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GEOLOGY OF THE SOUTHEASTERN PART OF THE CHAMA BASIN

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INTRODUCTION

The Chama basin is a shallow basinal structure merging to the northwest with the much larger San Juan Basin. It is bounded on the west by Gallina Mountain, Capulin Mesa, and northward extensions of the Nacimiento-San Pedro uplift. On the south it is bounded by the Jemez plateau, on the southeast by the Abiquiu-El Rito embayment of the Rio Grande trough, and on the northeast by the Brazos uplift.

The southern portion of the Chama basin is an area of high mesas and low plains, intricately dissected by the Rio Chama and its ephemeral tributaries. Exposed bedrock ranges from nonmarine Pennsylvanian siltstone of Des Moinesian age found in Arroyo del Cobre to the Los Pinos and Santa Fe formations of Tertiary age that conceal the older rocks along the southeast margin of the basin on the eastern edges of the Magote Peak and Canjilon SE quadrangles. Quaternary surficial deposits mask the bedrock in the low-relief areas of the high mesas as well as in many of the lower canyons and gullies.

The mapping on which this paper is based was done in 1956 and 1957 as part of the joint summer field camp operated by the Geology Department of the New Mexico Institute of Mining and Technology and the Louisiana State University. Six 7 1/2 quadrangles, the Echo Amphitheater, Ghost Ranch, Canjilon SE, Alire, Canjilon, and Magote Peak, were mapped, and the work will be issued as a bulletin of the New Mexico Bureau of Mines and Mineral Resources during the 1960-61 fiscal year. Sincere thanks are extended to the Presbyterian Church and to the staff of Ghost Ranch for permission to camp on Ghost Ranch property and for their generally helpful attitude. The U. S. Forest Service was most cooperative, providing water for the camps from their installations at Coyote and El Rito; rangers at Canjilon, Coyote, and El Rito provided much information regarding access roads and property ownership. All ranchers in this region were most gracious in allowing access over their property. The entire project was made possible through the cooperation of the College Division of the New Mexico Institute of Mining and Technology, the Louisiana State University, and the New Mexico Bureau of Mines and Mineral Resources.

GEOLOGY

The Chama Basin lies in a reentrant between the Rio Grande trough to the east and the northward extension of the Nacimiento uplift to the west. The Jemez volcanic plateau to the south conceals the relations between the southeastern part of the basin and the junction of the bounding structures. The basin is filled with late Paleozoic and Mesozoic sediments, over whose upturned edges to the east and south are spread Tertiary and Recent volcanic rocks and sediments. The southeastern part of the basin exhibits a gentle northwestward plunge; the southeastern margin is marked by several northeast- and north-trending faults, some filled with basaltic dikes, whose irregular displacements suggest late Tertiary adjustments to the sinking of the Rio Grande trough.

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STRATIGRAPHY

Pennsylvanian Rocks

In the north-central part of the Canjilon SE quadrangle in Arroyo Del Cobre, thin-bedded carbonaceous, gypsiferous, and micaceous siltstone is exposed along a small fault. A well-preserved flora, consisting predominantly of **Alethopteris serlii** (identified by C. B. Read, of the U. S. Geological Survey in a personal communication) is found in the upper part of this unit. Read states that these beds are either Des Moines or Missouri in age; probably Des Moines. About 35 feet of beds are exposed, and the upper contact is partly gradational.

A middle Des Moinesian fossil assemblage, apparently of marine origin, has been described by Muehlberger (1957) from Chavez Canyon, about 35 miles north of the Arroyo del Cobre exposures. Approximately 250 feet of grayish-red and brown siltstones and sandstones, calcareous in their upper part, here rest on Precambrian quartzite.

These limited exposures suggest a rather irregular coastline and relatively low-lying masses during Des Moines time along the eastern margin of the Chama Basin. Thickening of these Pennsylvanian rocks westward has been demonstrated by drilling in the San Juan Basin (see Bradish and Mills, 1950, and Wengerd and Matheny, 1958), although the irregular topography suggests by the differing environments of the two exposures extends to the northwestern part of the Chama Basin, where younger rocks rest directly on Precambrian, as in wells drilled on El Vado dome. A few miles east of these localities Precambrian rocks are exposed on which only Tertiary sediments are found.

The outcrop exposes insufficient section to determine whether these beds are more closely related to the Hermosa-Rico beds of the Colorado Pennsylvanian section or to the Magdalena group of the central New Mexico exposures.

Permian Rocks

South of 36° N. latitude in New Mexico the Permian beds are divided into the Abo, Yeso, Glorieta, and San Andres formations. North of that line the formations lose their distinguishing characteristics, and the strata are all assigned to the Cutler formation, a term borrowed from southwestern Colorado (Northrop and Wood, 1946).

Cutler Formation

The Cutler formation was described by Cross and Howe (1905) from exposures along Cutler Creek near Ouray, Colorado, where the formation comprised the "bright red sandstones, and lighter red or pinkish grits and conglomerates alternating with sandy shales and earthy limestones of varying shades of red" between the underlying Rico formation and the overlying Dolores formation.

Outcrops of the Cutler formation are limited to the Chama Canyon and its deeper tributaries to the south as far as Arroyo del Cobre, and to the canyon of El Rito Creek and some of its tributaries. In the southeastern corner of the Ghost Ranch quadrangle the formation is brought up on the southeast sides of a series of southwest-trending faults. The outcrops in the Chama Canyon are terminated on the east by faulting, where as elsewhere the exposures disappear westward and northward as a result of a gradual rise of the stream valleys and overlap by younger rocks.

The Cutler consists of a seemingly cyclic alternation of cross-bedded, purple, arkosic sandstones that are locally conglomeratic, and purple to orange mudstones. The arkosic sandstones, which average 10-15 feet in thickness, are resistant to erosion and form small cliffs; whereas the thicker, less competent mudstone units form slopes. All units exhibit rapid lateral changes in lithology. At least 1,500 feet of Cutler beds are present in the southeastern Chama Basin. The basal contact is exposed in Arroyo del Cobre, where a massive channel sandstone scours into the underlying Pennsylvanian shales to produce a relief of more than 35 feet.

Collections of vertebrate remains, principally **Limnoscelis** skeletons, were made from Arroyo del Cobre in 1877 by David Baldwin (Romer, 1950), and suggests an early Permian age for these Cutler beds. More extensive finds southwest of the mapped area near Arroyo de Agua in similar formational units are thought to be somewhat younger. Romer and Price (1940) suggests that the Arroyo del Cobre beds may be late Pennsylvanian (i. e., Virgil), which is not in conflict with the Des Moines flora of the underlying shales. However, the uppermost beds in Arroyo del Cobre are certainly lower Permian, and since no lithologic break could be found throughout the section, the entire thickness is mapped as Permian Cutler formation.

TRIASSIC ROCKS

Chinle Formation

The Chinle beds were first described by Gregory in 1916, from Chinle valley in northeastern Arizona, although an earlier paper by Gregory (1915) had established the name. The formation has since been recognized in parts of Arizona, Utah, Colorado, Nevada, and New Mexico. Northrop and Wood (1946) subdivided the Chinle formation of the Nacimiento Mountains of northern New Mexico into four units (ascending): (1) the Agua Zarca sandstone member; (2) the Saltiral shale tongue; (3) the Poleo sandstone lentil; and (4) the upper shale member. Although the units of Northrop and Wood appear to be locally distinct in the Ghost Ranch quadrangle, they are not everywhere distinguishable and do not serve as local units for mapping. For purposes of this report the Chinle formation is divided into two members, a lower sandstone member, which probably represents the Agua Zarca, Salitral, and Poleo of Northrop and Wood (1946), and an upper shale member.

Lower Sandstone Member.—The lower sandstone member of the Chinle crops out extensively in the southeast half of the Ghost Ranch quadrangle and over the northwest half of the Canjilon SE quadrangle. Good exposures are found along the Chama Canyon and in the larger tributory arroyos to the west in the Echo Amphitheater quadrangle; however, the unit is generally covered by soil and alluvium in the flat areas bordering the Chama Canyon and in the canyon of El Rito Creek. The contact of the lower Chinle with the underlying Cutler is unconformable. No angularity was measured at the contact in the Ghost Ranch quadrangle, but in the Echo Amphitheater and Youngsville quadrangles to the west and southwest, and in the Canjilon SE quadrangle to the east, angular discordance as great as 30 degrees has been noted at several localities. The western rim of Arroyo del Cobre exposes a northwesterly truncation of approximately 400 feet of Cutler by the lower Chinle. Where angularity exists, the basal Chinle consists of pebble conglomerate. The overlying beds consist of white, gray or buff quartzose to micaceous sandstone which weathers buff to brown. Bedding ranges from massive to slabby, and cross-bedding is exceedingly common. For the most part, the massive beds are coarse grained, whereas, the slabby beds range from medium to fine grained. Conglomerate lenses occur at various levels. Fossils are rare, but a few pieces of carbonized wood were noted. Thickness of the lower sandstone member does not exceed 250 feet, and the unit thins eastward and westward from the Ghost Ranch quadrangle.

