GEOLOGY OF THE ZUNI MOUNTAINS, VALENCIA AND McKINLEY COUNTIES, NEW MEXICO

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The Zuni Mountains are a low northwest-southeast trending range in northwestern New Mexico (see fig. 1). They extend for a distance of over 80 miles from longtitude 107°50′ W. and latitude 30°50′ N. to longtitude 108°45′ W. and latitude 35°40′ N. Between Ramah and Thoreau, New Mexico, the mountain block is over 30 miles wide but tapers to widths of less than a mile at either end.

Some of the earliest geologic work in the Zuni Mountains was that of Dutton (1885), who described the section exposed near Fort Wingate, New Mexico. Darton (1927) mapped the mountains in reconnaissance and outlined the principal structural features, although he retained some erroneous stratigraphic relationships. The discovery of uranium northeast of the mountains stimulated interest in the area, and considerable work has been done by the U. S. Geological Survey and the Atomic Energy Commission. Most of this work, however, is classified, and only a few measured sections (Baker, Dane, and Reeside, 1936; Harshbarger, Repenning, and Irwin, 1957) and a report by Smith (1954) have been published. The U. S. Geological Survey also has investigated the fluorite deposits of the Precambrian parts of the mountains (Goddard, in preparation).

Maximum elevations in the Zuni Mountains seldom exceed 9,000 ft., and the average relief is usually less than 1,000 ft. The resistant central core of igneous and metamorphic rocks is surrounded by alternating valleys and cuestas developed on the sedimentary formations. The cuestas have their steep faces inward toward the core of the mountains, with long gentle dip slopes facing outward. The flora and fauna vary from desert shrubs and animal

