Stratigraphy and Regional Tectonic Implications of Part of Upper Cretaceous and Tertiary Rocks East-Central San Juan Basin New Mexico

GEOLOGICAL SURVEY PROFESSIONAL PAPER 552

Prepared in cooperation with the Jicarilla Apache Tribe

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By Elmer H. Baltz

ABSTRACT

An area of about 1,300 square miles was mapped in parts of Rio Arriba, Sandoval, and McKinley Counties, N. Mex. The area is in the east-central part of the San Juan Basin, a large structural and drainage basin in the east-central part of the Colorado Plateaus province. Six physiographic sectors in the area are named here: the Penistaja Cuestas, Largo Plains, Tapicitos Plateau, Yeguas Mesas, San Pedro Foothills, and Northern Hogback Belt. The mapped area lies in the Central basin of the San Juan Basin and is bounded on the east by the Nacimiento and French Mesa-Gallina uplifts, where rocks ranging in age from Precambrian to Late Cretaceous crop out. Rocks of Late Cretaceous age crop out along the south and east margins of the area, and rocks of Tertiary age are at the surface in most of the area.

The oldest rocks mapped are those of the Mesaverde Group of Late Cretaceous age. The Mesaverde Group ranges in thickness from about 1,700 feet at the southwest to about 580 feet at the northeast; it is overlain by the Lewis Shale of Late Cretaceous age and intertongues with it. The Lewis Shale is about 1,900 feet thick in the northeastern part of the area but thins abruptly to about 500 feet thick in the southwestern part of the area as lower beds grade laterally into sandstone of the Mesaverde Group. The Lewis Shale is overlain conformably by the Pictured Cliffs Sandstone of Late Cretaceous age. The Pictured Cliffs, consisting of fine- to medium-grained soft sandstone with interbedded thin carbonaceous shale, is 235 feet thick in the subsurface of the southwestern part of the area. It becomes thinner to the northeast and is represented by thin beds of soft sandstone and shale, 35–45 feet thick, which grade northeastward into the upper part of the Lewis Shale in the northeastern part of the area.

The Pictured Cliffs Sandstone is overlain conformably by the undivided Fruitland Formation and Kirtland Shale of Late Cretaceous (Montana) age. These rocks are about 450 feet thick in the subsurface of the western part of the area, but the thickness ranges from less than 100 feet to almost 300 feet at outcrops along the eastern side of the area. Unit A, which is equivalent to part of the Fruitland Formation, is shale that contains fine- to coarse-grained sandstone and coal; it was deposited in coastal swamps, lagoons, and a brackish-water marine environment. Fossiliferous marine sandstone in unit A thickens northward at the surface and in the subsurface. Unit B, which is probably equivalent to part of the Kirtland Shale, consists of fine- to coarse-grained sandstone and interbedded shale resting with local unconformity on unit A. The undivided Fruitland Formation and Kirtland Shale were deposited in and on the margins of a shallow embayment of the Cretaceous sea which probably became landlocked, or nearly so, because of the rise of highlands north and east of the present San Juan Basin.

The undivided Fruitland Formation and Kirtland Shale are overlain unconformably by the Ojo Alamo Sandstone of Paleocene age. The Ojo Alamo ranges in thickness from 70 to 170 feet (locally) in the southern part of the area, but it is almost 200 feet thick in the northern part. The Ojo Alamo contains beds of shale but consists mainly of fine-grained to very coarse grained arkosic standstone containing lenses of pebbles and small cobbles. The Ojo Alamo was deposited by streams draining into the San Juan Basin from several sides. The principal source areas probably were the region that now comprises parts of the San Juan Mountains and the Brazos uplift. The Ojo Alamo Sandstone rests with erosional and slightly angular unconformity on Cretaceous rocks throughout the eastern, southern, and western parts of the Central basin. A pollen and spore flora in the Ojo Alamo indicates Paleocene age as does the intertonguing relation with the overlying Nacimiento Formation.

The Ojo Alamo Sandstone is overlain conformably by the Nacimiento Formation of Paleocene age, which ranges from 800 feet thick in the southern part of the area to 1,750 feet thick in the subsurface of the northern part. At outcrops along the east margin of the area, the thickness ranges from less than 500 feet to almost 1,400 feet because the Nacimiento was folded into northwest-trending anticlines and partly eroded prior to deposition of overlying rocks. In the southern part of the area the Nacimiento consists mainly of silty, sandy, clay shale, and includes some interbedded soft sandstone and a few resistant sandstone beds. To the north the Nacimiento contains a greater proportion (locally more than 50 percent) of sandstone. The northern facies is part of a huge apron of orogenic and volcanic debris eroded from highlands at the north and northeast and spread to the southwest into the San Juan Basin. The southern facies is composed partly of finer grained material deposited at the distal edges of the apron, but it includes also reworked Cretaceous sediments eroded from uplifted areas west and, probably, south of the basin. In the southern part of the area, the Nacimiento Formation is of early and middle Paleocene age, but farther north rocks of late Paleocene age probably are present also.

The Nacimiento Formation is overlain with erosional and angular unconformity by the San Jose Formation of Eocene age. The San Jose is the surface formation in most of the mapped area, and the parts preserved from erosion range in thickness from about 200 to 1,430 feet in the southern part of the area to as much as 1,800 feet in the northern part. Four mappable

lithologic units of the San Jose are here named: the Cuba Mesa Member; Regina Member; Llaves Member; and Tapicitos Member.

The Cuba Mesa Member, at the base of the formation, consists mainly of conglomeratic arkosic sandstone that is 220–350 feet thick at most places but is 782 feet thick at its type section. North, south, and west of this type section, the upper part of the Cuba Mesa Member tongues out into the Regina Member. The Regina Member, resting on the Cuba Mesa Member, consists of variegated shale, sandy shale, and some sandstone. The Regina Member ranges in thickness from about 600 feet in the southeastern part of the area to about 1,640 feet in the east-central part of the area, and about 900 feet at the type section in the northeastern part of the area. The variations in thickness are attributable in part to intertonguing between the Regina Member and the Cuba Mesa and Llaves Members, and in part to intramember thickening near the axis of the San Juan Basin. In the northeastern part of the area, most of the San Jose Formation is composed of thick beds of conglomeratic arkosic sandstone of the Llaves Member, which is about 1,300 feet thick at its type section. The lower part of the Llaves Member grades out southward into the Regina Member, but a persistent medial sandstone unit of the Llaves rests on the Regina in much of the north-central part of the area. The upper part of the Llaves Member, above the persistent medial sandstone, wedges out southwestward and westward into the Tapicitos Member. The Tapicitos Member consists of red shale and sandy shale and some lenticular resistant coarse-grained sandstone that are the youngest parts of the San Jose. The thickest preserved part of the Tapicitos Member is about 500 feet thick.

The arkosic conglomerates of the Cuba Mesa and Llaves Members were probably derived mainly from Precambrian terranes north and northeast of the present basin and, possibly, also southeast of the basin. Much of the Regina Member in the mapped area was derived from rocks of Mesozoic age eroded from the rising Nacimiento uplift. At places adjacent to the Nacimiento uplift, beds assigned to the Regina Member overlap the Cuba Mesa Member and older rocks including the Lewis Shale, indicating folding in this area during deposition of part of the Regina. The Central basin probably was filled by sediments of the San Jose Formation during Eocene time, and by Oligocene time these rocks may have lapped out of the basin onto the worn-down parts of the source areas.

Dikes of mafic igneous rocks of Miocene(?) age fill fractures in the San Jose Formation in the north-central part of the area. These northerly trending dikes are related to the large swarm of dikes farther north in the San Juan Basin.

Terrace gravel deposits occur in the San Pedro Foothills adjacent to the Nacimiento uplift. The topographically highest remnants of gravel may be as old as Pliocene and may correlate with the Bridgetimber Gravel of the northwestern part of the San Juan Basin. Deposits of gravel at lower altitudes are of Quaternary age and cap terraces and occur in the valleys of some of the present streams. Recent alluvium occurs in all the larger valleys of the area.

The northwest-trending axis of the San Juan Basin extends diagonally across the north-central part of the area. Rocks in the southwestern and western parts of the area dip gently northeast toward the axis. A series of northwest-plunging asymmetrical anticlinal noses in the southeastern part of the area were formed during several stages of folding in Cretaceous and late Paleocene time. The southeastern parts of the noses have been rotated vertically and tilted westward in the belt of sharp folding and local overturning along a synclinal bend west of the Nacimiento fault at the western side of the Nacimiento uplift. Surface stratigraphic information and well data indicate similar (pre-San Jose) subsurface folds farther north in the eastern part of the area. North of the Nacimiento uplift, the rocks of the eastern part of the area dip steeply west on a curved, west-facing monocline which forms the west flank of the French Mesa–Gallina uplift. There are a few small faults in the area, but the displacements on most of them are 200 feet or less.

The stratigraphy and structure of the mapped area provide evidence on Laramide deformation of the eastern and northeastern parts of the San Juan Basin and adjacent uplifts. The Nacimiento and Gallina faults at the east edge of the basin are high-angle reverse faults. Right shift occurred along these faults as the basin was downbuckled and shortened relative to the Nacimiento and French Mesa–Gallina uplifts during three stages of deformation—one in the late Paleocene, another in the early Eocene, and another later in Tertiary time. The deformation was caused by a deep-seated northeasterly oriented Laramide tangential compressional force. The San Pedro Mountain fault near the north end of the Nacimiento uplift was produced by local horizontal tension near the junction of the north-trending Nacimiento fault and the northeast-trending Gallina fault.

The northwest-trending Archuleta anticlinorium along the northeast margin of the present San Juan Basin probably originated as an intrabasinal arch in a large Late Cretaceous structural and sedimentary basin. Analysis of the structure of the Horse Lake and Willow Creek anticlines of the anticlinorium suggests that the southeastern part of the anticlinorium originated as a broad elongate dome that was upwarped and then deformed into an anticlinorium by the northeasterly oriented Laramide compressional force. The Nacimiento and Gallina faults and the southeast margin of the anticlinorium mark the Salado-Cumbres structural discontinuity—a regional structural discontinuity along which crustal blocks having differing orientations and competence yielded differently to the regional compressional force.

INTRODUCTION

The San Juan Basin, a large intermontane structural basin in the eastern part of the Colorado Plateaus physiographic province, contains a thick sequence of Cretaceous and lower Tertiary rocks which crop out in a large region of northwestern New Mexico and southwestern Colorado. The Cretaceous rocks have been studied in considerable detail in many parts of the basin because they contain large deposits of coal, oil, and natural gas. The Tertiary rocks contain classic vertebrate faunas of Paleocene and early Eocene age, but because these rocks do not contain economically important deposits of hydrocarbons and minerals, they have been of little interest to most geologists.

