

# New Mexico Geological Society

Downloaded from: <https://nmgs.nmt.edu/publications/guidebooks/54>



## *Economic geology of the Todilto Formation*

William R. Berglof and Virginia T. McLemore  
2003, pp. 179-189. <https://doi.org/10.56577/FFC-54.179>

*in:*  
*Geology of the Zuni Plateau*, Lucas, Spencer G.; Semken, Steven C.; Berglof, William; Ulmer-Scholle, Dana; [eds.],  
New Mexico Geological Society 54<sup>th</sup> Annual Fall Field Conference Guidebook, 425 p.  
<https://doi.org/10.56577/FFC-54>

---

*This is one of many related papers that were included in the 2003 NMGS Fall Field Conference Guidebook.*

---

## **Annual NMGS Fall Field Conference Guidebooks**

Every fall since 1950, the New Mexico Geological Society (NMGS) has held an annual [Fall Field Conference](#) that explores some region of New Mexico (or surrounding states). Always well attended, these conferences provide a guidebook to participants. Besides detailed road logs, the guidebooks contain many well written, edited, and peer-reviewed geoscience papers. These books have set the national standard for geologic guidebooks and are an essential geologic reference for anyone working in or around New Mexico.

### **Free Downloads**

NMGS has decided to make peer-reviewed papers from our Fall Field Conference guidebooks available for free download. This is in keeping with our mission of promoting interest, research, and cooperation regarding geology in New Mexico. However, guidebook sales represent a significant proportion of our operating budget. Therefore, only *research papers* are available for download. *Road logs*, *mini-papers*, and other selected content are available only in print for recent guidebooks.

### **Copyright Information**

Publications of the New Mexico Geological Society, printed and electronic, are protected by the copyright laws of the United States. No material from the NMGS website, or printed and electronic publications, may be reprinted or redistributed without NMGS permission. Contact us for permission to reprint portions of any of our publications.

One printed copy of any materials from the NMGS website or our print and electronic publications may be made for individual use without our permission. Teachers and students may make unlimited copies for educational use. Any other use of these materials requires explicit permission.

*This page is intentionally left blank to maintain order of facing pages.*

## ECONOMIC GEOLOGY OF THE TODILTO FORMATION

WILLIAM R. BERGLOF<sup>1</sup> AND VIRGINIA T. MCLEMORE<sup>2</sup>

<sup>1</sup>University of Maryland University College - Asia, Unit 5060 Box 0100, APO AP 96328-0100; <sup>2</sup>New Mexico Bureau of Geology and Mineral Resources, New Mexico Tech, 801 Leroy Place, Socorro, NM 87801

**ABSTRACT.**—The Jurassic Todilto Formation of northern New Mexico and southern Colorado is a distinctive lithostratigraphic unit in the San Juan Basin. It consists mostly of carbonates and evaporites in a thick section otherwise dominated by siliciclastic eolianites. The Todilto has broad and diverse economic importance in New Mexico. Limestone of the lower Luciano Mesa Member is the host for important uranium deposits, mostly north and west of Grants. Uranium was also produced from the Todilto near Laguna, with extremely minor production from elsewhere in the San Juan Basin. The Todilto uranium deposits are the largest known uranium deposits in limestone in the world, and appear to reflect a rare combination of circumstances. Intraformational folds in the Todilto, many of which localize uranium deposits, also appear to represent a somewhat unlikely combination of multiple origins; it is difficult to establish the relative importance of each process. Other commodities are produced from the Todilto Formation. Gypsum is produced from the upper Tonque Arroyo Member of the Todilto, which is more restricted in its occurrence than the limestone member. It has been quarried at several locations, with current production at White Mesa, near San Ysidro. At Cedar Crest, east of Albuquerque, the gypsum is sufficiently massive to be used as a raw material for sculpture, and is known to sculptors as Cedar Crest alabaster. Another product is limestone, produced from the lower Luciano Mesa Member. Most limestone quarries are in the Todilto outcrop belt between Gallup and Grants, with intermittent current production. The Todilto is believed to be the source rock for petroleum produced from the Entrada Sandstone in the San Juan Basin. Geologic hazards associated with mining in the Todilto Formation are not well documented, but presumed minimal, with the exception of local surface land subsidence in the Ambrosia Lake area. Indoor radon associated with uranium deposits in the Todilto is a potential hazard, but most of the known deposits and mines are in sparsely populated areas.

### INTRODUCTION

The Jurassic Todilto Formation is a widespread and distinctive lithostratigraphic unit in northern New Mexico and southwestern Colorado. The Todilto Formation overlies the Entrada Sandstone and is overlain by coastal plain and tidal flat deposits of the Summerville or Wanakah Formation. It was deposited within a Jurassic basin that occupied much of the present San Juan Basin and extended into northeastern New Mexico and southwestern Colorado (Fig. 1). It is correlated with the Pony Express Limestone Member of the Wanakah Formation in Colorado and the Curtis Formation in Utah (Green, 1982). This correlation has led some geologists to suggest that the Todilto Formation be reduced in rank to a member, a concept not accepted by the authors and by other geologists working in the southwestern United States. Therefore, the Todilto Formation will be considered a formation in this report.

The Todilto Formation includes a basal limestone, the Luciano Mesa Member (Lucas et al., 1995), consisting mostly of microlaminated, kerogenic limestone, which is 2-13 m thick, and is present everywhere in the Todilto depositional basin. This unit consists of three zones: a basal platy or laminated zone (2-5 m thick), a crinkly or crenulated zone (1-3 m thick), and an upper massive zone (from near zero to 2-5 m thick). This member crops out over an extensive area of northern New Mexico as well as part of southwestern Colorado. The more restricted Tonque Arroyo Member (Lucas et al., 1995) is largely gypsum, with anhydrite present in the subsurface, and reaches a maximum thickness of 61 m. It has a more limited outcrop belt (Fig. 1), varies widely in thickness, with numerous local pinchouts, and is absent in several areas where the limestone is well exposed, such as the area west of Grants where most of the known Todilto uranium deposits are found.

Todilto deposition took place during a short interval of Middle Jurassic time in a paralic salina with a maximum surface area of 88,000 km<sup>2</sup>, culminated by a gypsiferous evaporitic lake (Fig. 1; Lucas et al., 1985; Kirkland et al., 1995; Lucas and Anderson, 1996, 2000). The salina deposits are represented by the lower, limestone member (Luciano Mesa Member of Lucas et al., 1995) and the evaporitic lake deposits comprise the upper, gypsum member (Tonque Arroyo Member of Lucas et al., 1995).

As applied to the Todilto, the salina concept envisions an isolated or nearly isolated coastal body of saline water (brine-pool) that received both marine and non-marine water (Denison et al., 1998). This concept was developed in detail by Lucas et al. (1985), and has subsequently been supported by Kirkland et al. (1995) as well as by Denison et al. (1998), based in part on strontium isotope studies.

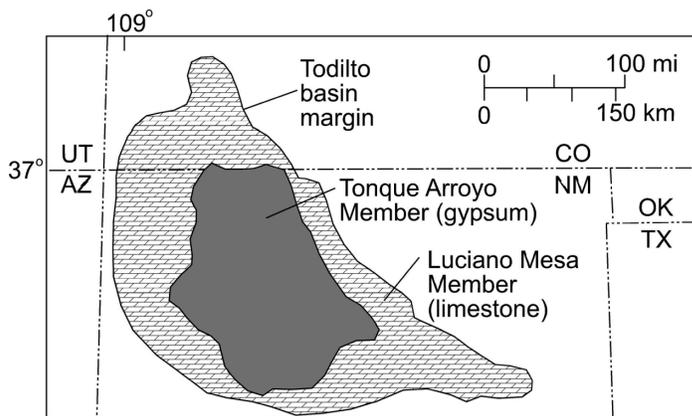


FIGURE 1. Depositional extent of the Todilto Formation in the San Juan Basin (after Lucas and Anderson, 2000).

## MINERAL RESOURCES

## Uranium

The Grants uranium district is well known for large resources of sandstone- and limestone-hosted uranium deposits (Fig. 2; McLaughlin, 1963; McLemore and Chenoweth, 1989; McLemore et al., 2002a; McLemore and Chenoweth, this guidebook). More than 100 uranium mines and occurrences are found in the Todilto Formation in New Mexico; 42 mines have yielded uranium production (McLemore, 1983; McLemore et al., 2002a). Most of these are in the Grants and Laguna districts, although minor occurrences are found in the Chama Basin (Abiquiu), Nacimiento Mountains, and Sanostee district in the Chuska Mountains. Mineralization extends into the underlying Entrada Sandstone or overlying Summerville Formation in a few areas. Uranium is found in the Todilto Formation only where the gypsum-anhydrite member is absent (Hilpert, 1969), most likely as a result of non-deposition. Numerous drill holes exceeding depths of 1000 ft in the Ambrosia Lake area of the Grants district encountered uranium minerals in the Todilto (McLemore, 1983).