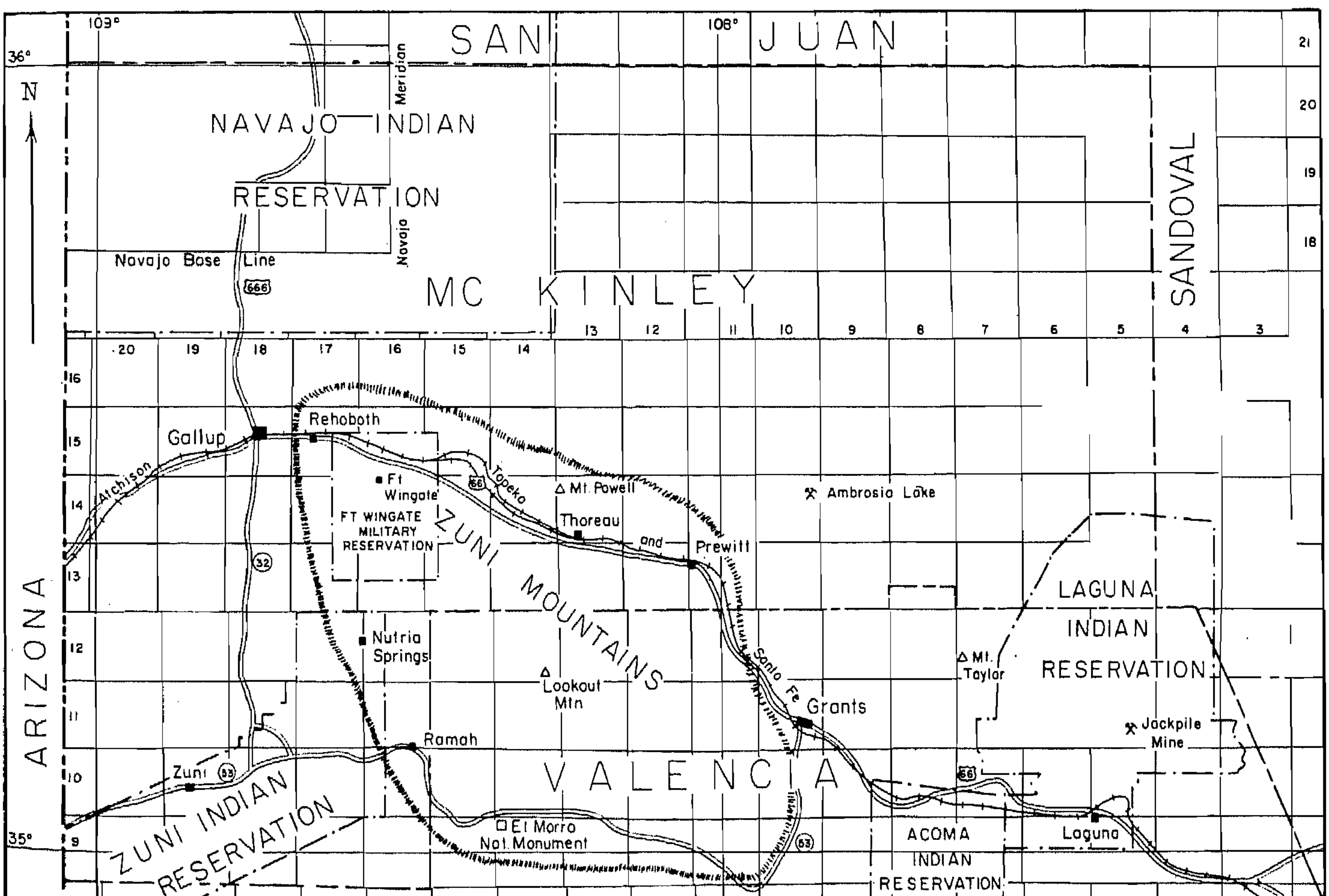

FIGURE 1. INDEX MAP OF PART OF NORTHWEST NEW MEXICO
SCALE 1:500,000

forms characteristic of the Sonoran life zone to Ponderosa pine forests with accompanying deer, bear, coyote, etc., characteristic of the Transition zone. Precipitation is low and extremely variable; some areas may receive as much as 25 in. annually, whereas adjoining regions only a few miles away may receive less than 10 in. Approximately one-quarter to one-third of the annual precipitation comes as snow in the winter months; the remainder is concentrated in summer thundershowers. Often the spring and fall months have little or no precipitation.

GEOLOGY

The Zuni Mountains usually are considered the southern boundary of the San Juan Basin, although extensions of the basin continue south of the mountains both east and west of the present uplift. The mountains are strongly asymmetrical, with vertical to overturned dips on the southwest flanks, and gentle dips of less than 10 degrees on the northeast side.

Rocks ranging in age from Precambrian(?) to Recent are exposed in the Zuni Mountains. Arkose and limestone dated by meager fossil remains as pre-Wolfcamp rest nonconformably on metamorphic and igneous rocks presumed to be Precambrian. These are overlain conformably or with slight disconformity by Permian, Triassic, Jurassic, and Cretaceous sediments. Extensive flows of late Tertiary and Recent basalt lap onto the southern and eastern flanks of the mountains, and a few small remnants of earlier basalt flows cap some of the highest peaks. The rocks dip away from the central core of the mountains and, except for monoclinal flexures associated with faulting or local doming near Precambrian outcrops, there are few folds developed. Faulting and jointing follow two patterns: radial to the Precambrian core, and tangential to it. The radial pattern is best developed around the northeast corner of the mountains, whereas the tangential pattern is predominant along the steep southwest flank.

STRATIGRAPHY

Precambrian(?) Rocks

The central core of the Zuni Mountains is composed of granite gneiss and metarhyolite, with minor amounts of schist and greenstone. These units are intricately folded and faulted and strongly metamorphosed. Exposures merely indicate a pre-Pennsylvanian(?) age, but lithologically they resemble other formations in New Mexico and Arizona known to be Precambrian in age.

Pennsylvanian(?) Rocks

Resting on Precambrian(?) rocks, and obviously derived therefrom, are conglomerate and arkose containing limestone beds which have been designated Pennsylvanian(?) in age. Fossils from the limestone lenses apparently are pre-Wolfcamp but cannot be determined more definitely. The conglomerate contains pebbles and boulders of gneiss and metarhyolite, as well as large fragments of quartz derived from quartz veins and pegmatites which cut the Precambrian(?) rocks. The limestone is also arkosic and impure, and generally lies about 40 to 50 ft. above the contact. However, some lenses of limestone lie directly on the Precambrian (?) basement. Nearly 125 ft. of beds are assigned to these units, but the upper contact is not well exposed, and the relations with the overlying Abo formation are not known. All the evidence points to a gradational change and a conformable contact.

Permian Rocks

Permian strata in the Zuni Mountains are assigned to the Abo, Yeso, Glorieta, and San Andres formations of the typical New Mexico section. Nearly 2,000 ft. of these beds are exposed, with the Yeso formation containing over half of the total.

Abo Formation

The Abo formation is red to chocolate-brown sandstone and siltstone, with numerous layers of conglomerate in the basal 200 ft. Crossbedded and evenly bedded layers alternate, with crossbedding predominant in the lower, more lenticular, sandstones and conglomerates, and even bedding most abundant in the upper standstones and siltstones. Thin layers of mudstone and claystone are interbedded with the coarser grained units. Fossils are rare, the most common being the impressions of plants, principally reeds and marshy-type flora. The Abo is a flood-plain deposit accumulated under both fluviatile and quiet-water conditions. It is from 600 to 650 ft. in thickness and is overlain conformably by the Yeso formation, although locally a few inches of relief indicate a slight hiatus.

Yeso Formation

The Yeso formation is divided into four members in the Zuni Mountains similar to local divisions which have been made elsewhere (Kelley and Wood, 1946; Wood and Northrup, 1946; Wilpolt and Wanek, 1951). In all cases the first, or lowest, member consists of a massive, crossbedded, quartzose, fine sandstone, to which the name Meseta Blanca sandstone member has been applied. Less uniformity in the upper part of the section has resulted in several members, to which local names are applied.