The present study covers an area of approximately 1,300 square miles (fig. 1) in the east-central part of the San Juan Basin. The study was made by the writer as part of a ground-water investigation of the southern part of the Jicarilla Apache Indian Reservation and

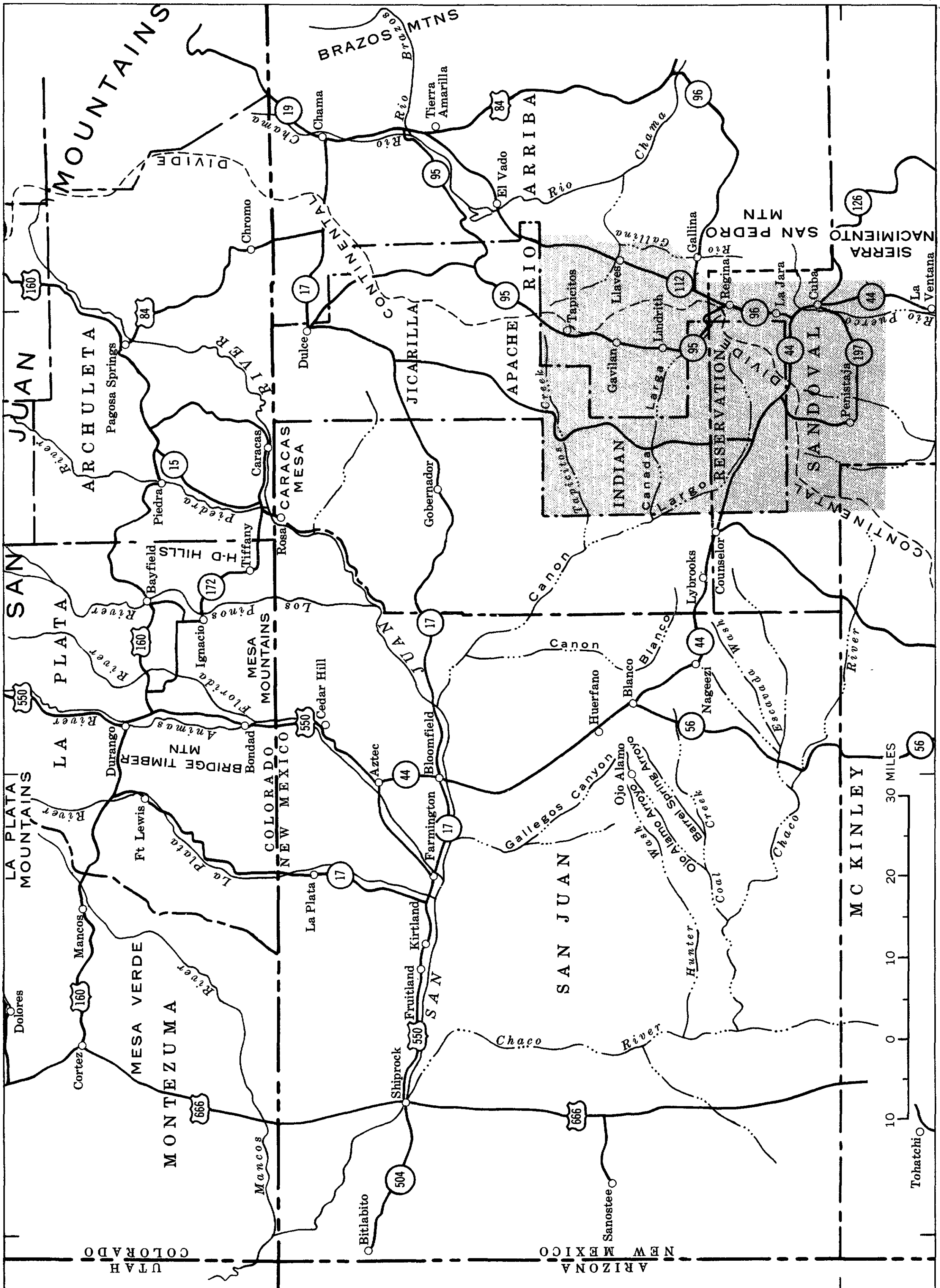

FIGURE 1.—Location of report area (stippled).

adjacent areas to the south and east by the U.S. Geological Survey. The results of the ground-water investigations are the subject of another report (Baltz and West, 1967). The present report gives only the geologic data and the conclusions they make possible. These data are of particular interest in the interpretation of the structural evolution of the region, because the stratigraphic relations and facies distributions of Upper Cretaceous and lower Tertiary rocks reflect the Laramide history of the San Juan Basin and some of its bounding uplifts.

PREVIOUS WORK

The geology of parts of the area of this report has been mapped and described briefly in several earlier reports. The southern and eastern parts of the area are parts of a much larger region mapped in reconnaissance by Gardner (1909), who also briefly described stratigraphic relations of Cretaceous and Tertiary rocks in this area (Gardner, 1910). Renick (1931) made a reconnaissance map of the rocks along the west side of Sierra Nacimiento and San Pedro Mountain, studied the stratigraphy and structure of these rocks, and discussed ground-water conditions in the east-central and southeastern parts of the area of the present report. Dane (1932) published a brief description of the uppermost Cretaceous and Paleocene rocks of the region. He also (1936) briefly examined and described rocks in the southern two tiers of township (Tps. 20–21 N., Rs. 1–5 W.) of the area of the present report and mapped them during a study of the La Ventana-Chacra Mesa coal field which lies south and southwest of the area of the present report.

Dane (1946) also published a chart and description of the stratigraphy of the uppermost Cretaceous and Tertiary rocks of the eastern side of the San Juan Basin. This included a description of the rocks in parts of a narrow belt in the eastern part of the area of the present report. Wood and Northrop (1946) mapped the Nacimiento Mountains (Sierra Nacimiento) and San Pedro Mountain, and the foothills to the west which were previously mapped by Renick (1931). The Dulce-Chama area mapped by Dane (1948) includes, at its southern end, the two northeasternmost townships (T. 26 N., R. 1 E., and R. 1 W.) of the area of the present report. A narrow strip including the east edge of the present area from the northern part of T. 22 N., R. 1. W., to the northeast corner of the area was mapped as parts of three master's theses of the University of New Mexico by Hutson (1958), Fitter (1958), and Lookingbill (1953). Subsequent to the present writer's (1959–61) fieldwork, parts of the south-central margin of the area were mapped by Hinds (1966) and Fassett (1966).

The southern part of the Jicarilla Apache Indian Reservation and much of the area to the east have not been mapped previously, and lithologic units of less than formational rank in Tertiary rocks have not been mapped previously in this region.

PRESENT WORK

Fieldwork for the present report was done mainly from May to October, 1959, and in May 1960. Subsequent fieldwork was done during brief periods in 1960 and the early part of 1961. All geologic mapping was done on aerial photographs.

A planimetric base map was compiled at the scale of 1 : 63,360 (1 in. = 1 mile) from parts of the La Ventana, Cuba, Llaves, and Horse Lake 15-minute quadrangle topographic maps of the U.S. Geological Survey, the 30-minute quadrangle planimetric maps of the New Mexico State Highway Commission Planning Survey, and the Resources Planning Map of the Jicarilla Indian Reservation. Geology mapped in the field on aerial photographs was plotted on the then available topographic maps and then transferred to the planimetric base. For the part of the area for which topographic maps were not then available, the geology was transferred directly from the aerial photographs to the planimetric base by means of the Saltzman overhead projector. The geology is shown on plate 1.

A study of the subsurface geology of the area was made by means of electric logs of wells drilled for oil and gas that were available in 1961. Subsurface data were correlated with surface stratigraphic sections measured in the field (pl. 2).

The study of the east-central part of the San Juan Basin was augmented by detailed work in other parts of the basin, and by reconnaissance examination of rocks in the region surrounding the basin during the course of other work for the U.S. Geological Survey in parts of 1951–63. This report is modified from the author's doctoral dissertation, presented in 1962 at the University of New Mexico.

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PHYSIOGRAPHY

DRAINAGE

Most of the area is drained by streams which flow westward intermittently to Canon Largo (pl. 1). The intermittent stream in Canon Largo flows northwest out of the area and discharges into the San Juan River (fig. 1).

The Continental Divide extends sinuously across the eastern and southern parts of the area, and the region east of the divide is in the Rio Grande watershed. Intermittent streams east of the divide in Rio Arriba County drain into the Rio Gallina, which flows intermittently to the northeast from San Pedro Mountain. Outside the area, the Rio Gallina flows into the Rio Chama, a major tributary of the Rio Grande. The extreme northeastern part of the area is drained by Archuleta Arroyo, which drains into the Rio Chama.

The western side of San Pedro Mountain in Sandoval County is drained by streams flowing intermittently westward to San Jose Creek. La Jara Creek and Rito de los Pinos both are perennial streams in their upper courses, but they become intermittent before reaching San Jose Creek. San Jose Creek flows intermittently southward between San Pedro Mountain and the Continental Divide to the vicinity of Cuba, where it joins the Rio Puerco.

The Rio Puerco flows southward and is the master stream for drainage of the southern part of the area. However, the Puerco flows perennially only in its upper course north of Cuba. Encino Wash and Arroyo San Ysidro drain southward and, outside the area, join Torreon Arroyo (also called Arroyo Torrejon on some maps), a southeast-flowing intermittent tributary of the Rio Puerco. Several small west-flowing streams such as Rito Leche, Nacimiento Creek, and Senorito Creek (in Senorito Canyon) have perennial streams of water in their upper courses on Sierra Nacimiento, but their flow becomes intermittent before reaching the Rio Puerco. The Rio Puerco joins the Rio Grande almost 120 miles south of Cuba.

LANDFORMS

Nearly all the San Juan Basin lies within the Navajo section of the Colorado Plateaus physiographic province (Fenneman and Johnson, 1946), a region of young plateaus and moderate to strong relief. The predominant type of erosion has been the stripping of nearly horizontal sedimentary rocks to leave outlying mesas and buttes along the interstream divides. Locally the major streams have incised soft Cretaceous and Tertiary rocks and have formed fairly deep, steep-walled canyons. The resulting landforms are related directly to the geologic structure and the lithologic character of Cretaceous and Tertiary rocks. These rocks consist of units of thick shale and interbedded thick to thin sandstone.

The sandstones are more resistant to erosion than the shales, and where the strata are nearly horizontal, sandstone forms mesas and broad benches. The easily eroded shale units form valleys and steep slopes between the sandstone units. Some of the thick shale units contain numerous beds of lenticular thin soft sandstone and sandy shale, which are only slightly more resistant to erosion than the enclosing shale beds. In places the differential erosion of rocks of this type has formed intricately dissected badlands. Where the strata are tilted steeply and eroded deeply, the resistant sandstone units form hogback ridges between broad valleys eroded in the intervening shale units.

The granite, which forms much of San Pedro Mountain and Sierra Nacimiento east of the mapped area, is more resistant to erosion than the sedimentary rocks preserved in the San Juan Basin. The steeply tilted sedimentary rocks at the west side of the mountains must have been mainly continuous across that region before uplift and erosion occurred. San Pedro Mountain and the Sierra Nacimiento are considered to be physiographically part of the Southern Rocky Mountains (Fenneman and Johnson, 1946); thus their western edge marks the eastern boundary of the Colorado Plateaus physiographic province in this region. North of San Pedro Mountain, the high mesas and plateaus lying east of the area of the present report are part of the Colorado Plateaus, and the eastern boundary of the physiographic province in this latitude is the Brazos Mountains, which lie nearly 40 miles northeast of the area of this report.

Six relatively distinct physiographic sectors in the mapped area are here named: Penistaja Cuestas, Largo Plains, Tapicitos Plateau, Yeguas Mesas, San Pedro Foothills, and Northern Hogback Belt. These sectors are shown in figure 2.

