNW, Sky Village NW; SY, San Ysidro.

The purpose of the study was to compare various aspects of the lithology and stratigraphy of the rocks in Sandoval County with the equivalent rock units that contain large uranium deposits in the Ambrosia Lake and Laguna districts. The aim was to determine if the apparent paucity of uranium mineralization in Sandoval County could be related to differences in the lithology and distribution of the rocks.

The boundaries of the Ambrosia Lake and Laguna districts are not shown in figure 1, because they are subject to change as new mines are developed. For the purposes of this report the Ambrosia Lake area or district is defined as the area that encompasses the uranium deposits west and northwest of Mount Taylor and near Ambrosia Lake, N. Mex. The Laguna area or district is defined as the area that encompasses the uranium deposits east and southeast of Mount Taylor and near Laguna, N. Mex. (fig. 1).

Only the outcrops of Jurassic age, the overlying lowermost rocks of Cretaceous age, and some deposits of Tertiary and Quaternary age were mapped as distinct units. The sedimentary rocks older than Jurassic were not differentiated.

Two areas (plate 1) were mapped separately; the San Ysidro–Cuba area to the north encompasses about 142 square miles (365 km^2) and the Majors Ranch area to the south encompasses about 70 square miles (182 km^2). The intervening area was not mapped, because rocks of Jurassic age are not exposed. The geology of the San Ysidro-Cuba area was mapped on parts of the following U.S. Geological Survey topographic maps: La Ventana NW, La Ventana SW, Sky Village NW, and Sky Village NE 7 1/2-minute quadrangles, and the San Ysidro 15-minute quadrangle. The geology of the Majors Ranch area was mapped on parts of the Sky Village NW, Sky Village, Casa Salazar, and Puerco Dam 7 1/2-minute quadrangles (fig. 1). The La Gotera 7 1/2-minute quadrangle, mapped geologically by Moench, Schlee, and Bryan (1965), adjoins the Puerco Dam quadrangle on the west. Only the upper 200–300 feet (61–91 m) of the Jurassic section is exposed in the Majors Ranch area; the entire Jurassic section is exposed throughout most of the San Ysidro–Cuba area.

The Majors Ranch area may be reached by traveling north on a graded dirt road that leaves U.S. Interstate Highway 40 where it crosses the Rio Puerco about 16 miles (26 km) west of Albuquerque. New Mexico State Highway 44 traverses the southern part of the San Ysidro-Cuba area and many dirt roads joining this highway promote easy access to most of the area.

Subsurface data in the form of lithologic and electric logs from several hundred holes drilled near and between the two mapped areas were made available by several companies who had explored for uranium. These data broadened the area of the study and were particularly useful for correlating units and for determining variations in the thickness of rocks beyond the outcrop.

Clay and zeolite minerals were identified from their X-ray diffraction patterns. Mounts of oriented, $<2\mu$m-size clay separates were X-rayed untreated, after treatment with glycol, and after heating to 500°C. Heavy minerals were separated using bromoform at 2.80 sp gr. Rock colors are from the "Rock-Color Chart" of the National Research Council (Goddard and others, 1948).

ACKNOWLEDGMENTS

The author is grateful to the officials of the Ranchers Exploration and Development Co., Western Nuclear Inc., The Anaconda Co., Kerr-McGee Corp., and the Phillips Petroleum Co. who made available their drill-hole data. Thanks are also given to Harlan Holen of the Grants, N. Mex., Branch Office of the U.S. Atomic Energy Commission who helped in the accumulation of many of these data.

PREVIOUS WORK

Renick (1931) mapped and described the rocks of Jurassic age in the area of this study. He did not subdivide the Morrison Formation into members and apparently mapped some sandstone at the top of the Morrison Formation as the Dakota Sandstone. What is considered Entrada Sandstone in this report was called Wingate Sandstone by Renick.

Wood and Northrop (1946), on their map of the same general area, also showed the Entrada Sandstone as Wingate and mapped the Morrison Formation as a single unit.

Craig and others (1955) showed the Recapture, Westwater Canyon, and Brushy Basin Members of the Morrison Formation extending to the east side of the San Juan Basin, and Freeman and Hilpert (1956, p. 323) published a measured section from a locality where the three members are described as distinct units. A measured section published by Craig (1959) indicates the presence of the Summerville Formation in the area of this report and also describes the Jackpile sandstone as a distinct unit in the Brushy Basin Member.

STRATIGRAPHY

The sedimentary rocks of Jurassic age are, in ascending order, the Entrada Sandstone, Todilto Formation, Summerville Formation, and the Morrison Formation. The Morrison Formation comprises three members, the Recapture Member at the base, overlain successively by the Westwater Canyon and Brushy Basin Members. A discontinuous sandstone unit at the top of the Brushy Basin Member is known as the Jackpile sandstone, an informal name of economic usage (Schlee and Moench, 1961).

The Chinle Formation of Late Triassic age underlies the Entrada Sandstone, and the Dakota Sandstone of Early and Late Cretaceous age overlies the Morrison Formation. The Chinle Formation and older strata are not differentiated on figure 2.

The interval between the top of the Morrison Formation and the base of the Entrada Sandstone is about 1,150 feet (350 m) in the Laguna, Majors Ranch, and San Ysidro-Cuba areas. The stratigraphic thickness within this interval is remarkably constant despite the variable