The Meseta Blanca sandstone member is a little over 600 ft. thick in the Zuni Mountains and consists of well-sorted, very fine orange sandstone in trough and festoon crossbedded units interbedded with thinner (1- to 3-ft.) flat-bedded layers. It weathers in massive rounded ledges.

The second member of the Yeso formation consists of thin-bedded, calcareous sandstone and siltstone, poorly sorted and strongly crosslaminated. The beds 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-in.) beds of mudstone alternate with thicker sandstone and siltstone beds. The second member averages about 50 ft. thick, and the contact is usually placed at the base of the first coarse-grained sandstone above the uniformly sorted Meseta Blanca member.

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 basal limestone bed is from 6 to 11 ft. thick; the middle unit is from 10 to 12 ft. thick and contains some fossil fragments (diagnostic forms are lacking, although some bryozoa and brachiopods can be recognized); the upper limestone layer is from 8 to 12 ft. thick. The three beds are separated from each other by from 40 to 50 ft. of alternating sandstone, siltstone, and mudstone. The sandstone beds contain many frosted grains and are generally friable, being only locally cemented by gypsum or calcite; siltstone and mudstone are softer, but not so friable, and are thinner bedded and occasionally shaly. The third member of the Yeso varies from 100 to 140 ft. in thickness, depending upon variations in the lithology separating the limestone beds. Rarely, a fourth limestone bed crops out about 30 ft. above the top of the third member, but it is much thinner, more lenticular, and lacks the continuity of the limestone layers of the third member.

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 distributed sparsely throughout the section. Depending upon the selection of the contact with the overlying Glorieta formation, the fourth member of the Yeso formation may vary in thickness from less than 100 ft. to nearly 200 ft. The Yeso-Glorieta contact in most instances is placed where the white to buff, well-sorted, massive, crossbedded sandstone beds in the upper part of the fourth member exceed in thickness and abundance the orange and red siltstone and mudstone units with which they are interstratified.

Glorieta Formation

The Glorieta sandstone is one of the most persistent cuesta formers in the Zuni Mountains; steep cliffs or long gentle dip slopes characterize its outcrops. It is white to buff, but weathers yellow to light brown because of small zones of hematitic or limonitic concretions. The bedding is sharply defined. Alternating crossbedded and evenly bedded units from 2 to 10 ft. in thickness truncate one another throughout the formation; ripple-marked bedding surfaces are common. Most of the bedding surfaces show relief from 6 in. to 1 ft., and crosslaminations characteristic of eolian, fluviatile, and beach deposition occur throughout the sandstone.

The Glorieta is a very pure well-sorted quartz sandstone, with well-rounded grains averaging about 1 mm in diameter. The thickness ranges from a little more than 100 ft. to over 200 ft., principally owing to variation in selection of the lower contact. The upper contact of the Glorieta formation is placed at the base of the first massive limestone bed of the overlying San Andres formation. In the southeastern part of the mountains, the Glorieta and San Andres formations are gradational, with alternating sandstone and limestone beds 10 to 20 ft. thick.

San Andres Formation

The San Andres is the uppermost Permian formation exposed in the Zuni Mountains. It is far removed from the type locality of the formation in south-central New Mexico, but the abundant fauna makes correlation certain. Some of the fauna also is closely related to the fauna of the Kaibab formation of Arizona (E. D. McKee, personal communication), and apparently the San Andres beds of the Zuni Mountains were deposited on a shallow shelf connecting the Permian seas of southeast New Mexico and west Texas with late Permian flooding of the Cordilleran geosyncline to the west.

Other than the intertonguing with the Glorieta in the southeast corner of the mountains, the San Andres formation is divisible into three members: A lower sparingly fossiliferous limestone member from 20 to 35 ft. thick; a middle sandstone member from 10 to 25 ft. thick, which very closely resembles the Glorieta sandstone; and a massive fossiliferous upper limestone member from 60 to 80 ft. 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 and blue-gray to white; 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 locally crossbedded and contains abundant calcareous cement and frosted sand grains. The upper member is massive gray limestone, which is very cherty in the upper portion, and which locally, particularly in the eastern part of the mountains, 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 and its abundant fossil remains.

The average thickness of the San Andres formation is slightly more than 100 ft. The upper surface, however, has undergone extensive erosion, and in some places the entire formation has been removed, where Triassic Chinle beds rest directly on the Glorieta sandstone. Where preserved, the San Andres has developed a karst topography, with sink holes filled with Triassic rocks. Relief as great as 100 ft., and commonly more than 25 ft., is found throughout the mountains on this buried karst surface.

TRIASSIC ROCKS

Darton (1928) divided part of the Triassic rocks of the Zuni Mountains into three units and correlated them with the classic threefold subdivision of northeastern Arizona; namely, the Moenkopi, Shinarump, and Chinle formations. Later work in Arizona (MeKee, 1951) indicates that the Moenkopi and Shinarump formations do not extend into New Mexico except for very thin tongues which represent the margins of the basin of deposition for these units, and thus the threefold subdivision of Darton takes place wholly within the upper or Chinle formation. Although the Wingate sandstone has long been considered Jurassic(?) in age, Harshbarger, Repenning, and Irwin (1957) present rather convincing faunal and stratigraphic evidence for a Triassic age for the formation, and it is so described herein.

