BULLETIN 31

Geology of the Thoreau Quadrangle, McKinley and Valencia Counties, New Mexico

BY CLAY T. SMITH

Structure, stratigraphy, and mineral and groundwater resources of a part of the northeast flank of the Zuni Mountains

1954

STATE BUREAU OF MINES AND MINERAL RESOURCES
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY
CAMPUS STATION SOCORRO, NEW MEXICO

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GEOLOGY OF THE THOREAU QUADRANGLE McKINLEY AND VALENCIA COUNTIES NEW MEXICO

BY CLAY T. SMITH

Abstract

The Thoreau 15-minute quadrangle is on the north flank of the Zuni Mountains, McKinley and Valencia counties, New Mexico. The Zuni Mountains represent a northwest-southeast- trending domal uplift forming the central southern margin of the San Juan Basin, a physiographic division of the Colorado Plateau. Rocks exposed in the Thoreau quadrangle are correlated with formations which are defined either

farther north and west on the Colorado Plateau or considerably south and east of the area on the edges of the Permian Basin of New Mexico and West Texas. The Yeso formation of Permian age, the oldest unit exposed in the Thoreau quadrangle, is overlain by the Permian Glorieta and San Andres formations. These beds are unconformably overlain by strata assigned to the Triassic Chinle formation which in turn underlies a series of sandstones and siltstones variously correlated with the Glen Canyon group, the San Rafael group and the Morrison formation of Jurassic age. The marine upper Cretaceous beds of the Dakota (?) and Mancos formations truncate the underlying beds and form the upper part of the geologic column. Two small patches of basalt are presumed to be of Tertiary or Quaternary age. Recent alluvium and detritus mask the relationship between the older rocks in many places.

Beds in the Thoreau quadrangle dip from 3 to 5 degrees northward or northeastward under the younger rocks of the central part of the San Juan Basin. The gentle homoclinal dip is interrupted by several persistent fault zones of small throw, Structures within the quadrangle appear to be closely related to and controlled by the uplift of the Precambrian core of the Zuni Mountains south of the mapped area.

Extensive deposits of uranium ores are being exploited to the east of the Thoreau quadrangle, and some mining has been done within the quadrangle. The uranium mineral occurrences are confined principally to the Jurassic and Cretaceous rocks. The beds which were particularly favorable to mineralization are shown in red on the geologic map (P1. 1). The ground-water resources of the area have not been developed to their maximum capacity, although conditions favorable to an extensive artesian circulation are present.

Introduction

Recent discoveries of uranium deposits along the north and east flanks of the Zuni Mountains in McKinley and Valencia counties, New Mexico, have focused attention upon the need for detailed geologic information in this region. National interest in uranium as well as sporadic production of coal, fluorite, and copper from the Zuni Mountains has prompted the New Mexico Bureau of Mines and Mineral Resources to publish pertinent information as rapidly as it can be assembled.

The Thoreau 15-minute quadrangle is on the north flank of the Zuni Mountains, McKinley and Valencia counties, New Mexico (see Fig. 1, P1. 1). U. S. Highway 66 follows a broad, east-west valley that divides the quadrangle approximately in half. The main line of the Atchison, Topeka and Santa Fe Railway parallels U. S. Highway 66. Secondary gravel.surfäced roads extend north and south from U. S. Highway 66 at a number of points and a network of unimproved truck trails and wagon tracks provides access to all parts of the quadrangle.

Mapping in the Zuni Mountains was done in 1948 and 1949 jointly by students from the New Mexico Institute of Mining and Technology, Socorro, New Mexico, and the California Institute of Technology, Pasadena, California. The work was continued in 1950 by students from the New Mexico Institute of Mining and Technology. Altogether some seventy students have participated in mapping in the Thoreau quadrangle. The geology of the Thoreau quadrangle was completed and checked in 1951. The work has been under the direction of Clay T. Smith of the New Mexico Institute of Mining and Technology; however, during the 1949 season Stewart M. Jones of the New Mexico Institute of Mining and Technology and Lloyd C. Pray of the California institute of Technology were co-directors of the summer student work. The author visited the 1949 camp several times and accepts full responsibility for the mapping as published herewith.

Gradational contacts between many map units allow considerable latitude in placing geologic boundaries as well as allowing variation in interpreting field relations defined by map symbols. Thus, some individuals may have interpreted a vaguely defined contact as “concealed,” while others may have interpreted the same contact as “approximately located”; such differences are particularly common along alluvium contacts. Donald C. Deibert and Robert A. Mitchell, field assistants during the 1951 season, are responsible for mapping more area within the quadrangle than other individuals of the student group. (See Mapping Index, P1. 1.)

Rock descriptions follow standard terminology and classification. Mudstone is used to describe a poorly-sorted, non- laminated sediment composed principally of clay-size particles. Such a rock differs from shale because of a lack of fissility or laminae and differs from claystone because of the poor sorting.

The cooperation of Dr. Richard H. Jahns of the California Institute of Technology, and the Division of Geological Sciences of that Institute, is gratefully acknowledged. T. 0. Evans, Chief Mining Engineer for the Atchison, Topeka and Santa Fe Railway, and his staff have provided opportunities for detailed study of the uranium occurrences and have been most hospitable at their headquarters at Prewitt, New Mexico. The

Denver office of the Atomic Energy Commission released locality maps of many of the uranium prospects which were on private land and closed to the author's inspection by the owners. C. G. Gunderson of Grants, New Mexico, has been extremely helpful throughout the entire period of the investigation. Completion of this report has been made possible only through close cooperation between the New Mexico Bureau of Mines and Mineral Resources and the College Division of the New Mexico Institute of Mining and Technology.

Geology

The Zuni Mountains form the central southern margin of the San Juan Basin, a physiographic division of the Colorado Plateau, Precambrian rocks in the core of the mountains are overlain successively by Pennsylvanian, Permian, Triassic, Jurassic, Cretaceous, and younger sedimentary rocks. In the Thoreau quadrangle only the upper parts of the Permian series and later sediments are exposed. The sediments are broken by faults which radiate from the Precambrian core of the mountains generally in northeasterly or northerly directions. Separations due to faulting vary from a few feet to several hundred feet and many of the radiating faults occur in echelon patterns.

Stratigraphy

SEDIMENTARY ROCKS

The sedimentary rocks exposed in the Thoreau quadrangle for the most part are correlated with formations which are defined farther north and west on the Colorado Plateau. Correlation by means of marine faunas is possible only at the top and bottom of the stratigraphic column, and most of the formations described in this investigation are identified by lithologic similarities. Numerous isolated stratigraphic sections have been measured in recent years, and names and correlations have been extended on scattered and disconnected evidence until considerable confusion exists concerning stratigraphic relationships. Accordingly, local names are introduced wherever the stratigraphic position of any unit is in reasonable doubt.

PERMIAN ROCKS

Yeso formation: The Yeso formation is the oldest unit exposed in the Thoreau quadrangle. Scattered outcrops of the upper parts of the formation were found adjacent to faults in the extreme southeast corner of the quadrangle. The uppermost portions of the formation also are exposed in the lower reaches of Bluewater Creek Gorge and other deeply incised canyons. The Yeso formation was named by Lee (1909, p. 12) from exposures in the Rio Grande Valley and subsequently was redescribed by Needham and Bates (1943, p. 1653-1667) from exposures on Mesa del Yeso a few miles northeast of Socorro, New Mexico. The formation has been subdivided into several members which have local significance in the Sierra Nacimiento (Wood and Northrop, 1946), in the Lucero Mesa area (Kelley and Wood, 1946), and along the east side of the Rio Grande depression (Wilpolt and Wanek, 1951).

In the Zuni Mountains a four-fold division is possible, although only the upper three units are exposed in the Thoreau quadrangle. The lowermost exposed beds, herein designated the second member, consist of thin-bedded, calcareous sandstone and siltstone, which are poorly sorted and strongly cross-laminated. The rocks are variegated with shades of pink, brown, yellow, orange, white, and red, and usually grade from finer-grained material at the base to coarse-grained sandstone near the top. Thin (1- to 6-inch) beds of mudstone alternate with thicker sandstone and siltstone beds. Three thin-bedded, slabby, blue to gray, fetid limestone beds characterize the third member of the Yeso formation and form one of the most characteristic marker horizons of the entire Zuni Mountains section. The lower limestone is from 6 to 11 feet thick; the middle unit is from 10 to 12 feet thick and contains some fossil fragments (diagnostic forms are lacking although some bryozoa and brachiopods can be recognized); and the upper limestone bed is from 8 to 12 feet thick, The three beds are separated from each other by from 40 to 60 feet of alternating sandstone, siltstone and mudstone. The sandstone beds contain many frosted grains and are generally friable, as a result of being only partly cemented by gypsum or calcite; siltstone and mudstone are softer but not as friable and are thinner-bedded, occasionally shaly. The fourth member of the Yeso formation is chiefly pink and variegated, poorly sorted, medium-coarse-grained sandstone and siltstone grading upward into well-sorted, medium-grained, white-buff sandstone. Thin, shaly siltstone and mudstone partings are sparsely distributed throughout the section.