Uranium minerals were observed in the Todilto Formation in the early 1920s, before the beginning of uranium mining in the Grants district. From 1950 through 1981, mines in the Grants district yielded 3,335.76 tons of  $U_3O_8$  from the Todilto Formation, amounting to slightly more than 2% of the total uranium produced from the entire Grants mining district (Table 1; Chenoweth, 1985; McLemore and Chenoweth, 1989). Uranium has

TABLE 1. Uranium production from the Todilto Formation, Grants district (Chenoweth, 1985). Figures are in tons  $U_3O_8$  in ore; w = withheld due to the limited number of operators. Totals reflect the withheld data.

YEAR	CIBOLA COUNTY	McKINLEY COUNTY	TOTAL
1950	0.03	—	0.03
1951	0.10	0.06	0.16
1952	3.49	22.91	26.40
1953	26.69	72.42	99.11
1954	53.61	145.77	199.38
1955	60.68	170.70	231.38
1956	43.67	152.09	195.76
1957	37.71	154.93	192.64
1958	85.98	158.06	244.04
1959	64.81	228.57	293.38
1960	9.07	198.87	207.94
1961	5.49	158.85	164.34
1962	13.28	131.59	144.87
1963	4.20	84.54	88.74
1964	3.35	75.05	78.40
1965	3.21	56.74	59.95
1966	0.04	57.71	57.75
1967	1.11	5.16	6.27
1968	—	8.10	8.10
1969	—	1.38	1.38
1970	—	13.65	13.65
1971	w	w	7.76
1972	w	w	74.25
1973	w	w	97.80
1974	w	w	65.33
1975	w	w	57.35
1976	w	w	77.28
1977	w	w	118.09
1978	—	149.46	149.46
1979	—	162.08	162.08
1980	—	153.60	153.60
1981	—	59.09	59.09
<b>TOTAL</b>	<b>698.40</b>	<b>2637.36</b>	<b>3335.76</b>

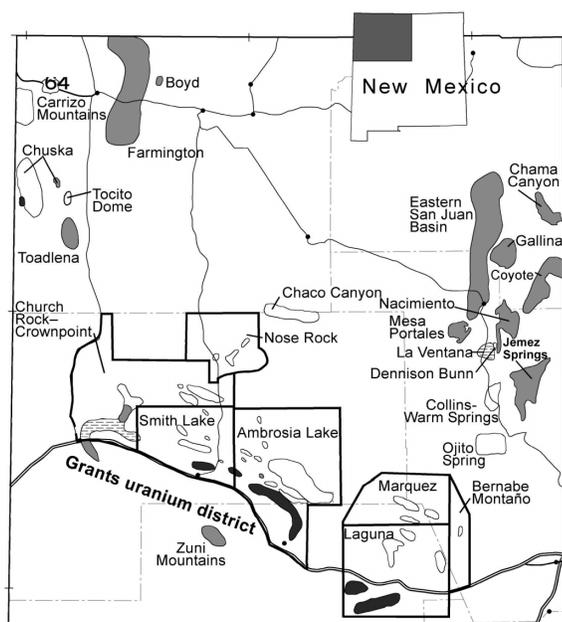


FIGURE 2. Uranium in the San Juan Basin, New Mexico (from McLemore and Chenoweth, 1989; McLemore, 2002).

not been produced from the Todilto Formation since 1981, and data describing the distribution and occurrence of uranium in the Todilto are widely scattered in published and unpublished reports and in company archives.

Uranium deposits in limestones are rare. Limestone is typically an unfavorable host rock for uranium because of low permeability and porosity and lack of suitable precipitants, such as organic mate-

rial. Uranium is found only in a few limestones in the world (Table 2), but the deposits in the Todilto are the largest and most productive. A set of unusual geological circumstances apparently allowed the formation of uranium deposits in the Todilto Formation.

The first uranium deposits discovered and mined consisted mostly of brightly-colored yellow minerals such as tyuyamunite, metatyuyamunite, and uranophane. Subsequently significant quantities of "black ore" containing uraninite (pitchblende), coffinite, and subsidiary vanadium oxide minerals were discovered as mining progressed. It became evident that the yellow minerals had formed by secondary near-surface oxidation (i.e., supergene alteration) of the primary black ores. Yellow minerals are rare to absent in the deeper mines. Lead-uranium isotopic dating of uraninite indicates that it formed shortly after the limestone was deposited; the yellow minerals formed at various later times (Berglof, 1992; Brookins, 1981b). A few deposits extend into the Entrada Sandstone, immediately below the Todilto, with uraninite filling pore spaces between sand grains.

#### Description of uranium-vanadium minerals

Uraninite is the predominant ore mineral in primary, unoxidized Todilto deposits, along with coffinite, fluorite, barite, hematite, and blue-black vanadium minerals such as paramontroseite and haggite (Table 3). Where the deposits have been oxidized, as in those found close to the surface, brightly-colored yellow tyuyamunite, metatyuyamunite, and uranophane are important ore minerals. Carnotite is not abundant in Todilto deposits; tyuyamunite and metatyuyamunite form preferentially in the high-calcium limestone environment.

Uraninite occurs in disseminations, blebs, and replacements along bedding planes and fractures, and may be irregularly disseminated throughout mineralized limestone. Locally, uraninite forms rims around pyrite and detrital grains within the limestone (Laverty and Gross, 1956). Where uraninite is abundant, the limestone may appear red from associated fine-grained hematite. Uraninite may be surrounded by a halo of yellow to orange supergene uranium minerals. The common amorphous or microcrystalline form of uraninite is pitchblende; it is found in most deposits.

TABLE 2. Areas in the world containing uranium deposits in limestones.

LOCATION	FORMATION	REFERENCES
Ferghana, Turkestan	Tyuya Muyun	Heinrich (1958)
Grants, New Mexico	Todilto Formation	Numerous
Sierra de Gomez, Sierra Blanca, Sierra de la Cal; Chihuahua and Durango, Mexico	Georgetown	Gabelman and Krusiewski (1967)
Pryor and Bighorn Mountains, Montana and Wyoming	Madison	Hart (1958)
Missouri	St. Genevieve	Gott et al. (1952), Gabelman (1956)

Coffinite is a less common primary uranium mineral and typically occurs as massive, brown to black replacements of the limestone. It is usually associated with uraninite, pyrite, and vanadium minerals; where it is found near the surface it is oxidized to form the yellow secondary gene minerals. Truesdell and Weeks (1960) note that it is not associated with fluorite-bearing uranium ore.

Paramontroseite is blue-black when collected underground. It occurs along fractures with abundant coarse calcite and minor barite. Botryoidal forms are found at the Flat Top and Barbara J #2 mines. At the Flat Top mine, thin veins, approximately 30-60 cm long and up to 1-2 cm thick, occur along the east limb of a north-trending fold in the massive limestone member. Haggite closely resembles paramontroseite.

Tyuyamunite occurs along with the related lower hydrate metatyuyamunite; the minerals differ in their water content and form reversibly from each other. The change from tyuyamunite to metatyuyamunite is readily observable in the laboratory and probably occurs frequently in nature depending on humidity conditions. The two minerals cannot be distinguished from each other in the field. Both minerals are calcium-bearing analogs of the well-known carnotite, which is common in many sandstone-type uranium deposits, and closely resemble it. Tyuyamunite and metatyuyamunite occur as massive to small scales, laths, and radial aggregates along fractures in the limestone. They are abundant in thin but conspicuous coatings on fractures and bedding surfaces in the limestone, and locally as platy crystals or in powdery masses. These yellow to green uranium minerals are the supergene alteration products of the primary uranium minerals and are common near the surface.

Uranophane is probably next in importance economically to uraninite and tyuyamunite, although it is not as abundant. It is a supergene alteration product of the primary uranium minerals. Uranophane occurs as yellow, finely-crystalline felted aggregates, bundles of acicular crystals, or as rosettes of megascopic acicular crystals. It typically coats fractures and locally bedding planes as radiating clusters of acicular crystals, and locally as thicker felted masses or showy acicular crystals in open spaces. It is most abundant in oxidized Todilto deposits that are low in vanadium. Beta-uranophane is suspected of occurring with uranophane, but has not been confirmed (Weeks and Thompson, 1954).

Boltwoodite is reported to occur in the Todilto deposits, but no additional information is given (Honea, 1961).

Schrockerite is rare in oxidized ore, but is locally an ore mineral. It occurs as light-green platy crystals, which fluoresce brilliant yellow-green in short-wave ultraviolet radiation. It also occurs as yellow, powdery to waxy impregnations and fracture coatings. Micaceous plates are locally common along fracture surfaces.

Curite is a rare yellow-orange to orange-red uranium mineral that occurs in fractures as thin aggregates. In the Section 25 shaft (sec. 25, T13N, R10W), south of the main haulage drift in a crosscut, curite occurred in a fracture as very small aggregates encrusting 5 mm calcite crystals, associated with uranophane (NMBGMR sample, collected by W. R. Berglof).

Hewettite and metahebettite are rare vanadium minerals that occur along fracture surfaces as fragile fibrous laths, bladed

TABLE 3. Minerals in the Todilto Formation uranium deposits. Additional minerals reported in the Todilto deposits, but where identification is not confirmed, include: jordisite, carnotite, autunite, rauvite, and uvanite. \* Samples at NMBMMR.