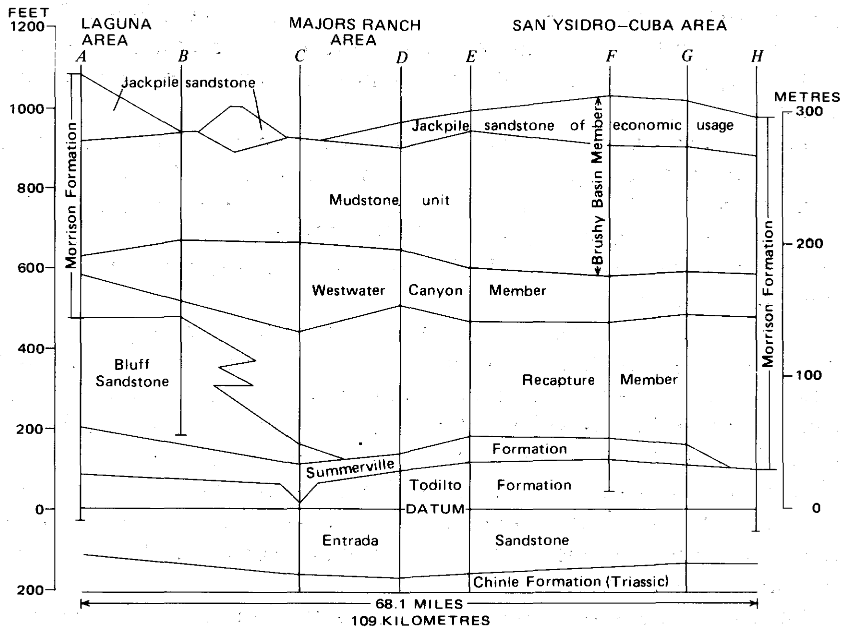

FIGURE 2. — Correlation of Jurassic formations between the Laguna and San Ysidro–Cuba areas. Line of section shown in figure 1. A. Anaconda drill hole, core log (Santos and Moench, 1971); B. Kerr McGee-Summit drill-hole 107–1, electric and gamma-ray log; C. Texaco Inc. Howard Major oil test, lithologic and electric logs and Anaconda drill-hole F–2396, electric and gamma-ray log; D. Humble Oil and Refining Santa Fe Pacific B1 oil test, lithologic and electric logs and Kerr McGee drill-hole RR-5, electric and gamma-ray log; E. Avila Oil Co. Odlum 1 oil test, lithologic and electric logs and measured section; F. Western Nuclear Inc. drill-hole J–9, electric and gamma-ray log; G. El Paso Natural Gas Elliot State 1 oil test, lithologic and electric logs; H. S. D. Johnson Heller State 1 oil test, lithologic and electric logs.

thicknesses of individual units. Figure 2 shows, in vertical section, the correlation of units as revealed by data from drill holes that penetrated either the Todilto Formation or the base of the Entrada Sandstone.

ENTRADA SANDSTONE

The Entrada Sandstone is exposed throughout most of the San Ysidro-Cuba area (pl. 1), where it forms sheer cliffs, steep slopes, and round-topped ridges.

The formation is 97–227 feet (30–69 m) thick and consists of a lower, silty unit and an upper, sandy unit. The silty unit is 26–59 feet (8–18 m) thick and is probably equivalent to the "medial silty member" of Harshbarger, Repenning, and Irwin (1957, p. 37). The sandy unit is probably equivalent to their upper sandy member (1957, p. 35).

The silty unit is composed mainly of siltstone but includes some very fine grained silty sandstone. The siltstone is light brown (5*YR* 6/4) to pale reddish brown. The lower part is flat bedded and slightly fissile; the upper part is structureless and weathers to rounded "hoodoo" shapes typical of the medial silty member elsewhere on the Colorado Plateau.

The most conspicuous feature of the upper, sandy unit is the contrast in color between its upper and lower parts. Typically, the lower part is light brown (5*YR* 6/4) and the upper part is bleached to nearly white with pale tints of green, yellow, and pink. Many gradations in color occur in the zone between the highly bleached top and the virtually unbleached bottom.

The sandstone is well to moderately well sorted and very fine, fine, and medium grained. Most of the grains are subangular to subrounded frosted quartz, a few of which have quartz overgrowths. Five to six percent of the grains are subangular feldspar, many of which are highly altered. Fewer than 2 percent of the grains are rounded to subrounded chert and rock fragments. The silt and smaller size fraction ranges from 5 to 15 percent. Heavy minerals are leucoxene, garnet, tourmaline, magnetite, apatite, and epidote, all of which constitute less than 0.1 percent of the rock.

The sandstone is very friable to moderately indurated. The cementing material is illitic and montmorillonitic clay where the sandstone is friable, and clay and calcite where it is indurated. Bedding is obscure to indistinct throughout much of the sandstone. Where the bedding is discernible the sandstone is mostly flat bedded but also exhibits some broad shallow crossbeds. The upper sandstone unit is atypical Entrada, lacking the prominent large-scale eolian-type crossbedding so characteristic of the Entrada elsewhere.

The Entrada Sandstone of Late Jurassic age overlies the Chinle Formation of Late Triassic age. Both to the north (Muehlberger, 1967, p. 18) and to the southwest (Moench and Schlee, 1967, p. 7) of the study area the Entrada rests on a scour surface carved in the underlying Chinle. At the few good exposures of this contact in the San Ysidro-Cuba area, as well as in an area 34 miles (55 km) to the northeast (Craig, 1959, section 83), no scour surface was noted at the base of the Entrada Sandstone. In the San Ysidro–Cuba area the only evidence of an unconformity is a reworked zone at the base of the Entrada Sandstone which contains chert pebbles and chips of claystone from the Chinle Formation (W. I. Finch, written commun., 1970).

TODILTO FORMATION

The Todilto Formation overlies the Entrada Sandstone above a sharp conformable contact and consists of a thin limestone unit and an overlying thick gypsum unit. The formation is 80–90 feet (24-27 m) thick throughout most of the area but ranges from 5 to 125 feet (1.5-38

m) in thickness. The limestone unit is 5–6 feet (1.5-1.8 m) thick in most places and is nowhere more than 10 feet (3 m) thick.

The limestone unit is moderate yellowish brown to light gray and is silty and slightly sandy, especially near its base. The limestone is thinly laminated and weathers to fissile and flaggy beds. Some specimens emit a fetid odor from freshly broken surfaces and thin seams of gypsum are interbedded with limestone, especially near the top of the unit.

The gypsum unit is light gray to nearly white, massive, and structureless. The lower part contains thin lenses of silty limestone; the upper part is nearly pure gypsum. Data from several drill holes indicate that in the subsurface the unit is largely anhydrite instead of gypsum.

The gypsum unit is not coextensive with the underlying limestone but seems to occupy an elliptically shaped area along the east side of the San Juan Basin (Hilpert, 1969, pl. 3). The long axis of the area trends north and the thickest part of the unit seems to center approximately over the area of outcrops in the San Ysidro-Cuba area. Although the gypsum unit is as much as 120 feet (37 m) thick, abrupt thinning occurs locally. In a small area in sec. 21, T. 15 N., R. 1 E., the gypsum unit is absent, probably having been removed by solution; the Summerville Formation there seems to rest conformably on the basal limestone.

SUMMERVILLE FORMATION

Conformably overlying the Todilto Formation in the southern part of the San Ysidro–Cuba area is 40–50 feet (12–15m) of strata discernibly different from the overlying Recapture Member of the Morrison Formation. Craig (1959, section 49, p. 13) called these strata "Summerville formation equivalent(?)." The unit consists of interstratified mudstone, claystone, siltstone, and sandstone. The mudstone, claystone, and siltstone are moderate brown (5*YR* 3/4) and grayish yellow green. The sandstone is pinkish gray, grayish orange pink, and pale reddish brown. The sandstone is fine and very fine grained and consists of subrounded to subangular quartz, a few percent of subangular feldspar, and less than 0.5 percent heavy minerals.