Measurements of the thickness of the Yeso formation are variable owing to the gradational nature of the upper and lower contacts. In areas south of the Thoreau quadrangle, complete sections of the upper three units usually average between 260 and 280 feet, and in the Thoreau quadrangle nearly 250 feet of rocks assigned to the Yeso formation are exposed along the Big Draw fault scarp; this thickness may be the result of repetition by faulting, although the limestone marker beds are not repeated in this exposure. The contact with the overlying Glorieta formation usually is placed where the white to buff, well-sorted, massive, cross-bedded sandstone beds in the upper part of the Yeso formation exceed in thickness and abundance the orange and red siltstone and mudstone units with which they are interstratified. Such a contact may range 50 feet stratigraphically between outcrops depending upon local depositional conditions.

Glorieta formation: The Glorieta sandstone was named by Keyes (1915, p. 257, 262) from exposures on Glorieta Mesa in Santa Fe County, New Mexico. The unit was raised to formational rank by Needham and Bates (1943, p. 1662-1664). In the Zuni area the Glorieta is a distinct mappable unit so the term "formation" seems applicable.

The Glorieta sandstone is exposed in the extreme southwestern part of the Thoreau quadrangle on the higher parts of slopes southwest of Bluewater Lake. It also is exposed in the gorge of Bluewater Creek east of the dam and in many of the deeper canyons south of Bluewater Canyon. The upper part of the unit is hard and resistant to erosion, and steep cliffs or long persistent dip slopes characterize its outcrops.

The Glorieta formation is a massive, persistent unit of variable thickness, It is white to buff but weathers yellow to light brown owing to small zones of hematitic or limonitic concretions. The bedding is sharply defined; alternating cross-bedded and evenly-bedded units from 2 to 10 feet in thickness truncate one another throughout the formation; ripple-marked bedding surfaces are common. Most of the bedding surfaces are undulating and irregular with relief from 6 inches to 1 foot. Festoon, tangential and steeply inclined torrential fore-set cross-laminations occur throughout the sandstone.

The Glorieta is a very pure, well-sorted, quartz sandstone with grains averaging about 1 mm. in diameter; the grains are well-rounded and smooth, although many are frosted and all are quite fresh and unaltered. The lower part of the formation is friable; the upper part is hard and well-cemented with silica. Concentrically banded hematite and limonite concretions up to ½ inch in diameter, usually with a quartz grain as a center, are irregularly distributed throughout portions of the formation; they are most abundant in the upper part of the formation.

The thickness ranges from 220 feet near the west edge of the quadrangle to 120 feet at the mouth of Bluewater Canyon. This difference does not indicate depositional thinning eastward but rather variation in the selection of the contact between the Glorieta sandstone and the underlying Yeso formation. The combined thickness of Yeso plus Glorieta remains relatively constant throughout the quadrangle.

The top of the Glorieta sandstone is conformable with the overlying San Andres limestone. Ten miles south of the Thoreau quadrangle, in Zuni Canyon, the gradation between Glorieta sandstone and San Andres limestone is marked by alternating sandstone and limestone beds 10 to 20 feet thick throughout much of the section. In the Thoreau quadrangle the contact is placed at the base of the first limestone bed in the sequence, and this surface is readily mapped throughout the area.

San Andres formation: The San Andres formation was named by Lee (1909, p. 23) from exposures in the San Andres Mountains in south-central New Mexico. The San Andres formation in the southern quarter of the Thoreau quadrangle forms northward-tilting dip slopes of wide extent.

In the Thoreau quadrangle the formation is readily divided into three members: a lower limestone member from 20 to 35 feet thick and sparingly fossiliferous; a middle sandstone member from 10 to 25 feet thick which very closely resembles the Glorieta sandstone; and a massive, abundantly fossiliferous, upper limestone member from 60 to 80 feet thick. The upper and lower limestone members form continuous ledges separated by a narrow slope cut on the middle sandstone member. The lower limestone is massive, blue-gray to white, and weathers gray. It is sandy near the base, grading upward into pure limestone with nodules and veinlets of calcite and sparse chert fragments. The middle sandstone is gray to yellow, medium-grained and friable; it is moderately well-sorted and contains abundant calcareous cement and frosted sand grains. The sandstone is massive, although local festoon and torrential cross-laminations are present. The upper member is massive gray limestone which is very cherty in the upper portion and locally contains thin sandstone lenses similar in appearance to the middle sandstone member. The upper limestone member characteristically is pinkish to reddish in its upper parts, and may be distinguished readily from the lower member by the pinkish color as well as by its abundant fossil remains.

The maximum measured thickness of the San Andres formation in the Thoreau quadrangle does not exceed 140 feet and most exposures average about 110 feet. The upper surface of the upper limestone member shows sink holes filled with Triassic rocks which are particularly well-illustrated in the area east of the Big Draw fault near Bluewater outside the quadrangle. West of the Thoreau quadrangle, relief of 25 to 50 feet is common on this buried karst topography, although within the quadrangle relief seldom exceeds 10 feet.

TRIASSIC ROCKS

Triassic rocks are exposed in a wide band over more than half the quadrangle from Bluewater Lake to the cliffs north of U. S. Highway 66. Darton (1928) mapped these units and correlated them with the type upper Triassic beds of northeastern Arizona. Although the Triassic rocks in the Thoreau quadrangle are readily divisible into three members, recent mapping in Arizona (McKee, 1951) indicates that the Moenkopi and Shinarump units probably do not extend as far east as the mapping by Darton (1928) would suggest. Accordingly, the Triassic rocks in the Thoreau quadrangle are mapped as Chinle formation and divided into three members.

Chinle formation: The Chinle formation, first described by Gregory (1917) from exposures in Chinle Wash, near Chinle, Arizona, was divided into four intergrading members described as Chinle “A”, Chinle “B”, Chinle “C”, and Chinle “D” from top to bottom respectively. Recent workers (Harshbarger, Repenning, and Jackson, 1951) have suggested that the Chinle “A” member of Gregory is really part of the overlying Wingate sandstone and that the type Chinle formation should be restricted to the lower three members.

The lower member of the Chinle formation in the Thoreau quadrangle is thin-bedded, fine-grained purple to white silty sandstone and massive chocolate brown to purple siltstone and mudstone. Thin, lenticular, pebble conglomerates and coarse-grained sandstone lenses occur throughout the section. The member is somewhat coarser near the base than higher in the section and grades upward into red-to-purple fine-grained sandstone and siltstone which are the predominant rock types. Locally, where the coarse-grained sandstone lenses and pebble conglomerate beds are concentrated near the base of the formation, some workers (Read, 1951) have suggested that the term “Shinarump conglomerate” be extended into the area. However, the pebble zones do not form mappable lithologic units over the entire quadrangle and thus have not been differentiated on the map (P1. 1). The lower member ranges in thickness from slightly less than 300 feet to nearly 500 feet—in part due to the irregularities of the erosional surface on the underlying San Andres formation. The lower member is gradational with the overlying middle sandstone member; as a result, differences in the location of the upper contact probably also have contributed to the wide range in measurements of thickness. It is generally true that, where the lower member is near its maximum thickness, the middle member is thin and, where the lower member is near its minimum thickness, the middle member is near its maximum thickness.

The top of the lower member generally is taken as the base of the first thick, cross-laminated, conglomeratic sandstone which marks the beginning of the lenticular, fluviatile sandstone deposition of the middle member of the formation. In the western part of the quadrangle, the upper beds of the lower member contain abundant fragments of petrified wood; logs up to 30 feet in length have been observed. The concentration of petrified wood at this horizon suggests correlation with the Chinle “C” of Gregory (1917), although the abundant overlying sand of the middle member is not common at the type locality of the Chinle “C”.