Upper shale member.—The upper shale member of the Chinle crops out in a belt of low, intricately dissected hills southeast of Mesa del Yeso and extends northeastward into the canyon of El Rito Creek in the Magote Peak quadrangle. A similar belt, southwest of Mesa Montosa, extends westward into the Chama River Canyon and southward along the base of Mesa Prieta in the Echo Amphitheater quadrangle. Other outcrops are found beneath erosional remnants of terrace gravels which rise above the generally lower Chinle surface in the southern part of the Ghost Ranch and Echo Amphitheater quadrangles, and in limited exposures beneath the El Rito conglomerates in the southwestern part of the Canjilon SE quadrangle. The contact between the lower and upper Chinle members is characterized by complex intertonguing relationships, and is difficult to place precisely, especially in areas where the contact zone is poorly exposed. The upper Chinle consists of interbedded and intertonguing variegated mudstones, siltstones, and sandstone, with red colors and finer grained facies predominating. Small, irregular bleached areas in the red mudstones are common, particularly in the upper portions of the member. The upper Chinle is a slope former for the most part; however, the upper 50 to 75 feet consists of interbedded sandstone and siltstone, which are more resistant to erosion and in many places forms the base of the Entrada cliffs. The upper Chinle has yielded an abundant fauna of terrestrial vertebrates, particularly reptiles of late Triassic age, in the vicinity of Ghost Ranch. Thichness of the upper Chinle shale member is 400-450 feet.

JURASSIC ROCKS

The Jurassic rocks of the southeastern Chama Basin are here divided into the San Rafael group and the Morrison formation. The San Rafael group comprises the Entrada and Todilto formations.

San Rafael Group

Entrada formation.—The Entrada formation was described and named for exposures at Entrada Point in the San Rafael Swell area of Utah by Gilluly and Reeside (1926). Baker, Dane, and Reeside (1947) concluded that the beds in the Fort Wingate, New Mexico, area, which had been named Wingate by Dutton (1885), actually correlate with the Entrada of Utah. They also stated that the Wingate formation, as the term is used in Utah, is an entirely different unit, which is not present in New Mexico. Believeing that the name Wingate is most securely affixed to the Utah rocks, Baker, Dane, and Reeside proposed dropping Fort Wingate as the type locality for the Wingate, and redefining the formation as the Wingate of Utah in order to agree with the popular usage. In this nomenclatorial scheme the old type section at Fort Wingate consists of rocks assigned to the Entrada formation, despite the fact that the term Wingate has 41 years priority over the term Entrada. Harshbarger, Repenning, and Irwin (1957), after a reexamination of the old Fort Wingate locality, concluded that Dutton's type section includes rocks customarily assigned to both the Wingate and the Entrada formations. The lower 355 feet is "composed of sedimentary rocks now considered to be the Wingate sandstone, as recognized throughout northeastern Arizona, southeastern Utah and parts of Western Colorado". The upper 303 feet at Fort Wingate correlates with the Entrada of the San Rafael Swell. Harshbarger, Repenning, and Irwin (1957), therefore, propose to restrict the term Wingate to the lower part of Dutton's original type locality. The cliff-forming Jurassic sandstones of the Chama Basin correlate with the upper half of the Fort Wingate section; hence, they are the Entrada formation of Baker, Dane, and Reeside (1947) and Harshbarger, Repenning, and Irwin (1957).

In the Ghost Ranch and Echo Amphitheater quadrangles the Entrada formation forms the steepest part of the slopes marking the escarpments of Mesa Montosa, Mesa del Yeso, Mesa Prieta, and Mesa de los Viejos. The rocks weather back in such a way as to produce rounded amphitheaters with overhanging cliffs. In the Magote Peak quadrangle the Entrada sandstone is often the only outcrop between the valley of El Rito Creek and the crest of Magote Ridge.

The Entrada rests unconformably upon the Chinle. However, in the quadrangles mapped there is little if any evidence of the unconformity; the contact is exceedingly sharp. The Entrada consists for the most part of well-rounded, well-sorted, quartz sand of fine to medium grain. Crossbedding is present throughout, but the long, sweeping fore-sets so characteristic of aeolian beds are confined to the lower part. The color of the fresh material is generally tan or white, but the weathered cliff faces show more diversity in color. In the southern tier of quadrangles, where exposures are excellent, the lower 120-150 feet of the Entrada weathers red, the next 25-50 feet is white, and the upper 50-75 feet weathers buff; the total thickness throughout the exposures ranges between 200 and 265 feet. However, rapid thinning to the north is exhibited in the Magote Peak quadrangle. The thickness in the southwestern corner of the quadrangle is about 200 feet, whereas in the northeast corner only 120 feet is present.

Todilto formation.—The name Todilto was applied by Gregory (1916) to the limestones and calcareous shales overlying the Wingate sandstone and underlying the Navajo sandstone in the Todilto Park area of McKinley County, New Mexico. Baker, Dane, and Reeside (1947) concluded that the beds underlying and overlying the Todilto at its type locality are, respectively, the Entrada sandstone and the Morrison formation. In an earlier paper, Baker, Dane, and Reeside (1936) had considered the Todilto to be the basal member of the Morrison formation, but in their revision (1947) they considered it a member of the Wanakah formation, which itself was elevated from the status of a member of the Morrison. The separation of the Todilto from the Morrison was based on the transitional nature of the Todilto-Entrada contact and the fact that in some places the Todilto-Morrison contact is disconformable. Northrop (1950) and Harshbarger, Repenning, and Irwin (1957) regarded the Todilto of northwestern New Mexico as a separate formation, and their usage is followed here. The character of the Entrada-Todilto contact strongly suggests that the Todilto be considered a part of the San Rafael group.

The Todilto formation crops out in a narrow continuous belt capping the Entrada, protecting it from erosion, and contributing to the formation of the overhanging cliff exposures. Exposures of the Todilto formation are very good in the Ghost Ranch and Echo Amphitheater quadrangles although, locally, where gypsum is developed, flowage and slumping have allowed great blocks to move downslope out of their normal stratigraphic position. Throughout the area the upper part of the unit is in many places covered by slump blocks of the overlying formations, and along El Rito Creek the entire formation is concealed with outcrops several thousand feet apart.

The contact between the Todilto and the underlying Entrada formation is conformable throughout the Ghost Ranch quadrangle. In some places (for example, the Arroyo del Yeso) intertonguing is evident.

Two members of the Todilto formation are recognized in the area, a lower member consisting of limestone and calcareous shale, and an upper gypsum member. The lower member occurs in each of the quadrangles mapped, whereas, the gypsum member is limited to exposures along the Arroyo Seco and the Rio Chama. Actually, the gypsum is best developed in areas to the west and south of the Ghost Ranch quadrangle, but even there it is discontinuous.

Lower member.—The lower member of the Todilto consists of dark-colored, fetid, fissile calcareous shales at the base, grading upward into very thin-bedded, gray, medium crystalline limestone and finally into more massive gray limestone. Locally the limestone contains blebs of gypsiferous material. The thickness of the member ranges from less than a foot to about 18 feet.

Upper member.—The contact between lower and upper members of the Todilto is gradational. Typically gypsum blebs and stringers appear in the limestones of the lower member and gradually become more important quantitatively higher in the section. Thus, it is difficult to pinpoint the contact between the two members; however, the contact can generally be picked within 2 or 3 feet. The upper member consists of white, massive gypsum with numerous and conspicuous shaly partings. It ranges from 0 to 105 feet in thickness; distribution is spotty, owing in part to extensive channeling before deposition of the overlying Morrison formation. Rapid changes in thickness are the rule rather than the exception, a change from zero to 80 feet having been observed in a horizontal distance of only about 100 feet. In general the thickness of the gypsum is greatest where the thickness of the underlying limestone is the least.

Morrison Formation

The Morrison formation was named by Eldridge (1896) for exposures near Morrison, Colorado, where the beds in question overlie the Lynkins formation (Permian-Triassic) and are in turn overlain by the Dakota sandstone. Although the formation is credited to Eldridge, the first reference to it in the literature was by Cross (1894), who noted the beds in the Pikes Peak area.

The Morrison crops out extensively throughout the quadrangles, forming the rather steep slopes between the lower Entrada-Todilto cliff and the upper Dakota cliff. Outcrops are found on the southern escarpments of Mesa del Yeso and Mesa Montosa and along the southern and eastern sides of Mesa de los Viejos; scattered outcrops are found on the west side of El Rito Creek. Despite the wide belt of outcrop, good exposures of the Morrison are rare.

Large blocks of the overlying Dakota sandstone break off and come to rest on the Morrison slope in extensive talus cones; this fact, plus the soft friable nature of the Morrison itself, greatly limits reliable exposures. The best exposed section lies just east of U. S. Highway 84 on the west end of Mesa Montosa.

The Morrison formation is here divided into two members, although contacts between these units cannot be drawn with certainty in many places. This twofold division is intended to express gradual changes in lithology rather than sharp breaks.

Lower member.—The contact of the Morrison formation with the underlying Todilto appears sharp whether the basal Morrison beds rest on the Todilto gypsum or the limestone. In most places where the Morrison rests on the limestone, the absence of the gypsum seems best explained by channeling. The lowest beds consist primarily of gray to cream-colored sandstones and siltstones, which are interbedded with lesser amounts of red and green mudstone. The lower beds grade upward into the main part of the member as the mudstone and siltstone units become predominant over the sandstone layers; no sharp boundary can be identified.