PENISTAJA CUESTAS

The southern part of the area is characterized by several major sloping topographic benches or cuestas extending from east to west as broad curved bands interrupted by narrow valleys and canyons. This sector is here named the Penistaja Cuestas. Each of the major cuestas is capped by a thick unit of sandstone, and the southern margin of each is a steep escarpment. Because the cuestas are cut by canyons at places,

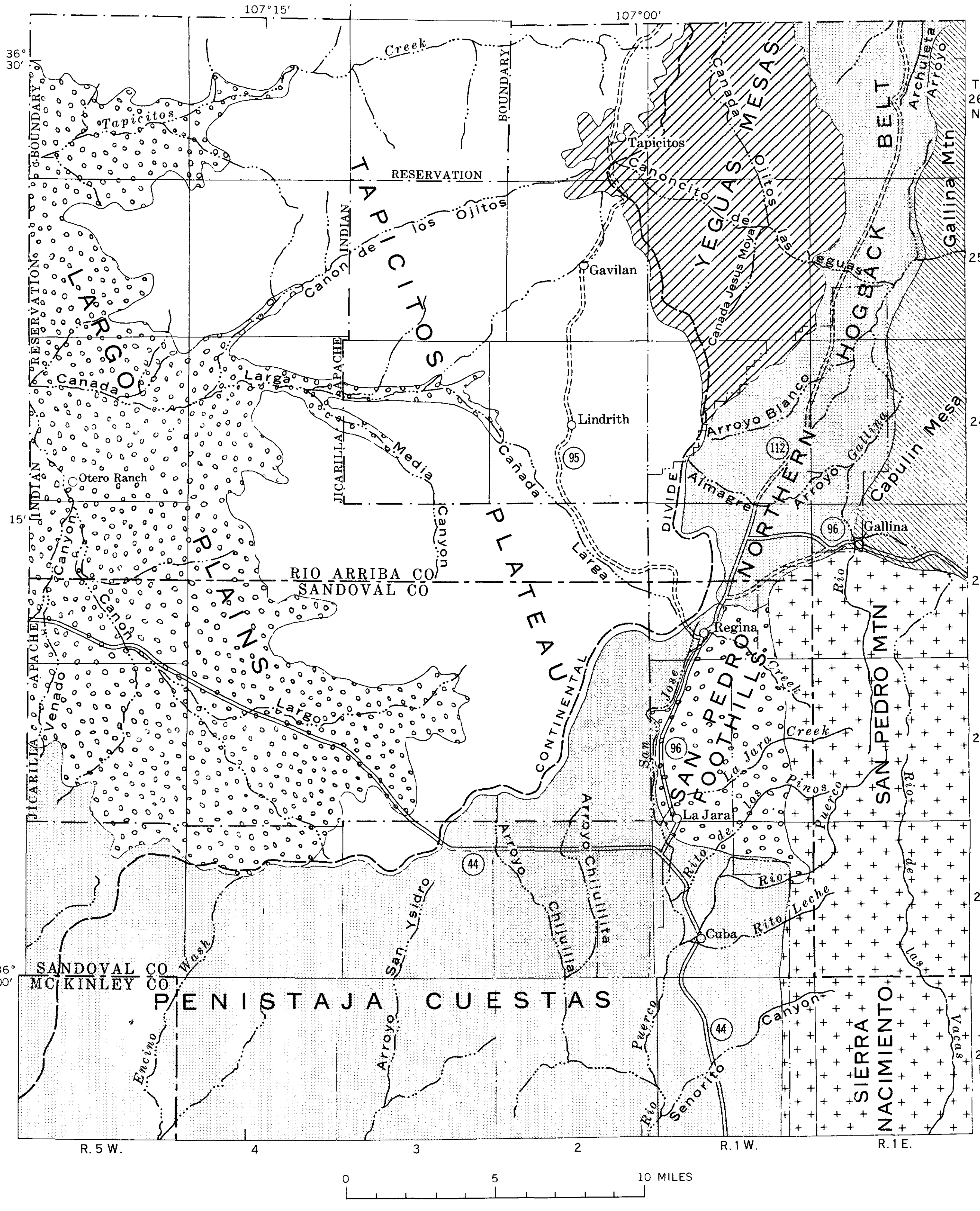


FIGURE 2.—Physiographic index map of east-central part of San Juan Basin and adjacent region, New Mexico.

their southern edges are sinuous, but in general the erosional escarpments face south, southwest, or southeast. Soft, shaly rocks overlying the sandstone units have been stripped back to the north, in places for several miles, so that the tops of the cuestas are mainly dip slopes cut on the upper surface of each sandstone unit. The cuestas in the western part of the sector slope northeast; in the central part they slope north; and in the eastern part they slope northwest. These varied directions of slope reflect the regional dips of the rocks.

Each cuesta is separated from the next cuesta to the north by an intervening band of valleys and low rounded hills cut in rocks that are mainly shale. Thin resistant beds in the shales cap low hills and minor benches. Near the northern edge of each belt of valleys and low hills, the land surface rises abruptly and culminates in the steep erosional escarpment forming the southern edge of the next sandstone-capped cuesta to the north. Streams that cross the shale units have broad alluviated valleys, but streams that cross the bench-forming sandstones have narrow valleys or flow in deep canyons. The drainage of the sector is to the south.

The southern and western boundaries of the Penistaja Cuestas sector are outside the area of this report. The northern boundary is defined as the Continental Divide between Regina and the northwestern part of T. 21 N., R. 4 W. West of there the boundary trends northwest to the upper part of Venado Canyon in T. 22 N., R. 5 W. This boundary includes within the Penistaja Cuestas the area of moderately great topographic relief and tilted rocks which is near the southern edge of the Central basin structural element of the San Juan Basin (Kelley, 1950). Along most of the northern boundary of the Penistaja Cuestas, the land surface slopes steeply north from a series of rugged mesas and cuestas to a region of nearly horizontal rocks and low topographic relief which is the Largo Plains. At the east the Penistaja Cuestas merge with the San Pedro Foothills, and with the steeply tilted rocks at the foot of Sierra Nacimiento.

Altitudes of the Penistaja Cuestas sector become higher from south to north. The altitude of the southernmost cuestas ranges from a little less than 6,600 feet in the extreme southwest corner of the area to a little more than 7,300 feet in the southeast corner. The highest altitudes are along the Continental Divide and range from 7,450 feet in the southwestern part of T. 22 N., R. 5 W., to about 7,700 feet in the southwestern part of T. 22 N., R. 2 W.

LARGO PLAINS

Canon Largo in the western part of the area is bordered on the northeast and on the southwest by broad plains that slope gently toward this intermittent stream. These plains, here named the Largo Plains, have been dissected mildly by the intermittent streams tributary to Canon Largo, and the region is thus one of broad low mesas separated by intervening swales and shallow valleys. In the west-central part of the area, Canon Largo is an entrenched stream flowing in a steep-walled canyon whose floor is almost 200 feet below the plains. Similarly, in the northwestern part of the area the lower courses of Tapicitos Creek and smaller tributaries of Canon Largo are steep-walled canyons incised deeply in the plains.

The plains bordering Canon Largo were formerly part of a broad valley that trended northwest and was graded to the San Juan River at a time when that river had not carved the deep canyon through which it now flows. The ancient valley of the Largo was as much as 10 miles wide in places and had a northwest gradient of about 7 feet per mile in the Jicarilla Apache Indian Reservation.

Altitudes along Canon Largo range from about 6,600 feet near Otero Ranch to a little more than 7,000 feet in the southwestern part of T. 22 N., R. 3 W. Southwest of Canon Largo the plains slope gently up to altitudes of about 7,000 feet, and the high cuestas and mesas of the Penistaja sector rise above the southwestern edge of the old valley. Northeast of Canon Largo the plains slope gently up to altitudes of 6,800–7,000 feet. At the northeastern edge of the old valley the intricately dissected mesas of the Tapicitos Plateau rise abruptly.

TAPICITOS PLATEAU

Most of the northern and central part of the area is a high plateau which has been greatly dissected by the west-flowing intermittent streams tributary to Canon Largo. The remnants of the plateau stand as broad irregular sandstone-capped mesas extending westward from the Continental Divide to the Largo Plains. The plateau is roughly triangular, becoming narrower to the south until it merges, around the east end of the Largo Plains, with the Penistaja Cuestas sector along the Continental Divide in T. 22 N., Rs. 2–3 W. The dissected plateau is here called the Tapicitos Plateau, for Tapicitos Creek, which heads in the eastern part of the upland.

The west boundary of the plateau is the sinuous steep erosional escrapment overlooking the Largo Plains. The eastern edge may be defined conveniently as the Continental Divide northward from the northeastern part of T. 21 N., R. 4 W. The high mesas and cuestas along the divide west of T. 21 N., R. 4 W. are erosional remnants of the Tapicitos Plateau, but they are more conveniently grouped with the Penistaja Cuestas sector. The Tapicitos Plateau extends far to the north of the present area of investigation.

Altitudes on the Tapicitos Plateau range from about 6,800 feet on the lower slopes to a little more than 7,600 feet at the tops of the highest mesas. Throughout the area there are numerous mesas whose tops are at altitudes ranging from 7,400 to 7,500 feet. This concordance of altitudes seems to indicate that a widespread erosional surface of relatively low relief characterized the plateau before the canyon-cutting erosional cycle during which the plateau was dissected and the Largo Plains were formed. (See fig. 4.)

YEGUAS MESAS

Near the northeast corner of the area, numerous high mesas rise about 500 feet above the general level of the Tapicitos Plateau. The long narrow mesas are separated by deep, steep-walled canyons cut in thick sandstone beds by the intermittent streams of Canoncito de las Yeguas and its tributaries. Topographic relief from tops of mesas to bottoms of adjacent canyons is as much as 1,000 feet in about half a mile at some places. This area of high mesas and deep canyons is here named the Yeguas Mesas sector.

Altitudes in Canoncito de las Yeguas range from about 7,000 feet at the east to a little more than 7,500 feet at the west. The highest mesas are along the east side of the sector where altitudes are as much as 8,500 feet. The altitude of the tops of the highest western mesas along the Continental Divide is nearly 8,000 feet.

The tops of many of the Yeguas mesas appear to be remnants of a high-level erosion surface that sloped westward. This surface may have been widespread formerly, because extensive areas of similar altitudes occur in the region east of the area of this report, and isolated mesas whose tops have altitudes of 7,700–8,000 feet occur along the Continental Divide on the Tapicitos Plateau in the eastern part of the area. A few isolated buttes and small mesas rising above the Tapicitos Plateau may be erosional remnants of the higher Yeguas Mesas surface, which was mainly destroyed by the erosional cycle that produced the lower Tapicitos Plateau surface.

SAN PEDRO FOOTHILLS

The foothills of San Pedro Mountain between the upper part of San Jose Creek and the upper part of the Rio Puerco are characterized by west-sloping terraces. The terraces extend west from San Pedro Mountain to the south-flowing main stem of San Jose Creek. The terraces are separated by west-trending valleys which are mainly broad and shallow at the west, but narrow and deep at the east. This area is here named the San Pedro Foothills sector. Deposits of gravel, composed mainly of granite derived from San Pedro Mountain, cap terraces at several different levels and occur also in the upper valleys of the major streams (fig. 3). In deep canyons cut below the levels of the

FIGURE 3.—View northeast across valley of Rio Puerco from NW¼ sec. 21, T. 21 N., R. 1 W., showing San Pedro Foothills and San Pedro Mountain. Tn, Nacimiento Formation of Paleocene age; Tsr, Regina Member of San Jose Formation of Eocene age. Prominent terrace on Regina Member at foot of mountain is capped by gravel of Tertiary or Quaternary age. Lower terraces are capped by gravel of Quaternary age.

terraces near the foot of San Pedro Mountain, nearly vertical Paleozoic, Mesozoic, and Tertiary sedimentary rocks are exposed. These rocks are beveled by the west-sloping terraces, and their structure and lithology have only minor influence on the landforms.

Altitudes at the west side of the foothills belt range from a little more than 7,000 feet in the valley of San Jose Creek south of La Jara to almost 7,600 feet at the head of the valley north of Regina. Altitudes at the top of some of the terrace-gravel deposits at the foot of San Pedro Mountain are a little more than 8,400 feet.