The middle member of the Chinle formation consists of medium- to thick-bedded, yellow-to-gray, hard sandstone and pebble conglomerate, strongly cross-bedded and with thin lenticular partings of purple-to-gray siltstone and mudstone. The sandstone and conglomerate beds are from 6 to 10 feet thick and exhibit repeated scouring and filling relationships. Fragments of petrified wood and fossil bone are common in the conglomeratic zones, particularly near the base of the member. The pebbles are almost entirely dark-colored chert or quartz, although local lenses of sandstone containing claystone or mudstone fragments resemble pebble conglomerate in structure and occurrence. The middle member ranges in thickness from about 110 feet west of Bluewater Lake to more than 200 feet in the eastern part of the quadrangle. Coarse sandstone lenses in the upper part of the lower member commonly are indistinguishable from sandstone beds in the middle member; the upper contact of the middle member is concealed by alluvium throughout much of the quadrangle, and elsewhere is marked only by a gradation from coarse-grained sandstone to fine-grained sandstone and siltstone, Such features contribute to the irregularity in thickness, Locally the middle member is an excellent aquifer.

The upper member of the Chinle formation is confined largely to the area north of U. S. Highway 66, which roughly marks the base of the member in the Thoreau quadrangle. South of the highway scattered remnants of the upper member occur on a dip slope formed by the middle sandstone member. Red, brown, and purple siltstone alternating with reddish-brown mudstone containing thin sandstone lenses are the principal rock types. Thin slabs of reddish-brown, cross-bedded sandstone which may correspond to the lower part of the Correo sandstone member of Kelley and Wood (1946) in the Lucero Mesa area are exposed 2 miles north of the highway. These grade upward into a limy siltstone and mudstone sequence which is characteristic of the upper part of Gregory's (1917) Chinle "B". In the upper 300 feet of the upper member, lenses and nodules of red, purple, brown and gray, fine-grained limestone are abundant, and about 35 feet below the top of the formation is an 8-foot bed of limestone conglomerate composed of cobbles and fragments of limestone cemented by sandy and silty calcareous mudstone. This uppermost limestone conglomerate bed long has been used as the upper contact of the Chinle formation, although a much better defined stratigraphic break occurs about 35 feet above it. The lower part of the upper member is entirely concealed by alluvium; well records reported by Darton (1928) suggest that much of the lower part of the member is variegated red, brown, and purple siltstone and mudstone, without much sandstone. Nearly 1,000 feet of sediments are included in the section between the uppermost exposures of the middle sandstone member and the lowest Jurassic formations.

Throughout the Thoreau quadrangle, the contact between the Triassic and Jurassic sediments is marked by a narrow zone of siltstone apparently derived from the redeposition of immediately adjacent upper Chinle beds, The siltstone contains small amounts of frosted sand grains typical of the overlying Wingate (?) formation together with coarse, angular fragments of white chert. The redeposited material occupies scour zones and channel fillings which were formed on the Chinle surface. Exposures are limited but the reworked zone ranges in thickness from a few inches to a maximum of 8 feet several miles west of the Thoreau quadrangle. Total thickness of the Chinle formation in the Thoreau quadrangle is nearly 1,600 feet.

JURASSIC ROCKS

The Jurassic formations of the Zuni Mountains have been the subject of much controversy and many of the problems are not yet solved. The classic three-fold division of the Jurassic rocks of the Colorado Plateau into the Glen Canyon group, the San Rafael group, and the Morrison formation is extended into the Thoreau quadrangle, although only a few of the formations or members are identified in the sequence.

Glen Canyon Group

Wingate (?) formation: The Wingate sandstone was named by Dutton (1885) from exposures north of old Fort Wingate. Originally the Wingate sandstone included all the prominent cliff-forming sandstones and associated rocks between the limestone conglomerate of the Chinle formation below and the Todilto limestone above. It is probable that the upper members of the Glen Canyon group either wedge out or are not recognizable as far east as the Thoreau quadrangle (Harshbarger, 1950) and that the rocks lying between the San Rafael group and the Chinle formation belong to the lower part of the Glen Canyon group or are Wingate sandstone in the restricted sense; they are called Wingate (?) formation in this report. Harshbarger, Repenning and Jackson (1951) proposed that the lowermost portion of original Wingate of Dutton (1885) be assigned as Glen Canyon group without formational designation, and that the remainder of the section be correlated with units of the overlying San Rafael group. Baker, Dane and Reeside (1947) suggested that the Fort Wingate locality of Dutton (1885) be abandoned as the type locality and that the term Wingate sandstone be used for the lower sandstone unit of the Glen Canyon group which is well exposed in the Glen Canyon of the Colorado River.

The Wingate (?) formation is exposed at the base of the prominent orange cliffs north of U. S. Highway 66, where it is a massive, friable, cross-bedded, well-sorted, coarse-grained, orange sandstone. The Wingate rests on a disconformity marked by channel fillings on the top of the Chinle formation, and extends as a steep slope or cliff of remarkably uniform sandstone to a disconformity with the overlying San Rafael group sediments. The sandstone is poorly cemented and well sorted, weathering to a fretted surface where cracks have been cemented with calcite or gypsum. White, angular chert fragments similar to those in the underlying channel fillings are sparsely distributed in the lower 2 feet of the formation. The Wingate (?) formation is entirely aeolian in the Thoreau quadrangle, although nonaeolian facies are recognized in Utah and Arizona.

The Wingate (?) formation increases in thickness from east to west in the Thoreau quadrangle; it is not completely exposed along the eastern margin of the quadrangle but probably is not more than 35 feet thick.

At the western edge of the quadrangle it is more than 90 feet thick, and 20 miles farther west at Fort Wingate, Harshbarger (1950) states it is nearly 300 feet thick; Silver (1948) reports progressive thinning and truncation of all the Jurassic rocks several miles southeast of the Thoreau quadrangle, so the thinning in the Thoreau quadrangle which is in a slightly south of east direction may be a local reflection of the broader relations.

San Rafael Group

Entrada sandstone: The Entrada sandstone was named by Gilluly and Reeside (1928) from exposures in the northern part of the San Rafael Swell in Utah. The sandstone has been traced eastward and southward through Colorado and into northern New Mexico. Baker, Dane, and Reeside (1947) assert that the massive cliffs at Fort Wingate, New Mexico, 20 miles west of the Thoreau quadrangle, originally named the Wingate sandstone by Dutton (1885) are identical with the Entrada sandstone. The lithology and sedimentary structures support this view, and the cliff-forming part of the sandstone sequence above the Wingate (?) and below the Todilto limestone is called Entrada sandstone in this report.

In the Thoreau quadrangle, the Entrada sandstone is readily divisible into two members: a lower, even-bedded, red-to-white, silty sandstone and an upper, cross-bedded, orange-to-white sandstone. The contact between the two units is marked by a change in grain size and sorting as well as by the difference in bedding and color. A narrow, white zone on the weathered cliff surface closely parallels the lithologic boundary between the two members and in some places coincides with it.

The lower member of the Entrada sandstone is fine-grained, massive (3- to 4-foot beds), mottled, red and white, silty sandstone. The red color appears to be surficial and to result from the weathering of thin red siltstone and mudstone partings. These partings combined with prominent vertical joints result in rectangular weathered blocks which have been called “rock babies” by the Indians on the Navajo Reservation. About 17 feet above the base the lower member locally contains a 2-foot zone of strongly cross-laminated (fluviatile?) sandstone and siltstone which is composed of the same material as the overlying and underlying silty sandstone. The lower member is about 40 feet thick in the Thoreau quadrangle. It rests on a slightly undulating surface with a relief of about 6 inches. The lower member shows a uniform, well-defined gradation into the upper member.

The upper member of the Entrada sandstone is massive, orange-red, friable, cross-bedded, medium- to coarse-grained and well sorted. Two grain sizes occur; the coarser grains are concentrated along the foreset planes of the cross-lamination. In those zones where the long tangential cross-beds are replaced by more evenly bedded material, the even-bedding is composed of tiny “rivulet” cross-laminae which truncate one another in a complex manner. In the upper 35 feet the sandstone becomes finer-grained and limy, and near the top of the formation there are lenses 1 to 3 inches thick of sandy limestone. In some places the lenses of sandy limestone in the upper member become thicker, and the interbedded sandstone thinner, so that the formation is gradational into the Todilto limestone. At other places the limestone beds of the Todilto truncate the cross-lamination in the Entrada sandstone with sharply angular unconformity. The upper member is 185 feet thick on the western edge of the quadrangle south of Mt. Powell; in the eastern part of the area it is only 150 feet thick. East of the Thoreau quadrangle this unit thickens and extends for many miles.

The upper and lower members of the Entrada sandstone were not mapped separately, owing to limitation of scale. Other investigators have suggested that the unit described here as the lower member of the Entrada sandstone may be the correlative of the Carmel formation of the San Rafael group (Harshbarger and Rappaport, 1950).