Chinle Formation

The Chinle formation is readily divisible into three members throughout the Zuni Mountains. These units cannot be correlated with the Chinle "A," "B," "C," and "D" members as originally described by Gregory (1917), but probably they represent parts of the "B" and "C" members.

The lower member 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. The thickness ranges from slightly less than 300 ft. to nearly 500 ft. This variation is caused in part by the irregularities of the erosional surface on the underlying San Andres formation. The top of the lower member generally is taken as the base of the first thick crosslaminated, conglomeratic sandstone which marks the beginning of lenticular, fluviatile sandstone deposition and the middle member of the formation. Along the northern flank of the mountains, the upper beds of the lower member contain abundant fragments of petrified wood; logs up to 30 ft. in length have been observed. The concentration of petrified wood in this zone suggests correlation with the Chinle "C" of Gregory (1917), although the overlying sandstone and conglomerate are not often observed in 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 crossbedded and with thin lenticular partings of purple to gray siltstone and mudstone. The sandstone and conglomerate beds are from 6 to 10 ft. thick and exhibit repeated scour-and-fill conditions. The thickness is not uniform, owing to variations in selection of the upper and lower contacts; outcrop sections generally range from 100 to 200 ft. thick, but a well drilled at Thoreau contained only 60 ft. of beds assignable to the middle member (Smith, 1954). The top of the middle member is usually taken where coarse, crossbedded sandstone grades into fine-grained sandstone and siltstone.

The upper member of the Chinle formation is poorly exposed throughout the mountains, forming a valley between cuestas cut on the middle sandstone member and the overlying Wingate and Entrada formations. Red, brown, and purple siltstones, alternating with reddish-brown mudstone containing thin sandstone lenses, are the principal rock types. The upper 300 ft. of the upper member is composed of lenses and nodules of red, purple, brown, and gray fine-grained limestone interbedded with sandy and silty calcareous mudstone; this limy zone also characterizes the upper part of the Chinle "B" of Gregory (1917). The upper member is about 1000 ft. thick on the north flank of the mountains and increases to nearly 1,400 ft. in thickness on the southwest side of the range.

Near the top of the upper member a 5- to 10-ft. bed of limestone conglomerate composed of cobbles and fragments of limestone cemented by sandy and silty calcareous mudstone has long been used as the upper contact of the Chinle formation. Along the north side of the mountains, however, the contact 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, angular fragments of white chert. The redeposited material occupies scour zones and channel fillings which were formed on the Chinle surface; as much as 8 ft. of relief occurs on this surface. On the south side of the range, the erosional surface is not present, and the Chinle is gradational with the overlying Wingate sandstone.

Wingate Sandstone

The Wingate sandstone was described originally by Dutton (1885) to include all the prominent cliff-forming sandstones and associated rocks between the limestone conglomerate of the Chinle formation below and the Todilto limestone above. Baker, Dane, and Reeside (1947) recognized the upper 300 ft. of Dutton's section that is Entrada sandstone; a unit much younger than the type Wingate sandstone. Baker, Dane, and Reeside (1947) suggested abandonment of the Fort Wingate type locality and proposed that the term Wingate sandstone henceforth be used for the lower sandstone unit of the Glen Canyon group, which is well exposed in the Glen Canyon of the Colorado River. However, Harshbarger, Repenning, and Irwin (1957) have shown that in northeastern Arizona and northwestern New Mexico there is an erosional unconformity at the top of the Wingate sandstone as defined by Baker, Dane, and Reeside (1947), and that, further, the Wingate sandstone of the Glen Canyon of the Colorado River intertongues with the Chinle "A" of Gregory (1917) and thus has closer affinities with the Triassic rocks than with the overlying Jurassic rocks. Accordingly, Harshbarger, Repenning, and Irwin (1957) restrict Dutton's Wingate sandstone to the lower 355 ft. of the section at Fort Wingate, New Mexico. In addition, because of the intertonguing, the Chinle "A" of Gregory (1917) now is included in the Wingate sandstone as the lower or Rock Point member, and the restricted sandstone at Fort Wingate is the upper or Lukachukai member.

The Rock Point member of the Wingate sandstone is not present on the north flank of the Zuni Mountains and is well exposed for only a short distance along the southwest flank. It is a series of alternating reddish-brown, evenly bedded, fine-grained sandstones and chocolate-brown, thin-bedded siltstone and mudstone. The sandstone beds are from 4 to 10 ft. thick, and the interbedded siltstone and mudstone range from 1 to 5 ft. in thickness. The contact with the underlying Chinle formation is gradational and is generally placed where the purplish calcareous siltstone of the Chinle gives way to the chocolate-brown siltstone and mudstone of the Rock Point member. The member thins rapidly eastward and, though it is nearly 15 ft. thick near Ramah, it may be absent in the extreme southeastern part of the mountains.