The bulk of the lower member consists of an alternating sequence of pale-brown, chocolate, or deep-purple mudstones and white to pale-gray siltstones. The siltstone beds average 10 feet in thickness; where not covered by rubble from above, they form low cliffs. The mudstone average 30 feet in thickness and generally form slopes. The lower member ranges between 300 and 400 feet in thickness.

Brushy Basin member.—Gregory (1938) named the Brushy Basin member for exposures in Brushy Basin, San Juan County, Utah. At the type locality it consists of 350 to 470 feet of "brightly banded shales, thin limestone, conglomerates, and sandstones" forming the top of the Morrison in the San Juan area. The member name is carried into the Chama Basin area on the basis of lithologic similarity and similar stratigraphic position. The contact between the lower member of the Morrison and the Brushy Basin is gradational. In the field, it is picked in the interval below the red claystone of the Brushy Basin and above the chocolate-colored mudstones of the lower member. The Brushy Basin consists for the most part of banded green and orange mudstones. There seems to be a change from a predominance of orange near the base to green near the top. Lenses of poorly sorted white to gray massive sandstone occur at intervals throughout the section. Of particular interest are a number of beds of brick-red, thoroughly indurated claystone which occur in the lower half of the member. The thickness of the Brushy Basin member is about 275 feet.

CRETACEOUS ROCKS

The age of the lowermost Cretaceous rocks in the southeastern part of the Chama Basin is in considerable doubt. In many outcrops, a threefold lithologic subdivision can be made; elsewhere, a single sandstone unit occupies all of the interval between the underlying Morrison formation and the fossiliferous overlying Mancos shale. Farther west in the San Juan Basin a sand and shale sequence of lower Cretaceous(?) age has been called the Burro Canyon formation (Stokes and Phoenix, 1948). In northeastern New Mexico alternating beds of black carbonaceous shale and coarse sandstone contain lower Cretaceous (Comanchean) fossils and are referred to the Purgatoire formation, (Stose, 1912). Stokes (1944) discussed the problem of the Jurassic-Cretaceous boundary and concludes that a thin layer of lower Cretaceous rock is probably present over much of the Rocky Mountain region, although not necessarily everywhere directly correlative.

In the southeastern Chama Basin the Cretaceous rocks are readily divisible into two major groups: a lower sandstone facies rarely more than 400 feet in thickness and an upper marine shale facies several thousand feet thick. Locally, in the Magote Peak quadrangle, and in most of the exposures along the south and west sides of Mesa de Los Viejos in the Alire quadrangle, the lower sandstone facies is further divisible into a lower conglomeratic sandstone, a medial carbonaceous siltstone and shale unit with sparse coal lenses, and an upper massive coarse-grained sandstone. Exposures are poor in many areas, and as a result these units are not everywhere mappable. Accordingly, the lower sandstone facies is mapped as Dakota(?) formation, although correlatives of the Burro Canyon or Purgatoire formations may be present in the lower beds.

Dakota (?) Formation

The Dakota sandstone was named by Meek and Hayden (1862) for exposures in Dakota County, Nebraska. The name has been applied rather loosely throughout the Rocky Mountain area to the basal sandstone of the Upper Cretaceous series. Present usage of the U. S. Geological Survey restricts "Dakota sandstone" to areas east of the front ranges, and Dakota(?) formation is applied in areas to the west. "Dakota(?) formation" does not imply time equivalence with the type Dakota sandstone; rather it indicates similar lithology and similar stratigraphic position.

The Dakota(?) formation occurs only in the northern part of the mapped area, where it forms the caprock of the several mesas as well as the eastern edge of Magote Ridge. The Dakota is perhaps the most resistant bed in the section; hence, it is almost invariably a cliff former. Often two sandstone cliffs separated by a narrow bench are found.

The contact between the Dakota and the subjacent Morrison is generally covered by detritus from the Dakota. Where exposed, the contact is unconformable, although no angularity could be detected in the limited exposures which were available.

The rocks mapped as Dakota(?) formation consist of a lower sandstone unit, a middle claystone unit not everywhere present, and an upper sandstone unit.

The lower sandstone unit consists of tan to white, medium to coarse-grained, well-sorted sand, which is thoroughly cemented with silica; it forms a prominent cliff. Some conglomerate beds are present particularly near the base, but they do not appear to persist laterally for any appreciable distance. Conglomerate is more prominent in the Magote Peak quadrangle and is less abundant to the west. Cross-bedding is common in the coarser zones. The lower sandstone unit ranges from 180 to 200 feet in thickness.

The middle unit consists of dark-gray silty claystone and sandy siltstone. Numerous thin beds of carbonaceous materials and even a few very thin restricted coal beds are present. The middle unit is usually poorly exposed. It intergrades with subjacent beds; hence, its thickness is difficult to ascertain exactly but is approximately 80-100 feet.

The upper unit, which forms the upper Dakota cliff, is essentially similar in lithology to the lower sands, and is about 100 feet thick. Conglomerate is less abundant, and the uppermost beds grade into the overlying shales.

Mancos Shale

The Mancos shale was named by Cross (1899) from exposures in the Mancos valley in and around the town of Mancos, Colorado. The formation now includes all the dark-gray marine shale tongues lying between the Dakota sandstones and the overlying Mesaverde formation. In the San Juan Basin to the west and south considerable intertonguing between the lower part of the Mesaverde and Mancos units is indicative of extensive transgressive and regressive relationships.

Faunal assemblages in beds in the southeastern part of the Chama Basin indicate units which can be correlated with the Graneros, Greenhorn, and Carlile members of the Mancos shale, and a thin platy-bedded, well-jointed limestone sequence was mapped as the Greenhorn throughout the Magote Peak, Canjilon, and Alire quadrangles. Approximately 1,800 feet of Mancos shale is exposed in the southeastern part of the basin.

The lower 75 to 100 feet of Mancos shale is light-gray to dark-gray calcareous shale, which is sandy at the base, where the contact with the Dakota(?) formation is gradational. Locally, concretions are abundant, and this unit probably represents the Graneros member as mapped farther north and west in the basin. Because of the gradational nature of the contact with the underlying Dakota(?) formation, the thickness is variable, and in some places sandstone layers may occur several feet above the base. The lighter colored shale is commonly more calcareous, and the darker colored areas, sometimes with shades of brown, are arenaceous.

Overlying the Graneros member is white-weathering well-jointed slabby limestone unit up to 35 feet in thickness; the jointing and bedding surfaces are so closely spaced that weathering yields a zone of white chips in the shaly soil, which serves as a persistent marker zone throughout the mapped area. This member has been correlated with the Greenhorn limestone member of the Mancos shale on the basis of its fossil content and lithology. The limestone beds of the Greenhorn are interbedded with gray calcareous shale and grade both upward and downward into darker calcareous shales; accordingly, the thickness is variable, depending upon where the contact is chosen; however, it is rarely less than 20 feet. The fracturing is remarkably uniform and very closely spaced, and characterizes most of the outcrops of the member.

The shale above the Greenhorn is uniformly drab, gray, thin-bedded, and poorly exposed. It is correlated with the Carlile member of the Mancos formation on the basis of stratigraphic position and fossil evidence. In the central and northern parts of the Chama Basin persistent sandy zones presumed to represent the Juana Lopez sandstone of Rankin (1944) are characterized by a brownish to yellowish weathered soil and slightly better resistance to erosion than the underlying shales. These sandy zones cannot be identified in the Magote Peak, Canjilon, and Alire quadrangles because of a lack of exposures, although some of the higher portions of Magote Ridge might be underlain by such units.

Fossils are abundant throughout much of the Mancos shale and detailed studies might allow further subdivisions in the section. Exposures are very poor, but a calculated thickness of nearly 1,800 feet of beds is assigned to the Mancos in the Magote Peak quadrangle. It is quite likely that the uppermost beds are correlatives of the Niobrara member of the Mancos, although this unit was not identified during the mapping in the southeastern part of the basin. All the Mancos units are so similar in lithology and grain size that excellent exposures are necessary to delineate the members; the Greenhorn member is the only series of beds that may be identified without fossil evidence in soil or weathered areas, and even it is not always mappable in thick soil or gravel areas.

Younger Cretaceous rocks are known in the northern part of the Chama Basin, but in the southeastern part, the Mancos is the latest Cretaceous unit present. The Mancos shale is overlain unconformably by Tertiary and Quaternary gravels and igneous materials which are related to the volcanic and glacial activity of the San Juan Mountains to the northwest in Colorado.

TERTIARY ROCKS

Tertiary rocks are represented by the El Rito formation, the Abiquiu tuff member of the Santa Fe formation, the Los Pinos formation, and the Sierra Negra basalt. Outcrops of these rocks are restricted to the eastern margins of the Magote Peak and Canjilon SE quadrangles.

In part these formations can be correlated with adjacent Tertiary successions. In Table 1 an attempt has been made to show the possible relationships with the well-known Tertiary sequence in the San Juan Mountains of southwestern Colorado, with the Tertiary rocks of the Rio Grande valley near Santa Fe, New Mexico, and with the Tertiary section of the Las Tablas quadrangle.