Typically, the argillaceous beds in the lowest 5–6 feet (1.5–1.8 m) are greenish gray, those in the upper part are brown. Scattered streaks and mottled zones of greenish gray occur in the upper part. Seams of limestone and gypsum are locally interbedded with argillaceous beds near the base and top of the formation.

Some of the colors as well as the texture of the sandstone in the formation are identical with those in the overlying Recapture Member. The moderate brown (5*YR* 3/4) here, however, is distinctive and occurs only in the 40–50 feet (12–15 m) of strata above the Todilto Formation. This color serves to distinguish the Summerville Formation from the Recapture.

The Summerville Formation can be traced as a distinct unit, northward to about lat 33°43′ N. (fig. 2). Northward from this point the stratigraphic interval is covered through a distance of 13 miles (21 km); and at the next exposure within the interval, at about lat 35°37′30″ N., and northward the Summerville Formation is absent.

MORRISON FORMATION

Contacts between the mappable units of the Morrison Formation are arbitrarily chosen because each member grades into and intertongues with adjacent ones. Only locally does an erosion surface separate the members. The choice of the contact between the Brushy Basin and Westwater Canyon Members illustrates the arbitrary basis used for selecting intraformational contacts.

The Morrison Formation, below the Jackpile sandstone and above the Recapture Member, consists of 350–450 feet (106–137 m) of alternating mudstone and sandstone strata. Mudstone strata are thicker and more numerous than sandstone strata in the upper part of the 350–450-foot interval, whereas the reverse is true in the lower part. The upper part is considered to be the Brushy Basin Member, the lower part is the Westwater Canyon Member. The contact is drawn so as to separate a sequence of strata that is more than 50 percent mudstone from that which is more than 50 percent sandstone. Where the proportion of mudstone and sandstone is about equal, the contact is drawn so as to avoid abrupt changes of stratigraphic horizon. Thus, sequences of strata that are about 50 percent each mudstone and sandstone are, in places, included in the Brushy Basin Member, and in other places in the Westwater Canyon Member.

RECAPTURE MEMBER

The Recapture Member as a whole is poorly indurated; many strike valleys are cut into the lower part of this member and the lower part is in most places covered by alluvium or talus. The upper part is well exposed throughout the San Ysidro–Cuba area, where it forms steep slopes below sandstone cliffs of the Westwater Canyon Member.

The member conformably overlies the Summerville Formation. The contact with the overlying Westwater Canyon Member is locally an erosion surface but, more commonly, is gradational or intertonguing.

The most conspicuous feature of the Recapture Member is the parallel red and nearly white color banding of the weathered outcrops. Bands of these colors 3–40 feet (1–12 m) thick alternate from top to bottom.

The member is 200–350 feet (61–107 m) thick and consists of sandstone, silty sandstone, and minor beds of sandy siltstone and mudstone. The sandstone is mainly pale red (10*R* 6/2) or pinkish gray but some is of gradations of intermediate color. At the top the sandstone is light greenish gray (5*GY* 8/1) in some places. The siltstone and mudstone range in color from very dusky red to pale reddish brown. The sandstone is mostly fine and very fine grained, and moderately well to poorly sorted; it consists of subangular to subrounded quartz, a small amount of angular feldspar, and rounded chert. Heavy minerals are magnetite, hematite, leucoxene, garnet, tourmaline, and zircon — all of which constitute less than 0.5 percent of the rock. Red mudstone and siltstone fragments and thin laminae of clay are common in the sandstone locally. The gradations of color of the sandstone from pink to red reflect an increase in the amount of interstitial red clay, which in one red sample comprised 18 percent of the rock.

Bedding is obscure to indistinct throughout much of the member but where the red clay laminae occur the sandstone is seen to be flat bedded and only locally ripple laminated. The parallel color banding also gives the impression that the unit as a whole is flat bedded.

In the Laguna area the Recapture is generally less than 100 feet (30 m) thick and is underlain by 200–300 feet (61–91m) of Bluff Sandstone. In the San Ysidro-Cuba area it is 200–350 feet (61–107 m) thick and the Bluff Sandstone is absent. Southward and westward from the San Ysidro–Cuba area drill-hole data indicate that the lower part of the Recapture Member grades laterally into the Bluff Sandstone (fig. 4). Where this occurs, the Bluff-Recapture interval is covered by younger strata, and so details of the facies change are not known.

WESTWATER CANYON MEMBER

Overlying the color-banded, fine-grained sandstone of the Recapture Member is a unit composed mainly of sandstone whose color and texture are distinctly different from those of the underlying strata. This unit is regarded as the Westwater Canyon Member. Locally absent, the unit is, in places, a single bed of sandstone about 40 feet (12 m) thick, elsewhere it is sandstone interbedded with mudstone as much as 240 feet (73 m) thick. Where the member dips gently, it crops out as cliffs, ledged slopes, and broad benches; where steeply dipping, it forms ridges, steep slopes, and narrow valleys.

The predominant color of the sandstone at the surface is what is usually called buff; the colors are various shades, commonly grayish orange to very pale orange. North of lat 35°40′ N. much of the sandstone ranges in color from reddish brown to pinkish gray. Uncommonly the sandstone is pale olive to yellowish gray. Subsurface data indicate that all the sandstone is light to medium gray or greenish gray at depth. Surface and near-surface oxidation of gray and greenish-gray sandstone most likely produced the buff color seen in outcrops.

The sandstone consists of at least 50 percent subangular to subrounded quartz, from 2 to 30 percent angular to subangular feldspar, small amounts of rounded chert and rock fragments, and less than 0.5 percent heavy minerals. Heavy minerals are leucoxene, zircon, tourmaline, garnet, magnetite, hematite, staurolite, and rutile. Fifty to eighty percent of the heavy minerals are opaque and of these, 80 to 90 percent is leucoxene. A small amount of black opaque minerals in some specimens is magnetic. No sulfides were observed in samples from the surface but small spotty concentrations of red iron-oxide indicate that pyrite is present at depth.

The clay-sized material ($<2\mu m$) disseminated in the sandstone is mostly mixed-layer illite-montmorillonite. Small amounts of chlorite and kaolinite were detected in a few samples. The kaolinite is visible in hand specimens as small rounded aggregates of platy crystals perched on some quartz grains. These aggregates do not appear to be replacing other aluminous silicate minerals in place.