MINERAL	CHEMICAL FORMULA	COLOR	LUSTER	COMMON CRYSTAL FORM IN TODILTO DEPOSITS	CRYSTAL CLASS
uraninite (pitchblende)*	UO <sub>2</sub>	black	submetallic to dull	massive to botryoidal, impregnations	isometric to amorphous
coffinite	U(SiO <sub>4</sub> ) <sub>1-x</sub> (OH) <sub>4x</sub>	black to brown	dull to adamantine	massive	tetragonal
montroseite (diaspore group)	(V,Fe)O(OH)	black	submetallic	blades	orthorhombic
paramontroseite (diaspore group)	VO <sub>2</sub>	black	submetallic	blades	orthorhombic
håggite	V <sub>2</sub> O <sub>2</sub> (OH) <sub>3</sub>	black to brown	dull	fibrous, blades	monoclinic
tyuyamunite*	Ca(UO <sub>2</sub> ) <sub>2</sub> (VO <sub>4</sub> ) <sub>2</sub> ·5-8½H <sub>2</sub> O	canary yellow to green	adamantine to waxy	radial aggregates, thin coatings, massive	orthorhombic
metatyuyamunite*	Ca(UO <sub>2</sub> ) <sub>2</sub> (VO <sub>4</sub> ) <sub>2</sub> ·3-5H <sub>2</sub> O	canary yellow to green	adamantine to waxy	radial aggregates, thin coatings	orthorhombic
uranophane*	Ca(UO <sub>2</sub> ) <sub>2</sub> (SiO <sub>3</sub> OH) <sub>2</sub> ·5H <sub>2</sub> O	yellow	vitreous to dull to greasy	blades, massive, fibrous	monoclinic
schroëckingerite	NaCa <sub>3</sub> UO <sub>2</sub> (CO <sub>3</sub> ) <sub>3</sub> SO <sub>4</sub> F·10H <sub>2</sub> O	yellow to green	vitreous to waxy	coatings, impregnations, micaceous plates	orthorhombic
curite*	Pb <sub>2</sub> U <sub>5</sub> O <sub>17</sub> ·4H <sub>2</sub> O	yellow to orange-red	yellow-orange to orange-red	vitreous	small blades
hewettite	CaV <sub>6</sub> O <sub>16</sub> ·9H <sub>2</sub> O	red	vitreous to silky to dull	fibers, needles, laths, coatings	monoclinic
metahewettite*	CaV <sub>6</sub> O <sub>16</sub> ·3H <sub>2</sub> O	red	vitreous to silky to dull	fibers, needles, laths, coatings	orthorhombic
santafeite*	(Mn,Fe,Al,Mg) <sub>8</sub> Mn <sub>8</sub> (Ca,Sr,Na) <sub>12</sub> (VO <sub>4</sub> ) <sub>16</sub> (OH,OH <sub>2</sub> ) <sub>20</sub> ·8H <sub>2</sub> O	black to brown	black, subadamantine	acicular crystal rosettes	orthorhombic
cuprosklodowskite*	Cu(UO <sub>2</sub> ) <sub>2</sub> Si <sub>2</sub> O <sub>7</sub> ·6H <sub>2</sub> O	yellow to green	dull	flecks on santafeite	orthorhombic
grantsite	Na <sub>4</sub> CaV <sub>12</sub> O <sub>32</sub> ·8H <sub>2</sub> O	green to black	subadamantine	fibrous, blades	monoclinic
goldmanite (garnet group)	Ca <sub>3</sub> (V,Fe,Al) <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>	green to brown-green	vitreous to dull	anhedral grains, dodecahedrons	hexagonal
rutherfordine	UO <sub>2</sub> CO <sub>3</sub>	yellow	dull	fibrous	orthorhombic
sklodowskite	Mg(UO <sub>2</sub> ) <sub>2</sub> Si <sub>2</sub> O <sub>7</sub> ·6H <sub>2</sub> O	yellow	vitreous	needles	orthorhombic
calcite*	CaCO <sub>3</sub>	white to black to clear	vitreous to dull	rhombohedron, massive, blades	hexagonal
fluorite*	CaF <sub>2</sub>	purple to clear	vitreous	massive	cubic
barite*	BaSO <sub>4</sub>	brown	vitreous to dull	massive, bladed	orthorhombic
pyrite*	FeS <sub>2</sub>	brassy yellow, brown-red	metallic	blebs to cubic disseminations	cubic
marcasite	FeS <sub>2</sub>	brassy yellow	metallic		
hematite*	Fe <sub>2</sub> O <sub>3</sub>	red to reddish brown	earthy	massive, pseudomorph cubic after pyrite	hexagonal
galena	PbS	gray	metallic	blebs	cubic
quartz	SiO <sub>2</sub>	white to clear	vitreous	small crystals	hexagonal

aggregates, or coatings, most abundantly at the F-33 mine, sec. 33, T12N, R9W. A sample at the NMBGMR is an earthy, fragile fibrous aggregate, probably formed in fractures or void spaces. Lovering (1956) also reported these minerals.

A small amount of santafeite was found as a new mineral in a limited area of sec. 25 and 26, T13N, R10W, near an area of prior uranium mining (Sun and Weber, 1958; Dunn and Peacor, 1986), and was initially thought to be ardenite. These two minerals are in fact closely related, having similarities in crystal chemistry, and are difficult to distinguish from one another (Moore et al., 1985). Santafeite occurs as small rosettes, 2-3 mm across, and as radially dispersed, acicular, black to brown crystals. Yellow-green cuprosklodowskite occurs as small flecks on the santafeite (Sun and Weber, 1955).

Goldmanite, discovered as a new mineral, is a vanadium-rich garnet related to andradite and grossular; it occurs at the Sandy mine in the Laguna area (Moench and Schlee, 1967) where a uranium-vanadium deposit in the Todilto Formation and Entrada Sandstone was intruded by a basaltic sill of probable late Tertiary age (Moench and Meyrowitz, 1964). Small crystals of goldmanite formed in vanadium-rich zones of the metamorphosed deposit. Subsequent to its discovery, goldmanite and related vanadium-bearing garnets have been found in at least 20 localities around the world in a wide variety of geological environments (e.g., references in Uher et al., 1994); these include the Franklin Marble, adjacent to the zinc ore deposits at Sterling Hill, New Jersey (Dunn and Frondel, 1990). It is also known from the Leoville carbonaceous chondrite (Simon and Grossman, 1992), the first reported occurrence in a meteorite.

Doloresite, a black vanadium mineral often showing a bronze-like tarnish, is reported to occur in Todilto deposits in sec. 33, T12N, R9W (Stern et al., 1957). Rutherfordine occurs as yellow masses of matted fibers (Lovering, 1956; Northrop, 1959). It is a rare supergene alteration of uraninite. Sklodowskite occurs as rare lemon-yellow needles in Todilto deposits (Lovering, 1956; Everhart, 1951; Northrop, 1959).

A black, shiny, vitreous mineral was found in the 8810 stope of Anaconda's F-33 mine (S. R. Austin, unpubl. U.S. Atomic Energy Commission petrographic report, 1959). The mineral is found with calcite. Petrographic studies indicate that it is a molybdenum sulfide, probably jordisite.

Carnotite has been reported frequently, generally by visual examination. Much of the early literature referred, incorrectly, to the Todilto ore as carnotite ore. However, the predominant yellow mineral referred to as carnotite is usually tyuyamunite or metatyuyamunite. Carnotite may occur in the Todilto deposits, but it is not usually found in carbonate hosts (Northrop, 1959).

Autunite was reported by Rapaport (1955), but only by visual identification. The material may have been schroëckingerite, which has been positively identified in the Todilto.

Rauvite and uvanite are uranium vanadates that have been reported to occur in Todilto deposits, but have not been confirmed (Rapaport, 1955; Northrop, 1959).

Grantsite was discovered as a new greenish-black vanadium mineral in the F-33 deposit in sec. 33 and 34, T12N, R9W, and at three additional localities in Colorado and Utah (Weeks et al.,

1964). It has apparently not been recognized elsewhere since the original discoveries.

### Description of gangue minerals

Coarsely crystalline black calcite and paragenetically later white calcite are common in fractures and open spaces.

Fluorite occurs as very small crystals (less than 2-3 mm across) and fine-grained irregular replacements; known occurrences are roughly coextensive with uranium minerals, and probably are not related to fluorite vein deposits in the nearby Zuni Mountains mining district. Purple to purple-black fluorite is common, but some workers (Rapaport, 1952) report clear fluorite. Fluorite and uraninite are intergrown in some areas (Peters, 1956; Laverty and Gross, 1956); fluorite is locally cut by later calcite and late fluorite is zoned (Laverty and Gross, 1956).

Blades of clear to smoky brown barite are common in mineralized zones, and, like fluorite, known barite occurrences are roughly coextensive with uranium deposits.

Pyrite is common as an accessory mineral, and is infrequently observed coating scalenohedral calcite crystals.

Hematite is one of the more common iron oxide minerals found in the Todilto deposits, occurring as massive disseminations or as pseudomorphic cubes, 0.3-1 mm across, after pyrite (Rapaport, 1952). Hematite is often associated with concentrations of uraninite, and thus high-grade uraninite ore may appear distinctly red. Cryptomelane and psilomelane are also known as minor accessory minerals.