El Rito formation

The El Rito formation was named by H. T. U. Smith from exposures in the Abiquiu 30-minute quadrangle of New Mexico (H. T. U. Smith, 1938). It is the oldest of the Tertiary beds in the southwestern part of the Chama Basin, and unconformably overlies older formations. Within the Abiquiu 30-minute quadrangle, important localities are to be found in the Ortega Mountains, along El Rito Creek, and east of Arroyo del Cobre. Smith describes the formation as follows:

> "It comprises sandstone, conglomerate, and breccia — all of which have a characteristic brick-red color. The rock is well consolidated and commonly stands in steep cliffs. The pebbles are dominantly of quartzite, and volcanic material is absent. The maximum thickness of the formation is 200 feet."

The El Rito formation, as exposed in the area under consideration, is very similar to this description. However, its areal extent is somewhat larger than that indicated on Smith's map. The lithology of the formation is well displayed in steep slopes along El Rito Creek and in valleys east of Arroyo del Cobre. Boulder-conglomerate beds are numerous and are separated by micaceous, arkosic sandstones. The matrix material varies in grain size from coarse-grained to silt-size particles, and has reddish-orange to reddish-brown color. The fragments in the conglomerate beds are for the most part well rounded, range in size from boulder to pebble, and nearly all are made up of a bluish-gray quartzite, very similar to the Ortega quartzite (Just, 1937), exposed extensively in the Ortega Mountains. The degree of rounding of the quartzite boulders suggests that the lower part of the El Rito is derived from reworked sediments and is a second- or third-generation conglomerate. In the upper part, beds appear, which contain pebbles and cobbles of schist, gneiss, and feldspar fragments, in addition to the quartzite fragments; the conglomerate

Table 1.

Series	SE San Juan region, Larsen & Cross, 1956	Las Tablas region Barker, 1958	El Rito Creek area, present report	Rio Grande Valley
Pliocene	Hinsdale formation —peneplanation—	Dorado basalt — unconformity — Cisneros basalt —unconformity—	Sierra Negra basalt —unconformity(?)—	Santa Fe formation
Miocene	Fisher quartz latite and Los Pinos gravel —unconformity— Other Miocene rocks present	Los Pinos formation: Cordito member Jarita basalt Biscara-Esquibel member Biscara member —unconformity— Present	(North) Cordito member / (South) Abiquiu tuff Not Present	------?------ Galisteo formation
Oligocene	Possibly present	Not present	—unconformity—	
Eocene	Present	Ritito conglomerate —great unconformity—	El Rito formation —great unconformity—	
Pre-Tertiary	Present	Precambrian	Permian to Upper Cretaceous	Pennsylvanian? or older to Upper Cretaceous

here has a shingly appearance.

Outcrops of the El Rito formation are confined to the southeast corner of the Magote Peak quadrangle and the east half of the Canjilon SE quadrangle. It is estimated that at least a 400-foot thickness of the formation is present east of Madera Canyon. A number of outcrops of the El Rito formation are also present near the crest of Magote Ridge.[1]

Similar outcrops are name "Canjilon till of the Cerro (?) glacial stage" on H. T. U. Smith's map of 1938. The present authors consider at least part of the boulders and gravels on Magote Ridge as forming the El Rito formation; particularly the exposures on the east side of Magote Peak. Extensive exposures are not present in this area, but boulders and pebbles of the bluish-gray quartzite are found on the surface in large quantities. These boulders are very similar, both in shape and composition, to the boulders found in the El Rito conglomerate. Evidence that these boulders have reached their present location due to large-scale glacial transport — at least 8 miles according to H. T. U. Smith (1936) — was not found. Smith also points out the presence of hummocky terrane forms near Magote Ridge, and its association with the quartzite-boulder fields. However, this kind of topography is also present along lower elevations of the ridge. The necessary condition for the development of hummocky terrane at this elevation seems to be presence of Mancos shale, an incompetent bed, in which solifluction and landsliding can readily take place, particularly under periglacial conditions.

The major difference in interpretation of the geologic features on Magote Ridge is to be found in the provenance of the metamorphic-rock boulders. Whereas H. T. U. Smith, (1936) advocated glacial transport during the Pleistocene, the present authors look upon the boulders as having attained their present location during El Rito time, with subsequent rearrangement during later periods, particularly during the Pleistocene.

The El Rito formation overlies older formations (Cutler, Agua Zarca, Chinle, Entrada, and Mancos shale) with an angular unconformity. The average dip is six degrees to the southeast. The El Rito formation is overlain by the Abiquiu tuff member of the Santa Fe formation.

The deposition of the El Rito was the result of strong vertical movements which uplifted the Brazos Mountains to the north and east. Active erosion stripped the uplift of its veneer of sediments, and exposed the Ortega quartize, a process which apparently had been repeated several times during Paleozoic and Mesozoic times. The El Rito formation accumulated as a torrential stream deposit, with little or no sorting of the erosive products. The red matrix of sand and silt probably was derived from the "red beds" of the Cutler-Agua Zarca-Chinle sequence rather than bring the result of weathering and sedimentation under tropical climatic conditions, as suggested by H. T. U. Smith (1938). The torrential conditions of sedimentation were, of course, not amendable to the preservation of fossils in these beds. As fossil evidence is entirely lacking, the age of the El Rito formation is uncertain; likely it is early Tertiary, possibly Eocene in age.

Abiquiu tuff member of the Santa Fe formation

The Abiquiu tuff was named and described by H. T. U. Smith (1938) from exposures near Abiquiu, New Mexico. He described the main body as a stream-laid deposit of tuff and volcanic conglomerate. It consists of well-bedded, fine-grained material and where exposed in the lower elevations weathers to steep, almost vertical slopes.

The Abiquiu tuff is exposed in the southeast corner of Canjilon SE quadrangle. The formation consists essentially of very light-gray to very pale-orange silty tuff and micaceous, tuffaceous sandstone. A thin-bedded to laminated appearance is most common. It overlies the El Rito formation unconformably and has an average dip of four degrees to the south-southeast. Good exposures are found on the west slope of Sierra Negra, and here at least 1,350 feet of Abiquiu tuff is present. In areas to the east and north where beds continuous, or at least correlative, with the type Abiquiu tuff are present, considerable variations are found. Conglomeratic layers and coarse-grained sandstones predominate over the finer grained tuffaceous layers, and torrential type cross-bedding replaces the more evenly bedded zones. East of El Rito Creek such beds are interlayered with one another, and it is apparent that the upper part of the Abiquiu tuff member, as well as the lower part of the Santa Fe formation, is equivalent to the upper part of the Los Pinos formation of Butler (1946) and Barker (1958). The upper contact with the overlying Santa Fe formation is gradational, and the selection of the contact is arbitrary.

Los Pinos formation

A sequence of waterlaid sands, gravels, and conglomerates exposed east of El Rito Creek in the Magote Peak quadrangle is believed to represent part of the Los Pinos formation. This formation was first recognized in the Summitville quadrangle of southwestern Colorado and was named the Los Pinos gravel by Atwood and Mather (1932). It was found to thicken considerably where it extends southward into New Mexico. Larsen and Cross (1956, p. 185 and 186) discuss the Los Pinos gravel extensively and point out that its thickness does not exceed 500 feet in Colorado.

A careful study by Butler (1946) showed that in the Tusas-Tres Piedras area of New Mexico, the Los Pinos gravel can be subdivided into four members; he was the first to use the term Los Pinos formation. Butler's terminology was adopted by Barker (1958) in his work on the Las Tablas quadrangle, which adjoins the Magote Peak sheet to the northeast. Extensive areas in the southwest part of the Las Tablas quadrangle are underlain by the uppermost (Cordito) member of the Los Pinos formation, and it seems likely that the outcrops along El Rito Creek are a continuaation of these exposures. The thickness of the Los Pinos formation here has increased and exceeds 2,000 feet.

In the Magote Peak quadrangle the Los Pinos formation is exposed along the steep east bank of El Rito creek. The formation presumably overlies beds of the El Rito formation, a relationship similar to the one present in the southwest portion of the Las Tablas quadrangle. Here, the Cordito member rests on the Ritito conglomerate, which is considered the equivalent of the El Rito formation.

The Los Pinos formation can be subdivided into two units, which, however, have not been separated on the geologic map. The lower unit, the base of which is not exposed, consists of about 600 feet of friable tuffaceous sandstones and siltstones, and intercalated, discontinuous gravel beds. Cross-bedding and channel features attest to deposition in stream environment. Larger, conglomeratic fragments in these beds consist of volcanic boulders, often considerably decomposed, and a minor quantity of quartzite

[1] This ridge is referred to as Canjilon Divide by H. T. U. Smith (1936), but is named Magote Ridge on the Magote Peak quadrangle map, published in 1953.

and other metamorphic rocks.

The upper unit, at least 70 feet in thickness, is conglomeratic in nature, and contains very large boulders, up to 4 feet in diameter, of andesitic and quartz latitic volcanic rocks. This unit is well cemented and is a conspicuous cliff former.