Grain sizes range from very coarse and conglomeratic to very fine but the medium to fine-grained sizes predominate. At least 80 percent of most samples consists of fine- and medium- grained sandstone; in these the fine-grained fraction ranges from 43 to 81 percent and the medium-grained fraction from 8 to 37 percent. The fine- to medium-grained sandstone is most prevalent in the lower part of the unit; the coarse-grained rocks occur mostly in lenses in the upper part. Conglomeratic sandstone, in lenses rarely more than 6 inches (15 cm) thick, consists of rounded chert pebbles with mudstone and siltstone fragments set in a coarse- to fine-grained matrix of quartz and feldspar. The degree of sorting varies from fairly good to poor in individual beds. Some samples contain as much as 18 percent silt and smaller sized material but most samples contain less than 10 percent.

Cross-stratification is mainly of the low-angle, large-scale type and in many places the sandstone seems to be flat bedded. Very little torrential-type cross-stratification was observed.

The sandstone ranges from very friable to well indurated depending on the type and amount of cement present. The very friable sandstone contains only clay cement and is generally grayish orange to very pale orange. The well-indurated sandstone is generally reddish brown and contains both calcite and iron-oxide cement. Much of the calcite-cemented sandstone is luster mottled.

Interbeds between sandstone lenses are mainly mudstone and sandy siltstone. The mudstone is predominantly grayish yellow green and less commonly pale brown and moderate orange pink. The sandy siltstone is generally grayish red (10*R* 4/2).

The intertonguing relationships of the Westwater Canyon Member in the study area (cross sections pl. 2) are very similar to those in the Ambrosia Lake area (Santos, 1970, pl. 1). Some properties of the member differ in the two areas. In the Ambrosia Lake area crossbedding is mainly of the torrential type and the sandstone is mainly medium grained and contains little disseminated clay. In the area of this report, crossbedding is mainly of the large-scale simple type and the sandstone is mainly fine grained and contains a notable, but not large, quantity of disseminated clay. Red sandstone is more abundant in the Ambrosia Lake area.

BRUSHY BASIN MEMBER

The Brushy Basin Member ranges in thickness from 300 to 350 feet (91–107 m) in the San Ysidro–Cuba area and from 200 to 350 feet (61–107 m) in the Majors Ranch area. The member consists of two units. A lower, mudstone unit crops out as steep slopes, ledges, and ridges. The upper, sandstone unit is the Jackpile sandstone, which forms sheer cliffs, ledges, and ridges.

MUDSTONE UNIT

The mudstone unit consists of thick clayey and silty beds alternating with somewhat thinner sandstone and conglomerate lenses. Although some of the sandstone lenses attain a thickness of 40 feet (12 m), most are less than 20 feet (6 m) thick. No attempt is made to show individual sandstone lenses in the mudstone unit on the geologic map as was done in the adjacent Laguna area (Moench and others, 1965), nor are the sandstone lenses described herein as a separate unit.

The clayey and silty beds are of various colors but the most prevalent are pale olive to yellowish gray. Less common colors are reddish brown (10*R* 4/6) to moderate reddish orange and the least common are yellowish browns near 10*YR* 4/2. Near the north end of the San Ysidro-Cuba area clayey strata in the lower half of the mudstone unit are mostly reddish orange and in the upper half they are shades of green near 10*Y* 6/2. Smith, Budding, and Pitrat (1961, p. 5) described a similar color distinction in the Chama Basin to the north. In the south end of the area color variation between the upper and lower parts is not evident.

Beds between the sandstone lenses, in order of decreasing abundance, are mudstone, siltstone, and claystone, all of which are slightly to very sandy in many places. Keller (1962, p. 81) described the clay minerals in these beds as mainly montmorillonite and mixed layer illite-montmorillonite. During the present study many well-indurated siltstone beds, generally less than 6 inches (15 cm) thick, were found to contain as much as 75 percent zeolite minerals. Red siltstone (about 10*R* 5/4) contains mainly clinoptilolite; greenish-gray siltstone (about 10*Y* 8/2) contains mainly analcime. The clinoptilolite replaces shards of volcanic glass, the shapes of which are well preserved and show no evidence of abrasion. The analcime replaces some shards but the bulk of this zeolite is concentrated in fracture-filling veinlets. Other minerals in the siltstone are quartz, feldspar, calcite, and, in small amounts, clay. Interbedded clayey material less than 1 inch (2.5 cm) from the siltstone beds contain either no zeolites or less than can be detected in X-ray diffractometer patterns of the bulk samples. These Upper Jurassic rocks are the oldest in the United States in which clinoptilolite has been reported (R. A. Sheppard, written commun., 1972).

The zeolitic siltstone beds are particularly prevalent in the orange basal part of the mudstone unit near the north end of the San Ysidro-Cuba area. Southward their numbers decrease and only a few analcime-bearing siltstone beds were found in the Majors Ranch area. Analcime was recently discovered in a sample of siltstone collected in one of the large uranium mines in the Laguna area (W. L. Chenoweth, written commun., 1969). This sample is from the Jackpile sandstone.

Much of the sandstone in the mudstone unit, particularly that in lenses 20–40 feet (6–12 m) thick, resembles the sandstone in the Westwater Canyon Member, each having the same color, grain size, degree of induration, and type of cross-stratification. The bulk of the sandstone in these lenses is fine and medium grained; coarse-grained and conglomeratic zones are concentrated in the thickest part of some lenses. Coarse-grained and conglomeratic zones in the Westwater Canyon Member are less common than in the sandstone lenses of the mudstone unit. Where the lenses thin to 5 feet (1.5 m) or less, the sandstone is typically fine to very fine grained, is very light gray, and contains abundant silica cement.

Some thin lenses in the mudstone unit consist of sandstone that does not resemble the sandstone in the Westwater Canyon Member. One type, in lenses generally less than 3 feet (1 m) but as much as 8 feet (2.4 m) thick, is fine to very fine grained and is pinkish gray (5*YR* 8/1) and yellowish gray (5*Y* 8/1). The sandstone is invariably well indurated with silica or calcite cement and resembles the sandstone in the thin parts of lenses of Westwater Canyon-type sandstone in the mudstone unit. A second type of sandstone, generally in lenses less than 10 feet (3 m) thick, is poorly sorted, fine, medium, and coarse grained and is variegated light and dark gray, brown, yellow, pink, and purple. Manganese and iron oxides commonly stain weathered surfaces, and this second type of sandstone is generally well indurated with calcite and silica cement. Also conspicuous, but not numerous, are lenses of conglomerate as much as 7 feet (2.1 m) thick which contain chert and quartzite pebbles as large as 2 inches (5 cm) in diameter and mudstone and siltstone cobbles as large as 6 inches (15 cm) in diameter.