The Lukachukai member of the Wingate sandstone is present on both the north and south flanks of the mountains. It commonly is a massive, friable, cross-bedded, well-sorted, coarse-grained, orange sandstone. It is eolian throughout, except for about 30 ft. of coarse conglomerate which intertongues with the Rock Point member near Ramah, and which is considered to be the basal Lukachukai member. The Lukachukai member also thins eastward and is less than 25 ft. thick at the eastern margin of the mountains. The 355 ft. of the Lukachukai member reported by Harshbarger, Repenning, and Irwin (1957) at Fort Wingate seems to be a maximum for the Wingate sandstone throughout the Zuni Mountains, since the combined Rock Point and Lukachuski members near Ramah probably do not exceed 250 ft. in thickness.

JURASSIC ROCKS

Several Jurassic formations are found in the Zuni Mountains. The range is very close to the southern margin of deposition of most of these units, and many of them disappear between the northern and southern flanks.

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. Eastward from the type locality two facies are recognized: A lower silty sandstone and mudstone unit ("hoodoo" or red bed facies) typical of exposures at the type locality, and an upper clean sandstone unit ("slick rim" facies). Harshbarger, Repenning, and Irwin (1957) have recognized in the western part of the Navajo Reservation a lower clean sandstone facies below the red bed facies, and thus refer to the beds lithologically similar to the type Entrada as the "medial silty member." The medial silty member and the upper sandy member are both present in the Zuni Mountains, although they are not coextensive.

The medial silty member of the Entrada sandstone is fine-grained, massive (3- to 4-in. beds) mottled red and white, silty sandstone. The red color is mostly surficial and results from the weathering of thin red siltstone and mudstone partings. Such partings, combined with prominent vertical jointing, yield the rounded, rectangular, weathered blocks which are the source of the name "hoodoo" or "rock baby" so often applied to this unit. On the north flank of the mountains, the medial silty member is between 40 and 50 ft. in thickness and apparently continues for several miles east of the range. It is absent on the south flank. The medial silty member rests on the Lukachukai member of the Wingate sandstone with slight erosional disconformity and a relief of about 6 in. The medial silty member grades upward into the upper sandy member.

The upper sandy member of the Entrada sandstone is massive, orange-red, friable, crossbedded, medium- to coarse-grained, well-sorted sandstone. Two grain sizes occur; the coarser grains are concentrated along the foreset planes of the crosslamination. In those places where long tangential crossbeds are replaced by more evenly bedded material, the even bedding is composed of tiny crosslaminae which truncate one another in a complex manner. The upper 35 ft. of the member is finer grained and limy, and locally, near the top of the unit, lenses of sandy limestone 1 to 3 in. thick occur. As the sandy limestone thickens and the interbedded sandstone thins, the Entrada grades into the overlying Todilto limestone. Elsewhere the limestone beds of the Todilto sharply truncate the crosslamination in the upper member of the Entrada sandstone. The upper sandy member thins from 253 ft. in thickness at the west end of the range to 150 ft. in thickness north of Thoreau, and then thickens to over 200 ft. east of the mountains. It thins rapidly down the southwest flank and pinches out a few miles east of Ramah.

Todilto Limestone

The Todilto limestone is a very thin-bedded (1- to 6-in.) dark-gray, dense, fine-grained rock. In places it contains sparse fish scales and ostracod remains, but in general it is nonfossiliferous. There are very thin partings (½ to 1 in.) of calcareous green-gray shale and siltstone. Near the top and bottom of the formation, lenses of calcareous or gypsiferous sandstone and siltstone are interbedded with the limestone. Because of the variation in the upper and lower contacts, the Todilto limestone ranges from 7 to 30 ft. in thickness along the north side of the Zuni Mountains. It thins rapidly to the south and pinches out a few miles southwest of Fort Wingate, between Rehoboth and Nutria Springs.

Thoreau Formation

The Thoreau formation was introduced by Smith (1954) to include the closely related units which are assigned variously to the Summerville formation (Gilluly and Reeside, 1928), Bluff sandstone (Gregory, 1938), and Cow Springs Sandstone (Harshbarger, Repenning, and Jackson, 1951). On the north flank of the Zuni Mountains, the Thoreau formation can be divided into a lower, even-bedded member and an upper, crossbedded member; on the south flank the distinction between the members is not clear cut, and the two units are not separable.

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-in.) mudstone 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 member grade upward into well-sorted, medium- to fine-grained sandstone containing sparse siltstone and mudstone interbeds and partings; crossbedded layers become more abundant.

The upper member of the Thoreau formation consists of massive crosslaminated, medium-grained, poorly sorted sandstone. Even-bedded zones from 2 to 5 ft. thick containing abundant red, black, and brown chert fragments alternate with crosslaminated layers from 5 to 11 ft. thick. Mottled red and greenish staining and local concretionary weathering are common.