Microscopic galena crystals are associated with high-grade uraninite; much of the lead in the galena may have been derived from decay of uranium.

### Paragenesis

The Flat Top mine was one of the few Todilto mines studied in detail (Gabelman, 1970). The primary mineralization stage occurred with the deposition of (early to late) hematite, manganese oxides, pyrite, fluorite, barite, vanadium oxides, pitchblende and coffinite, and a late pyrite. Late mineralization consisted of large calcite, hematite, and manganese minerals, and was followed by supergene alteration to yellow uranium minerals.

A similar sequence is described from the Barbara J #1 mine (Gabelman and Boyer, 1988). Primary mineralization consists of pitchblende and coffinite with (in order of abundance) calcite, manganese oxides, hematite, fluorite, barite, and pyrite. Supergene alteration formed tyuyamunite and uranophane.

At the La Jara mine calcite was deposited first, followed by uraninite and vanadium clay replacing the calcite. Subsequently, montroseite and tyuyamunite were deposited along the rims of the clay minerals and as fracture fillings (E. B. Gross, unpubl. U.S. Atomic Energy Commission petrographic report, 1958).

To summarize the sequence of events, deposition of limestone was followed by folding and fracturing which produced permeability in the limestone. Recrystallization, additional fracturing, and dissolution of the limestone occurred. An early stage of fluids deposited chlorite, dolomite, and illite in the fractures and was probably accompanied by additional dissolution. The primary mineralization stage occurred next with deposition of early

fluorite and pyrite, followed by deposition of uraninite and coffinite, locally intergrown with pyrite, barite, and fluorite. Pyrite, barite, and fluorite also occur along fractures and bedding planes in barren limestone within several feet of the uranium ore bodies. This stage was followed by deposition of calcite, barite, vanadium clay minerals, and pyrite. Iron and manganese oxides were deposited as the fluids were depleted in uranium and vanadium. Supergene alteration to yellow and green uranium minerals occurred at various times following the primary mineralization.

### Structure

Mineable uranium ore bodies in the Todilto are generally localized along folds that are predominantly intraformational, ranging widely in size and geometry (Fig. 3). Several types of folds and fold-like structures, on different scales, are present within the Todilto in the Grants uranium district; not all are known to have influenced the location of uranium mineralization. These include: regional large-scale folds affecting the Todilto and units above and below it; large-scale intraformational folds with mappable axes (Fig. 3); mounds or pillow-like structures within the limestone; and several types of small-scale intraformational folds. The latter include sharp folding of varve-like thin bedding; within-layer folds resembling those described elsewhere as “enterolithic”; and microfolding of thin layers, including the “crinkly” bedding common in the middle and upper portions of the Luciano Mesa Member of the Todilto. The large-scale intraformational folds have clearly influenced the location of uranium deposits in the Todilto, presumably by providing zones of permeability through which mineralizing solutions moved. Not all of the folds are mineralized, but almost all primary uranium deposits in the Todilto are associated with the folds. Many

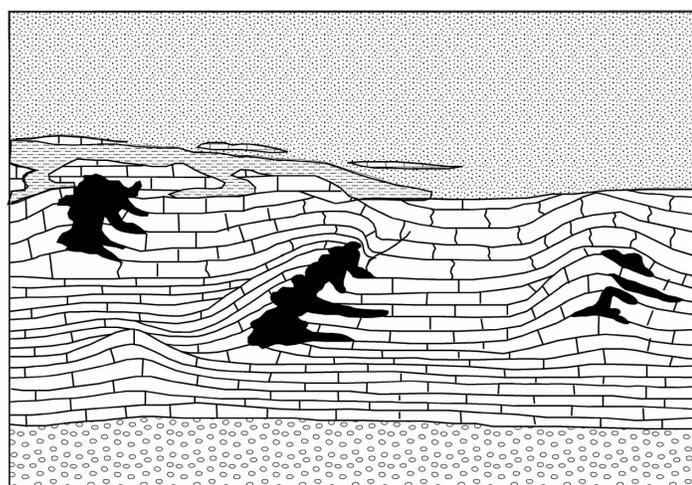


FIGURE 3. Control of Todilto uranium deposits by intraformational folds and fractures (modified from Finch and McLemore, 1989).

folds were exposed in underground or surface mines that are now inaccessible; others are exposed on rim outcrops. Deposits in the Laguna district and small deposits distant from Grants (Sanostee, Box Canyon) also were associated with folds of this type.

The origin of the ore-controlling folds has remained controversial since they were first recognized during initial development and mining of Todilto uranium deposits shortly after 1950. An early suggestion (Rapaport, 1952) that the ore-controlling intraformational folds relate to Laramide tectonic activity seems unlikely, as later U-Pb isotopic dating of uraninite indicates that the deposits formed in Jurassic time shortly after the host rocks were deposited.

Evidence of soft-sediment deformation is prominent within the Todilto intraformational folds, consistent with their early formation. One hypothesis is that the weight of encroaching sediments of the overlying Summerville Formation deformed the soft lime muds of the Todilto. Some folds resemble tepees; along with small-scale enterolithic folds, these could relate at least in part to forces of crystallization or hydration of calcite and gypsum.

Slumping under the influence of gravity is a possible mechanism for the formation of folds, but it is not clear if slopes in the Todilto depositional basin were sufficient to initiate such movement. Earthquakes occurring during sedimentation are increasingly recognized as a possible cause of soft-sediment deformation, producing “seismites” (e.g., Etensohn et al., 2002), which can develop even on gentle slopes. Tectonic activity during Todilto deposition is possible; active folding appears to have influenced the geometry of mineralized sandstones in the younger Morrison Formation (Moench and Schlee, 1967). Some Todilto folds resemble ones occurring in the Pleistocene Lisan Formation along the Dead Sea in Israel and Jordan, believed to be a sedimentological analog of the Todilto in a different tectonic setting (McCrary, 1985; Warren, 1989). The Lisan folds apparently formed at least in part from seismogenic processes (El-Isa and Mustafa, 1986; Marco and Agnon, 1995).

The trends of some 1000 mappable fold axes for the Todilto intraformational folds were measured in the field, or obtained from published or unpublished mine maps. Representative rose diagrams of fold axis trends are in Figures 4-6. The relationships in these diagrams are typical; in some areas or mines the folds exhibit a preferred orientation, while in others the trends yield a nearly random pattern. Similar variability in fold trends in the Laguna district is shown in 534 readings compiled by Moench and Schlee (1967). The available fold data for the Todilto do not uniquely support any one of the hypotheses for the origin of the folds.

The variety of folds and fold-like structures in the Todilto suggests that they may have multiple origins. It is difficult to establish the relative importance of the various processes that may have contributed to the formation of these structures.

### Age of uranium deposits

Geochronologic studies of Colorado Plateau uranium deposits began around 1950 during the early years of the “uranium boom,” but detailed studies in the Grants district were not published until more than 30 years later, after most mining had ended. Early work in Utah and Colorado yielded mostly discordant U-Pb ages;

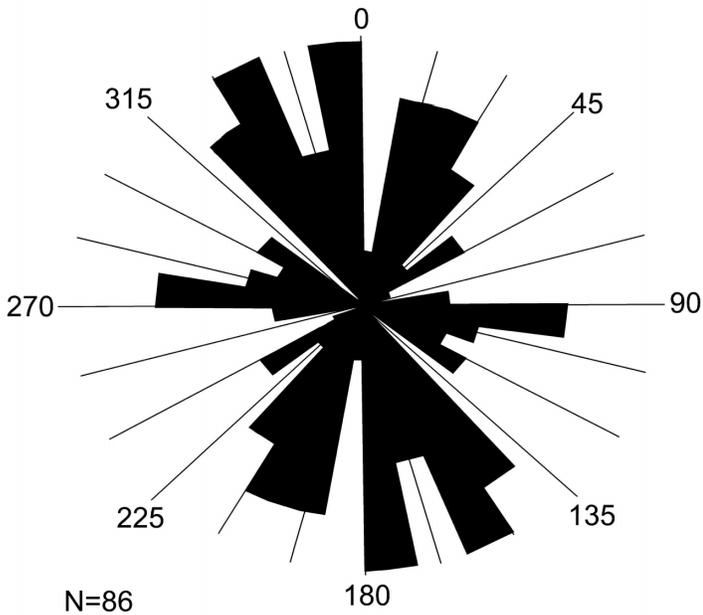


FIGURE 4. Rose diagram of fold axis trends for the Barbara J #2 mine (N=86), showing a pattern that, together with data shown in Figures 5 and 6, does not clearly support a single method of origin.

these nevertheless suggested a late Cretaceous to early Tertiary (Laramide) age for several deposits, similar to the vein-type deposits of the Colorado Front Range (Stieff et al., 1953; Stieff and Stern, 1956). This idea was influential throughout the 1950s and early 1960s. Geologic studies in Grants and other districts,