JACKPILE SANDSTONE OF ECONOMIC USAGE

The upper, sandstone unit of the Brushy Basin Member is the Jackpile sandstone of economic usage. Zero to 165 feet (0–50 m) thick, its thickness and distribution, as determined by data from 630 drill holes and by study of outcrops, are shown on plate 2. The unit is exposed in a narrow zone north of the area shown on plate 2 to the northern boundary of the San Ysidro-Cuba area but is absent through a strike distance of about 4,000 feet (1220 m) near lat 35°55′N. (pl. 1).

The most conspicuous feature of the Jackpile sandstone is its near-white color, especially near the top of the unit. The color is due to abundant white clay which coats sand grains and fills interstices. In some places the clay is stained very pale shades of green, yellow, and pink. In addition to white, the Jackpile sandstone is pinkish gray, yellowish gray, grayish orange, and moderate red. The red sandstone occurs mostly north of lat 30°40′ N. (pl. 1) where sandstone in the Westwater Canyon Member is also red.

The unit consists mostly of sandstone but locally contains green and red clayey lenses as much as 5 feet (1.5 m) thick near the base and 35 feet (10.7 m) thick near the top. The sandstone is fine, medium, and coarse grained and the sorting ranges from poor to moderate in individual beds. Silt and clay-size detritus ranges from 3 to 25 percent. Eighty percent or more of most samples consists of fine- and medium-grained sand; in these, the fine-grained fraction ranges from 46 to 84 percent and the medium-grained fraction, from 10 to 37 percent. Rounded to subrounded quartz comprises 75 to 95 percent of the sandstone, subrounded to angular feldspar, 1 to 20 percent. Overgrowths on quartz grains are common and a single sample may contain both unaltered and highly altered feldspar. Heavy minerals are leucoxene, zircon, tourmaline, garnet, and rutile, all of which constitute less than 0.2 percent except in one sample, a red sandstone, which contains 0.36 percent heavy minerals. Calcite, hematite, and clay are the cementing materials. Where clay alone is the cement the sandstone is very friable.

In white sandstone the clay is mainly kaolinite, and, subordinately, mixed-layer illite-montmorillonite and chlorite. Grayish-orange sandstone contains mainly mixed-layer illite-montmorillonite, sparse chlorite, and little or no kaolinite. Some pale-yellow samples contain about equal amounts of kaolinite and mixed-layer illite-montmorillonite. Grayish-orange sandstone occurs most commonly in the lower part of the unit, and white sandstone is common in the upper part. There is, thus, a change in clay mineral composition with depth; kaolinite is abundant near the contact with the overlying Dakota Sandstone and its abundance decreases with distance below the contact.

Leopold (1943), Schlee and Moench (1961), and Granger (1962) have discussed the kaolinization of sandstone truncated by the pre-Dakota erosion surface in northwestern New Mexico. Decomposition of relatively unstable aluminum-silicate minerals by downward-percolating corrosive solutions is thought to have produced some of the kaolinite in these strata. It is questionable, however, whether all the kaolinite was derived from the decomposition of detrital grains in the kaolinized sandstone. The clay, rather than occurring invariably in discrete clots that might suggest alteration in place, pervades the entire fabric of the sandstone in a manner that suggests precipitation from a fluid solution. The ions in the solution may have been derived from throughout the Jackpile sandstone from the kaolinized and unkaolinized zones as well as from the underlying and interbedded clayey strata.

As an alternative to downward-percolating corrosive solutions to account for the kaolinization, the author proposes that water carrying the appropriate ions, as it reached the pre-Dakota erosion surface, entered an environment in which kaolinite was precipitated. This hypothesis better explains the presence of altered and unaltered feldspar in many samples of both grayish-orange and white sandstone in about equal amounts than by postulating downward-percolating corrosive solutions decomposing minerals in the kaolinized zone only.

Cross-stratification is conspicuous throughout the Jackpile sandstone and is mainly of the high-angle medium-scale torrential type. The strike and dip of crossbeds were measured in several areas and the directions were plotted on rose diagrams (pl. 2). Three of the rose diagrams north of lat 35°30′ N. show definite southward trend of dips; though the other diagrams on plate 2 show some scatter, a southerly component is discernible on most of them. The diagrams suggest that the most probable direction of paleostreamflow was from north to south across the San Ysidro-Cuba area and at least part of the Majors Ranch area. The inferred direction of streamflow indicates a source of the Jackpile sandstone somewhere north of the San Ysidro–Cuba area.

Schlee and Moench (1961) described the Jackpile sandstone and its distribution in the Laguna area. In the study area its distribution (pl. 2) is somewhat different. A northeast-trending channel, like those in the Laguna area, is indicated by contours in the southern part of plate 2 but elsewhere, well-defined channels are not conspicuous. The maximum thickness of the unit in the Laguna area is somewhat greater than in the study area. In most other respects, such as texture, composition, and degree of alteration, the Jackpile sandstone is virtually identical in both areas. One difference is the orientation of crossbedding. In the Laguna area crossbedding planes dip mostly northeastward (Schlee and Moench, 1961, p. 138), whereas in the study area they dip mostly southward, southeastward, and southwestward.

DAKOTA SANDSTONE AND MANCOS SHALE

The older map unit of Cretaceous age shown on plate 1 includes the Dakota Sandstone and lower part of the Mancos Shale in the Majors Ranch and southern part of the San Ysidro–Cuba area. In the northern part of the San Ysidro–Cuba area it includes only the lower part of the Dakota Sandstone (Dane, 1960, p. 48). The upper boundary of this Cretaceous unit was chosen for convenience in mapping. In the central and northern part of the San Ysidro–Cuba area the boundary is drawn at the top of a continuous, well-exposed sandstone bed about 40 feet (12 m) above the Morrison Formation. To the south the contact is drawn at the top of a persistent sandstone bed 220 feet (67 m) above the Morrison Formation. This sandstone bed, as well as underlying and overlying strata, was mapped as Mancos Shale by Moench and Schlee (1967, p. 23). In the Laguna area, Dane, Landis, and Cobban (1971, p. B19) considered the uppermost of three sandstone beds beneath the main body of the Mancos Shale to be the Twowells Sandstone Tongue of the Dakota Sandstone and the marine shale below the Twowells Sandstone Tongue to be the Whitewater Arroyo Shale Tongue of the Mancos Shale. In the present report the two sandstone beds below the Whitewater Arroyo Shale Tongue are considered to be unnamed tongues of the Dakota Sandstone and the marine strata below each sandstone bed to be unnamed tongues of the Mancos Shale. The Twowells Sandstone Tongue appears to pinch out in the Majors Ranch area and it is the first sandstone below the Whitewater Arroyo tongue that extends into the southern part of the San Ysidro-Cuba area. The top of this sandstone was chosen as the contact with the upper part of the Mancos Shale in the Majors Ranch and southern part of the San Ysidro–Cuba area. Strata above this bed are too poorly exposed for identifying the horizon used as the contact to the south.