At the type section, northwest of Thoreau, New Mexico, the lower member is a little over 200 ft. thick, and the upper member is 184 ft. thick. The formation thins to the east, and both members total about 250 ft. in thickness at the eastern end of the mountains. On the south flank of the range, the Thoreau formation is slightly over 200 ft. of massive sandstone at Inscription Rock, in El Morro National Monument.

On the north flank of the mountains, Harshbarger, Repenning, and Irwin (1957) interpret the Thoreau formation as consisting of the upper sandy facies of the Summerville formation (lower member) overlain by a tongue of the Cow Springs sandstone (upper member). On the south flank of the range, they interpret the Thoreau formation as the Cow Springs sandstone.

Morrison Formation

The Morrison formation is present only along the north flank of the Zuni Mountains, extending, however, a short distance along the southwest side. All the Morrison units are beveled out by erosion between Nutria Springs and Ramah, and the overlying Dakota(?) sandstone of Cretaceous age rests directly on the Thoreau formation. Three subdivisions of the Morrison are recognized along the north flank of the mountains, but their correlation with type Morrison members is not clear. Local names are used because of the confusion resulting from interpretation of the section by different individuals.

The lowest member of the Morrison formation is the Chavez member (Smith, 1954), which consists of alternating variegated, greenish siltstone, purplish to reddish, sandy mudstone, and white to buff, coarse-grained, conglomeratic sandstone. Individual beds vary in thickness, and the upper part of the member intertongues with, and is scoured by, the overlying Prewitt member (Smith, 1954), so that thicknesses ranging from less than 100 ft. to over 200 ft. have been measured at various points. In most cases the Chavez member forms a ledgy slope between the cliffs of the underlying upper Thoreau formation and the overlying Prewitt member.

The Prewitt member of the Morrison formation overlies the Chavez member along a surface which locally shows marked erosion, and conglomeratic sandstone of the Prewitt may scour channels into Chavez mudstone with a relief of 4 to 5 ft.; elsewhere the two members intertongue. The Prewitt member is a brown-weathering, massive, coarse-grained, crossbedded, light pinkish-red, conglomeratic sandstone. Locally, interbeds and lenticular layers of purplish siltstone and mudstone occur. The Prewitt member averages between 175 to 200 ft. in thickness over much of the north flank of the mountains; at the west end, north of Fort Wingate, it is about 150 ft. thick, and to the east, south of Grants, it is absent.

The upper member of the Morrison formation is the Brushy Basin member of Gregory (1938). Along the north flank of the Zuni Mountains, the Brushy Basin member shows marked changes 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. Toward the western end of the mountains, the entire section may be soft, silty sandstone with conglomeratic lenses. Such sandstone facies may be as much as 135 ft. thick, whereas the mudstone and siltstone facies may not exceed 75 ft. in thickness. Even where mudstone is absent, the soft yellowish-gray silty sands of the Brushy Basin member are distinguished readily from the conglomeratic beds of the Prewitt member.

Other interpretations of the Morrison section along the north flank of the mountains are possible. For example, Harshbarger, Repenning, and Irwin (1957), in a series of measurements taken near Thoreau, lump the lower half of the Prewitt member of this paper with the Chavez member and assign the combination to the Recapture member of the Morrison; the upper half of the Prewitt member is combined with sandstone beds in the base of the Brushy Basin member and called the Westwater Canyon member. Finally, the remaining 50 ft. of the Brushy Basin member is placed in that member (see below).

MORRISON SECTION NEAR THOREAU, NEW MEXICO

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Member	Thickness	Member	Thickness
Brushy Basin	100 ft.	Brushy Basin	51 ft.
Prewitt	185 ft.	Westwater	127 ft.
Chavez	100 ft.	Recapture	207 ft.
Total Morrison	385 ft.	Total Morrison	385 ft.

No commercial uranium mineralization has ever been found in the Prewitt member as defined by Smith (1954) and as used in this paper. However, such deposits as the Jackpile mine, north of Laguna, New Mexico, and most of the Ambrosia Lake ores occur in sandstone units within the Brushy Basin member or in sands near the top of what Harshbarger, Repenning, and Irwin (1957) have assigned to the Westwater Canyon member.

The Morrison formation varies greatly in thickness; pre-Dakota erosion and lateral gradation cause the beds to range from 350 ft. to over 500 ft. in thickness. Although the upper contact is an erosional disconformity, the relief on the surface is seldom over 1 or 2 ft. There is a regional angularity because the overlying Dakota rests on successively lower beds in the section to the south. This slight angularity, however, cannot be detected in individual outcrops, and the Morrison and Dakota beds appear to be conformable.

CRETACEOUS ROCKS

Cretaceous rocks surround the Zuni Mountains, with the oldest formations lapping up onto the outer flanks of the range. Most of the detailed stratigraphy of these beds lies beyond the limits of the mountain block. Thus, the complex transgressive-regressive, marine-nonmarine history now classic in the San Juan Basin is little reflected in the mountains.