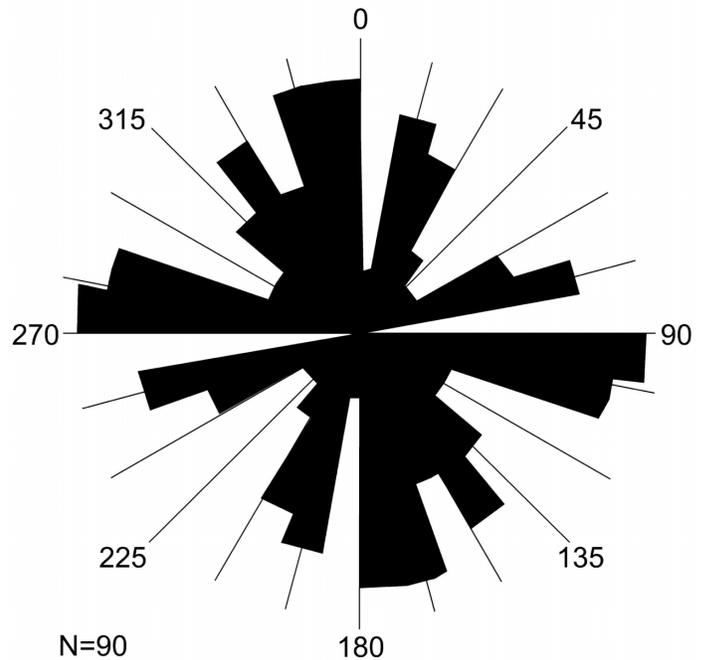


FIGURE 6. Rose diagram of fold axis trends for Section 25 (N=90), showing a pattern that does not clearly support a single method of origin.

and slowly accumulating new geochronologic data, then suggested that many Plateau deposits are in reality much older, often approaching the age of their host rocks (Hilpert and Moench, 1960; Miller and Kulp, 1963; Moench and Schlee, 1967; Ludwig et al., 1984; Berglof, 1992; Ludwig and Simmons, 1992.)

The following conclusions have been reached for the Grants district from geochronologic studies published since around 1980. At Ambrosia Lake and Smith Lake, primary (trend) ore formed early in the history of the host sandstones of the Upper Jurassic Morrison Formation, at 130 Ma or earlier, based on U-Pb data and Rb-Sr and K-Ar ages of clay minerals pencontemporaneous with uranium minerals (Brookins, 1980; Ludwig et al., 1984). Redistributed (stack) ore and an oxidized uranium mineral (uranophane) at Ambrosia Lake have late Tertiary U-Pb ages of 3 to 12 Ma (Ludwig et al., 1984; Brookins, 1981a), consistent with geologic evidence for remobilization of uranium. Redistributed Morrison ore in the Church Rock area is as young as Pleistocene (Ludwig et al., 1982); redistribution was not extensive at Smith Lake. Primary deposits in the Morrison at Laguna may be younger than at Ambrosia Lake, but limited age data are inconclusive. The age of primary deposits in the Middle Jurassic Todilto Formation is 150-155 Ma, close to the age of the Todilto; these deposits are older than those in the Morrison (Finch, 1991; Berglof, 1992; Berglof and McLemore, 1996). Secondary Todilto uranophane yields U-Pb ages of 3 to 7 Ma (Brookins, 1981b), confirming Tertiary redistribution of uranium in this formation as well.

Most U-Pb ages from all ore-bearing horizons are discordant, attributed mainly to open-system behavior involving migration of radiogenic Pb and relatively long-lived intermediate daughter isotopes in the <sup>238</sup>U decay chain. Under this interpretation the

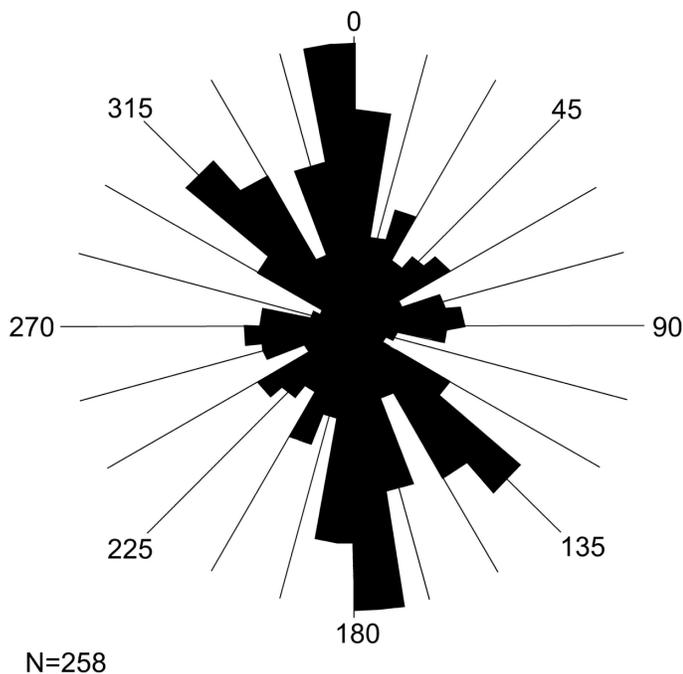


FIGURE 5. Rose diagram of fold axis trends for the Flat Top mine (N=258), showing a pattern, contrasting with those of Figures 4 and 6, that does not clearly support a single method of origin.

$^{207}\text{Pb}/^{235}\text{U}$  age is the most reliable, and generally yields a minimum age. However, some ages are concordant. In addition, concordia diagrams provide meaningful conclusions from discordant age data. Migration of  $^{238}\text{U}$  daughters and subsequent decay to  $^{206}\text{Pb}$  produces anomalous radiogenic  $^{207}\text{Pb}/^{206}\text{Pb}$  ratios and resulting apparent ages in many samples (Ludwig et al., 1984; Berglof, 1992). Some  $^{207}\text{Pb}/^{206}\text{Pb}$  "ages" are greater than 1000 Ma in Morrison and Todilto samples that are deficient in  $^{206}\text{Pb}$ . By contrast, excess  $^{206}\text{Pb}$  produces a negative or "future" age of -840 Ma for one Todilto sample; four ages ranging from -19 to -580 Ma for Ambrosia Lake, Smith Lake and Church Rock; and an extreme of -13000 Ma for one Ambrosia Lake sample ( $^{207}\text{Pb}/^{206}\text{Pb} = 0.008$ ). Such anomalies were not observed in early studies, and provide especially strong evidence of complex open-system behavior.

Based on a range of paleontological and other evidence, the age of the Todilto Formation is believed to be middle Callovian (Lucas et al., 1985). Over the years many proposed geologic time scales have been published. Many of these have disagreed with regard to the estimated ages of stage boundaries in the Jurassic; e.g., reviews by Pálffy (1995) and Gradstein et al. (1995). According to the estimates for the Callovian stage boundaries proposed by Gradstein et al. (1995), the Todilto may have been deposited around 160 Ma, consistent with the estimated age of primary uranium mineralization not long afterward at about 150-155 Ma.

### Origin

The origin of the Todilto uranium deposits remains controversial. The most likely origin involves an unusual set of geologic circumstances. The organic-rich limestones accumulated in a sabkha environment near the edge of the Todilto salina, above the permeable Entrada Sandstone. Intraformational folds developed shortly after the deposition of the limestone, possibly after partial deposition of the overlying Summerville Formation that locally deformed the Todilto muds, producing at least some of the intraformational folds in the limestone. Uraniferous waters derived from a highland to the southwest migrated through the Entrada Sandstone. These waters were then drawn into the Todilto limestone through evapotranspiration or evaporative pumping. Uranium precipitated in the presence of organic material within the intraformational folds and associated fractures and dissolution cavities in the limestone (Fig. 3; Rawson, 1980; Finch and McLemore, 1989).

The most likely source rocks for uranium in both Todilto and Morrison deposits in the Grants district, as well as other deposits in the Colorado Plateau region, were voluminous volcanoclastics derived from volcanic island arcs that existed west of the North American plate during Triassic and Jurassic time (Granger and Finch, 1988; Finch, 1991, 1992, 1996).

### Gypsum

New Mexico ranked seventh in gypsum production among 20 gypsum-producing U.S. states in 2000 (McLemore et al., 2002b). Gypsum is a soft mineral (hardness of 1.5-2) with the formula  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ , and is typically formed in sedimentary environments. Gypsum is used primarily in the manufacture of wallboard for homes, offices, and commercial buildings; other uses include the manufacture of portland cement, plaster of Paris, and as a

soil conditioner. Gypsum production from the Tonque Arroyo Member of the Todilto forms the basis of New Mexico's current gypsum industry, with most recent production having been from a quarry at White Mesa, near San Ysidro, north of Albuquerque.

Gypsum has been mined from White Mesa in the Nacimiento Mountains (sec. 14, 16, 28, T15N, R1E) since the 1950s. Production since 1960 has amounted to more than \$20 million in cumulative value. The first production was for use in agriculture, and the gypsum was shipped as far as the San Luis Valley in southern Colorado (Logsdon, 1982). The largest mine is the White Mesa mine; a smaller operation, the G and W mine, yielded gypsum in the 1980s for use as a soil conditioner. It is mined from a dipslope (10-20°) at White Mesa. The gypsum is used to manufacture wallboard at the Centex Bernalillo plant. Reserves are abundant and mining will probably continue far into the future.