Bryan and McCann (1936) briefly examined the San Pedro Foothills as part of a study of the physiography of the upper Rio Puerco; they postulated that the terraces are remnants of two pediments that were cut to the grades of two older and higher temporary erosional levels of San Jose Creek and the Rio Puerco. According to Bryan and McCann, the higher and older postulated pediment, which they called the La Jara pediment (p. 160–164), extended as a sloping surface from the foot of the San Pedro Mountain to San Jose

Creek and was overlain by an almost continuous veneer of gravel. The postulated lower and younger erosion surface, called the Rito Leche pediment (p. 164), was a broad surface between the Nacimiento Mountains and the Rio Puerco south of Cuba. In the San Pedro Foothills, the Rito Leche pediment was represented by the narrow low terraces or benches along the edges of the San Jose Creek and its tributaries. These terraces are higher than the floor of the present valley but are lower than the postulated La Jara pediment.

A more detailed study by the present writer indicates that the physiographic history of the San Pedro Foothills sector is more complex than that envisioned by Bryan and McCann, and that the concept of the La Jara pediment is incorrect. The gravel deposits (see pl. 1) are not as extensive as indicated by Bryan and McCann, and they are on several distinctly different west-sloping surfaces (fig. 3), rather than on one general surface as required by the concept of the La Jara pediment.

The highest gravels are on narrow remnants of what may have been a pediment surface. This surface slopes away from San Pedro Mountain at altitudes ranging from about 8,000 to 8,400 feet and may be equivalent to the highest erosional surface in the Yeguas Mesas. Other mesas whose tops are at altitudes of from 7,700 to 8,000 feet occur at places along the Continental Divide west of San Pedro Mountain, and the tops of these mesas also may be remnants of the erosional surface capped by the highest gravel deposits on the flanks of San Pedro Mountain.

Most of the lower level gravel deposits are much longer than they are wide, and they extend westward from deep canyons cut in Precambrian granite on the west side of San Pedro Mountain. At some places the gravel deposits are thickest in their central parts and thinner at their edges. It seems probable, therefore, that most of the lower level gravel was deposited in stream channels cut in soft Cretaceous and Tertiary rocks during early stages of erosion of the foothills belt. During later stages of erosion the gravels protected the immediately underlying soft rocks; thus the former stream channels are now gravel-capped terraces. The old interstream areas, consisting mainly of soft Tertiary rocks not protected by gravel, were more susceptible to erosion and were worn away, probably by lateral migration of the streams to the edges of their gravelly channels, where they were able to cut into the soft Tertiary rocks to form the present valleys. Comparison of gradients and altitudes of some of the gravel-capped terraces indicates that the streams which deposited the gravel were captured only recently by San Jose Creek. Prior to this, some of the streams probably drained westward, and the Continental Divide was at the crest of Sierra Nacimiento and San Pedro Mountain. The west-flowing upper course of San Jose Creek east of Regina seems to have been the last tributary to be captured. Formerly it probably flowed to the west through the gap in the Continental Divide (traversed by State Highway 95) just west of Regina, and into the upper part of Canada Larga. The altitude of the gravel-capped terrace along upper San Jose Creek east of Regina is about 7,500 feet. The altitude of the gap in the Continental Divide west of Regina is a little less than 7,500 feet.

NORTHERN HOGBACK BELT

Extending northward from the San Pedro Foothills, along the northeast side of the area of investigation, is a belt of long narrow sandstone hogback ridges separated by alluvial valleys which are mainly parallel to the ridges. The hogback ridges are breached by gaps through which the intermittent streams of the belt drain eastward to Rio Gallina. This hogback belt is geologically a continuation of the San Pedro Foothills, but the hogback belt has been more deeply eroded and consequently has different landforms. Differential resistance to erosion of the steeply tilted sedimentary rocks has caused valleys to be cut in the shale units, leaving the more resistant sandstone beds as nearly parallel hogback ridges rising above the intervening valleys. The name Northern Hogback Belt is applied to this sector to distinguish it from the hogback belt parallel to the front of Sierra Nacimiento south of the area mapped.

The major topographic feature of the Northern Hogback Belt is the high, narrow sandstone ridge in the eastern part of the belt (fig. 4). Although this hogback is cut at places by transverse gaps, it forms a nearly continuous ridge from the upper tributaries of San Jose Creek northward beyond the northern part of the area. The altitude of the top of this hogback is more than 7,800 feet at some places. The hogback rises 400–600 feet above the flanking valleys. Sandstone beds of stratigraphically higher formations form ridges west of the main hogback, but these sandstones are less resistant to erosion, and the hogbacks to the west are, for the most part, topographically lower. Also, the north-south continuity of the western hogbacks is interrupted by broad transverse alluviated valleys and low terraces. In most of the hogback belt west of the main hogback, altitudes range from a little less than 6,900 feet to about 7,400 feet; however, the large hogback (or steeply sloping cuesta) in the western part of T. 26 N., R. 1 E., attains the highest altitude—8,447 feet—of the Northern Hogback Belt.

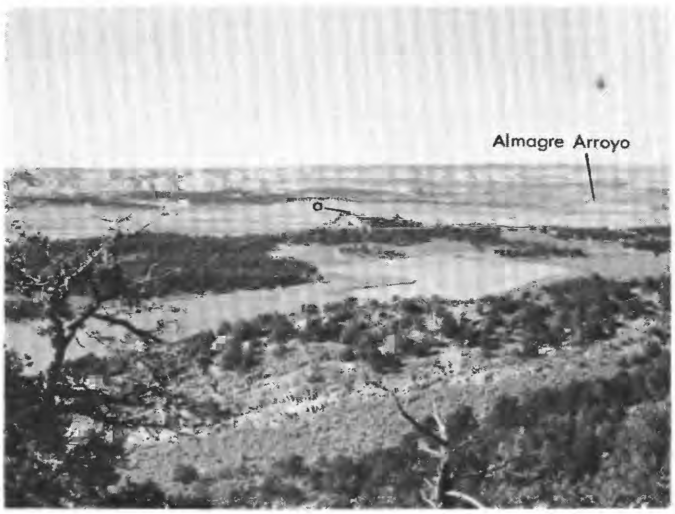


FIGURE 4.—View northwest from sec. 14, T. 23 N., R. 1 W., across Northern Hogback Belt to east edge of Tapicitos Plateau. Steeply dipping sandstone of main hogback in foreground is La Ventana Tongue of Cliff House Sandstone of Mesaverde Group of Cretaceous age. Valley beyond is underlain by Lewis Shale of Cretaceous age. Sandstone rib at *a* is in Fruitland and Kirtland Formations of Cretaceous age. Valley and badlands in background are cut in Regina Member of San Jose Formation.

The upper valleys of Arroyo Blanco and Almagre Arroyo are cut in soft gently dipping Tertiary rocks and do not have the characteristic landforms of the Northern Hogback Belt. These valleys, however, are at lower altitudes than the Tapicitos Plateau west of the Continental Divide, and they drain to the east. Therefore, they are included in the Northern Hogback Belt.

CLIMATE

The recorded average annual precipitation in the area ranges from 16.71 inches at Gavilan to 11.91 inches at Otero Ranch (New Mexico State Engineer, 1956, p. 277–280, 294). The average monthly precipitation is least in June and greatest in July and August. In general, the wettest part of the area is the east side, and the topographically higher parts receive more precipitation than the lower parts. The amount of precipitation decreases to the west, and the southwest corner of the area is the driest part.

According to published records of the New Mexico State Engineer (1956), the average frost-free season is 77 days (June 25–Sept. 10) at Gavilan (alt 7,350 ft).

VEGETATION

The vegetation varies with altitude and precipitation. The lower valleys and plains support sparse grass and, locally, thick growths of sagebrush. Near springs, and in some of the valleys where the water table is near the surface, cottonwoods grow. On the slopes and lower ridges and hills, particularly in sandy soil, juniper and piñon pine are the common trees. The juniper-piñon zone merges upward into stands of ponderosa pine which grow on the sandstone-capped cuestas of the Penistaja sector, the mesas of the Tapicitos Plateau and Yeguas Mesas, the sandstone ridges of the Northern Hogback Belt, and the gravel-capped terraces of the San Pedro Foothills. Scrub oak is common in the upper part of the juniper-piñon zone and with the ponderosa pines. Ponderosa pines clothe the slopes of the Sierra Nacimiento and San Pedro Mountain and merge upward with stands of spruce and fir, which grow on the higher parts of the mountains and on north-facing canyon walls. Groves of aspen are common in the moister parts of the mountains.

STRATIGRAPHY

Rocks ranging in age from Precambrian to Recent are exposed in the Nacimiento uplift and the eastern part of the San Juan Basin. The nomenclature, age, and thickness of these rocks are summarized in table 1. Shown in figure 5 are the structural elements of the San Juan Basin and adjacent regions that are mentioned in the discussion of the stratigraphic units.

The oldest rocks of the region are igneous and metamorphic rocks of Precambrian age which form a basement on which younger sedimentary rocks rest. The Precambrian rocks form the bulk of San Pedro Mountain and Sierra Nacimiento and have been penetrated at depths of 13,000 feet or more in wells drilled in the eastern part of the San Juan Basin. Precambrian rocks exposed in the Nacimiento uplift were described by Renick (1931, p. 12–13) as being mainly coarsely crystalline granite with some dikes of finely to coarsely crystalline basic igneous rock and quartz veins. There are a few outcrops of mica schist into which the granite probably was intruded.

Paleozoic rocks lie on the Precambrian basement and consist of thick beds of limestone, shale, sandstone, and conglomerate of Mississippian, Pennsylvanian, and Permian age. These rocks are present at places in the higher parts of Sierra Nacimiento and San Pedro Mountain and crop out also on the lower slopes of the mountains (Renick, 1931, p. 13–24; Wood and Northrop, 1946; Northrop, 1950, p. 26–46; Armstrong, 1955, p. 6–17; Fitzsimmons and others, 1956, p. 1936–1940). Paleozoic rocks are present also in the subsurface of the San Juan Basin.