Dakota(?) Formation

Following long-established custom, the earliest upper Cretaceous sandstones in the Zuni Mountains are termed Dakota(?) formation. Because of the transgressive relationships, it is likely that the rocks designated Dakota(?) on the north flank of the uplift are somewhat older than those similarly named on the south flank.

The Dakota(?) formation consists of massive, crossbedded, 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.

The thickness is variable, ranging from less than 100 ft. to more than 200 ft. Part of the variation results from changes in the beds themselves and part from the selection of the upper contact, which is arbitrarily placed on the last persistent sandstone below abundant marine fossils. Since some of the upper sands of the Dakota(?) formation often contain lenses of marine fossils, the entire unit might well be considered a basal sandstone of the overlying Mancos shale.

Mancos Shale

The Mancos shale is gray-black, platy, and calcareous, with a few thin-bedded silty or sandy lenses. North of the mountains it exhibits complex intertonguing with the overlying formations of the Mesaverde group, and south of the mountains it thins markedly as the edge of the marine basin is approached. The lower main mass of the shale is about 700 ft. thick north of the mountains, not including the Mulatto and Satan tongues, which have been recognized much higher in the Cretaceous section. South of Ramah, about 400 ft. of shale is exposed between the Dakota(?) formation and the overlying Gallup sandstone.

Gallup Sandstone

The Gallup sandstone originally was defined by Sears (1925) as the lowest member of the Mesaverde formation in the Gallup-Zuni area. For the most part it lies beyond the limits of the Zuni Mountains, although sandstones south and west of Ramah and along the western edge of the mountains belong to this unit. Along the western edge of the mountains, the Gallup sandstone is massive, coarse-grained, brownish-buff to white sandstone, with interbedded shale and coal. There are commonly three sandstone beds; the lowest of these tongues downward into the Mancos shale, and the upper two enclose the coal horizons. Southward the sands tend to coalesce and rise in the section, and near Ramah a single massive sandstone bed marks the Gallup sandstone.

The thickness at the west end of the mountains just east of Gallup is nearly 250 ft. The unit thins to the east and north, being less than 200 ft. thick south of Ramah.

TERTIARY ROCKS

Tertiary formational units have not been distinguished in mapping in the Zuni Mountains. Sediments, other than thin ash beds, pyroclastic rocks, or soil layers between basaltic lava flows, are not known in the mountains. On the top of Mt. Powell, on the north flank of the range, and capping Lookout Mountain, in the central part of the uplift, are remnants of basaltic lava. These are thin flows which are apparently related to a thin, widespread sheet possibly derived from the Mt. Taylor volcanic activity to the east (Hunt, 1938).

Goddard (in preparation) has suggested that the fluorite veins which cut the Precambrian core of the mountains may be Tertiary in age and related to deep-seated Tertiary intrusive rocks which are not exposed, but which may be responsible in part for the doming of the uplift. Most of the evidence is contradictory and inconclusive, since none of the younger rocks are in contact with the Precambrian rocks, and since the Pennsylvanian arkose resting on the Precambrian surface contains boulders of quartz, indicating that at least some of the quartz veins are pre-Pennsylvanian in age.

TERTIARY(?) AND QUATERNARY ROCKS

The eastern and southeastern parts of the Zuni Mountains plunge beneath an extensive cover of basaltic lava. Many of these flows are very recent, some being controlled by the present topographic surface and drainage. Many are associated with recent cinder cones which show little or no erosion. Others are much older and may be pre-Quaternary. It seems reasonable to conclude that eruptive activity began with the Mt. Taylor volcanism late in the Tertiary and has continued intermittently to the present.

Several alluvial stages are represented in stream terraces throughout the mountains, and recent 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 several areas, as much as 50 ft. of windblown sand has accumulated.

STRUCTURE

The Zuni Mountains form an elongate, asymmetrical dome, with a gentle northern and northeastern flank and a somewhat steeper southern flank grading into vertical and overturned beds along the southwest margin. The eastern end has been downfaulted, so that the mountain structure may extend farther east buried in the subsurface.

Folding is relatively minor, although several shallow synclines and anticlines, roughly parallel to the northwest-southeast axis of the uplift, are found south of Inscription Rock. Local monoclinal flexures are associated with some of the small faults or en echelon fault zones, but these commonly die out within a few miles. The largest of these monoclinal flexures is the Nutria Monocline (Kelley, 1951), which forms the southwestern boundary of the mountains. Along the Nutria Monocline, some overturning of beds has been observed, and faulting has broken the monoclinal symmetry along much of the zone. The older rocks have been forced upward and southwestward over the Cretaceous rocks of the Zuni basin, implying considerable compression stress (Kelley, 1951).

Faulting follows two distinct patterns: fracture, radial to the Precambrian core and the axis of the uplift, and fractures tangential to the Precambrian core and parallel to the axis of the uplift. The radial pattern is best developed around the northeastern corner of the mountains. The tangential pattern follows the southern flank and western end of the range. Rarely, as in the case of the Bluewater fault zone (Smith, 1954), a radial fault merges with a tangential fracture.