The Los Pinos formation, exposed in the Magote Peak quadrangle, is apparently an extension of the Cordito member of the same formation, found in the Las Tablas quadrangle. Whereas the Los Pinos formation was probably formed in a series of stream channels and associated gravel fans, the Abiquiu tuff, to which it is closely related, accumulated in a lacustrine or flood-plain environment. Such conditions would explain the existence of even bedding and good sorting in the Abiquiu tuff, in contrast with the channel features and poor sorting, characteristic of the Los Pinos gravel.

The Los Pinos formation undoubtedly represents an extensive sand and gravel apron, developed south and east of the San Juan Mountains. Erosional debris was transported far to the southeast, where Precambrian rocks were exposed and fragments of quartzite mingled with transported tuffaceous and other volcanic material. As pointed out by Cross and Larsen (1956, p. 192), the sources of the volcanic material may be widespread.

IGNEOUS ROCKS

Sierra Negra basalt

Dikes and flows of basaltic composition are present in the southern part of the Canjilon SE quadrangle. The dikes have a maximum width of 25 feet and consist of dull-black basalt, with greenish-brown altered olivine phenocrysts. Vesicular and amygdaloidal textures are found in some part of the basalt, joining is perpendicular to the walls of the dikes, and secondary calcite occurs as vein filling.

The dikes are intruded along zones of weakness, as many wedge out and have their continuation in faults. The Cerrito de la Ventana dike, for example, separates the El Rito formation on the west from Abiquiu tuff on the east. In the southwest corner of the Canjilon SE quadrangle a basalt dike transects the red silts of the Cutler formation. Up to a few inches away from the contact the host rock is bleached to a pale-yellow color; no evidence of recrystallization, however, is found. In the southeastern part of the same quadrangle several dikes intrude the El Rito and Abiquiu formations. Owing to greater resistance to the erosive forces, the basalt dikes stand out as conspicuous ridges above the surrounding sediments.

Rocks of basaltic composition cap Sierra Negra. The basalt is of the same appearance as the dike rocks and occurs in the form of a flow, at least 90 feet thick, which overlies the Abiquiu tuff.

Microscopic examination of two thin sections, one from a dike and one from Sierra Negra flow, show that the rocks have the composition of olivine basalt. Olivine occurs as large euhedral to subhedral grains up to 4 mm, which have been partly or completely altered into a greenish-brown mass of iddingsite and other alteration products. Augite forms a few porphyritic phenocrysts, which exhibit a zonal structure: the outer zone of the crystals is deeper brown in color, shows strong dispersion, and has a larger extinction angle than the core. These features would indicate that the outer zone is made up of titaniferous augite. The major portion of the pyroxene occurs as fine-grained (less than 0.3 mm), short prismatic, rounded grains in the groundmass of the rock.

Plagioclase feldspar is present in subordinate amounts and occurs as thin laths scattered throughout the groundmass; its average grain size is 0.5 mm. From the composite twinning according to the Carlsbad and albite laws, its average composition was determined as albite-rich labradorite.

Biotite and basaltic hornblende are minor constituents. Most prominent among the accessory minerals are apatite, in the form of thin elongated crystals, and various iron oxides, the latter scattered through the groundmass in small euhedral crystals. In the dike rock, carbonate material occurs as vesicle-filling mineral, together with a pale-green, lowbirefracting alteration product of olivine (smectite-chlorite ?), which lines the walls of the cavities.

A determination of the forsterite contact of the olivine was made by Mr. John H. Carman, using the method of Yoder and Sahama (1957). Assuming less than 5% orthosilicates other than forsterite and fayalite, an apparent forsterite content of 77.6 mol% is indicated for the dike rock, and 80.1 mol% for the flow. The difference between these two values is well within the standard deviation error of measurement.

On the basis of its petrographic composition and present elevated position, the Sierra Negra basalt and accompanying dikes can be correlated with the Pliocene Hinsdale volcanic sequence of the San Juan Mountains.

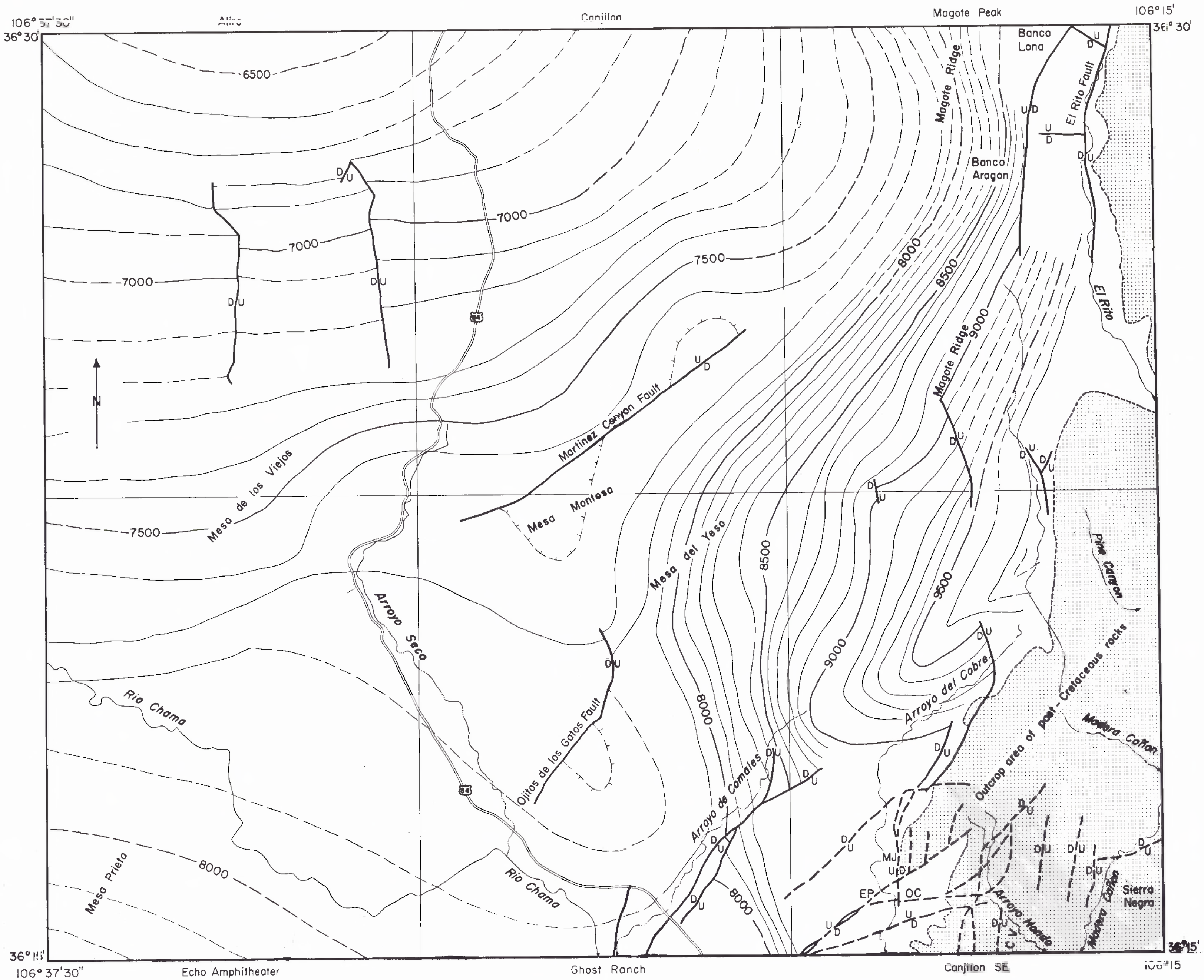
QUATERNARY ROCKS

Broad areas along the Chama River, many of the larger tributary valleys, and some of the higher mesas in the southeastern part of the Chama Basin are covered by terrace gravels and alluvium which are here assigned to the Quaternary period, but which may be Tertiary in part.

Terrace Gravels

Terraces composed of cobbles and pebbles of granite, gneiss, schist, quartzite and metarhyolite are widespread in the southern half of the Ghost Ranch and Echo Amphitheater quadrangles. In places in the eastern part of the Ghost Ranch quadrangle the terraces reach elevations in excess of 7,400 feet; however, toward the southwest there is a general decline in terrace height until, near the Rio Chama, most deposits occur within the elevation range of 6,200 and 6,400 feet. Terrace relationships are rather complex. It is certain that several separate episodes of terrace building are represented in the southwestern part of the area near the Rio Chama. However, the relationship of the higher terraces in the east-central part of the area to the lower ones near the Rio Chama is not clear. The higher level of the terraces in the east seems to suggest that they are older. However it is interesting to note that the southwesterly decline in terrace level parallels the dip of the Mesozoic rocks and is of approximately the same magnitude. Also, the tops of the high level eastern terrace remnants invariably slope gently toward the southwest. The degree of slope is such that if these eastern terraces were projected to the southwest, their level would approximately coincide with that of the terraces near the Rio Chama. It seems most logical, therefore, to assume that the two levels of terraces are of approximately the same age. The southwesterly decrease in terrace level was probably caused by crustal warping after the deposition of the gravels.