The Paleozoic rocks are overlain by a thick sequence of Mesozoic rocks consisting of sandstone and shale of Triassic, Jurassic, and Cretaceous age. Triassic red

TABLE 1.—*Age, nomenclature, and thickness of rock units in the Nacimiento uplift and the eastern part of the San Juan Basin, N. Mex.*

[Compiled partly from Renick, 1931; Dane, 1936; Wood and Northrop, 1946]

Era	System	Series	Lithologic unit	Thickness (feet)
Cenozoic	Quaternary	Recent and Pleistocene	Alluvium in valleys	0–100+
			—Unconformity—	
		Pleistocene	Terrace gravel and gravelly stream-channel alluvium in the upper parts of some valleys	0–100±
			—Unconformity—	
	Quaternary or Tertiary	Pleistocene or Pliocene	Gravel capping high terraces	0–100±
			—Unconformity—	
	Tertiary	Miocene(?)	Lamprophyre dikes	
			—Unconformity—	
		Eocene	San Jose Formation	200±–1,800
			—Unconformity—	
		Paleocene	Nacimiento Formation	≤537–1,750
			Ojo Alamo Sandstone	70–200
			—Unconformity—	
Mesozoic	Cretaceous	Upper Cretaceous	Kirtland Shale and Fruitland Formation undivided	100±–450
			Pictured Cliffs Sandstone	0–235
			Lewis Shale	500–1,900
			Mesaverde Group: La Ventana Tongue of Cliff House Sandstone	37–1,250 (Total thickness 560–1,825±)
			Mesaverde Group: Menefee Formation	345–375
			Mesaverde Group: Point Lookout Sandstone	110–200±
			Mancos Shale	2,300–2,500
		Upper and Lower Cretaceous	Dakota Sandstone	150–200
			—Unconformity—	
	Jurassic	Upper Jurassic	Morrison Formation	350–600
			Todilto Formation	60–125
			Entrada Sandstone	≤227
			—Unconformity—	
	Triassic	Upper Triassic	Chinle Formation	1,050±
			—Unconformity—	
Paleozoic	Permian		Cutler Formation	500–950+
			—Local unconformity—	
	Carboniferous: Pennsylvanian	Upper and Middle Pennsylvanian	Magdalena Group: Madera Limestone	0–800+
		Lower Pennsylvanian	Magdalena Group: Sandia Formation (upper clastic member of Sandia Formation of Wood and Northrop, 1946)	0–200
			—Unconformity—	
	Carboniferous: Mississippian	Upper Mississippian	Arroyo Penasco Formation (lower limestone member of Sandia Formation of Wood and Northrop, 1946)	0–158
			—Unconformity—	
Precambrian			Granite and metamorphic rocks	

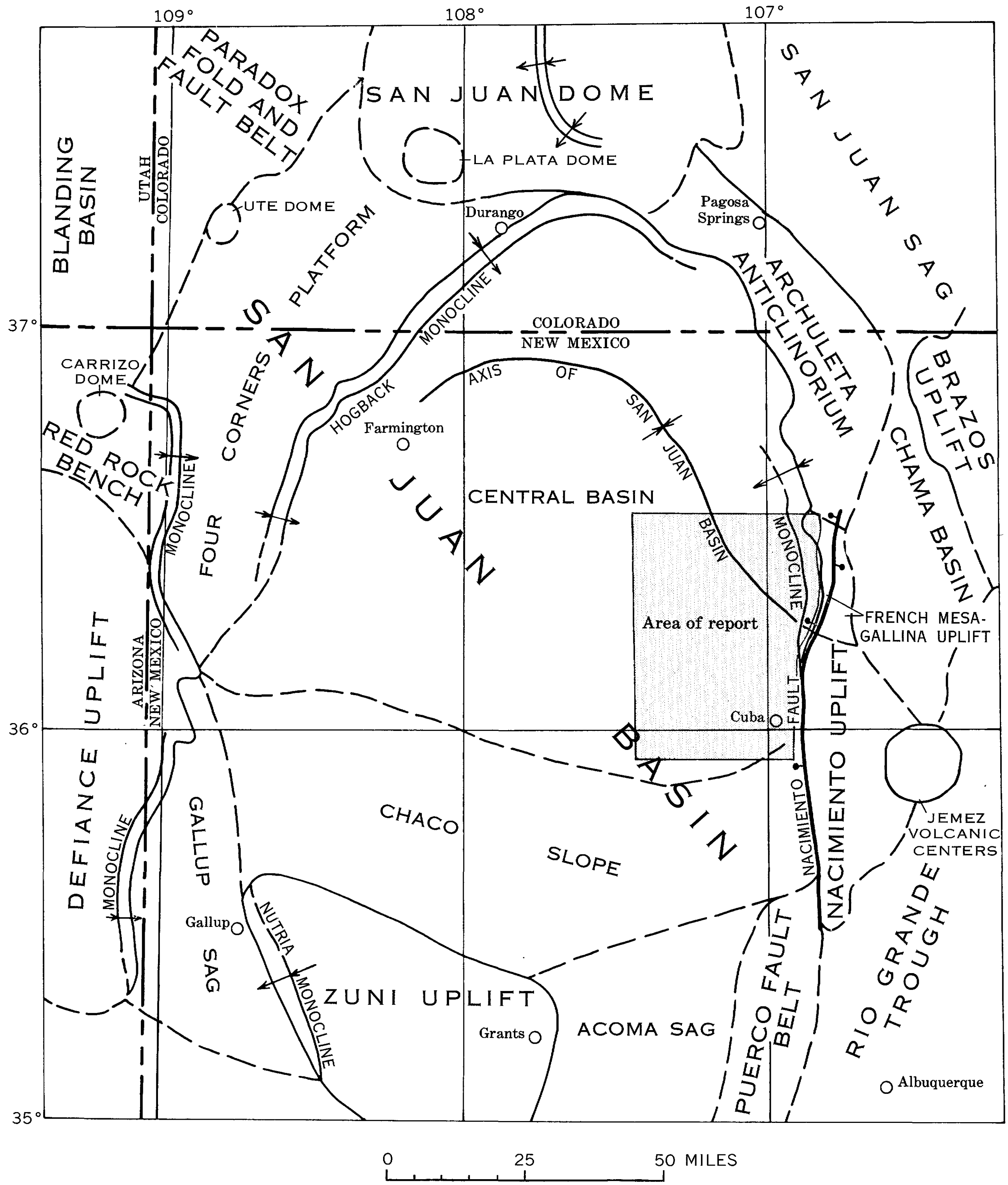


FIGURE 5.—Structural elements of the San Juan Basin. Modified from Kelley (1951, p. 125; 1955, fig. 2) and Kelley and Clinton (1960, fig. 2).

beds are present in a structural sag between San Pedro Mountain and Sierra Nacimiento and crop out also in the belt of steeply dipping rocks at the western edge of the mountains. Jurassic rocks also crop out in this belt along the edge of the mountains. Cretaceous rocks consisting of thick units of sandstone and shale crop out in the belt of steeply dipping rocks and are the surface rocks in much of the San Juan Basin outside the Central basin. The Mesozoic rocks are present also in the subsurface of the San Juan Basin.

Cenozoic rocks consisting of thick units of sandstone and shale of early Tertiary (Paleocene and Eocene) age are the surface rocks in most of the Central basin.

The Cretaceous and lower Tertiary rocks with which the present report is primarily concerned are restricted mainly to the Central basin, and rocks older than Tertiary age are at depths of more than 3,000 feet in the southern part of the Jicarilla Apache Reservation. The oldest rocks mapped in the present investigation are those of the Mesaverde Group of Late Cretaceous age. Rocks older than this are shown on the geologic map (pl. 1) as Cretaceous and older rocks, undivided. These rocks, ranging in age from Precambrian to Late Cretaceous as shown in table 1, crop out at the eastern margin of the area, and were mapped by Renick (1931), Wood and Northrop (1946), Lookingbill (1953), Hutson (1958), and Fitter (1958).

ROCKS OF CRETACEOUS AGE

MESAVERDE GROUP

DEFINITION

The Mesaverde Group of Late Cretaceous age was named by Holmes (1877, p. 252). The name was applied to the thick sequence of sandstone, shale, and coal that forms Mesa Verde in southwestern Colorado. Collier (1919, p. 296–297) divided the Mesaverde at the type locality into three formations. In ascending order these are the Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone. The Mesaverde Group has been mapped continuously from the type locality in Colorado (Wanek, 1954) across the San Juan Basin into the area of the present report (Bauer, 1916, pl. 64; Reeside, 1924, p. 13–16; Dane, 1936, p. 93–109).

Because of the complexity of the stratigraphy of the Mesaverde Group and the consequent uncertainty of regional correlations, earlier workers in the southern and eastern parts of the San Juan Basin did not use the formational subdivisions (Point Lookout, Menefee, and Cliff House Formations) of the type locality. The rocks of the Mesaverde Group in the southeastern part of the area of the present report were mapped by Renick (1931), Dane (1936), and Wood and Northrop (1946) as the Mesaverde Formation. In this region Dane mapped a basal sandstone which he correlated with the upper part of the Hosta Sandstone Member of the Mesaverde Formation of the southern San Juan Basin. Above the rocks called the Hosta Sandstone Member by Dane (1936) in the eastern part of the basin is a sequence of interbedded sandstone, shale, and coal beds which Dane correlated with the Gibson Coal Member and the Allison Member of the Mesaverde Formation of the southern San Juan Basin. The uppermost unit of the Mesaverde in the eastern part of the basin is a ledge-forming sequence of sandstone beds which Dane (1936, p. 108) named the La Ventana Sandstone Member.

Later, as the result of extensive mapping, correlation of the units of the Mesaverde throughout the basin became possible. Beaumont, Dane, and Sears (1956, p. 2156–2157) raised the Mesaverde to group status everywhere in the San Juan Basin. The Hosta Sandstone Member mapped by Dane (1936) in the eastern San Juan Basin was designated as a tongue of the Point Lookout Sandstone. The Gibson Coal Member (upper part) and the Allison Member of Dane (1936) in the eastern San Juan Basin were designated as the Cleary Coal Member and Allison Member of the Menefee Formation. The La Ventana Member was designated as the La Ventana Tongue of the Cliff House Sandstone.

The present writer did not subdivide the Mesaverde Group into Point Lookout Sandstone, Menefee Formation, and La Ventana Tongue of the Cliff House Sandstone during reconnaissance mapping of these rocks. A threefold division of the Mesaverde Group was observed, however, at all localities where the group is completely exposed in the eastern part of the area, and a threefold nature is apparent in electric logs of wells.

EXTENT AND THICKNESS

The Mesaverde Group is exposed almost continuously from south to north along the eastern margin of the area and is continuously distributed in the subsurface of the region west of the mountains.

In the southern part of T. 20 N., R. 1 W., the Mesaverde Group is well exposed south of San Pablo Canyon, where its upper beds, the La Ventana Tongue of the Cliff House Sandstone, form a high hill on the crest of the northwest-plunging San Pablo anticline. Beneath the La Ventana are slope-forming carbonaceous shale and sandstone of the Menefee Formation underlain by thin ledge-forming sandstone of the Point Lookout Sandstone. North of there the Mesaverde Group is sharply folded at the foot of Sierra Nacimiento and San Pedro Mountain. The Mesaverde beds dip steeply west and in places are vertical or are overturned slightly and dip east at high angles. Because of the steep dips the outcrop belt of the Mesaverde is narrow along the foot of the mountains. In the San Pedro Foothills, the Mesaverde Group is covered by Quaternary gravel in some places.

North of San Pedro Mountain the west dip of the Mesaverde becomes less steep and the outcrop belt is wider. The thick sandstone of the La Ventana Tongue of the Cliff House Sandstone forms the high eastern hogback in the Northern Hogback Belt. The Menefee Formation and the Point Lookout Sandstone form steep slopes and small ridges east of the main hogback (fig. 6).

FIGURE 6.—The Mesaverde Group in the Northern Hogback Belt. View to the north from sec. 14, T. 23 N., R. 1 W. Kpl, Point Lookout Sandstone; Kmf, Menefee Formation; Klv, La Ventana Tongue of Cliff House Sandstone. French Mesa–Gallina uplift on the skyline, center and right. Yeguas Mesas on skyline at left.

According to Renick (1931, p. 43–44) the Mesaverde is 564 feet thick in sec. 35, T. 21 N., R. 1 W. His lower sandstone member is the Point Lookout Sandstone, which is about 180 feet thick. His middle coal-bearing member is the Menefee Formation, which is about 347 feet thick. His upper sandstone member is the La Ventana Tongue of the Cliff House Sandstone, which is about 37 feet thick. Farther west in the subsurface, the thickness of the entire Mesaverde Group increases to about 840 feet at the Sun Oil 1 McElvain well in sec. 23, T. 21 N., R. 2 W. In the southwestern part of the area the Shell Oil 1 Pool Four well in sec. 22, T. 21 N., R. 5 W., penetrated about 1,700 feet of rocks assigned to the Mesaverde Group.