The radial faults attain maximum displacements in a zone about 2 to 4 miles outward from the Precambrian core. The maximum stratigraphic throws are usually from 200 to 600 ft., and these displacements die out rapidly along the strike; most of the radial faults are from 3 to 6 miles in length, although the Bluewater fault zone (Smith, 1954) is known to extend continuously for a distance of over 40 miles. Over at least 20 miles of this length, however, the fault is of the tangential type.

The tangential faults in general show less stratigraphic throw (usually less than 200 ft.) than the radial faults but are much more persistent along the strike. Strike lengths probably average more than 10 miles, and the Dan Valley fault, which cuts part of the eastern Precambrian core, may extend nearly the full length of the range.

The radial faults commonly have the eastern block depressed, and nearly all the tangential faults show depression of the northern block. Very little lateral movement can be detected on any of the fractures; all are predominantly dip-slip features.

Bucher and Gilkey (1953) made a detailed study of the fracture pattern, particularly the joints in the Glorieta sandstone, and concluded that the Zuni Uplift was primarily the result of vertical forces. Jointing and fracturing within the Precambrian core do not necessarily substahtiate this conclusion (Goddard, personal communication). The regional fault pattern, combined with the monoclinal folding, would suggest that compressive stresses oriented about N. 60° E. might satisfy the structural pattern for nearly all the southern part of the San Juan Basin, as well as the Zuni Mountains.

GEOLOGIC HISTORY

The Precambrian history of the Zuni Mountains is complex. Sediments and basic volcanic rocks were deposited and then intruded by large granitic masses. Fine-grained acidic rocks, possibly intrusive as well as extrusive, developed, and the entire mass was slightly metamorphosed. No record of early Paleozoic sedimentation remains, although J. B. Huddle (unpublished lecture) has suggested that a northeast trending axis of a Mississippian basin occupied the present site of the Zuni Mountains.

During Pennsylvanian time, the Precambrian rocks of the mountains were rejuvenated and began to contribute sediments to surrounding basins. Only a small amount of material was accumulated before the seas withdrew and nonmarine deposition began, and spread over the entire mass. As deposition continued, the flood-plain deposits of the Abo and Yeso formations were deposited. Late in Permian time, the area was sufficiently depressed for the Permian seas of the east and west to join along a narrow seaway, and the marine limestone of the San Andres formation was formed. Slight uplift at the end of the Permian forced a withdrawal of the sea and initiated a long period of erosion, during which karst topography was developed on the surface of the San Andres beds; locally they were worn away completely. Minor flood-plain deposits to the west indicate that the area was a broad upland contributing sediments to a seaway far to the west.

By the beginning of the upper Triassic, the entire area had been worn to a surface of low relief broken only by sink holes and solution valleys in the limestone. Streams from the east began to build a broad flood plain, and large thicknesses of mud and silt accumulated as the Chinle formation. Toward the end of the Triassic period, a positive area, the Navajo Highland (Smith, 1951), developed to the south and southwest of the Zuni Mountains, and sand dunes migrated northeastward across the flood plain to form the Wingate sandstone. An interval of erosion followed, during which a marine basin developed to the northwest in Utah. Renewal of uplift on the Navajo Highland caused another encroachment of sand dunes across the flood plain, and the upper sandy member of the Entrada was formed. The Todilto limestone developed in a basin with restricted circulation, although its extent to the east is not easily explained. Uplift on the Navajo Highland very nearly kept pace with erosion, and large quantities of fairly uniform sandstone deposits were spread northward during most of Morrison time. Minor fluctuations and shifting of stream channels created variations in the sequence. During this period, the Zuni Mountains apparently also were affected by the uplift, and sedimentation south of them was blocked.

The lower Cretaceous was a period of continued erosion, during which the entire area was beveled and then invaded by the upper Cretaceous sea. The strand line lay sometimes north and sometimes south of the mountains, and a very complex sequence of marine and nonmarine shales and sandstones was developed. Laramide folding and uplift rejuvenated the mountains, and continued erosion in the early Tertiary removed much of the cover developed during the Cretaceous inundation. During the middle and late Tertiary, widespread volcanism covered much of the uplift. Renewed uplift caused erosion of nearly all the lava, and the later eruptions either broke through the flanks of the mountain mass or flowed around the edges, particularly to the south and east. Intermittent Quaternary uplift and erosion has developed the present topography.

ECONOMIC GEOLOGY

Timber and fluorite have been the principal economic products from the Zuni Mountains. Minor showings of copper in the arkose overlying the Precambrian have been prospected, but no production is recorded. Scattered occurences of uranium mineralization have been reported from the San Andres formation, the Chinle formation, the Todilto limestone, various beds in the Morrison formation, and the Dakota(?) formation. Some small ore bodies from the Todilto limestone, north of Prewitt, and a fair production from sandstones in the Morrison, west of Fort Wingate, are the only commercial developments. The bulk of the uranium mineralization lies to the northeast of the mountains and appears to be related to structures in the adjoining basins rather than influenced by the Zuni Mountain block.

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