The composition of the gravels leaves no doubt that the main source area was an igneous and metamorphic



Contour interval 100 feet;
contours drawn on base of
Cretaceous sediments; faults
simplified for clarity

STRUCTURE CONTOUR MAP OF THE SOUTHEAST CHAMA BASIN, NEW MEXICO

CV- Cerrito de la Ventana
EP- El Puertecito
MJ- Las Minas Jimmie
OC- Ojito Carrizo

1 0 1 2 3 4 5 Miles

terrane. If one assumes that the drainage at the time of terrace formation was similar to the modern drainage, at least in gross aspect, then the Brazos Mountains to the north and the San Pedro Mountains to the west emerge as the most logical source areas.

Alluvium

The low plains in the south-central part of the southern tier of the quadrangles are covered by a thin mantle of silt which is largely of local derivation and probably wind laid for the most part. The canyons of the Rio Chama and some of its tributaries contain much unconsolidated material ranging from fine sand to cobbles. Some of this material is of local origin, but much of it was derived from igneous and metamorphic sources.

Structural Geology

The Chama Basin is separated from the San Juan Basin to the west by a low sill which marks the position of the Archuleta arch. According to Kelley (1955), this arch forms a connection between the Nacimiento uplift in New Mexico and the San Juan Dome in southwestern Colorado. To the southeast a definite boundary for the basin cannot be established. On the northeast side, the basin is bounded by the Brazos uplift. Both the Brazos and Nacimiento uplifts are old structural elements that can be traced back to Pennsylvanian time (Read and Wood, 1947). However, they attained their present elevated position during the Laramide orogeny, coupled with late Tertiary fault adjustments.

The most conspicuous structural features in the southeastern Chama Basin are the gentle regional dips of the Mesozoic and older sediments to the north and west, broad open folds, and steep, normal faults, many of which have a north to northeast trend.

Folding and regional dip

The rocks in the Alire, Echo Amphitheatre, and the northern part of the Canjilon quadrangles are so nearly horizontal that very minor local flexures can cause profound changes in the direction of strike. Thus, local measurements of strike and dip often tend toward confusion rather than clarification of the overall structural pattern, particularly as these measurements may have been taken on cross-bedded strata. However, when changes in elevation of key horizons are noted over larger areas, the true regional dip and strike become clear. With these facts in mind, a structure contour map on the base of the Cretaceous has been prepared for the six quadrangles (fig. 1). Many of the structural features of the region can be recognized on this map.

In the Alire, Canjilon, and Echo Amphitheatre quadrangles, the regional dip of the sediments is north and northwest and usually does not exceed a few degrees. In the central portion of the latter quadrangle the position of the beds is almost horizontal; here an east-trending structural terrace is developed south of the Chama River. In the Ghost Ranch and Magote Peak quadrangles, the homoclinal dip of the Mesozoic sediments remains to the west and northwest, but increases to values of 10°-12° in the Magote Peak quadrangle. Structurally, this quadrangle represents the highest part of the area.

Some very shallow fold structures are superimposed on this regional, basinal pattern. One of the most striking is the Arroyo del Cobre anticline, named after the arroyo of the same name. This structure is a southwest-plunging anticline. The resistant Agua Zarca member of the Chinle formation has been breached by erosion along the axis of the fold, exposing a thick section of Permian Cutler beds in the walls of Arroyo del Cobre. The Agua Zarca member makes up the rim of the canyon, and forms a long dip slope to the northwest. Further north this limb grades into the west-dipping homocline of Magote Ridge. The northeast flank of the Arroyo del Cobre structure is less distinct, mainly due to the presence of numerous faults and the unconformable overlap of the Tertiary El Rito formation and the Abiquiu tuff.

Faulting

Many short faults with relatively small displacements are found in all six quadrangles; in addition, faults with lengths up to six miles and with stratigraphic throws of 200 feet or more are present. Although in most cases the dip angle of the fault plane cannot be determined with certainty, most faults seem to be steeply inclined or vertical. Their prevalent strike varies between N. 20° W. and N. 70° E. (see fig. 1). The west and northwest sides are downthrown in most cases, although exceptions to this rule can be observed on the Banco Aragon fault and the Martinez Canyon fault.

In the Canjilon quadrangle a major northeast-southwest-trending fault follows the course of Martinez Canyon and extends into the quadrangle to the south; it is here named the Martinez Canyon fault. It has been traced for 7 miles across the two quadrangles. Along its northern half the Dakota formation is present on either side of the fault, but the indicated drag from strike and dip observations shows that the southeast block is downthrown. The southwest extension of the Martinez Canyon fault follows a Dakota escarpment, and its trace is obscured by landslide debris west of Mesa Montosa. Near the southwestern end the Martinez Canyon fault is intersected by another fault, trending N. 33° W. in the northern part, and changing in direction to N. 10° W. farther south. Near Arroyo Seco this cross-fault has a stratigraphic throw of about 120 feet, with the downthrown side to the west, the displacement being calculated from the Todilto beds. The cross-fault transects the Morrison and Dakota formations of the western end of Mesa Montosa and loses its identity in the shales of the Brushy Basin member, although it may well be a southern extension of a fault extending several miles to the north in the eastern part of the Alire quadrangle.

In the Ghost Ranch quadrangle, two faults deserve special mention. One of them, here called the Ojitos de los Gatos fault, strikes N. 45° E. through the central part of the quadrangle. About half a mile northeast of Ojitos de los Gatos this fault apparently bifurcates with the west branch heading in a general northerly direction. The east branch disappears beneath talus slightly northeast of the bifurcation, but the Entrada-Todilto scarp on the southeast flank of Mesa del Yeso may represent a northeasterly continuation. Near the place of bifurcation the fault brings the Entrada formation of the northwest block into contact with Chinle beds of the southeast block. At this point the fault's maximum stratigraphic throw is about 200 feet.

The other major fault is found in the southeastern part of the quadrangle and is here called the Arroyo de Comales fault. It exhibits some bifurcation and slight changes in trend, but in general strikes about N. 30° E. The maximum observed stratigraphic throw is 220 feet; brecciated zones, up to 10 feet in width, accompany the faulting. The dip of the fault, where determinable, is 70° NW.

In the northeast corner of the Magote Peak quadrangle, several faults have a north-south trend. A prominent fault, here called the Banco Aragon fault, extends from the SE ¼ Sec. 33, T. 26 N., R. 6 E., in a northern and northeastern direction across Banco Aragon and Banco Lona. The fault has a stratigraphic throw of 200 feet, with with the downthrown side to the east. Two shorter faults, almost parallel and to the west of the Banco Aragon fault, also have the eastern block downthrown. About 1 mile east and almost parallel to the Banco Aragon fault, runs the El Rito Creek fault; this fault, which follows the course of El Rito Creek for a distance of at least 5 miles, has a stratigraphic throw of approximately 60 feet and has the downthrown side of the west.

Faulting in the southern half of the Canjilon SE quadrangle is highly complex in nature. Because of the presence of Tertiary rocks in this part of the area, many of the faults can be dated as pre-El Rito or post-El Rito in age. Fault gouge and breccia, and occasionally calcite veins, are found in the major fault zones.

Local names have been given to faults and fault systems in order to facilitate the description and interpretation of these faults. In general, a genetic significance should not be attached to the grouping of more than one fault in a system.

The Las Minas Jimmie fault system has a predominant north to northeast trend. It consists of a number of faults, more or less paralleling the east rim of Arroyo del Cobre. A northern branch of the system crosses the canyon near its head and offsets the Cutler-Agua Zarca contact of the northwest rim. Some of the faults of this system show evidence of post-El Rito movement.

The El Puertecito fault is exposed in the southwest corner of the Canjilon SE quadrangle and trends northeast through El Puertecito. In its southern part, lenticular fault slices containing beds of the Agua Zarca formation are present in the fault zone. The fault has its downthrown side to the southeast. The northeast extension of the El Puertecito fault meets one of the major north-trending faults of the Las Minas Jimmie system about 1,000 feet north of Ojito Carrizo, and a possible extension continues northeast from this point into the Agua Zarca beds east of Las Minas Jimmie. Various north-trending branches of the El Puertecito fault are found here.

The fault south of the El Puertecito fault extends from the southwest corner of the quadrangle northeastward for approximately 2½ miles, where it disappears under the beds of the El Rito formation. Movement along this fault has been down to the southeast, with a stratigraphic throw of 200-300 feet. This fault is pre-El Rito in age.

Complex faulting near the upper part of the Arroyo Hondo exposes the Cutler and Agua Zarca formations as a lens-shaped horst on the El Rito dipslope. The stratigraphic displacement of the faults bordering this horst is found to be a minimum of 600 feet when these outcrops are compared with outcrops of the same formations farther west.

The Cerrito de la Ventana fault system in the southeast corner of the Canjilon SE quadrangle consists of six subparallel faults, three of which are extensions of basalt dikes. Tertiary formations are displaced along these faults.

The major characteristics of the above-mentioned faults can be summarized as follows:

1. Wherever the angle of dip of the fault can be established, the faults are of the high-angle, normal type.
2. The stratigraphic throw of the faults averages 200 feet or more.
3. With the exception of the Martinez Canyon and Banco Aragon faults, most faults have their downthrown side to the west or north. However, the complexly faulted southern half of the Canjilon SE quadrangle exhibits no such general pattern.
4. Many faults bifurcate near their ends and terminate in incompetent beds.