Todilto limestone: Gregory (1917) named the Todilto limestone from exposures in Todilto Park, New Mexico, about 75 miles northwest of the Thoreau quadrangle. Considerable confusion exists in the literature concerning the stratigraphic position of the Todilto limestone, and not all authors are in agreement. This report follows the correlation suggested by Baker, Dane, and Reeside (1947) that the Todilto is equivalent to some part of the Curtis or Summerville formations, In the Thoreau quadrangle, the Todilto beds cap the Entrada sandstone cliff. The Todilto has become economically important owing to its content of uranium minerals; it is shown in red on the geologic map (P1. 1).

The Todilto limestone is a very thin-bedded (1 to 6 inches), dark-gray, dense, fine-grained rock. In places it contains sparse fish scales and ostracod remains, but in general it is nonfossiliferous. Very thin partings (½ to 1 inch) of calcareous green-gray shale and siltstone yield a slabby weathered surface. Locally, gypsum occurs as massive deposits above the limestone or as cement or lenticular masses in the siltstone and shales. In places, lenses of calcareous and gypsiferous sandstone and siltstone are interbedded with the limestone. The Todilto limestone rests with sharp unconformity on truncated cross-bedded Entrada sandstone in some places, and in others it is gradational with the Entrada sandstone. The limestone grades upward into sandstone of the Thoreau formation by thinning of limestone beds and thickening of alternating sandstone beds. The upper contact usually is placed at the last continuous limestone layer.

Owing to the nature of its lower contact, the Todilto limestone, as mapped, ranges in thickness from about 7 feet to a maximum of about 30 feet; the average thickness is probably from 12 to 15 feet. The uranium minerals generally occur in the upper 10 feet of the limestone. The proportion of uranium minerals generally is greater where sandstone lenses are numerous in the upper beds of the formation than where the rock is dominantly limestone.

Thoreau formation: The Thoreau formation is named by the writer for exposures along the cliffs north of the town of Thoreau in the northern part of the Thoreau quadrangle. The type section was measured on the west edge of the quadrangle south of Mt. Powell in Secs. 9 and 17, T. 14 N., R. 13 W.

The Thoreau formation is divided into a lower, even-bedded member and an upper, cross-laminated member; the distinction between the two units is not clear-cut, although the upper member generally is more massive and coarser-grained than the lower member. The gradual change in grain size and sedimentary structures apparently represents a gradually rising source area for the sedimentary materials, and continued filling of the brackish water basin in which the Todilto limestone was precipitated. The close relationships of the Thoreau formation to the Todilto limestone and the marked lithologic break at the top of the upper cross-bedded member suggest its inclusion with the San Rafael group as herein described. At least part of the Thoreau is equivalent to the Red Mesa formation of Hoover (1950). Stratigraphically, the lower member occupies the position of the Summerville formation, and the upper member corresponds to the Bluff sandstone member of the Morrison formation. Craig and Holmes (1951) have suggested that the Bluff sandstone member of the Morrison formation is more properly a member of the Summerville formation.

The lower member of the Thoreau formation consists of alternating, poorly-sorted, thin-bedded, brown, red, and white siltstone and sandstone beds with thin (1 to 6 inches) mud- stone layers near the base; local limestone lenses and limy siltstone mark the gradation between Thoreau sandstone and the underlying Todilto limestone. The lower beds of the Thoreau formation grade upward into well-sorted, medium- to fine-grained sandstone containing sparse siltstone and mudstone interbeds and partings; cross-bedded layers become more abundant and the upper sandstone beds of the lower member resemble the massive sandstone of the upper member.

The upper member of the Thoreau formation consists of massive, cross-laminated, medium-grained, poorly-sorted sandstone. Even-bedded zones from 2 to 5 feet thick containing abundant red, black, and brown chert fragments alternate with cross-laminated layers from 5 to 11 feet thick, The cross-bedded layers are somewhat coarser-grained than the even-bedded strata and have long sweeping foresets; mottled red and greenish staining with some concretionary weathering is common. The bedding becomes more massive and obscure near the top of the unit; the top beds have been eroded to depths ranging from 2 to 5 feet, and the resulting scours are filled by the overlying sandstone.

At the type locality, a little more than 200 feet of beds are assigned to the lower member of the Thoreau formation and 184 feet of beds are placed in the upper member. The beds thin to the east, and at the eastern margin of the quadrangle the formation is about 275 feet thick. Most of the thinning is in the lower member of the formation; the massive, cross-bedded upper sandstone member remains between 175 and 200 feet in thickness.

Morrison Formation

Chavez member: The Chavez member of the Morrison formation is named by the writer for the excellent exposures on the small mesa east of the Chaco Canyon road about 5 miles north of Chavez Siding on the Atchison, Topeka and Santa Fe Railway. The type section was measured in Sec. 9, T. 14 N., R. 13 W., south of Mt. Powell near the western edge of the Thoreau quadrangle. In general appearance the Chavez member resembles the Recapture shale member of the Morrison formation to which it may be equivalent.

The Chavez member consists of alternating, variegated, greenish siltstone, purplish-to-reddish sandy mudstone, and white-to-buff, coarse-grained, conglomeratic sandstone. Locally, the units contain silty layers and mud-ball zones, and much of the sandy material is strongly cross-laminated. The beds of sandstone range from 3 to 6 feet thick, siltstone from 1 to 3 feet thick, and the mudstone layers from 3 inches to 2 feet thick. Chert and chalky feldspar (?) grains are common in the upper part of the formation. A variegated red, purple, and green mudstone bed nearly 15 feet thick occurs near the top of the formation.

The Chavez member, about 160 feet thick in the type section, thins to the west. It is nearly 200 feet thick along the eastern boundary of the quadrangle. However, individual beds vary in thickness, and the upper part of the member locally intertongues with the Prewitt member. Thus, thicknesses of less than 100 feet have been measured near the Chaco Canyon road.

Prewitt sandstone member: The Prewitt sandstone member of the Morrison formation is a massive, reddish-brown, cliff-forming sandstone named by the writer for its excellent exposures along the cliffs north of U. S. Highway 66, north of Prewitt, New Mexico. The type section was measured south of Mt. Powell in the western part of the Thoreau quadrangle in Sec. 9, T. 14 N., R. 13 W. The stratigraphic interval of the Westwater Canyon sandstone member of the Morrison formation in southeast Utah and northeast Arizona is approximately equivalent to the position of the Prewitt sandstone member in the Thoreau quadrangle. For this reason some investigators (Rappaport, 1950) extend the Westwatér Canyon sandstone member into the Thoreau quadrangle and apply it to all of the sandy facies in the upper part of the Morrison formation. In the Thoreau quadrangle, distinct differences in lithology and sedimentary structures occur between the Prewitt sandstone member and overlying sandstone lenses which herein are considered equivalent to the Brushy Basin shale member. The differences become far less distinct to the west; locally, west of Fort Wingate, New Mexico, a contact between Westwater Canyon sandstone or Prewitt member and sandstone lenses in the Brushy Basin shale member cannot be mapped. The Prewitt member contains no uranium deposits, whereas sandstone lenses in the Brushy Basin shale member have been found to be mineralized. The contact between these members has been drawn throughout the quadrangle because of its economic significance.

The Prewitt sandstone is a brown-weathering, massive, coarse-grained, cross-bedded, light pinkish-red, conglomeratic sandstone. It is poorly sorted and contains from 10 to 15 per cent red chert and chalky feldspar (?) grains and small (5 mm.) green mud balls. The base of the sandstone fills scours in the underlying Chavez mudstones with a relief of about 4 to 5 feet. Near the base of the member is a 4-foot purplish siltstone layer very similar to the underlying Chavez member. In the central part of the member a similar thick purplish siltstone layer with a great range in thickness occupies the central portion of the sandstone cliff for many miles. Above this siltstone the sandstone is much coarser-grained with pebbles from 12 to 19 mm. in diameter; the coarsest material is concentrated along the foreset planes of the cross-lamination. Lenticular layers of purplish siltstone and mudstone occur in the upper part of the sandstone.

The Prewitt sandstone is between 185 and 190 feet thick in the type section and does not change appreciably in thickness throughout the Thoreau quadrangle. Thinning is evident east of the quadrangle and some thinning is apparent much farther west. Local thinning occurs where conglomeratic channel lenses are absent.

Brushy Basin shale member: The Brushy Basin shale member of the Morrison formation was named by Gregory (1938) from exposures in Brushy Basin in San Juan County, Utah. The variegated sandstone, siltstone and mudstone beds of the Brushy Basin shale member are typical of the Morrison formation at the type locality near Morrison, Colorado.