In the northeastern part of the area the entire Mesaverde Group is about 630 feet thick in the subsurface at the Reading and Bates 1 Duff well in sec. 24, T. 24 N., R. 1 W. Fitter (1958, p. 19 and p. 49–51) reported that, in sec. 5, T. 24 N., R. 1 E., the basal (Point Lookout) sandstone is approximately 95 feet thick, the medial coal-bearing sequence (Menefee) is about 375 feet thick, and the upper sandstone (La Ventana Tongue of the Cliff House) is about 110 feet thick.

LITHOLOGY

The Point Lookout Sandstone consists of buff, gray, and tan sandstone beds that range in thickness from 1 to 30 feet. The Point Lookout is mainly medium grained but contains a few beds of fine-grained sandstone and also some beds of shale.

The Menefee Formation consists of shale and interbedded sandstone and thin coal beds. The shale is light to dark gray and usually carbonaceous, containing at places lenses of coal and coaly shale. The sandstone beds are white, gray, buff, and brown lenticular stream-channel deposits of fine to coarse quartz sand.

The La Ventana Tongue of the Cliff House Sandstone consists of gray, buff, and orange-brown sandstone and some interbedded thin gray shale. The lower part of the La Ventana at most places consists of several beds of medium-grained sandstone as much as 30 feet thick. The upper part of the La Ventana at most places consists of thinner tan to orange-brown fine- to medium-grained sandstone with gray shale interbedded.

The lithology, stratigraphic relations, and fossils of the Mesaverde Group indicate that most of it was deposited during a major retreat and readvance of the Cretaceous sea across the region of the present San Juan Basin. The Point Lookout Sandstone was deposited mainly as near-shore marine sand during the retreat of the sea. The Menefee Formation is a terrestrial deposit laid down mainly when the strandline of the sea was north of the area of the present report. The La Ventana Tongue of the Cliff House Sandstone was deposited in a near-shore marine environment as the Cretaceous sea again advanced southwestward across the San Juan Basin.

CONTACTS

The Point Lookout Sandstone is gradational into the underlying Mancos Shale of Late Cretaceous age. This gradation occurs in a thin zone at the base of the Point Lookout where thin tongues of the Point Lookout Sandstone are interbedded with thin tongues of the Mancos Shale. The contact of the Point Lookout and the overlying Menefee Formation is generally sharp but appears to be conformable. The contact of the Menefee Formation and the overlying La Ventana Tongue of the Cliff House Sandstone appears to be gradational, and there may be considerable intertonguing between the units locally.

The contact of the La Ventana and the overlying Lewis Shale of Late Cretaceous age is gradational by intertonguing. The intertonguing relationship made reconnaissance mapping of the contact difficult. The top of the Mesaverde Group was mapped arbitrarily as the top of the highest ledge-forming thick sandstone of the La Ventana Tongue. This arbitrarily assigned contact is not at the same stratigraphic position across the area. At some places, particularly in the southern part of T. 20 N., R. 1 W., thin sandstone beds are intercalated in thick gray shale arbitrarily assigned to the lower part of the Lewis Shale. These sandstone beds thicken to the south and merge into the upper part of the La Ventana as the intervening shale beds wedge out southward. Thus, the top of the La Ventana Tongue becomes stratigraphically higher southward. The upper contact of the Mesaverde Group in the southeastern part of the area, as shown on the geologic map (pl. 1), cuts across lithologic boundaries, and to the south it is slightly higher stratigraphically than in areas farther north.

AGE

According to Reeside (1924, p. 16) the flora and invertebrate faunas of the Mesaverde Group are of Montana age. Thus the age of the Mesaverde is about middle Late Cretaceous.

LEWIS SHALE

DEFINITION

The Lewis Shale of Late Cretaceous age was named by Cross, Spencer, and Purington (1899, p. 4) for exposures near Fort Lewis, Colo., where it lies on the Cliff House Sandstone of the Mesaverde Group. The thick body of gray shale with some interbedded thin fine-grained standstone and nodular limestone beds that rests on the Mesaverde Group throughout the area of the present report was mapped as the Lewis Shale by Renick (1931), Dane (1936), and Wood and Northrop (1946).

EXTENT AND THICKNESS

The Lewis Shale is exposed in a belt adjacent to and west of the Mesaverde Group, and the structural attitudes of both are similar. The Lewis Shale is exposed in a wide area in T. 20 N., R. 1 W., where it is folded on the northwest- plunging San Pablo anticline. The outcrop belt becomes narrower to the north, and in the San Pedro Foothills steeply dipping soft rocks of the Lewis Shale are discontinuously exposed. In the Northern Hogback Belt the Lewis Shale dips steeply west and crops out on low hills rising above alluviated valleys west of the hogback formed by the Mesaverde Group.

Renick (1931, p. 50) measured a section from the top of the Mesaverde to the base of what he classified as the Puerco Formation in secs. 2–4, T. 20 N., R. 1 W.; he gave a thickness of about 1,660 feet for the Lewis Shale. Renick probably included in the upper part of the Lewis Shale rocks which Dane (1936) mapped as the Kirtland Shale, and which the present writer has mapped as the Pictured Cliffs Sandstone of Late Cretaceous age and the undivided Fruitland Formation and Kirtland Shale, also of Late Cretaceous age. The combined thickness of the Pictured Cliffs and the undivided Fruitland and Kirtland is about 170 feet in secs. 8 and 9, T. 20 N., R. 1 W. Thus, the Lewis Shale as mapped by the present writer is about 1,490 feet thick in the southeastern part of the area. The Sun Oil 1 McElvain well drilled in sec. 23, T. 21 N., R. 2 W., penetrated about 1,530 feet of Lewis Shale. Dane (1936, p. 111) estimated that the Lewis is only 550–600 feet thick south of Mesa Piedra Lumbre (Mesa Portales on pl. 1 of the present report). In the southwestern part of the area, the Shell Oil 1 Pool Four well in sec. 22, T. 21 N., R. 5 W., penetrated about 500 feet of sandy shale assigned to the Lewis.

In the north-central part of the area, the Magnolia Petroleum 1 Jicarilla D well in sec. 24, T. 26 N., R. 3 W., penetrated about 1,470 feet of shale assigned to the Lewis. In the northeastern part of the area, the Reading and Bates 1 Duff well in sec. 24, T. 24 N., R. 1 W., penetrated about 1,900 feet of Lewis Shale. From all these figures it is apparent that the Lewis Shale thins from northeast to southwest across the area of the present report. Much of this thinning takes place in a short distance in the subsurface of the southwestern part of the area. The rapid thinning occurs also at the surface south of the area, and both Renick (1931, p. 44–45) and Dane (1936, p. 109–111) recognized that the thinning was largely the result of a facies change. The lower part of the Lewis Shale intertongues with the upper part of the La Ventana Tongue of the Cliff House Sandstone and grades laterally into the upper part of the La Ventana. Thus, as the Lewis becomes thinner to the southwest, the La Ventana becomes thicker by an equivalent amount, both at the surface and in the subsurface.

LITHOLOGY

The Lewis Shale is composed of light- to dark-gray fissile clay shale with a small proportion of interbedded siltstone, fine-grained sandstone, and nodular concretionary limestone. At most places the lower 100 feet, approximately, of the Lewis Shale contains several thin beds of sandstone. Some of these beds can be traced laterally into the La Ventana Tongue of the Cliff House Sandstone.

At places, thin beds of fine-grained sandstone were observed to become calcareous as they were traced northward and to grade laterally into thin highly fossiliferous concretionary limestone beds. In the Northern Hogback Belt a thin concretionary limestone forms a persistent marker bed which crops out on small low ridges rising above the valleys carved in the Lewis. This limestone contains numerous well-preserved shells of ammonites, gastropods, and pelecypods. The stratigraphic position of this marker bed is near the base of the upper one-third of the Lewis Shale. Thin limestone and calcareous siltstone beds occur at other stratigraphic positions also.

In the subsurface of the southwestern part of the area the Lewis Shale is very sandy and silty. There the Lewis is only 500–600 feet thick, and these beds are stratigraphically equivalent to the clay shale of the upper part of the Lewis of the northern part of the area. The stratigraphic interval represented by the upper 800–1,000 feet of the Mesaverde Group in the subsurface of the southwestern part of the area is probably equivalent stratigraphically to the lower 800–1,000 feet of clay shale of the Lewis of the northern part of the area.

The marine invertebrate fossils and the lithology of the Lewis Shale indicate that it was deposited in an offshore marine environment, after the southwestward advance of the Cretaceous sea during which the lower part of the La Ventana Tongue of the Cliff House Sandstone was deposited. Most of the Lewis Shale in the east-central part of the San Juan Basin was deposited at a time when the strandline of the Cretaceous sea was southwest of the present area of investigation.

CONTACTS

The contact of the Lewis Shale and the underlying Mesaverde Group is transitional and intertonguing. The contact of the Lewis Shale and the overlying Pictured Cliffs Sandstone also is transitional and intertonguing. Intertonguing relationships are suggested at the surface in the southeastern part of the area. At the south side of Mesa Portales (in the SE¼ sec. 7, T. 19 N., R. 2 W.) the Pictured Cliffs is about 116 feet thick, whereas in the SW¼ sec. 25, T. 20 N., R. 2 W. (locality 1a, pl. 1), the Pictured Cliffs is about 65 feet thick and contains a few beds of shale (pl. 2). Part of this diminution of thickness is probably the result of intertonguing between the Lewis and the Pictured Cliffs. However, exposures of the base of the Pictured Cliffs are too widely separated to demonstrate the intertonguing by actual tracing of beds. Toward the northeast in the NW¼ sec. 20, T. 20 N., R. 1 W., the lower part of the Pictured Cliffs is represented by only a few thin tongues of sandstone interbedded with thick beds of shale. In this area very thin beds of sandstone in the upper part of the Lewis Shale are probably tongues of the Pictured Cliffs.

Farther north on the outcrop the Lewis Shale is overlain conformably by several beds of fine-grained standstone and interbedded shale that represent the Pictured Cliffs Sandstone (pl. 2). Between sec. 23, T. 21 N., R. 1 W., and sec. 4, T. 25 N., R. 1 E., the zone of sandy shale and shaly sandstone that represents the Pictured Cliffs is included with the undivided Fruitland Formation and Kirtland Shale on the geologic map (pl. 1) because the Pictured Cliffs is too thin to delineate separately at the scale of the map. At outcrops north of sec. 4, T. 25 N., R. 1 E., the rocks equivalent to the Pictured Cliffs become, by lateral gradation a zone of sandy silty shale that is included with the Lewis Shale. Here the Lewis is overlain conformably by soft sandstone of the undivided Fruitland Formation and Kirtland Shale.

In the subsurface of the southwestern part of the area, an intertonguing relationship causes the top of the Lewis Shale to rise stratigraphically to the northeast as the lower part of the Pictured Cliffs tongues out in that direction (pl. 3). Intertonguing between the Lewis Shale and the Pictured Cliffs Sandstone is indicated elsewhere in the subsurface (pls. 4, 5).

AGE

The Lewis Shale contains a fauna equivalent to part of the upper and middle beds of the Pierre Shale of the Great Plains region (Reeside, 1924, p. 18) and is of Late Cretaceous (Montana) age.

PICTURED CLIFFS SANDSTONE

DEFINITION

The Pictured Cliffs Sandstone of Late Cretaceous age was named by Holmes (1877, p. 248). The name was applied to the massive ledges of marine sandstone exposed north of the San Juan River west of Fruitland, N. Mex. Reeside (1924, p. 18) redefined the formation to include the massive sandstone ledges of Holmes and also the sequence of interbedded shale and sandstone beneath them and above the Lewis Shale.