The younger map unit of Cretaceous age (pl. 1) is the upper part of the Mancos Shale. At least 750 feet (229 m) thick, it consists mainly of gray fossiliferous shale with few sandstone interbeds.

STRUCTURE

The deformation that produced the present structural features probably began in late Paleocene or early Eocene time and continued episodically into late Tertiary time. No pre-Dakota folds like those in the Laguna district (Moench and Scchlee, 1967, p. 36) were found in the area of this study. The age of deformation is fixed by the relationship of strata of early Tertiary age a few miles north of the San Ysidro–Cuba area. The San Jose Formation of early Eocene age overlies the Nacimiento Formation of Paleocene age along the erosional unconformity. Locally there is an angular discordance of as much as 30° between the two formations (Baltz, 1967, p. 54). In the southern part of the San Ysidro–Cuba area, undeformed strata of the Santa Fe Group of middle Miocene to Pleistocene(?) age lap across folded strata of Late Cretaceous age.

Moench and Schlee (1967, p. 105) and Granger, Santos, Dean, and Moore (1961, p. 1190) found that uranium ore deposition predates and is not controlled by the structural features formed during this period of deformation in either the Ambrosia Lake or Laguna district. Whatever uranium ore deposits that may exist in the study area are probably not controlled by tectonic structures, and so only a brief description of the main structural features in presented.

The dominant structural feature in the San Ysidro–Cuba area, the northerly trending Nacimiento fault (pl. 1), juxtaposes Precambrian crystalline rocks on the east against Paleozoic and Mesozoic strata on the west and marks the eastern boundary of the San Juan Basin. The maximum structural relief across the fault is at least 10,000 feet (3,000 m). The fault plane is fairly straight and several subsidiary fault traces branch from the main fault locally. It was described as a thrust fault by Renick (1931, p. 71) and by Wood and Northrop (1946). The main fault plane dips about 80° E. and is actually a high-angle reverse fault.

West of the Nacimiento fault and also near its southern terminus northerly and northwesterly trending folds have deformed strata as young as Late Cretaceous. The configuration of the northwesterly trending folds suggests compressive forces probably related to lateral movement along the fault.

In the Majors Ranch area, strata dipping gently to the southeast are displaced by numerous northeasterly trending faults. In the southern part of the San Ysidro–Cuba area faults of the same trend are present. Strata are displaced as much as 900 feet (275 m) in the Majors Ranch area, and locally are sharply folded along some of the faults.

No direct evidence is available for dating the faulting in the Majors Ranch area. The faults there may be related to subsidence of the San Juan Basin which began in early Tertiary time, or possibly they are related to subsidence of the Rio Grande depression which continued into Pleistocene time.

DISTRIBUTION OF MINOR ELEMENTS

Of the more than 70 samples collected, 10 samples of Jackpile sandstone and 7 of Westwater Canyon Member sandstone were selected for analysis by semiquantitative spectrographic and radiometric methods to determine the element distribution in the study area. These include red and grayish-orange sandstone from both stratigraphic units and white sandstone from the Jackpile sandstone. The samples selected were collected where deposits of uranium would most likely be found — at old prospect workings, near boundaries of abrupt changes in color, and where carbonaceous material was visible. Some samples were collected at places where uranium was considered least likely to be found.

None of the 17 samples contains more than 0.003 percent uranium and most contain less than 0.001 percent. The element distribution in no way reflects differences in color or origin of the sample in either of these stratigraphic units. When elements measured near their limit of detection are ignored, all samples from the Jackpile sandstone contain a nearly identical distribution of elements; those from the Westwater Canyon Member also contain a nearly identical distribution which differs slightly from that in the Jackpile sandstone. These analyses indicate that the element distribution in each unit is probably uniform throughout the study area and additional analyses presumably would not reveal any irregularity in distribution.

If elements measured at or very near their limit of detection are disregarded, the minor-element distribution in the Jackpile sandstone in the area of this study is very similar to that of sandstone in the Laguna district containing comparable concentrations of uranium. Also, the element distribution in the Westwater Canyon Member in the area of this study is similar to that in the Ambrosia Lake district. The analyses used for comparison are of samples which, though they contain less than 0.006 percent uranium, were collected near ore deposits in the Laguna and Ambrosia Lake districts. The close similarity of element distribution in these samples to that in samples from areas remote from known ore deposits indicates a fairly uniform pattern of element distribution in each sandstone unit over broad areas.

DISTRIBUTION OF HEAVY MINERALS

There seems to be no correlation between heavy-mineral content and color of sandstone in either the Jackpile sandstone or Westwater Canyon Member. The heavy-mineral content in 7 of 8 samples of Jackpile sandstone ranges from 0.03 to 0.11 percent and is less than 0.1 percent in most samples. One of 3 samples of red Jackpile sandstone contains 0.3 percent heavy minerals; the other 2 samples of red Jackpile sandstone contain less than 0.1 percent. Heavy-mineral content in 9 samples of Westwater Canyon Sandstone ranges from 0.04 to 0.3 percent, and in the 3 of these which are red sandstone, from less than 0.1 to 0.3 percent. Opaque minerals constitute less than half the heavy minerals in samples of Jackpile sandstone and most of these are leucoxene. Magnetite in small amounts is present in some samples, mostly as angular grains. Hematite is conspicuous in the red samples. Opaque minerals constitute more than half the heavy minerals in samples of Westwater Canyon sandstone and most of these are leucoxene. Both rounded and angular grains of magnetite occur in most samples and in slightly greater quantity than in samples of Jackpile sandstone. The angular and faceted grains of magnetite probably were inclusions in unstable minerals that were destroyed during diagenesis.

There also seems to be no correlation between heavy-mineral content and the type and amount of clay in the Jackpile sandstone. White, kaolinite-rich samples of Jackpile sandstone contain about the same amount and same kind of heavy minerals as montmorillonite-rich grayish-orange samples and as samples that contain scarcely any clay.

These data indicate that the differences in color and clay content of sandstone in the study area are not reflected in the heavy-mineral content in a manner that might give some clue to the type and intensity of alteration which produced the differences. The hematite present in the red sandstone may have been altered from magnetite, but the presence of both magnetite and hematite indicates that hematite may be the alteration product of some minerals other than magnetite.