Much of the faulting seems to have been the results of differential movements of the basin elements, notably the floor of the basin to the west and the Brazos uplift to the east. This caused a tensional-stress field between the basin proper and the adjacent uplift, which in turn gave rise to the formation of normal faults in the sedimentary cover. Many faults exhibit branching near their ends and terminate in incompetent beds, such as the Cutler formation, the upper Chinle formation, the Upper Jurassic beds, or the Mancos shale. Owing to the bifurcation, the stratigraphic throw becomes distributed over a number of smaller faults, which in turn die out in the incompetent beds.

GEOLOGIC HISTORY

The Precambrian history of the southeastern part of the Chama Basin is obscure, since the only Precambrian rocks exposed lie east of the basin proper. The principal deposits are quartz sandstones, conglomerates, and some fine-grained sediments, with minor amounts of basaltic volcanic rocks and rhyolitic hypabyssal intrusive rocks. Intense folding and deformation in Precambrian time were accompanied by metamorphism of the rocks to low and moderate rank: these beds comprise the Ortega quartzite and Hopewell series of Just (1937) and have been studied recently in much more detail by Barker (1958). Following the folding and metamorphism there was intrusion of several plutonic bodies of granite and granodiorite, and finally emplacement of pegmatites accompanied by hydrothermal metamorphism. Continued erosion beveled the beds to a surface of gentle relief.

In the northwestern part of the San Juan Basin early Paleozoic rocks are present in a fairly complete sequence. However, if any of the early Paleozoic section was deposited in the Chama Basin it must have been eroded before the advent of Pennsylvanian time, since Pennsylvanian sediments rest directly upon Precambrian rocks locally along the eastern margin of the basin. By Pennsylvanian time erosion had reduced the terrain to an irregular topography with islands of Precambrian rocks projecting above the sea, as well as lagoonal or swamp areas being developed along highly irregular coast lines. The presence of arkose and clastic material interbedded with limestone in the Pennsylvanian rocks to the south and west suggests that intermittent uplift and orogeny was occurring concurrently with deposition. The irregular shelf and island topography must have extended over a large area of northern New Mexico well beyond the confines of the Chama Basin.

The Permian Cutler formation, containing only minor amounts of fine sediment, indicates that the source areas of the quartzite and metamorphic boulders in the conglomerates are not far removed from the depositional sites. Late Pennsylvanian marine conditions were gradually supplanted during the Permian by floodplain conditions with innumerable braided channels; torrential floods must have been common since complexly cross-bedded coarse grained sediments predominate. Vertebrate fossils found in the Cutler in Arroyo del Cobre and to the southwest around Arroyo del Agua suggest that only a brief hiatus, if any, occurred between Pennsylvanian and Permian time in this area; some of the forms could be Virgilian while others higher in the section are definitely Permian.

During late Permian or early Triassic time slight uplift took place to the east or conversely the basin sank slightly because the Triassic beds bevel the underlying Cutler units to the east. The angularity is slight and the conditions under which the Triassic beds accumulated were not very different from the Permian rocks. However, by late Triassic time the area had been reduced to a low featureless surface over which accumulated several hundred feet of non-marine silt and mud. The terrain has been likened to a savannah-like environment with sluggish rivers flowing across broad grasslands and with scattered forested areas in the uplands. Colbert (1950) has described the environment as deduced from the fossil evidence: "The association of Chinle fossils in northern New Mexico would seem to point to a stream and lowland ecology. Here in association are found fresh-water clam shells and fish, aquatic stereospondyl amphibians and the aquatic phytosaurs. It is probably that **Typothorax** was more of an upland animal than its relative, **Machaeroprosopus,** while the little dinosaur, **Coelophysis,** certainly must have been an inhabitant of fairly dry land, across which it could move about with great agility. But these upland forms probably came down to the streams frequently, with the result that they are found in association with the more typically aquatic vertebrates."

Following a hiatus during which only slight erosion and little or no crustal disturbance took place, the Entrada formation was deposited as a widespread sand sheet under partly fluviatile, partly aeolian, and perhaps, partly marine conditions. The bedding structures in the Entrada sandstone are complex and suggest an alternate wetting and drying of the sand with continuous rearrangement of the bedding during accumulation. By late middle Jurassic time the area became part of a restricted marine environment and the fetid, thin-bedded limestone layers of the Todilto formation were precipitated. As salinity increased in the restricted environment gypsum was also precipitated. The marked irregularity of the gypsum deposits as observed today is not readily explained; small steep-sided gypsum "reefs" or basins are illogical, and there is no evidence for gypsum "dunes" similar to the White Sands, New Mexico, area. Local solution and channeling of the gypsum layer could occur but must have taken place before the deposition of the overlying Morrison sandstones and mudstones. The contact between the gypsum and the overlying Morrison is sharp and shows some erosional unconformity, but there are no gypsum fragments contained in the overlying clastics. Apparently recent erosion or solution has had little effect upon the distribution of gypsum.

During late Jurassic time the mudstones and siltstones of the Morrison formation were deposited across a vast area of low relief. Numerous bentonitic layers and glass shards attest to volcanic activity which occurred some distance away from the depositional basin. Far to the west and northwest of the Chama Basin the lower part of the Morrison formation was deposited by meandering streams giving rise to lenticular sand layers which are persistent for many miles. In the southeastern part of the Chama Basin sandstone is minor in amount and represents only occasional channeling by streams. Conditions seem to be a repetition of the environment of the upper part of the Chinle formation; fossils have not been reported from this area, although dinosaur remains from the upper part of the Morrison formation are well known elsewhere. By Morrison time the local highs on the Precambrian surface which probably contributed some sediment to the early sandstones of the Chinle formation had been completely reduced and covered by several layers of younger rocks.

Only slight erosion occurred before Lower Cretaceous seas began to invade the Rocky Mountain region, although some of the structurally higher Precambrian surfaces were stripped of any earlier sedimentary cover. The evidence is inconclusive in the Chama Basin as to whether Lower Cretaceous rocks were deposited in the basin, although such rocks are known both to the east and west of the area. However, the Dakota(?) sandstone was deposited across the entire area as the beach and lagoonal sand of the advancing Upper Cretaceous sea. The complex intertonguing of marine and non-marine deposits which accompanied the transgressions and regressions of the Upper Cretaceous sea have been discussed at great length by numerous authors (See bibliography accompanying Dane's paper in this guidebook). Evidence of such relationships has been removed by post-Cretaceous erosion in the southeastern part of the Chama Basin. However, the beds to the north suggest that this area was almost continuously submerged although very close to the shoreline during Mesaverde time.

The close of Cretaceous sedimentation was marked by the Laramide revolution which raised the entire Rocky Mountain region above sea level and effectively outlined the San Juan Basin; the earlier positive areas of the Brazos uplift and the Nacimiento uplift were markedly rejuvenated and began contributing sediment to the adjacent basins. The southeastern part of the Chama Basin was only slightly affected by the folding and faulting, and the intense deformation which accompanied the Laramide orogeny in other areas is absent.

Paleocene and Eocene rocks are known to the west in the adjacent San Juan Basin but the El Rito formation is the oldest preserved Tertiary unit in the southeastern part of the Chama Basin. The El Rito is a fanglomerate derived from the newly formed highlands to the north and east and contains practically no volcanic material; in the upper part of the formation metamorphic materials other than quartzite are present, but the well rounded cobbles of quartzite which make up much of the lower part of the unit strongly suggests that most of the El Rito beds are second or third generation sediments derived from the Pennsylvanian, Permian, and Triassic rocks which were stripped off the rejuvenated Brazos highland.

North and west of the Chama Basin volcanism may begun nearly contemporaneously with the Laramide orogeny and by Oligocene time most of the uplift areas were buried by an extensive series of flows, tuffs, and other volcanic debris. Intermittent volcanism continued throughout most of Tertiary time, accompanied by deposition of volcanic conglomerate, sandstone, and ash along the flanks of the old uplifts and off the slopes of the newly built volcanic peaks. Local alluvial fans and fanglomerates, interbedded with thin flows, accumulated and coalesced to form broad debris sheets which filled and smoothed older topographic irregularities. The Abiquiu tuff member of the Santa Fe formation and the Los Pinos formation belong to this group of deposits; these units were deposited from perhaps early Miocene until late Pliocene, although not continuously, nor everywhere contemporaneously, during this interval.

In late Tertiary time faulting was renewed and many of the earlier faults were rejuvenated although the movements were not necessarily of the same magnitude nor in the same direction as the previous displacements. Some new faults were initiated and many served as feeder chanels for the Pliocene, Pleistocene, and Recent basalt flows which seem to represent the dying stages of the extensive volcanism.