In the Thoreau quadrangle, the beds of the Brushy Basin shale member of the Morrison formation show marked change in lithology along the strike. Typically, the rocks are variegated green, gray, and yellow, thin-bedded, calcareous siltstones and mudstones locally containing lenses of coarse sandstone and conglomerate. In some places, coal and carbonaceous debris are interbedded with the sandstones and siltstones. Locally, the entire section may be soft, silty sandstone with conglomeratic lenses. These sandstone facies exhibit the maximum thickness of 135 feet, whereas mudstone and siltstone facies are as little as 75 feet thick. The Brushy Basin member averages slightly over 100 feet thick. Where sandstone is prominent, carnotite may be present, and considerable uranium ore has been found at this horizon in the Thoreau and neighboring quadrangles. Carnotite is commonly associated with coal or carbonaceous material.

The Brushy Basin grades laterally into thin-bedded sandstone to the west and south, and grades into siltstone and variegated mudstone to the east and north. It is overlain with erosional disconformity by sandstone beds of the Dakota (?) formation of upper Cretaceous age. Some of the differences in thickness may be due to disconformity at the top of the member.

CRETACEOUS ROCKS

Dakota (?) formation: Along the western slope of the Rocky Mountains it long has been the custom of geologists to call the lowest sandstones of the upper Cretaceous sequence “Dakota formation” with little regard for the time equivalence of these beds with type Dakota sandstone, This practice has been followed in the Thoreau quadrangle, although it is recognized that because of the overlap relationships between marine and nonmarine Cretaceous rocks in this area, the beds called Dakota (?) formation in the Thoreau quadrangle may not be similar or equivalent to beds called Dakota (?) formation east of Mt. Taylor (Sears, Hunt, and Dane, 1934 and 1936).

The Dakota (?) formation consists of massive, cross-bedded, buff-to-brown, conglomeratic sandstone with thin, gray shale layers. The formation commonly is separated into two cliffs, by a narrow zone of platy, thin-bedded sandstone with numerous shaly layers which locally contain carbonaceous shale beds and some low-rank coal. Most of the coal beds are lenticular and occur in the base of the formation or in the shaly, thin-bedded zone in the central part of the formation.

The thickness of the Dakota (?) formation changes from place to place because of the gradational contact with the overlying Mancos shale. It ranges from 100 to 150 feet in thickness, averaging about 135 to 140 feet. The lower cliff is from 50 to 55 feet in thickness and is thin-bedded with low angle cross-bedding. The upper cliff is more massive than the lower and exhibits torrential cross-bedding and some pebble conglomerate zones; it reaches a maximum thickness of from 65 to 70 feet. The alternating siltstone and shale between the cliffs range from 15 to 20 feet thick and in places appear only as a coaly layer which is exposed on a single cliff composed of both upper and lower sandstones.

The upper contact of the Dakota (?) formation is placed at the upper surface of a persistent, even-bedded, greenish-gray sandstone which characteristically weathers dark greenish-brown. This sandstone contains thin gritty zones and abundant micaceous flakes. Locally, at this horizon, sandstone lenses which weather the same color are composed of abundant shell fragments. The beds selected as uppermost Dakota (?) formation occur between 20 and 100 feet below an abundantly fossiliferous zone in the Mancos shale. When fossiliferous beds mark the lithologic break between Dakota and Mancos, the transition from nonmarine to marine conditions is not clear-cut. Thus, much of the material mapped as Dakota (?) formation in the Thoreau quadrangle could as well be considered a basal sandstone unit of the Mancos shale. This formation has become economically important for its uranium content, especially to the east of the Thoreau quadrangle.

Mancos shale: The Mancos shale was named by Whitman Cross (1899) from exposures near the town of Mancos, Colorado. The unit since has been extended to include nearly all the gray-black marine shales which mark the first major marine inundation of upper Cretaceous time in the Rocky Mountain region. In northwest New Mexico large-scale marine and nonmarine intertonguing between rocks referred to the Mancos and Mesaverde formations has been studied in some detail and the relations are well-known (Sears, Hunt, and Hendricks, 1941; Pike, 1947).

The lower part of the Mancos shale is well-exposed along the extreme northern edge of the Thoreau quadrangle, and the upper part lies north of the area boundaries. The beds are gray-black, platy, calcareous shale with a few local thin-bedded silty or sandy lenses. The sandy beds are abundantly fossiliferous in many localities, and much of the lower part of the formation contains fossils. The commonest forms are *Gryphea new berryi* and *Inoceramus sp?. Exogyra columbella* and fragments of a large *Ostrea sp?* are less common, From 200 to 300 feet of Mancos shale is exposed within the boundaries of the Thoreau quadrangle and an additional 400 to 500 feet is estimated north of the quadrangle boundary.

QUATERNARY ROCKS

Alluvium: Several alluvial stages are represented in stream terraces throughout the quadrangle, and debris fills most of the canyon floors. Most of the material is derived locally and is similar to the rocks upon which it is deposited. In the northern part of the quadrangle the alluvial debris is fine silt or sand, much of it windblown; in the southern part of the quadrangle cobbles of limestone and red sandstone are mixed with Precambrian granitic debris. In the broader valleys the alluvium is of sufficient thickness to constitute a storage zone for ground water which supplies local ranch needs during wet seasons.

IGNEOUS ROCKS

TERTIARY AND QUATERNARY ROCKS

Basalt: Basaltic lava flows are exposed at two places in the Thoreau quadrangle. The oldest flows occur as two small erosional remnants capping Mt. Powell and an adjacent ridge in the extreme northwest corner of the quadrangle.

The basalt is about 75 feet thick on Mt. Powell and may represent several flows, although exposures are too poor to determine the relationships.

A few other high-level erosional remnants of basaltic lava are known west of the Thoreau quadrangle, but no dikes or feeders for the flows have been mapped. The remnants lie at elevations above 8,000 feet and may represent the remains of a very widespread thin sheet which is related to a part of the Mt. Taylor volcanic activity (Hunt, 1938).

A basaltic flow which had its source in a well-preserved cinder cone east of the quadrangle fills much of Bluewater Valley east of the quadrangle. A small lobe of the flow which is included in the southeastern part of the quadrangle ranges from a few feet to nearly 20 feet in thickness. Numerous cinder cones and very recent basaltic flows occur east and south of the quadrangle; estimates of the ages of such rocks range from the Pleistocene epoch to less than 2,000 years; some certainly have occurred during the present cycle of erosion and some are not much earlier than the present topographic surface. Relationships east of the quadrangle suggest that the lava of the Bluewater Valley is one of the more recent flows.

Structure

Beds in the Thoreau quadrangle dip gently northward or northeastward, from 3 to 5 degrees, under the younger rocks of the central part of the San Juan Basin. The gentle homoclinal dip is interrupted by several persistent fault zones of small throw, Structures within the quadrangle appear to be closely related to and controlled by the uplift of the Precambrian core of the Zuni Mountains south of the mapped area.

In the southern part of the quadrangle the beds dip more steeply, gradually flattening toward the northern boundary. Locally, near fault zones, steeper dips and aberrant dip directions have resulted from drag along the faults. Local steepenings in the regional dip such as are found in the southwest corner of the quadrangle are probably the result of faulting in the underlying crystalline rocks. Farther west, such local flexures pass into small faults along the strike and back into flexures.

The fault zones in the southern part of the quadrangle radiate from the Precambrian core of the mountains. In the southeast corner of the quadrangle, several faults associated with the Big Draw fault zone strike N. 45° E. to nearly east. Farther north a smaller fault which is well exposed in the gorge of Bluewater Creek strikes from N. 30° E. to N. 45° E. To the west the Bluewater fault zone strikes almost north. The fault zone east of Andrews ranch along the eastern edge of the quadrangle may be a northern continuation of the Big Draw fault zone or may be related to structures farther east beyond the limits of mapping. The radially-arranged faults die out or are greatly reduced in throw as they approach the Precambrian contact; likewise their displacements diminish northeastward, so that they attain maximum displacements in a zone from 2 to 4 miles north or northeast of the Precambrian outcrops. Many of the fault zones are *en echelon***,** and separations along individual fault surfaces are very complex.