Anhydrite is present in the subsurface throughout the Todilto basin and has been encountered in drill holes. At White Mesa quarrying has removed sufficient gypsum that some anhydrite is exposed in the lower 15 meters of the deposit, diluting the gypsum to the extent that this material is not mined (McLemore, 1996).

Todilto gypsum is used at the Rio Grande Portland Cement plant east of Albuquerque (Austin and Barker, 1998); it is combined with the ground cement clinker to retard setting time. Gypsum used at this plant was formerly produced from the San Felipe Pueblo, but is now obtained from White Mesa (G. S. Austin, personal commun., 1998).

Todilto gypsum from Cedar Crest, east of Albuquerque, has an unusual local use. It may be sufficiently massive to be an appropriate raw material for sculpture, and is known to sculptors as Cedar Crest alabaster (Maynard et al., 1991).

### Limestone

Limestone has been produced for crushed stone from the Luciano Mesa Member of the Todilto Formation at several different locations in New Mexico, especially in the outcrop belt between Grants and Gallup. Crushed stone is one of the most accessible natural resources and is a major basic raw material used by construction, agriculture, and other industries. Despite the low value of its basic products, the crushed stone industry is a major contributor to and an indicator of the economic well being of any city, county, state, or country. Crushed stone is quarried throughout New Mexico and is used in concrete aggregate, bituminous aggregate, roadstone and coverings, riprap, railroad ballast, and other construction uses.

At a typical quarry in the Todilto near Thoreau, New Mexico, the Gallup Sand and Gravel Co. produces a variety of limestone rock products from the Todilto (F. A. Kozeliski, personal commun., 2002). Quarrying begins with the removal of an average of approximately one meter of soil and overburden overlying the economic-grade limestone. The thickness of remaining limestone suitable for production may be up to about five meters. The rock is drilled and blasted and carried to a primary crusher. The crushed limestone is then screened and depending on the desired product some may be conveyed to secondary crushers and then to a final screening. The company adjusts the precise details of its

operations according to the anticipated end uses of the limestone products. At various times the products may include riprap rock, filter rock, road metal aggregate, concrete aggregate, and various rock chip and specialty gradations.

### Petroleum in the Entrada Sandstone

Evaporites such as the Todilto have traditionally been considered to be unlikely source rocks for petroleum (Evans and Kirkland, 1988), but have been increasingly recognized as potential sources as knowledge of the evaporitic environment has evolved. The Todilto is recognized as the most likely source for petroleum in the underlying Entrada Sandstone in several oil fields in the San Juan Basin (Vincelette and Chittum, 1981). Brown (1977) appears to have been the first to suggest that Entrada oil traps were formed on sand dune topography within the Entrada, with the overlying Todilto Formation forming a caprock seal. Vincelle and Chittum (1981) developed this concept further, suggesting that the Todilto is the source rock for the oil present in the Entrada, and that the oil was trapped by topographic relief developed on preserved eolian sand dunes at the top of the Entrada Sandstone.

These concepts have been confirmed or applied in several subsequent studies. For example, Chittum (1985) reported on addition seismic exploration establishing the presence of sand dunes within the Entrada Sandstone and thinning of the Todilto across the dunes. Massé and Ray (1995) reviewed 3-D seismic prospecting techniques used in evaluating Entrada prospects, consistent with the dune model.

Black (1999a, 1999b) noted that surface indications of oil can be observed on Entrada and Todilto outcrops in the Hagan basin far from the producing areas in the San Juan Basin, with the Todilto again being the most likely source of the oil.

Lucas and Kietzke (1986) suggested that the Todilto could have petroleum potential in northeastern New Mexico, but this possibility does not appear to have been further investigated.

## GEOLOGICAL HAZARDS

### Radon

Radon is a potential environmental hazard, especially where it becomes concentrated in houses or other buildings where people congregate. It is a radioactive gas, one of the daughter products of the decay of uranium. The predominant radon isotope in nature is  $^{222}\text{Rn}$ , which is part of the  $^{238}\text{U}$  decay chain. It has a half-life of approximately four days, allowing it to accumulate in potentially hazardous quantities where a source is present. Elevated radon concentrations are thus likely around uranium deposits or uranium tailings (McLemore and Hawley, 1988). Most areas near known uranium deposits or mine waste derived from Todilto uranium deposits in New Mexico are very sparsely populated, and most surface and underground mines have been reclaimed. Radon hazards in these areas appear minimal.

A limited number of limestone quarries in the Todilto have been developed in areas where uranium was known to occur or was previously mined; for example, the Griego pit in sec. 20, T11N, R9W

(Cedar mine) and the Andrews pit in sec. 19, T14N, R11W (Billy the Kid mine). Most crushed limestone from quarries of this type has been used for road construction and thus is not likely to yield a substantial radon hazard within enclosed structures.

### Karst

Geologic hazards related to mining of mineral deposits in limestone and potential karst terrains such as the Todilto Formation include removal of rock that results in subsidence (i.e., formation of induced sinkholes and caves); lowering of the ground water table (locally resulting in subsidence); contamination of ground water (e.g., waste water discharge, acid mine drainage); and changes in ground-water flow patterns (including increased mine water drainage).

The effects of mining in karst in New Mexico, including the Todilto Formation, are poorly documented. Many of the uranium mines developed in the Todilto Formation are shallow surface mines with limited potential hazards. However, several Todilto mines in the Ambrosia Lake subdistrict of the Grants district were underground operations and surface subsidence has occurred in these areas (V. T. McLemore, unpubl. field investigations). These mines were for the most part above the water table and probably did not impact the local aquifers.

## CONCLUSIONS

The Jurassic Todilto Formation is one of the most distinctive and widely recognized lithostratigraphic units in the southwestern United States. It has diverse economic importance in New Mexico as the host rock for uranium deposits near Grants, as the basis for New Mexico's gypsum mining industry, as a source rock for petroleum in the San Juan Basin, and as a local source for a variety of crushed limestone products. The Todilto is not known to be associated with significant geological hazards, but because it contains uranium deposits it does have the potential for producing local radon gas accumulations. There also are potential land subsidence hazards in areas of previous uranium mining or of limited karst development in the limestone.

## ACKNOWLEDGMENTS

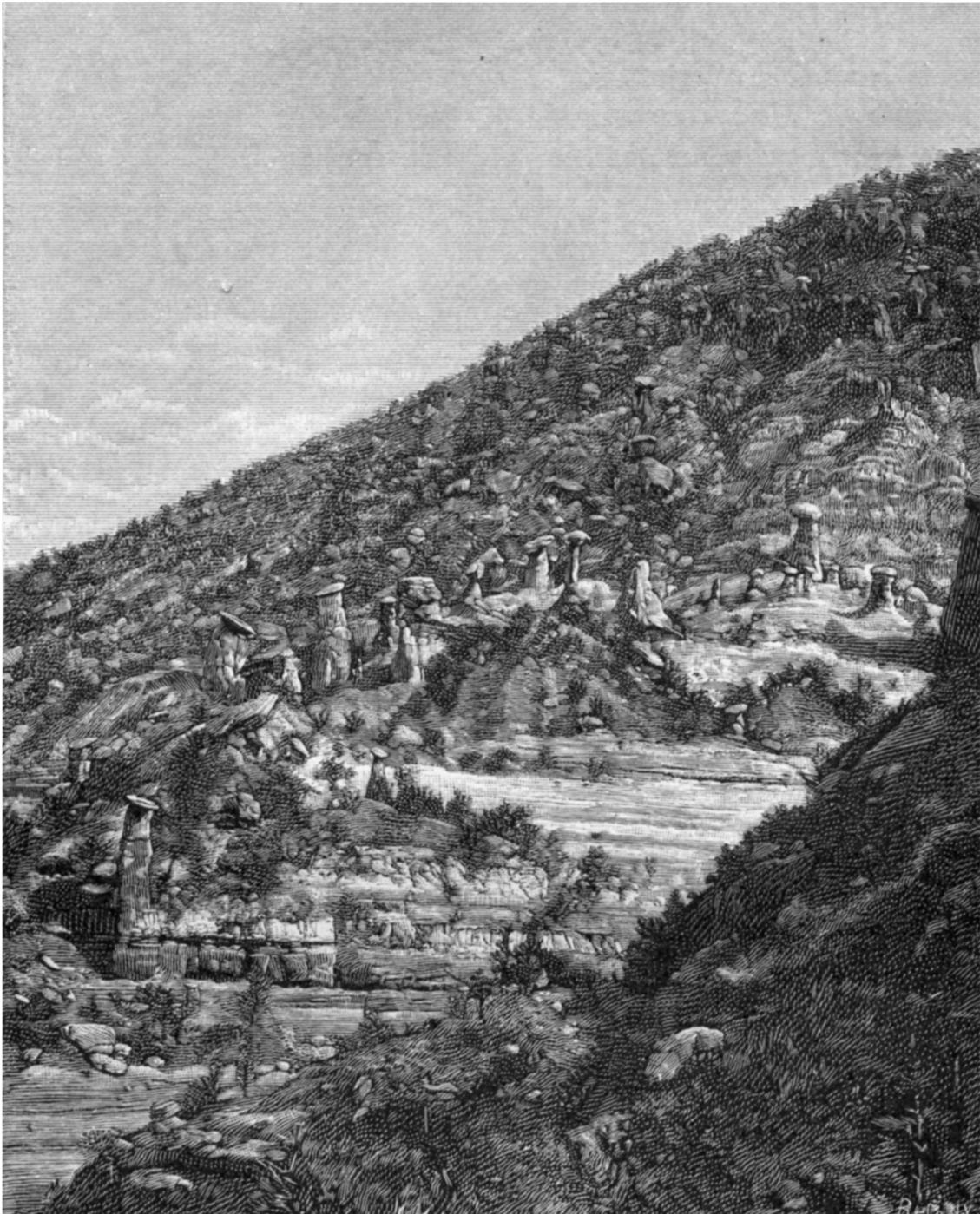
Figure 2 was drafted by the NMBGMR Cartography Department. Steven Semken, Kate Zeigler, and William Chenoweth reviewed an earlier draft of this report. This paper is part of ongoing research on mineral resources in New Mexico and adjacent areas at NMBGMR, Peter Scholle, Director and State Geologist.