The Pictured Cliffs Sandstone crops out in a nearly continuous narrow band around the north, west, and south sides of the Central basin and has been mapped continuously by other investigators (Bauer, 1916; Reeside, 1924; Dane, 1936) from the type locality into the southern part of the present area of investigation. The

Pictured Cliffs is the stratigraphically lowest formation studied in detail during the present investigation.

EXTENT AND THICKNESS

The Pictured Cliffs Sandstone crops out above the Lewis Shale in the southeastern part of the area, and a zone of thin sandstone, siltstone, and interbedded shale that represents the Pictured Cliffs was traced along the east side of the area as far north as sec. 4, T. 25 N., R. 1 E. The Pictured Cliffs is present in the subsurface of most of the area.

In the southern part of T. 20 N., R. 2 W., the lower part of the Pictured Cliffs forms low, gently sloping benches of rusty-weathering sandstone above the Lewis Shale. The upper part forms steep slopes and cliffs of soft sandstone in the lower part of the erosional escarpment at the east side of Mesa Portales. On the south slope of the butte in the SW¼ sec. 25, T. 20 N., R. 2 W., the exposed part of the Pictured Cliffs is about 65 feet thick (loc. 1a, pls. 1, 2). To the northeast the Pictured Cliffs is covered by alluvium in the valley of the Rio Puerco.

Dane (1936, p. 112; 1946) reported that the Pictured Cliffs Sandstone is not present east of the Rio Puerco. However, the formation is present and recognizable in secs. 17, 19, and 20, T. 20 N., R. 1 W., although its beds are thin and poorly exposed in places. In this part of the area the Pictured Cliffs forms small sloping benches at the foot of the mesa northwest of the broad sloping valley cut in the Lewis Shale by Senorito Creek. In the NW¼ sec. 20, T. 20 N., R. 1 W., the Pictured Cliffs is about 65 feet thick. The upper part consists of ledge-forming sandstone and some interbedded slightly carbonaceous shale, all about 25 feet thick. The lower part is silty shale containing thin beds of concretionary siltstone and sandstone and is about 35 feet thick. Two beds of fine-grained sandstone in the upper part of the Lewis Shale are probably tongues of the Pictured Cliffs.

Northward from sec. 17, T. 20 N., R. 1 W., to about the center of sec. 23, T. 21 N., R. 1 W., the Pictured Cliffs Sandstone is about 45 feet thick and consists of clay shale and interbedded thin rusty-weathering concretionary sandstone and siltstone overlain by soft thin shaly sandstone that is slightly carbonaceous.

In the San Pedro Foothills and in the Northern Hogback Belt, this sequence of shale, concretionary siltstone and sandstone, and overlying soft shaly sandstone is exposed at some places and was found at other places by digging through a thin soil cover. In this region the thickness of the Pictured Cliffs varies but averages about 35 feet. North of sec. 23, T. 21 N., R. 1 W., the Pictured Cliffs dips steeply west or is vertical or overturned slightly, and its outcrop belt is very narrow. For this reason the Pictured Cliffs north of sec. 23, T. 21 N., R. 1 W., was not mapped as a separate unit but was included with the overlying undivided Fruitland Formation and Kirtland Shale, although the Pictured Cliffs is a recognizable unit as far north as sec. 4, T. 25 N., R. 1 E.

In a landslide scar in the NE¼ sec. 4, T. 25 N., R. 1 E., the Pictured Cliffs is about 58 feet thick and consists of sandy or silty shale and several thin beds of silty fine-grained sandstone containing carbonized plant fragments. Here all but the upper few feet of the Pictured Cliffs has graded northward into a unit that is little more than a sandy, silty zone at the top of the Lewis Shale. From this area north the rocks equivalent to the Pictured Cliffs were considered to be part of the Lewis Shale and were mapped with it.

The Pictured Cliffs Sandstone is distributed widely in the subsurface as determined by a study of electric logs of wells drilled for oil and gas. The Pictured Cliffs is about 235 feet thick at the J. D. Hancock 1 Brown well in sec. 33, T. 21 N., R. 5 W. (pl. 3). The thickness diminishes northeastward as the lower part of the Pictured Cliffs wedges out into the upper part of the Lewis Shale, and the Pictured Cliffs is only about 105 feet thick at the Humble Oil and Refining 1 Jicarilla B well in sec. 22, T. 22 N., R. 5 W. Northeastward from this well the thickness increases slightly because of intertonguing with the overlying undivided Fruitland Formation and Kirkland Shale, and then the thickness diminishes gradually because thin sandstone tongues of the Pictured Cliffs wedge out into the upper part of the Lewis, and also because the Pictured Cliffs thins depositionally. At the Magnolia Petroleum 1 Cheney-Federal well in sec. 8, T. 26 N., R. 2 W., a zone of interbedded shaly sandstone, siltstone, and interbedded silty sandy shale about 80 feet thick is correlated with the Pictured Cliffs Sandstone.

In the subsurface of the eastern part of the area, the Pictured Cliffs thins to the northeast, but it persists as a thin unit of sandy silty shale and shaly sandstone as it does in the outcrops (pl. 4). The spontaneous-potential and resistivity curves of the Pictured Cliffs are recognizable but poorly defined on the electric logs of some wells in the east-central part of the area. Cuttings from some of these wells indicate that the Pictured Cliffs is present, and its stratigraphic position was confirmed by correlation of several persistent units in the Lewis Shale that have distinctive electrical characters. In most logs of areas where the Pictured Cliffs contains gas, the spontaneous-potential and resistivity curves are well defined.

The thickness of the Pictured Cliffs Sandstone in the subsurface tends to be most uniform across the area in a north-northwest direction (pl. 5). The formation thins east-northeastward. Because of the exaggerated vertical scale of the correlation diagrams (pls. 3–5), the Pictured Cliffs of the subsurface is shown as a separate unit even where it is thin, and it is not combined with the Fruitland Formation and Kirtland Shale in the diagrams.

LITHOLOGY

The Pictured Cliffs Sandstone is composed of varied proportions of thin- to thick-bedded sandstone, siltstone, and shale. In the subsurface of the southwestern part of the area, the Pictured Cliffs is mainly sandstone but contains beds of siltstone and shale. Northeastward the Pictured Cliffs thins, and as judged from electric logs of wells, the thinning is accompanied by a gradual change from a predominantly sandstone facies to one of thin argillaceous fine-grained sandstone, siltstone, and interbedded shale.

At the surface west of the Rio Puerco in the southeastern part of the area, the Pictured Cliffs is composed mainly of very fine grained to medium-grained sandstone (pl. 2). In the SW¼ sec. 25, T. 20 N., R. 2 W., the lower part of the Pictured Cliffs is mainly soft yellowish-brown to buff sandstone about 15 feet thick. The middle part of the sandstone is tangentially crossbedded and forms rusty-weathering ledges. Above the sandstone is olive-colored soft clay shale, about 5 feet thick, overlain by soft sandstone and interbedded, poorly exposed shale about 10 feet thick. The upper part of the Pictured Cliffs is about 35 feet thick and consists of two beds of fine- to medium-grained slightly micaceous sandstone separated by a 3-foot bed of gray clay shale. The Pictured Cliffs is overlain by soft argillaceous, shaly, carbonaceous to coaly sandstone assigned to the undivided Kirtland Shale and Fruitland Formation.

The upper part of the Pictured Cliffs was traced southwestward outside the area to sec. 7, T. 19 N., R. 2 W. At this locality it is a sandstone, 71 feet thick, which Dane (1936, p. 116) described in a stratigraphic section as being the basal sandstone of the Kirtland Shale (pl. 2). However, the lithology of this sandstone is similar to that of the underlying rocks classified as Pictured Cliffs, and it contains casts of *Ophiomorpha* (formerly called *Halymenites*), indicating its marine origin. Both factors indicate that it is part of the Pictured Cliffs. Here the total thickness of the Pictured Cliffs is about 116 feet.

East of the Rio Puerco in the southeastern part of the area, the sandstone beds of the lower part of the Pictured Cliffs become very thin, fine grained, and somewhat concretionary. The sandstone at the base of the formation in the NW¼ sec. 20, T. 20 N., R. 1 W., is about 2.5 feet thick and, at places, forms brown-weathering concretions. Above the basal sandstone is light- to dark-gray sandy shale, about 35 feet thick, containing thin concretionary siltstone and sandstone beds. The upper part of the Pictured Cliffs is about 22.5 feet thick and consists of two beds of fine- to medium-grained sandstone interbedded with shale. Above the Pictured Cliffs at this locality is a unit of olive-gray carbonaceous very sandy clay shale and thin sandstone containing marine fossils, which is about 15.5 feet thick. These rocks are probably equivalent to the carbonaceous shale and sandstone of the lower part of the Fruitland and Kirtland Formations west of the Rio Puerco.

Many of the beds of the Pictured Cliffs contain lignitized fragments of fossil plants which are scattered through the rock and form very thin mats on bedding planes. This type of carbonaceous material is associated with marine invertebrate fossils and characterizes the Pictured Cliffs at places on the eastern side of the area.

The Pictured Cliffs in the SW¼NW¼ sec. 23, T. 21 N., R. 1 W., has at its base a brown-weathering concretionary calcareous sandy siltstone about 1.5 feet thick. Above this is soft slightly carbonaceous sandy silty shale and interbedded thin lenticular fine-grained sandstone, all about 33.5 feet thick. Above this, the upper part of the Pictured Cliffs is composed of soft fine- to medium-grained sandstone alternating with slightly carbonaceous sandy and silty clay shale containing thin lenses of fine-grained sandstone. The sandstone and sandy shale beds range in thickness from 2.5 to 7 feet, and the total thickness of the upper part of the Pictured Cliffs is about 28 feet. The Pictured Cliffs is overlain by a soft yellowish buff sandstone 14.5 feet thick, which is assigned to the undivided Fruitland Formation and Kirtland Shale.

North of this locality, in the San Pedro Foothills and Northern Hogback Belt, the lithology of rocks representing the Pictured Cliffs (but mapped with the overlying Fruitland and Kirtland) is generally similar to that of the sequence described above. At most places the Pictured Cliffs consists of a lower unit of shale and interbedded thin rusty-weathering concretionary sandstone, 20–25 feet thick, and an upper unit of two or more soft fine-grained shaly sandstones whose combined thickness is 15–20 feet. The proportion of shale increases northward, and in sec. 4, T. 25 N., R. 1 E., the Pictured Cliffs consist mainly of shale that contains several thin beds of siltstone and fine-grained sandstone.

North of that area this unit of silty sandy shale was mapped as part of the Lewis Shale.

The lithology and marine fossils of the Pictured Cliffs Sandstone indicate that these rocks were deposited in littoral and offshore marine environments at a time when the shoreline of the Cretaceous sea was retreating northeastward across part of the area investigated. At places in the San Pedro Foothills, notably at the outcrops in sec. 23, T. 21 N., R. 1 W., part of the Pictured Cliffs consists of thin highly lenticular bodies of fine-grained sandstone interbedded with carbonaceous siltstone and clay shale containing abundant lignitized plant fragments. The lenticular sandstone bodies range in thickness from less than 1 inch to as much as 7 feet. The lateral extent of the lenses varies from a few inches to hundreds of feet, but many of the lenses are only a few inches to a few feet in length. The lithology of these rocks is strikingly similar to the lithology of sediments presently accumulating on extensive tidal flats at the edge of the North Sea in northern Germany. These sediments were described and illustrated with a core by Hantzschel (1939, p. 197–203). According to Hantzschel, the tidal mud consists of soft unctuous water-soaked slime that is composed mainly of fine silt and clay containing a small amount of sand and shell fragments of various invertebrates. Fine plant detritus also is present, and excrement of marine organisms gives the mud its unctuous quality. The North Sea tidal-flat deposits are stratified, with intercalations of thin layers of fine sand in the argillaceous substance. The bedding is seldom strictly parallel but is streaky and lenticular. The alternating layers wedge out rapidly, and their thickness is not uniform. The irregular bedding is caused by frequent reworking of the sediments by tidal and wind-driven currents of varying strength and direction.