The maximum stratigraphic throw along the Big Draw fault zone is shown in the extreme southeast corner of the quadrangle where it ranges between 400 and 600 feet. This separation dies out rapidly northeast and southwest from these exposures. The smaller faults in Bluewater Canyon have throws of from 30 to 100 feet, and these too die out along the strike. The Bluewater fault zone is the most persistent in the quadrangle and has been mapped almost continuously from the south to the north quadrangle boundary. The zone is obscured by alluvium north of U. S. Highway 66, but its extension is exposed in the cliffs of Jurassic rocks and along the Chaco Canyon road. Although locally complicated, this fault zone follows an echelon pattern in which each successive fault surface shows its maximum separation either northwest or southeast of the preceding fault surface. Individual fracture surfaces seldom extend more than 2 or 3 miles. On the extreme north end of the zone, the fault surface which marks the extension of the fault zone beyond the limits of the quadrangle begins as a monoclinal fold in Cretaceous rocks which grades into a fault about 1/4 mile south of the north edge of the quadrangle. Bluewater Lake conceals a similar echelon pattern which might also show monoclinal folding if exposures were continuous; locally, along the eastern shore line, the beds dip westward at moderate angles. Maximum stratigraphic throw along the Bluewater fault zone ranges from 200 to 400 feet, although the average is probably less than 100 feet. The fault zone which lies along the eastern edge of the quadrangle east of Andrews ranch has the largest displacement of any of the faults mapped; the maximum stratigraphic throw is over 700 feet. This decreases to the north, and the fault is concealed by alluvium south of the Entrada cliffs. Faulting near Haystack Mountain east of the quadrangle may be an echelon extension of the Andrews ranch zone; however, recent basalt flows and alluvium completely cover the critical outcrops.

Economic Geology

The economic resources of the Thoreau quadrangle are many and varied. Currently, uranium deposits are the most important of the known mineral resources. Ground-water resources have not been developed to their maximum capacity. Sandstone blocks for constructional purposes have been quarried from the Glorieta sandstone. Road metal for fill and surfacing is obtained from several beds. Scattered bands of sheep and cattle graze this area. Timber has been cut from many of the slopes.

URANIUM DEPOSITS

Uranium first was discovered in the Thoreau quadrangle in 1949 by students attending the joint summer geology field camp of the California Institute of Technology and the New Mexico Institute of Mining and Technology. Coatings of tyuyamunite were found on outcrops of Todilto limestone east of Andrews ranch north of Prewitt. Little significance was attached to the discovery because of the limestone host rock and the apparent lack of large tonnage reserves. A Navajo Indian, Paddy Martinez, in the spring of 1950, located other deposits at Haystack Mountain east of the quadrangle on land owned by the A.T.&S.F. Railway Company. These occurrences were much more extensive and warranted additional prospecting; when the A.T.&S.F. Railway Company began a sampling and evaluation program on their properties, numerous other showings were located as a result of intensive prospecting.

The original discoveries were confined to Todilto limestone and the best deposits are east of the Thoreau quadrangle. Additional prospecting has resulted in the discovery of ore in sandstone lenses in the Brushy Basin shale member of the Morrison formation. Recent reports have confirmed the presence of uranium mineralization in the Dakota (?) sandstone and in sandstone beds of the Mesaverde formation overlying the Mancos shale. The two principal ore-bearing horizons in the Thoreau quadrangle, the Todilto limestone and the Brushy Basin shale member of the Morrison formation, are colored red on the geologic map (P1. 1). A potential third zone, the Dakota sandstone, is exposed above the Brushy Basin shale member. The Todilto limestone has been thoroughly prospected and most of the known occurrences are claimed and indicated on the map (P1. 1); however, the sandstone beds of the Brushy Basin member of the Morrison formation and the Dakota sandstone have not been as thoroughly examined.

The uranium mineralization can be divided into two distinct types. (1) Tyuyamunite [$Ca\ (U0_2)_2\ (V0_4)_{2\text{-}}\ 3H_2O$] concentrated along cracks and fracture surfaces and disseminated in Todilto limestone associated with uraninite [$U0_2$], uranophane [$Ca\ (VO)_2\ Si_2O_7 6H_2O$], hematite and other minerals in minor amounts; and (2) carnotite [$K_2(U0_2)_2\ (V0_4)_{2\text{-}}\ 3H_2 0$] disseminated in sandstone (Brushy Basin shale member of Morrison formation, Dakota sandstone or Mesaverde formation) with some carbonaceous material, uraninite, limonite, schrockingerite [$NaCa_3\ (U0_2)(C0_3)_3(SO_4)\ F.10\ H_2O$], and manganese oxides in small amounts. Locally, Type 1 is referred to as limestone ore and Type 2 as sandstone ore. The uranium minerals are usually very fine-grained and powdery, though relatively large secondary crystals do occur in vugs or solution cavities. The bright yellow color and the radioactivity usually are sufficient to distinguish the uranium bearing material from barren yellow-stained rocks. Some ore, of both types, is dark and the yellow color is not obvious.

The largest dimensions of the ore bodies are parallel to the bedding of the enclosing sediments, although in some places concentrations of minerals do cut across the bedding planes. The mineralized bodies range in size from areas containing a few hundred tons to large areas containing more than 100,000 tons, The grade of the ore is not available for publication, but most of the material averages somewhat lower grade than the ores currently being mined farther north and west in the Colorado Plateau.

Ore in the Todilto limestone generally is restricted to beds from 2 to 5 feet below the top of the formation and is about 5 feet thick. Locally, because of favorable fracturing, the ore may extend throughout a 10- to 15-foot width which in places may be the entire thickness of the formation.

The sandstone ore is concentrated along scour zones or along thin irregular mudstone layers. Mineralized zones (called "rolls" by the miners) cut across the bedding with a crescentic cross section. The sandstone beds are lenticular channel fillings and the edges of such channels seem to be favorable loci for deposition. Most of the deposits found to date are in the lower half of the Brushy Basin member and near the tops of sandy zones within the unit. Occurrences in Dakota (?) sandstone and in the Mesaverde formation are similar, but not well known.

Nearly all the land in the Thoreau quadrangle which might be favorable for uranium prospecting is held as Indian land, private ranches, or by the A.T.&S.F, Railway Company. Small tracts of Federal and State land occasionally are available; some private ranch lands do not hold mineral rights, but a detailed investigation of title is necessary to establish ownership on any discovery.

GROUNDWATER RESOURCES

Several units of the different, formations are potential ground-water producers. The lower sandstone and conglomerate beds of the Abo formation underlie all of the quadrangle at depths ranging from about 600 feet along the southern margin to several thousand feet at the northern edge. The deep A.T.&S.F. Railway Company wells at Chavez tap sandstone beds either in the base of the Glorieta formation or in the uppermost part of the Yeso formation. Locally, the middle sandstone member of the San Andres formation and the Dakota sandstone may be good aquifers. A few shallow wells have been sunk in the alluvium of some of the larger stream valleys; these have capacities dependent entirely upon annual precipitation and thickness of alluvium.

Yeso formation: The outcrop area of the Yeso formation is limited and recharge is correspondingly small. Much of the formation is fine-grained sandstone or siltstone, contains some gypsum, and lacks adequate permeability to serve as a good aquifer. However, in the upper part of the formation sandstone beds similar to the overlying Glorieta sandstone are much coarser-grained and more permeable. Water of variable quality should be available from these units at depths ranging from 200 to 300 feet in the southern part of the quadrangle and at depths ranging from 1,000 to 1,500 feet in the valley north of U. S. Highway 66. Several springs in the gorge of Bluewater Creek probably are derived from either the basal beds of the overlying Glorieta sandstone or from sandstone beds in the upper Yeso formation. The quality of the water produced from the A.T.&S.F. Railway Company wells at Chavez from this horizon or slightly higher is excellent.

Glorieta sandstone: Recharge to the Glorieta sandstone is particularly extensive in the southwest corner of the Thoreau quadrangle and farther south. However, the extensive exposures are mostly in the top of the sandstone, where permeability is low because of abundant calcareous cement. The lower part of the sandstone is much more permeable and, since the contact between the Yeso formation and the Glorieta sandstone is somewhat arbitrarily located, the zone of good water accumulation probably crosses the formational boundary in many places. However, the gypsum content of the upper beds of the Yeso formation will reduce markedly the quality of the water if wells penetrate appreciable footages of the Yeso beds. Drilling depths are from a few feet in the southern part of the quadrangle to more than 1,000 feet in the valley north of U. S. Highway 66. Many springs in the gorge of Bluewater Creek below Bluewater Lake are at several different levels within the sandstone and apparently represent permeable zones separated by less permeable material. One of the best springs is only a few feet below the top of the formation about half a mile east of Bluewater Lake. This spring which flows, an estimated 5 to 6 gallons per minute serves many Indian families as well as supplying most of the needs of a small fishing resort at the lake. However, it is obvious that this spring as well as several others in the vicinity derives most of its flow from the accumulated storage provided by Bluewater Lake; the recharge area for these springs is exceedingly small. Quality of water in the Glorieta sandstone is extremely variable. Water derived from the basal beds is of excellent quality, but water accumulated in the upper parts of the formation contains considerable calcium carbonate. A well completed in June 1952 at Thoreau yielded an artesian flow of 6 gallons per minute of good quality water from depths of from 1,081 to 1,250 feet. The log of this well, supplied through the courtesy of the U. S. Geological Survey, Ground Water Branch, Navajo Project, Holbrook, Arizona, suggests that the upper portion of the Yeso formation, as well as the entire thickness of the Glorieta formation, is water-bearing. The formational names and stratigraphic interpretations, shown on the following log, are those of the author and do not necessarily represent the opinions of the U. S. Geological Survey.