URANIUM OCCURRENCES AND EXPLORATION

Uranium occurs in coal, carbonaceous shale, and carbonaceous sandstone near the top of La Ventana Mesa east of the settlement of La Ventana (pl. 1). The uraniferous beds are in a zone below the base of the La Ventana Tongue of the Cliff House Sandstone of Late Cretaceous age. The 132,000 short tons (120,000 metric tons) of coal and carbonaceous shale are estimated to contain an average of 0.10 percent uranium. Uranium is also known to occur in carbonaceous shales of the Dakota Sandstone east of La Ventana Mesa (Bachman and others, 1959, p. 295), and many weak radioactive anomalies were detected in these same strata at numerous places in the study area. Gabelman (1956, p. 310) described a peat bed reported to contain 1.4 percent uranium at the base of the Dakota Sandstone.

Thirty tons of ore averaging 0.12 percent U_3O_8 was mined from a sandstone bed in the Brushy Basin Member and is the only production recorded from the Morrison Formation in the study area. The mine is located 2.3 miles (3.7 km) southeast of the old CCC camp just east of New Mexico State Highway 44 about 17 miles (27 km) by road north of San Ysidro (Kittleman and Chenoweth, 1957, p. 6). Anomalous radioactivity was detected in this same area near the base of the Jackpile sandstone and near the top of the Westwater Canyon Member. Radioactive anomalies were also detected in the Morrison Formation 2 miles (3.2 km) north of the mine.

Anomalous radioactivity occurs in the lower 1–1.5 feet (0.3–0.45 m) of the Entrada Sandstone along 0.2+ mile (0.3+ km) of outcrop southwest of Cachana Springs and west of State Highway 44 (pl. 1). An indeterminate secondary yellow uranium mineral occurs as spots and films in pale-greenish-gray, chert-bearing siltstone (W. I. Finch, written commun., 1970). A sample of this material contains 0.002 percent equivalent uranium.

Many holes have been drilled in the San Ysidro–Cuba, Majors Ranch, and adjoining areas to explore for uranium deposits. Most of the holes penetrated the Westwater Canyon Member, but some were drilled only through the Jackpile sandstone. Data from 630 holes indicate that radioactive anomalies occur in the Jackpile sandstone or Westwater Canyon Member throughout most of the area explored. In a few holes weak anomalies were detected near the top of the Recapture Member and in the Mancos Shale and Dakota Sandstone.

About 2.5 miles (4 km) west of the Majors Ranch area uranium-bearing rock was intersected at several horizons in the Westwater Canyon Member and in the Jackpile sandstone. Nearly all 30 holes drilled in that area penetrated mineralized zones.

EVALUATION OF URANIUM ORE POTENTIAL

More than 20 years of exploration for uranium deposits in sandstone in the western interior of the United States has shown that many ore deposits have several characteristics in common. Almost all ore deposits occur in continental, fluvial arkosic sandstone and almost all are closely associated and interbedded with argillaceous strata that are, in part, altered volcanic ash. Uranium in most of the deposits is closely associated with organic carbonaceous material and is generally found near the interface of oxidized and unoxidized sandstone, usually in the unoxidized sandstone. The oxidized sandstone may be various shades of red, orange, and yellow and generally contains no pyrite. The unoxidized sandstone, below the zone of weathering, may be white, gray, or greenish gray. The presence or absence of some or all of these characteristics has been used in evaluating the economic potential of untested areas and in guiding exploration for uranium ore deposits.

Many of the characteristics associated with uranium ore deposits in sandstone are common in the area of this study. Most of the sandstone in the Morrison Formation above the Recapture Member is arkosic. The arkosic sandstone is, moreover, mainly white, gray or greenish gray below the zone of weathering. Red sandstone occurs in a large area north of lat 35°40′ N. (pl.1), and indeed some uraniferous sandstone was mined in an area where an interface between oxidized and unoxidized sandstone is exposed. The interface between red sandstone and weathered gray sandstone which is exposed north of Cachana Spring almost certainly extends to the north in the subsurface. A good target area for exploration would be along that northward extension.

The Brushy Basin Member intertongues with the lower part of the Jackpile sandstone and with the upper part of the Westwater Canyon Member and is composed chiefly of greenish-gray argillaceous strata. Similar strata are interbedded with sandstone in the Westwater Canyon Member. Shard structures in these strata attest to their volcanic origin (Shawe, 1968, p. B29; Keller, 1962, p. 58; Waters and Granger, 1953, p. 6).

In the Ambrosia Lake district carbonaceous material is considerably less abundant in exposures of Morrison sandstone than in the subsurface. In the study area, too, very little carbonaceous material exists in exposures of the Morrison. Several nonradioactive occurrences were noted during the course of this study, and Kittleman and Chenoweth (1957, p. 9) described an occurrence of what they called asphaltite. But, as in the Ambrosia Lake district, the amount of carbonaceous material at the surface does not necessarily reflect the amount at depth, where large amounts could conceivably be present.

Granger, Santos, Dean, and Moore (1961, p. 1197) listed three possible sources for the carbonaceous material in the Ambrosia Lake ores: (1) water-soluble humic compounds derived from highly vegetated swamps that covered Morrison during deposition of the Dakota Sandstone, (2) streams that transported dissolved humic compounds from vegetated areas in the headwaters during Morrison deposition, and (3) water-soluble humic compounds derived from debris that was trapped in the Morrison sands. They favored the first-listed possibility. The same three sources could have supplied carbonaceous material to the Morrison sands in the area of this report.

Black shales representing swampy conditions are abundant in the area of this report where they rest directly on the Jackpile sandstone. Elsewhere, probably to the south where the pre-Dakota erosion surface truncates successively older strata, black shales may have been in contact with Morrison sands older than the Jackpile. An excellent source is thus available to supply carbonaceous material to the arkosic sandstone.

The apparent paucity of uranium ore deposits in the study area may be related in some way to the differences (p. 10, 14) between units of the Morrison Formation there and the equivalent units in the Ambrosia Lake and Laguna districts. Variations in properties of the sandstone in the several areas involved include a slight difference in grain size, degree of sorting, thickness, and differences in type and orientation of crossbedding. Any attempt to demonstrate how differences in these properties, singly or in combination, might preclude the possibility of ore deposition is subject to many serious objections.

The orientation of crossbeds in the Jackpile sandstone suggests different source areas. A uranium-poor source area may have supplied detritus to the area of this study and this could account for the absence of ore deposits. The similarities in most of the other properties of this unit in the Laguna district and the area of this study do not support the idea of different source areas.

If no ore deposits exist in the study area, their absence is most likely due to a possible absence of carbonaceous material to precipitate uranium from solution. Although sources are available for carbonaceous material, the conditions under which water-soluble humates precipitate may never have existed there.