The northern part of the Chama Basin was extensively glaciated during the Pleistocene, particularly in the higher elevations, and three stages, Cerro, Durango, and Wisconsin, are recognized. H. T. U. Smith (1938) described bouldery conglomerate on the crest of Magote Ridge as the Canjilon till and ascribed these beds to the Cerro glacial stage; however, the present authors favor the following explanation for the outcrops found on Magote Ridge. The El Rito formation once covered Magote Ridge and may well have been continuous with the El Rito exposed east of El Rito Creek and in the vicinity of Pine Canyon. On the ridge itself, the formation was resting on Mancos shale. After El Rito time, erosion removed large parts of the formation and left only small patches as an intermittent veneer on Magote Ridge. Subaerial weathering may have removed a considerable amount of the sandy and silty matrix, which is largely responsible for the red color of the conglomerate. At the same time, the exposed boulders were subject to weathering resulting in some cases in a rotted appearance of the fragments (Smith, 1936). With further dissection of the ridge, landsliding started to take place and hummocky relief developed. It is quite possible, as H. T. U. Smith (1938) has pointed out, that solifluction and landsliding became pronounced under the periglacial conditions of the Pleistocene, and that many features were formed at that time.

Continued post-glacial erosion has developed the numerous terraces and alluvial fill found in the larger valleys. In areas where Cretaceous shales form the surface rocks and along the over-steepened slopes of the mesas extensive landsliding is continuing; blocks of sandstone, conglomerate or volcanic material may be found several thousand feet from their original position.

APPENDIX I

Composite Section of Cutler Formation—Arroyo del Cobre

Unit No.	Description	Thickness in Feet
	Triassic - Lower Chinle (Agua Zarca member)	
	Pale-yellowish orange (10 YR 8/6) * medium to coarse subrounded sandstone interbedded with dark yellowish orange (10 YR 6/6) limestone and quartz pebble conglomerate	
	———— slight angular unconformity ————	
	Permian - Cutler formation	
	"A" Member. Thickness — 355'	
1.	Coarse to very coarse, friable, arkosic sandstone with limonite stain. Light gray (N 8)	70
2.	Very coarse, angular, copper-bearing shaly sandstone. Light gray (N 8)	20
3.	Medium-to coarse, subangular, micaceous, arkosic, shaly sandstone, with limestone concretions and interbedded bluish gray shale and siltstone. Grayish-orange (10 YR 7/4)	70
4.	Coarse- to very coarse chloritic, arkosic micaceous, shaly sandstone in small lenses. Yellow-green (5 GY 7/2)	7
5.	Variegated mudstone and siltstone with yellowish-gray limestone lenses. (10 R 4/2) reddish-gray)	4
6.	Variegated mudstone and siltstone. Grayish-red-purple (5 RP 4/2)	34
7.	Very coarse, very friable, angular, arkosic micaceous sandstone. Pale-greenish-yellow (10 Y 8/2)	25
8.	Dark-reddish-brown and grayish-red variegated mudstone and siltstone.	75
9.	Variegated mudstone and siltstone (reddish-brown, 10 R 4/2) with yellowish-gray limestone lenses interbedded with a coarse- to very coarse subangular, arkosic, micaceous, shaly sandstone. Grayish-red-purple and yellowish-gray (5 RP 4/2 and 5 GY 7/2)	38
10.	Very coarse, friable, arkosic, angular, micaceous shaly sandstone (grayish-red-purple, 5 RP 4/2) interbedded with variegated reddish-gray (10 R 4/2) mudstone and siltstone. An erosional unconformity of considerable extend occurs at the bottom of this member.	12
	"B" Member. Thickness — 272'	
1.	Very coarse, friable, arkosic, angular, micaceous shaly sandstone (grayish-red-purple, 5 RP 4/2) interbedded with variegated reddish-gray (10 R 4/2) mudstone and siltstone.	26
2.	Coarse- to very coarse, subangular, arkosic, micaceous, shaly sandstone. Green-yellow (5 GY 7/2)	34
3.	Variegated mudstone and siltstone, showing a cobble-appearing type of weathering. Grayish-red (10 R 4/2)	54
4.	Variegated mudstone and siltstone. Grayish-red (10 R 4/2)	12
5.	Coarse- to very coarse, angular, arkosic, micaceous, friable sandstone mottled from yellow-gray (5 Y 7/2) to grayish-purple-red (10 R 4/2)	31
6.	Variegated mudstone and siltstone (reddish-gray, 10 R 4/2) and interbedded medium to coarse, subangular, micaceous, crossbedded sandstone (pale reddish-purple, 5 RP 6/2), and a yellowish-gray limestone-pebble conglomerate.	10
7.	Mottled to banded limestone pebble conglomerate. Very light gray (N 8), brownish gray (5 YR 4/2) and medium gray (N 5)	4
8.	Very coarse, subangular, arkosic slightly micaceous sandstone. Medium light-gray (N 6).	7
9.	Pale reddish-purple (5 RP 6/2) micaceous, sandy mudstone and siltstone to reddish-gray (10 R 4/2) mudstone and siltstone interbedded with yellowish-gray mottled, crystalline limestone. Pale reddish-purple (5 RP 6/2) medium to very coarse, arkosic, subangular, shaly sandstone	27

* Color designations according to the Munsell color chart distributed by the Geol. Soc. of America, 1951.

10. Fine to medium, subangular, micaceous, arkosic shaly sandstone (grayish yellow-green, 5 GY 7/2) interbedded with a variegated mudstone and siltstone (reddish-gray, 10 R 4/2) which weathers to a conglomeratic texture. 67

"C" Member Thickness — 339'

1. Mottled reddish-gray (10 R 4/2) very fine to fine, subangular, arkosic micaceous, shaly sandstone. 17
2. Reddish-gray (10 R 4/2) to light-gray variegated, micaceous mudstone and siltstone with interbedded grayish yellow-green (5 GY 7/2) fine to medium, subangular, micaceous, arkosic, shaly sandstone 17
3. Variegated mudstone and siltstone (reddish-gray, 10 R 4/2) containing striated calcite rhombs. 22
4. Fine to medium, subangular, very micaceous, arkosic, shaly sandstone. Light-gray (N 7). 32
5. Reddish-gray (10 R 4/2) variegated, fissle, micaceous mudstone 9
6. Pale reddish-purple (5 RP 6/2) very fine, subangular, arkosic micaceous, shaly sandstone. 4
7. Dark reddish-brown (10 R 3/4) micaceous mudstone 11
8. Fine, subangular, micaceous, arkosic sandstone. Grayish-yellow-gray (5 GY 7/2) 8
9. Reddish-gray (10 R 4/2) variegated mudstone and siltstone 12
10. Yellowish-gray (5 Y 8/1) mottled, crystalline limestone 5
11. Variegated, micaceous, sandy mudstone (dark reddish-brown 10 R 3/4) interbedded with pale reddish-purple (5 RP 6/2) fine to medium, subangular, micaceous, arkosic shaly sandstone and some dark reddish-brown (10 R 3/4) siliceous shale. 38
12. A series of interbedded grayish-green (5 GY 7/2) fine to medium subangular, arkosic, very micaceous shaly sandstone, dark reddish-brown (10 R 3/4) variegated, micaceous, sandy mudstones, and some light-gray (N 7) fine to medium, angular arkosic, very micaceous shaly sandstone. 35
13. Moderate reddish-orange (10 R 6/6) coarse to very coarse arkosic, micaceous, subangular, porous sandstone with a well-rounded quartzite boulder conglomerate interbedded. 40
14. Micaceous, angular, pyritic, very fine to fine sandy shale. Greenish-gray (5 GY 6/1) 5
15. Grayish-red (10 R 4/2) very fine to fine, angular, micaceous, shaly sandstone showing iron stain 12
16. Very fine to fine, angular, micaceous, shaly sandstone (green-gray, 5 GY 6/1) 35
17. Grayish orange-pink (5 YR 7/2) medium to coarse, angular micaceous, shaly sandstone. 15
18. Grayish-red (10 R 4/2) medium to coarse, angular, micaceous shaly sandstone 5
19. Variegated, micaceous mudstone and siltstone. Dark reddish-brown (10 R 3/4) 10
20. Blackish-white micaceous, arkosic, carbonaceous, subangular shaly sandstone (5 B 9/1) 7

"D" Member. Thickness — 567'

1. Red, gray, brown, and purple variegated siltstone and mudstone with thin interbedded sandstone beds and conglomerate lenses capped by massive, poorly sorted, micaceous sandstone of variable thickness. 210
2. Interbedded mudstone, siltstone, and sandstone. Siltstone and mudstone are well-indurated, red-reddish brown, layers from 3' to 30' in thickness; sandstones are micaceous, arkosic, locally conglomeratic, fine-coarse grained and fairly well sorted. Conglomeratic layers locally scour the underlying mudstones and siltstones. 155
3. Massive purplish-red to light gray siltstone and mudstone. Some interbedded micaceous, well-sorted, sandstone layers with subrounded grains 145
4. Medium-grained, subrounded, arkosic, quartzose sandstone, strongly cross bedded, reddish to grayish in color. 22
5. Buff to white, massive, cross-bedded, sandstone. Subrounded coarse grains; arkosic, with limonitic and clay cement. Lenticular, scouring the underlying Pennsylvanian shales with a relief of 20' to 30' 35

Erosional Unconformity

Pennsylvanian - Hermosa(?) formation (Des Moines)
Micaceous, carbonaceous, gypiferous, gray-green shale containing well preserved remains of **Alethopteris serlii** 35

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