LOG OF THOREAU SCHOOL WELL NO. 2

	Thickness (feet)	Depth (feet)
QUATERNARY:		
ALLUVIUM: (aeolian and fluviatile)		
Light brown, coarse to very fine silty calcareous quartz sand, sorting poor	20	20
Light brown, very coarse to very fine silty calcareous quartz sand with limestone fragments, sorting poor	60	80
Grayish orange pink, very coarse to very fine silty calcareous sand with limestone fragments, sorting poor	50	130
Total thickness alluvium	130	
TRIASSIC:		
CHINLE FORMATION:		
Upper member:		
Pale red, l0R6/2,* sandy calcareous siltstone with mudstone fragments	40	170
Pale red, 5R-6/2, medium to fine calcareous quartz sand, sorting fair	10	180
Pale red, 5R-6/2, silty coarse to *very* fine calcareous quartz sand with limestone fragments, sorting poor	20	200
Pale red, 10R-6/2, sandy calcareous siltstone with limestone fragments	10	210
Pale red, 10R-6/2, silty medium to very fine calcareous quartz sand, sorting poor	20	230
Pale red, 10R-6/2, sandy calcareous siltstone	30	260
Pale red, 10R6/2*, medium to very fine calcareous quartz sand with limestone fragments	20	280
Pale red, 10R-6/2, medium to very fine calcareous quartz sand with fragments of limestone and silt-stone, sorting poor	40	320
Pale red, 10R-6/2, silty calcareous mudstone	10	330
Pale red, l0R-6/2, sandy siltstone with mudstone fragment	10	340
Pale red, 10R-6/2, medium to fine calcareous quartz sand, sorting fair with fragments of siltstone and limestone	20	360
Thickness upper member (incomplete)	230	
Middle member:		
Pale red, coarse to very fine calcareous quartz sand with limestone fragments, sorting poor	10	370
Pale red, 10R-6/2, sandy siltstone with fragments of mudstone and limestone	10	380
Pale red, 10R-6/2, very coarse to very fine silty calcareous quartz sand with limestone fragments, sorting poor	10	390
Pale red, 10R-6/2, very coarse to very fine silty calcareous quartz sand with fragments of chert, sorting poor	30	420
Total thickness middle member	60	
Lower member:		
Grayish red purple, calcareous claystone	10	430
Pale red, 10R-6/2, sandy calcareous siltstone with limestone fragments	20	450
Light brownish gray, silty calcareous mudstone	40	490
Pale red, 10R-6/2, medium to fine calcareous quartz sand, sorting fair with fragments of chert and limestone (possible top of lower member)	10	500
Pale red, 10R-6/2, sandy calcareous silty mudstone	30	530
Grayish red, calcareous siltstone	10	540
Grayish red purple, silty calcareous mudstone	30	570
Grayish red, 5R4/2,* calcareous siltstone	40	610
Pale red, 10R-6/2, silty calcareous mudstone	50	660
Pale red, 5R-6/2, silty calcareous mudstone and claystone	40	700
Pale red, 5R-6/2, sandy siltstone with claystone fragment	20	720

	Thickness (feet)	Depth (feet)
Pale red, 5R-6/2, sandy mudstone and claystone	110	830
Pale red, 5R-6/2, silty calcareous mudstone with muscovite and limestone fragments	50	880
Approximate thickness lower member (incomplete)	+460	
Pale red, 5R-6/2, silty calcareous mudstone with muscovite and fragments of claystone and limestone and sand and gypsum. (The base of the Triassic and the top of the Permian formations are somewhere in this 160-foot interval)	160	1,040
Approximate thickness Chinle formation (incomplete)	+900	
SAN ANDRES FORMATION:		
Middle sand member:		
Very pale orange, fine to very fine calcareous quartz sand, sorting good	10	1,050
Lower member:		
Pale red, 5R-6/2, silty calcareous mudstone and clay-stone with sand grains	30	1,080
Approximate total thickness San Andres formation	+50	
GLORIETA FORMATION:		
Very pale orange, medium to very fine calcareous quartz sand, sorting good	20	1,100
Very pale orange, coarse to very fine calcareous quartz sand, sorting poor	10	1,110
Very pale orange, medium to very fine calcareous quartz sand, sorting fair	20	1,130
Pale red, 10R6/2*, sandy calcareous siltstone with biotite	10	1,140
Very pale orange, fine to very fine silty calcareous quartz sand, sorting fair	20	1,160
Total thickness Glorieta formation	80	
YESO FORMATION:		
Grayish orange pink, silty mudstone with biotite	10	1,170
Pale reddish brown, sandy calcareous siltstone	10	1,180
Pale red, l0R6/2*, sandy calcareous siltstone with gypsum	10	1,190
Pale red, 10R-6/2, sandy calcareous siltstone	60	1,250
Total thickness of Yeso formation penetrated (incomplete)	90	

*Munsell designation, Rock-Color Chart, Distributed by Geological Society of America, 1951

San Andres formation: Extensive exposures on the dip slopes in the southern part of the Thoreau quadrangle provide large recharge areas for the San Andres formation. However, the limestone members of the formation are massive and only slightly permeable. Cavernous limestone, at the top of the formation could provide considerable storage. The middle sandstone member is almost impermeable owing to calcareous cement, although local permeable zones are present. The small amount of water available in the San Andres formation is of poor quality because of the limestone host rock. The top of the formation is at the surface at Bluewater Lake and is less than 1,000 feet below the surface along the Chaco Canyon road in the central part of the quadrangle.

Chinle formation: The extensive exposures in the central part of the quadrangle give the Chinle formation a recharge area nearly equal to that of all other formations combined. However, the porosity and permeability of most of the beds are low and the capacity to yield water is far less than those of much less extensive units. The lower member of the Chinle formation may contain water locally at the contact with the underlying San Andres formation, either in sand-filled sink holes in the limestone or in sand and fine-grained conglomerate lenses which occur sporadically at this horizon. The accumulations are erratic and this zone is not a satisfactory water source. In the areas where this horizon might be sought, depths should range from 150 to 600 feet.

The middle sandstone member of the Chinle formation should be the best potential aquifer in the northern half of the Thoreau quadrangle. Darton (1928, p. 146) reported artesian flow from a well which penetrated this member at old Chavez station. The sandstone member has an extensive recharge area on the dip slope immediately south of U. S. Highway 66, and the coarse sandstone and conglomerate favors high permeability and porosity for the entire unit, However, the Ground Water Branch of the U. S. Geological Survey has found the water from this unit to be consistently bad and not fit for stock even when mixed with other supplies. Accordingly, recent drilling has avoided water production from this member.

The upper member of the Chinle formation is very similar in lithology to the lower member; it lacks some of the coarser lenses which occur in the base of the lower member and thus is less pervious than the remainder of the formation. The extensive covering of alluvium and the southerly slope of its general outcrop area make recharge to this member difficult despite the extensive surface area. This unit serves as the impervious cover which preserves artesian flow conditions in the underlying middle sandstone member.

Wingate (?) formation: The Wingate (?) formation is exposed at the base of the massive cliffs north of U. S. Highway 66 but because of its protected position it has essentially no recharge area. The sandstone is very porous, but contains some gypsum cement particularly along joint fractures which would tend to increase the sulphate hardness of any contained water. The sandstone is too thin in the Thoreau quadrangle to afford much storage capacity, and this feature, coupled with its lack of recharge, reduces its potential as an aquifer.