Despite the lack of success of exploration to date, the close similarity of many features in the area of this study to those in known producing areas indicates that further exploration is warranted. The radioactive anomalies detected in the Recapture Member, the Dakota Sandstone, and the Mancos Shale together with the reported occurrences of uranium in the Entrada Sandstone, Morrison Formation, Dakota Sandstone, and the Mesaverde Group in the study area indicate that uranium-bearing solutions have permeated the strata here. Of particular interest is the discovery of ore-grade material in both the Jackpile and Westwater Canyon sandstone just 2.5 miles (4 km) west of the Majors Ranch area.

REFERENCES CITED

Bachman, G. O., Vine, J. D., Read, C. B., and Moore, G. W., 1959, Uranium-bearing coal and carbonaceous shale in the La Ventana Mesa area, Sandoval County, New Mexico, *in* Uranium in coal in the western United States: U.S. Geol. Survey Bull. 1055, p. 295–307.

Baltz, E. H., 1967, Stratigraphy and regional tectonic implications of part of Upper Cretaceous and Tertiary rocks, east-central San Juan Basin, New Mexico: U.S. Geol. Survey Prof. Paper 552, 101 p.

Craig, L. C., 1959, Measured sections of Morrison and adjacent formations: U.S. Geol. Survey open-file report.

Craig, L. C., and others, 1955, Stratigraphy of the Morrison and related formations, Colorado Plateau region, a preliminary report: U.S. Geol. Survey Bull. 1009-E, p. 125–168.

Dane, C. H., 1960, The boundary between rocks of Carlile and Niobrara age in San Juan Basin, New Mexico and Colorado: Am. Jour. Sci., v. 258A (Bradley volume), p. 46–56.

Dane, C. H., Landis, E. R., and Cobban, W. A., 1971, The Twowells Sandstone Tongue of the Dakota Sandstone and the Tres Hermanos Sandstone as used by Herrick (1900), western New Mexico, *in* Geological Survey research 1971: U.S. Geol. Survey Prof. Paper 750–B, p. B17–B22.

Freeman, V. L., and Hilpert, L. S., 1956, Stratigraphy of the Morrison formation in part of northwestern New Mexico: U.S. Geol. Survey Bull. 1030-J, p. 309–334.

Gabelman, J. W., 1956, Uranium deposits in paludal black shales, Dakota sandstone, San Juan Basin, New Mexico, *in* Page, L. R., Stocking, H. E., and Smith, H. B., compilers, Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations International Conference on Peaceful Uses of Atomic Energy, Geneva, Switzerland, 1955: U.S. Geol. Survey Prof. Paper 300, p. 303–319.

Goddard, E. N., and others, 1948, Rock-color chart: Washington, D. C., Natl. Research Council.

Granger, H. C., 1962, Clay minerals in the Morrison Formation and their spatial relation to the uranium deposits at Ambrosia Lake, New Mexico, *in* Short papers in geology, hydrology, and topography: U.S. Geol. Survey Prof. Paper 450-D, p. D15–D20.

Granger, H. C., Santos, E. S., Dean, B. G., and Moore, F. B., 1961, Sandstone-type urnaium deposits at Ambrosia Lake, New Mexico — and interim report: Econ. Geology, v. 56, no. 7, p. 1179–1210.

Harshbarger, J. W., Repenning, C. A., and Irwin, J. H., 1957, Stratigraphy of the uppermost Triassic and Jurassic rocks of the Navajo country [Colorado Plateau]: U.S. Geol. Survey Prof. Paper 291, 74 p.

Hilpert, L. S., 1969, Uranium resources of northwestern New Mexico: U.S. Geol. Survey Prof. Paper 603, 166 p.

Keller, W. D., 1962, Clay minerals in the Morrison Formation of the Colorado Plateau: U.S. Geol. Survey Bull. 1150, 90 p.

Kittleman, L. R., and Chenoweth, W. L., 1957, Uranium occurrences on the Goodner lease, Sandoval County, New Mexico: U.S. Atomic Energy Comm. TM-184, open-file report, 12 p., Grand Junction, Colo.

Leopold, L. B., 1943, Climatic character of the interval between the Jurassic and Cretaceous in New Mexico and Arizona: Jour. Geology, v. 51, no. 1, p. 56–62.

Moench, R. H., and Schlee, J. S., 1967, Geology and uranium deposits of the Laguna district, New Mexico: U.S. Geol. Survey Prof. Paper 519, 117 p.

Moench, R. H., Schlee, J. S., and Bryan, W. B., 1965, Geologic map of the La Gotera quadrangle, New Mexico: U.S. Geol. Survey Geol. Quad. Map GQ-371.

Muehlberger, W. R., 1967, Geology of Chama quadrangle, New Mexico: New Mexico Bur. Mines and Mineral Resources Bull. 89, 113 p.

Renick, B. C., 1931, Geology and ground-water resources of western Sandoval County, New Mexico: U.S. Geol. Survey Water-Supply Paper 620, 117 p.

Santos, E. S., 1970, Stratigraphy of the Morrison Formation and structure of the Ambrosia Lake district, New Mexico: U.S. Geol. Survey Bull. 1272-E, 30 p.

Santos, E. S., and Moench, R. H., 1971, Measured sections of the Morrison Formation and related rocks in northwestern New Mexico: U.S. Geol. Survey open-file report.

Schlee, J. S., and Moench, R. H., 1961, Properties and genesis of the "Jackpile" sandstone, Laguna, New Mexico, *in* Peterson, J. A., and Osmond, J. C., eds., Geometry of sandstone bodies: Tulsa, Am. Assoc. Petroleum Geologists, p. 134–150.

Shawe, D. R., 1968, Petrography of sedimentary rocks in the Slick Rock district, San Miguel and Dolores Counties, Colorado: U.S. Geol. Survey Prof. Paper 576-B, 34 p.

Smith, C. T., Budding, A. J., and Pitrat, C. W., 1961, Geology of the southeastern part of the Chama Basin: New Mexico Bur. Mines and Mineral Resources Bull. 31, 57 p.

Waters, A. C., and Granger, H. C., 1953, Volcanic debris in uraniferous sandstones and its possible bearing on the origin and precipitation of uranium: U.S. Geol. Survey Circ. 224, 26 p.

Wood, G. H., and Northrop, S. A., 1946, Geology of the Nacimiento Mountains, San Pedro Mountains, and adjacent plateaus in parts of Sandoval and Rio Arriba Counties, New Mexico: U.S. Geol. Survey Oil and Gas Inv. Map 57.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1975—677-308/32