## REFERENCES

- Austin, G. S. and Barker, J. M., 1998, Cement and concrete—production and use in New Mexico: *New Mexico Geology*, v. 20, p. 33–43.
- Berglof, W. R., 1992, Isotopic ages of uranium deposits in the Todilto Limestone, Grants district, and their relationship to the ages of other Colorado Plateau deposits: *New Mexico Geological Society, Guidebook 43*, p. 351–358.
- Berglof, W. R. and McLemore, V. T., 1996, Geochronologic studies in the Grants uranium district, New Mexico (abs.): *New Mexico Geology*, v. 18, p. 42.
- Black, B. A., 1999a, Hydrocarbon indications in the Entrada Sandstone and the

- Todilto Formation on the outcrop in the Hagan embayment: New Mexico Geological Society, Guidebook 50, p. 17-18.
- Black, B. A., 1999b, Oil and gas exploration in the Hagan embayment of the Española basin: New Mexico Geological Society, Guidebook 50, p. 441-444.
- Brookins, D. G., 1980, Geochronologic studies in the Grants mineral belt; *in* Rautman, C. A., compiler, Geology and mineral technology of the Grants uranium region, 1979: New Mexico Bureau Mines Mineral Resources, Memoir 38, p. 52-58.
- Brookins, D. G., 1981a, Primary uranophane from the Ambrosia Lake uranium district, Grants mineral belt, USA: Mineralium Deposita, v. 16, p. 3-5.
- Brookins, D. G., 1981b, U-Pb Ages for U(VI) hydrosilicates, Grants, New Mexico: Isochron West, no. 32, p. 25.
- Brown, R., 1977, Ojo Encino, Papers Wash and Snake Eyes Oil Fields, McKinley and San Juan Counties, New Mexico; *in* Fassett, J. E., Jentgen, R. W., Black, B. A., Molenaar, C. M. and Woodward, L. A., Second day road log from Red Mountain oil field to El Vado Lake via Pueblo Pintado, Star Lake, Torreon, Cuba and Llaves: New Mexico Geological Society, Guidebook 28, p. 22-24.
- Chenoweth, W. L., 1985, Historical review of uranium production from the Todilto Limestone, Cibola and McKinley Counties, New Mexico: New Mexico Geology, v. 7, p. 80-83.
- Chittum, W. E., 1985, Southeast San Juan Basin, *in* Gries, R. R. and Dyer, R. C., eds., Seismic Exploration of the Rocky Mountain Region: Rocky Mountain Association of Geologists and Denver Geophysical Society, p. 151-156.
- Denison, R. E., Kirkland, D. W. and Evans, R., 1998, Using strontium isotopes to determine the age and origin of gypsum and anhydrite beds: Journal of Geology, v. 106, p. 1-17.
- Dunn, P. J. and Frondel, C., 1990, An uncommon margarite/corundum assemblage from Sterling Hill, New Jersey: The Mineralogical Record, v. 21, pp. 425-427.
- Dunn, P. J. and Peacor, D. R., 1986, Santafeite, a re-examination and new empirical formula: Mineralogical Magazine, v. 50, p. 299-300.
- El-Isa, Z. H. and Mustafa, H., 1986, Earthquake deformations in the Lisan deposits and seismotectonic implications: Geophysical Journal of the Royal Astronomical Society, v. 86, p. 413-424.
- Ettensohn, F. R., Rast, N. and Brett, C. E., eds., 2002, Ancient seismites: Geological Society of America, Special Paper 359, 190 p.
- Evans, R. and Kirkland, D. W., 1988, Evaporitic environments as a source of petroleum; *in* Schreiber, B. C., ed., Evaporites and hydrocarbons: New York, Columbia University Press, p. 256-299.
- Everhart, D. L., 1951, Geology of uranium deposits—A condensed version, with mineral tables by Muriel Mathez: U.S. Atomic Energy Commission, Report RMO-732, 33 p.
- Finch, W. I., 1991, Maps showing the distribution of uranium-deposit clusters in the Colorado Plateau uranium province: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2080.
- Finch, W. I., 1992, Uranium provinces in North America (abs.); *in* Abstracts, 29th International Geological Congress, Kyoto, Japan, v. 1, Symposium I-3-42, p. 196.
- Finch, W. I., 1996, Uranium provinces of North America—their definition, distribution and models: U.S. Geological Survey, Bulletin 2141, 18 p.
- Finch, W. I. and McLemore, V. T., 1989, Uranium geology and resources of the San Juan Basin; *in* Finch, W. I., Hoffman, A. C., Jr. and Fassett, J. E., eds., Coal, uranium, and oil and gas in Mesozoic rocks of the San Juan Basin: Anatomy of a giant energy-rich basin: 28th International Geological Congress, Field Trip Guidebook T120, p. 27-32.
- Gabelman, J. W., 1956, Uranium deposits in limestone: U. S. Geological Survey, Professional Paper 300, p. 387-404.
- Gabelman, J. W., 1970, The Flat Top uranium mine, Grants, New Mexico: U. S. Atomic Energy Commission, Report RME-4112, 81 p.
- Gabelman, J. W. and Boyer, W. H., 1988, Uranium deposits in Todilto Limestone, New Mexico: the Barbara "J" No. 1 mine: Ore Geology Reviews, v. 3, p. 241-276.
- Gabelman, J. W. and Krusiewski, S. V., 1967, Uranium deposits of Mexico: U.S. Atomic Energy Commission, Report RME-4009, 27 p.
- Gott, G. B., Wyant, D. G. and Beroni, E. P., 1952, Uranium in black shales, lignites, and limestones in the United States; *in* Selected papers on uranium deposits in the United States: U.S. Geological Survey, Circular 220, p. 31-35.
- Gradstein, F. M., Agterberg, F. P., Ogg, J. G., Hardenbol, J., Van Veen, P., Thierry, J. and Huang, Z., 1995, A Triassic, Jurassic and Cretaceous time scale; *in* Berggren, W. A., Kent, D. V., Aubry, M.-P. and Hardenbol, J., eds., Geochronology, time scales and global stratigraphic correlation: SEPM Special Publication 54, p. 95-126.
- Granger, H. C. and Finch, W. I., 1988, The Colorado Plateau uranium province, USA; *in* Recognition of uranium provinces, International Atomic Energy Agency, p. 157-193.
- Green, M. W., 1982, Origin of intraformational folds in the Jurassic Todilto Limestone, Ambrosia Lake uranium mining district, McKinley and Valencia Counties, New Mexico: U. S. Geological Survey, Open-file Report 82-69, 29 p.
- Hart, O. M., 1958, Uranium deposits in the Pryor-Big Horn Mountains, Carbon County, Montana, and Big Horn County, Wyoming: Second United Nations International Conference on the Peaceful Uses of Atomic Energy, v. 2, p. 523-526.
- Heinrich, E. W., 1958, Mineralogy and geology of radioactive raw materials: New York, McGraw-Hill Book Co., Inc., 654 p.
- Hilpert, L. S., 1969, Uranium resources of northwestern New Mexico: U.S. Geological Survey, Professional Paper 603, 166 p.
- Hilpert, L. S. and Moench, R. H., 1960, Uranium deposits of the southern part of the San Juan Basin, New Mexico: Economic Geology, v. 55, p. 429-464.
- Honea, R. M., 1961, New data on boltwoodite, an alkali uranyl silicate: American Mineralogist, v. 46, p. 12-25.
- Kirkland, D. W., Denison, R. E. and Evans, R., 1995, Middle Jurassic Todilto Formation of northern New Mexico and southern Colorado: Marine or non-marine?: New Mexico Bureau of Mines and Mineral Resources, Bulletin 147, 37 p.
- Laverty, R. A. and Gross, E. B., 1956, Paragenetic studies of uranium deposits of the Colorado Plateau: U.S. Geological Survey, Professional Paper 300, p. 195-202.
- Logsdon, M. J., 1982, Gypsum resources of New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 182, p. 43-48.
- Lovering, T. G., 1956, Radioactive deposits in New Mexico: U.S. Geol. Survey, Bulletin 1009-L, p. 315-390.
- Lucas, S. G. and Anderson, O. J., 1996, The Middle Jurassic Todilto salina basin, American Southwest; *in* Morales, M., ed., The continental Jurassic: Museum of Northern Arizona, Bulletin 60, p. 470-482.
- Lucas, S. G. and Anderson, O. J., 2000, The Todilto salina basin, Middle Jurassic of the U.S. Southwest; *in* Gierlowski-Kordesch, E. H. and Kelts, K. R., eds., Lake basins through space and time: AAPG Studies in Geology 46, p. 153-158.
- Lucas, S. G., Anderson, O. J. and Pigman, C., 1995, Jurassic stratigraphy in the Hagan Basin, north-central New Mexico: New Mexico Geological Society, Guidebook 46, p. 247-255.
- Lucas, S. G., Kietzke, K. K. and Hunt, A. P., 1985, The Jurassic system in east-central New Mexico: New Mexico Geological Society, Guidebook 36, p. 213-242.
- Lucas, S. G. and Kietzke, K. K., 1986, Stratigraphy and petroleum potential of the Jurassic Todilto Formation in northeastern New Mexico; *in* Ahlen, J. L., Hanson, M. E. and Zidek, J., eds., Southwest section of AAPG transactions and guidebook of 1986 convention, Ruidoso, New Mexico: Socorro, New Mexico Bureau of Mines and Mineral Resources, p. 121-127.
- Ludwig, K. R., Rubin, B., Fishman, N. S. and Reynolds, R. L., 1982, U-Pb ages of uranium ores in the Churchrock uranium district, New Mexico: Economic Geology, v. 77, p. 1942-1945.
- Ludwig, K. R., Simmons, K. R. and Webster, J. D., 1984, U-Pb isotope systematics and apparent ages of uranium ores, Ambrosia Lake and Smith Lake districts, Grants Mineral Belt, New Mexico: Economic Geology, v. 79, p. 322-337.
- Ludwig, K. R. and Simmons, K. R., 1992, U-Pb dating of uranium deposits in collapse breccia pipes of the Grand Canyon region: Economic Geology, v. 87, p. 1747-1765.
- Massé, D. J. and Ray, R. R., 1995, 3-D prospecting for Entrada Sandstone reservoirs on the southeastern flank of the San Juan Basin, New Mexico; *in* Ray, R. R., ed., High-definition seismic: 2-D, 2-D swath, and 3-D case histories: Rocky Mountain Association of Geologists, High-Definition Seismic Guidebook, p. 143-160.
- Marco, S. and Agnon, A., 1995, Prehistoric earthquake deformations near Masada, Dead Sea graben: Geology, v. 23, p. 695-698.
- Maynard, S. R., Woodward, L. A. and Giles, D. L., 1991, Tectonics, intrusive rocks, and mineralization of the San Pedro-Ortiz porphyry belt, north-cen-