Entrada sandstone: The Entrada sandstone forms the prominent cliff north of U. S. Highway 66 but because of its topographic expression has a very limited recharge area. The degree of sorting and extensive cross-bedding favor excellent porosity and permeability so that the sandstone should serve as an excellent aquifer if water could be introduced into it. Locally, small springs occur at the contact between the Entrada sandstone and the overlying Todilto limestone near the base of the steep slope cut on the Jurassic rocks below the Dakota (?) sandstone. The flow of these springs is too small to be gauged, although one well west of the quadrangle provides water from this horizon for about ten Navajo families. Except for narrow areas at the north ends of the prominent mesas formed on the Entrada cliffs, drilling depths are in excess of 1,000 feet over most of the northern margin of the quadrangle. The quality of water may be poor because of the proximity of the Todilto limestone and the gypsum which may accompany it.

Todilto limestone: The Todilto limestone caps nearly all the mesas formed on the top of the Entrada sandstone cliffs so that in the area between the Chaco Canyon road and Andrews ranch considerable recharge surface is exposed. The formation is very platy and thin-bedded and therefore has exceptional permeability for a limestone unit. However, it is quite thin and has little storage capacity. The water is of poor quality; in some places it is hardly fit for cattle or sheep.

Thoreau sandstone: The Thoreau sandstone is exposed principally in cliffs or steep slopes and has a limited recharge area. The lower member is too fine-grained and silty to serve as a good aquifer. The upper member is coarser-grained and strongly cross-bedded. The formation is quite thick and has many of the characteristics necessary for the storage and accumulation of ground water; however, the lack of an adequate recharge area limits its potential.

Morrison formation: The Prewitt sandstone member of the Morrison formation is the most favorable unit of the Morrison for ground-water accumulation. The underlying Chavez member is dominantly siltstone and mudstone and has low permeability, whereas the overlying Brushy Basin shale member is only locally permeable, owing to the occurrence of sandstone lenses. The Prewitt sandstone crops out almost entirely as a cliff across the quadrangle and thus has a greatly restricted recharge area. Given a means of introducing water into the formation, the overlying Brushy Basin shale member and the underlying Chavez member provide all the conditions for artesian flow. The sandstone should lie at depths not in excess of 300 feet along the northern edge of the quadrangle. The quality of water should be good, although no tests have been made.

Dakota (?) formation: The Dakota (?) formation has an extensive recharge area on the dip slope near the northern margin of the quadrangle. The coarse, conglomeratic sandstone is an excellent aquifer, and most of the wells drilled in Cretaceous rocks immediately north of the Thoreau quadrangle develop artesian circulation in the Dakota (?) formation beneath the Mancos shale. The lower part of the formation is more favorable for ground water and in a few places along the northern boundary of the quadrangle shallow wells yield water from the basal sands of the formation. Water from the topmost beds of the formation is of poor quality, owing to contamination from the overlying Mancos formation.

Mancos shale: The Mancos shale forms the impervious cap rock for the underlying Dakota (?) formation. Lenticular sandstone beds in the upper part of the Mancos shale, which are exposed beyond the boundaries of the Thoreau quadrangle, may provide local sources of water.

Alluvium: Most of the water supply for the local inhabitants in the quadrangle is derived from shallow wells in alluvium. Owing to the limited capacity and the dependence upon seasonal precipitation, these wells fluctuate greatly; during the summers of 1950 and 1951 many went dry. Much of the alluvium is alternating sandstone and siltstone or claystone and can be used for the construction of stock tanks, although seepage losses are high. The alluvium is an inadequate reservoir for most water requirements.

Structure has little effect on ground-water supplies except to provide nearly ideal conditions for artesian circulation along the north flank of the Zuni Mountains. In the extreme southeast corner of the quadrangle, the Big Draw fault and associated breaks channel circulation of ground water from the recharge area farther south and west into narrow valleys and limited storage areas. In other parts of the quadrangle, faulting has little effect upon distribution of ground water.

MISCELLANEOUS RESOURCES

Crushed rock, and flagstone have been produced commercially from the Thoreau quadrangle. Limestones in the Yeso formation and in the San Andres formation contain fetid zones and methane odor may be detected on some freshly broken surfaces; however, petroleum production seems unlikely within the quadrangle. Small lenses of coal containing up to a few tons of subbituminous material are found in places in the basal part of the Dakota (?) formation.

Sand and gravel quarried from the middle sandstone member of the Chinle formation provided the subgrade for U. S. Highway 66 and Todilto limestone crushed to about -1 inch was used for the final asphalt surfacing coat on the same road. The Todilto limestone also is used extensively for secondary gravel-surfaced roads in this part of the state.

Slabby sandstone in the upper member of the Chinle formation has been quarried for flagstone for local use.

Ponderosa pine grows readily on outcrops of Glorieta sandstone and many areas have been logged two or three times since about 1860. Much of the area now is within the Cibola National Forest and only limited cutting is allowed; on private plots many individuals cut railroad ties for the A,T.&S.F. Railway Company.

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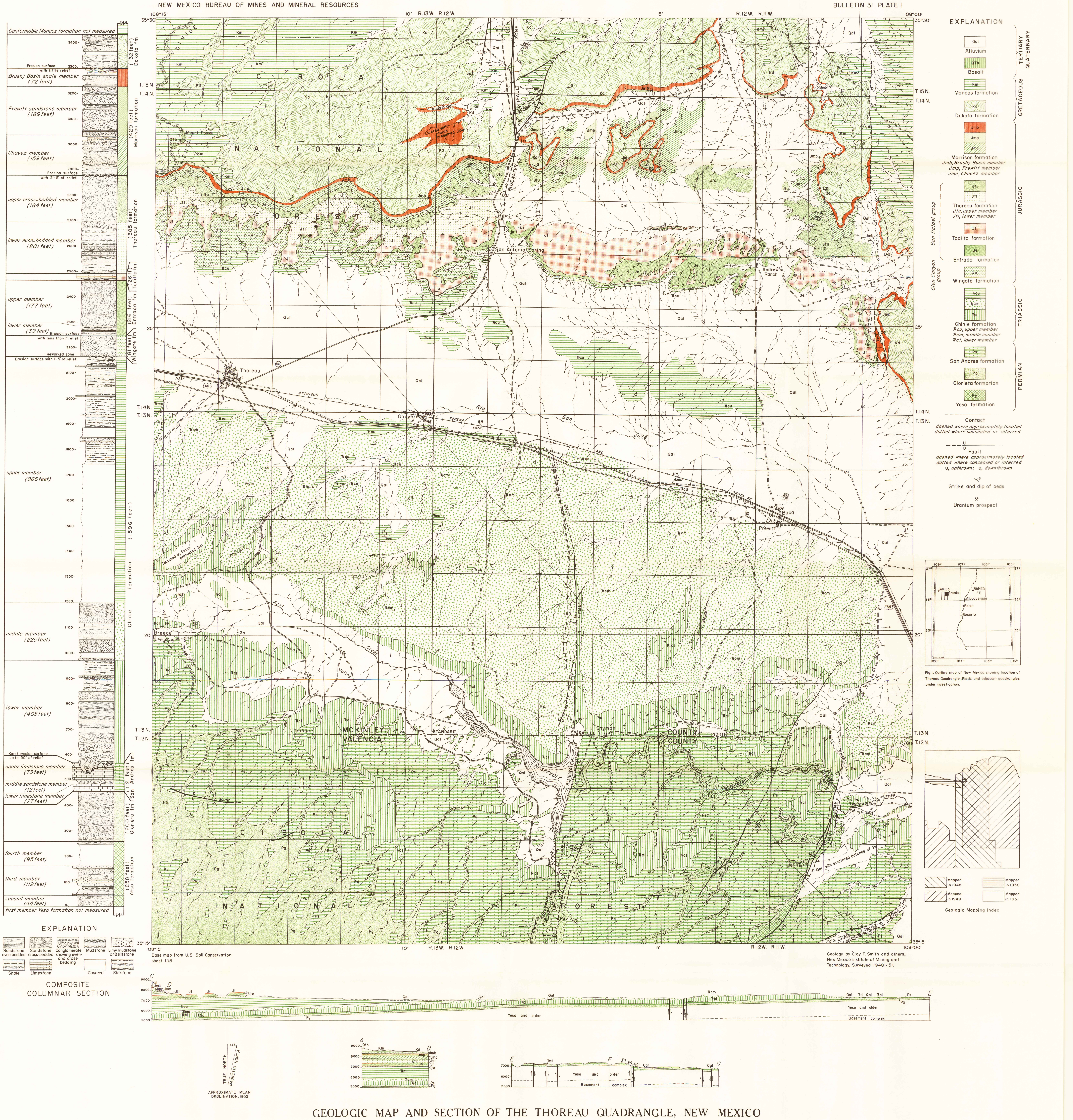

GEOLOGIC MAP AND SECTION OF THE THOREAU QUADRANGLE, NEW MEXICO