- tral New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 137, p. 57-69.
- McCrary, M. M., 1985, Depositional history and petrography of the Todilto Formation (Jurassic), New Mexico and Colorado [M.S. thesis]: Austin, University of Texas, 183 p.
- McLaughlin, E. D., Jr., 1963, Uranium deposits in the Todilto Limestone of the Grants District; *in* Kelley, V. C., compiler, Geology and Technology of the Grants uranium region: New Mexico Bureau of Mines and Mineral Resources, Memoir 15, p. 136-149.
- McLemore, V. T., 1983, Uranium and thorium occurrences in New Mexico—distribution, geology, production, and resources, with selected bibliography: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 183, 1541 p.
- McLemore, V. T., 1996, Mineral Resources in the Jemez and Nacimiento Mountains, Rio Arriba, Sandoval, Santa Fe and Los Alamos Counties, New Mexico: New Mexico Geological Society, Guidebook 47, p. 161-168.
- McLemore, V. T., 2002, Uranium in New Mexico: New Mexico Bureau of Geology and Mineral Resources, Decision-Makers Field Conference 2002, p. 30-34.
- McLemore, V. T. and Chenoweth, W. L., 1989, Uranium Resources in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Resource Map 18, 36 p.
- McLemore, V. T., Donahue, K., Krueger, C. B., Rowe, A., Ulbricht, L., Jackson, M. J., Breese, M. R., Jones, G. and Wilks, M., 2002a, Database of the uranium mines, prospects, occurrences, and mills in New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open file Report 461, CD-ROM.
- McLemore, V. T. and Hawley, J. W., 1988, Preliminary geologic evaluation of radon availability in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 345, 31 p.
- McLemore, V. T., Hoffman, G. K. and Pfeil, J. J., 2002b, Minerals industry in New Mexico in 1998-2000: New Mexico Geology, v. 24, p. 19-28.
- Miller, D. S. and Kulp, J. L., 1963, Isotopic evidence on the origin of the Colorado Plateau uranium ores: Geological Society of America Bulletin, v. 74, p. 609-629.
- Moench, R. H. and Meyrowitz, R., 1964, Goldmanite, a vanadium garnet from Laguna, New Mexico: American Mineralogist, v. 49, p. 644-655.
- Moench, R. H. and Schlee, J. S., 1967, Geology and uranium deposits of the Laguna District, New Mexico: U.S. Geological Survey, Professional Paper 519, 117 p.
- Moore, P. B., Shen, J. and Araki, T., 1985, Crystal chemistry of the  $_{-2}[M_2^{3+}\phi_2(TO_4)_2]$  sheet: structural principles and crystal structures of ruzite, macfalite and orientite: American Mineralogist, v. 70, p. 171-181.
- Northrop, S. A., 1959, Minerals of New Mexico, revised ed.: Albuquerque, University of New Mexico Press, 665 p.
- Pálffy, J., 1995, Development of the Jurassic geochronologic scale: Hantkeniana, v. 1, p. 13-25.
- Peters, W. C., 1956, Uranium-fluorite deposits: Uranium Information Digest, v. 3, p. 7-8, 25, 30.
- Rapaport, I., 1952, Interim report on the ore deposits of the Grants District, New Mexico: U.S. Atomic Energy Commission, Report RMO-1031, 19 p.
- Rapaport, I., 1955, General geology of the Grants, New Mexico uranium area: Uranium Information Digest, v. 2, p. 17-18.
- Rawson, R. R., 1980, Uranium in Todilto Limestone (Jurassic) of New Mexico—example of a sabkha-like deposit; *in* Rautman, C. A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources, Memoir 38, p. 304-312.
- Simon, S. B. and Grossman, L., 1992, Low-temperature exsolution in refractory siderophile element-rich opaque assemblages from the Leoville carbonaceous chondrite: Earth and Planetary Science Letters, v. 110, p. 67-75.
- Stern, T. W., Stieff, L. R., Evans, H. T., Jr. and Sherwood, A. M., 1957, Doloresite, a new vanadium oxide mineral from the Colorado Plateau: American Mineralogist, v. 42, p. 587-593.
- Stieff, L. R. and Stern, T. W., 1956, Interpretation of the discordant age sequence of uranium ores: U.S. Geological Survey, Professional Paper 300, p. 549-555.
- Stieff, L. R., Stern, T. W. and Milkey, R. G., 1953, A preliminary determination of the age of some uranium ores of the Colorado Plateau by the lead-uranium method: U.S. Geological Survey, Circular 271, 19 p.
- Sun, M. and Weber, R. H., 1955, Ardenite from the Grants uranium district, New Mexico (abs.): American Mineralogist, v. 40, p. 338.
- Sun, M. and Weber, R. H., 1958, Santafeite, a new hydrated vanadate from New Mexico: American Mineralogist, v. 43, p. 677-687.
- Truesdell, A. H. and Weeks, A. D., 1960, Paragenesis of uranium ores in Todilto Limestone near Grants, New Mexico, *in* Geological Survey Research, 1960: U.S. Geological Survey, Professional Paper 400-B, p. B52-B54.
- Uher, P., Chovan, M. and Majzlan, J., 1994, Vanadian-chromian garnet in mafic pyroclastic rocks of the Malé Karpaty Mountains, Western Carpathians, Slovakia: Canadian Mineralogist, v. 32, p. 319-316.
- Vincelette, R. R. and Chittum, W. E., 1981, Exploration for oil accumulations in Entrada Sandstone, San Juan Basin, New Mexico: American Association of Petroleum Geologists Bulletin, v. 65, p. 2546-2570.
- Warren, J. K., 1989, Evaporite Sedimentology: Englewood Cliffs, Prentice-Hall, Inc., 285 p.
- Weeks, A. D., Lindberg, M. L., Truesdell, A. H. and Meyrowitz, R., 1964, Grantsite, a new hydrated sodium calcium vanadate from New Mexico, Colorado and Utah: American Mineralogist, v. 49, p. 1511-1526.
- Weeks, A. D. and Thompson, M. E., 1954, Identification and occurrence of uranium and vanadium minerals from the Colorado Plateaus: U.S. Geological Survey, Bulletin 1009-B, p. 13-62.



Dutton's (1885, fig. 13) woodcut photograph, described as "eroded towers, capped with large blocks of sandstone, which had fallen from the Dakota sandstone, nearly a thousand feet above. The protection which these afforded to the softer calcareous sandstone on which they lay caused the gradual formation of columns by the slow dissolution of the surrounding rock."