The similarity of the North Sea tidal-flat sediments and the lenticular sandstone and carbonaceous shale of the Pictured Cliffs in the San Pedro Foothills may indicate that part of the region of the Nacimiento uplift was slightly emergent or was a shoal area during deposition of the Pictured Cliffs. No evidence was found to indicate that the region of the Nacimiento uplift contributed much if any sediment to the Pictured Cliffs sea. Most of the sediment of the Pictured Cliffs Sandstone in this part of the basin was probably derived from the region southwest and west of the San Juan Basin.

The Pictured Cliffs crops out continuously around the southern, western, and northern margins of the Central basin (fig. 5). However, Dane (1946) found that the outcropping Pictured Cliffs of the northern part of the basin grades southward into the Lewis Shale along the eastern margin of the Central basin. This gradation is similar (but opposite in direction) to the northward gradation of the Pictured Cliffs into the Lewis Shale that occurs in the area of the present report, as was recognized earlier by Dane (1946). Thus, at outcrops along much of the east-central margin of the basin, from the northern edge of T. 25 N., R. 1 E., to the southern edge of T. 31 N., R. 1 W., the Pictured Cliffs is not present. In this area the stratigraphic interval of the Pictured Cliffs is occupied by silty, sandy upper beds of the Lewis Shale. Subsurface data from other parts of the basin indicate that the silty, sandy upper part of the Lewis Shale that is equivalent to the Pictured Cliffs persists northwestward across the structurally deepest part of the Central basin nearly to the northwestern edge in Colorado. This body of shale divides the Pictured Cliffs into southwest and northeast lobes which merge in the northwestern part of the Central basin near the outcrops on the Hogback monocline southwest of Durango, Colo. Thus, the Pictured Cliffs is a horseshoe-shaped body of sand that is open to the southeast (fig. 7). It should be pointed out here that the southwest and northeast lobes of the Pictured Cliffs, as used in this report, are not quite the same as the two lobes described by Silver (1950, fig. 4 and p. 112). Part of the subsurface northeast lobe of Silver is probably equivalent to southwestward-thinning sandstone beds included in the undivided Fruitland Formation and Kirtland Shale by the present writer. This is explained in a later section of this report.

The distribution and the directions of gradation into shale of the lobes of the Pictured Cliffs seem to indicate that during Montana time, highlands had risen north and northeast of the San Juan Basin, and that the Pictured Cliffs was deposited in a restricted northwest-trending embayment of the Cretaceous sea (fig. 7). Sediments of the northeast lobe of the Pictured Cliffs probably were derived from areas north and northeast of the basin (Dane, 1946), whereas sediments of the southwest lobe were derived from source areas to the southwest.

CONTACTS

The Pictured Cliffs Sandstone rests conformably on the Lewis Shale and intertongues with it. At the surface west of the Rio Puerco in the southeastern part of the area, the Pictured Cliffs is overlain conformably by carbonaceous to coaly shale and thin sandstone and siltstone, which are the basal parts of the undivided Fruitland Formation and Kirtland Shale. Also, at many places north of sec. 20, T. 24 N., R. 1 E., the Pictured Cliffs is overlain conformably by sandy carbonaceous shale containing silicified wood and thin

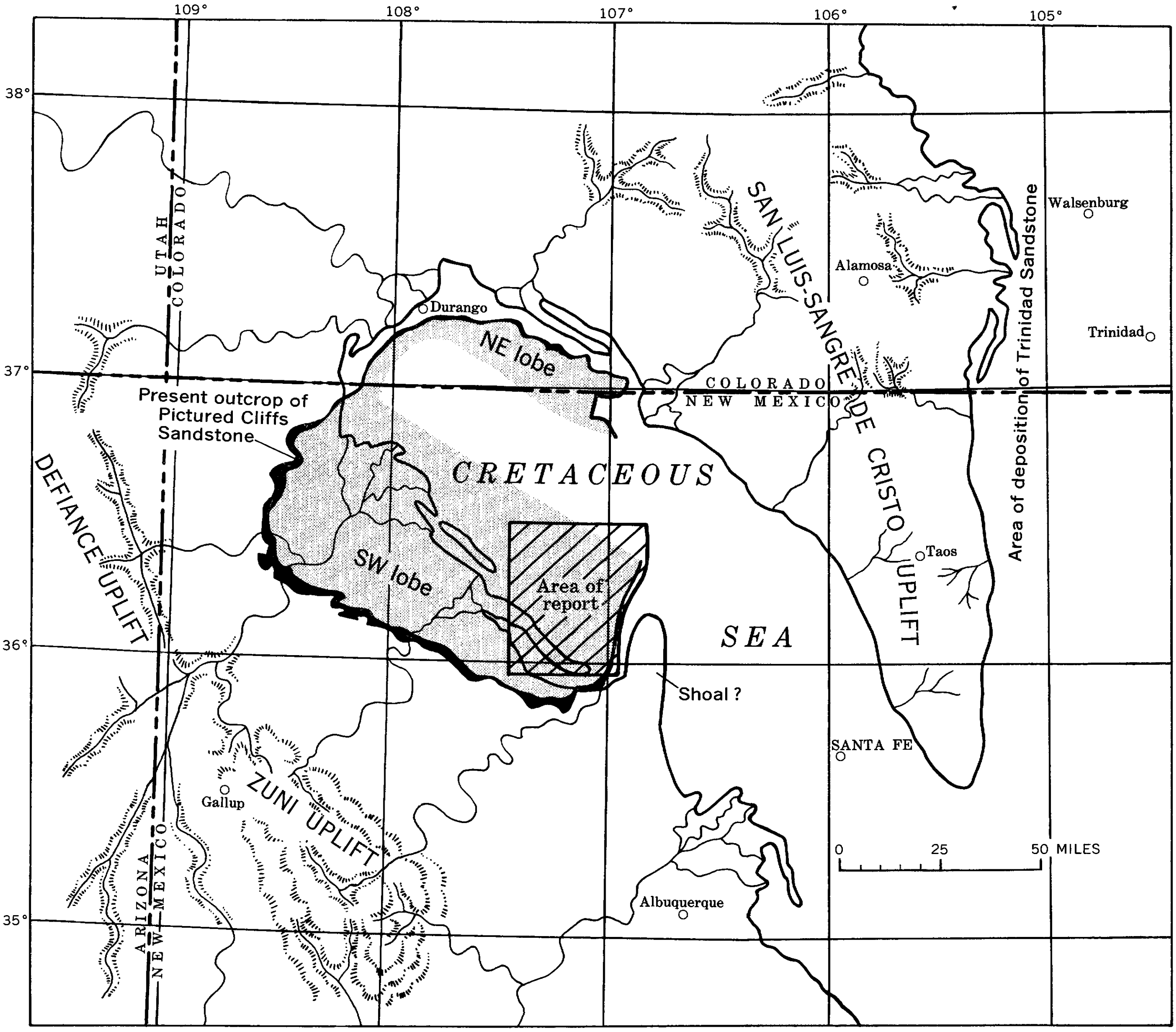


FIGURE 7.—Probable paleogeography of parts of northern New Mexico and southern Colorado during late stage of deposition of Pictured Cliffs Sandstone. Present subsurface distribution of Pictured Cliffs shown by stippled pattern. Fruitland Formation was deposited in coastal swamps and flood plains contemporaneously with deposition of the Pictured Cliffs in littoral and offshore areas.

rusty-weathering siltstone and fine-grained sandstone (pl. 6). These beds, 15–30 feet thick, are probably equivalent to shaly carbonaceous to coaly beds above the Pictured Cliffs in the subsurface, and to the soft carbonaceous shale and sandstone of the Fruitland and Kirtland at the surface west of the Rio Puerco. These carbonaceous shale beds seem to be absent at most places where the Fruitland and Kirtland are exposed in the San Pedro Foothills. At many of these places, the Pictured Cliffs is overlain with slight erosional unconformity by thin to thick coarse-grained sandstone whose stratigraphic position in the Fruitland and Kirtland is higher than the carbonaceous shale. Locally, the upper part of the Pictured Cliffs is thin or absent. These relations appear to be the result of local unconformity caused by scouring or channeling; they seem to indicate that slight uplift or folding occurred in the San Pedro Mountain area not long after deposition of the oldest beds of the Fruitland and Kirtland.

In the subsurface the Pictured Cliffs is overlain conformably by interbedded shale, coal, thin sandstone, and siltstone which are the lower part of the undivided Fruitland Formation and Kirtland Shale. Correlations of electric logs indicate that the Pictured Cliffs intertongues with the Fruitland and Kirtland (pls. 3–5). The northeastward stratigraphic rise of the top of the Pictured Cliffs as the result of intertonguing seems to be confirmed by comparison of the position of the top of the Pictured Cliffs with the position of persistent electric-log "marker" units in the upper part of the Lewis Shale.

AGE

According to Reeside (1924, p. 19), the Pictured Cliffs in the western part of the Central basin contains a littoral marine fauna of late Montana (Late Cretaceous) age. Fossils collected from the Pictured Cliffs south of the present area of investigation also were considered to be Montana age by Reeside (Dane, 1936, p. 112). The Pictured Cliffs is a homotaxial equivalent of the Trinidad Sandstone of Late Cretaceous age in the Raton basin of northeastern New Mexico and southeastern Colorado, although the southwestern lobe of the Pictured Cliffs probably is mainly older than the Trinidad. Similarly, the Pictured Cliffs is a homotaxial equivalent of the Fox Hills Sandstone of Late Cretaceous age in the Central Rocky Mountains and Great Plains. However, the Fox Hills was deposited as the Cretaceous sea retreated across areas far to the northeast of the San Juan Basin, and thus is younger than the Pictured Cliffs.

FRUITLAND FORMATION AND KIRTLAND SHALE UNDIVIDED

DEFINITION

A thin but stratigraphically complex sequence of shale, coal, siltstone, and fine- to coarse-grained sandstone lies on the Pictured Cliffs Sandstone in the area of the present report. Gardner (1909, pl. 1) and Renick (1931) apparently included part of these rocks with the underlying Lewis Shale and part with the overlying rocks assigned by them to the Puerco Formation. Dane (1936, p. 112) found that the sequence of shale, siltstone, and sandstone is equivalent to rocks mapped on the western side of the Central basin by Bauer (1916), Bauer and Reeside (1921), and Reeside (1924) as the Fruitland Formation and the overlying Kirtland Shale, both of Late Cretaceous age. The Fruitland Formation, which lies conformably on the Pictured Cliffs Sandstone, consists of varied proportions of interbedded sandstone, shale, and coal. The formation was named by Bauer (1916, p. 274) for exposures along the San Juan River near Fruitland, N. Mex.

The Kirtland Shale, which lies on the Fruitland Formation, consists of varied proportions of sandstone and shale similar to the Fruitland Formation but containing little or no coal. The Kirtland Shale was named by Bauer (1916, p. 274) for exposures along the San Juan River between Kirtland and Farmington, N. Mex. Bauer differentiated and mapped a sequence of lenticular sandstones and interbedded shale within the Kirtland as the Farmington Sandstone Member. Reeside (1924, p. 21–22) applied the terms "lower shale member" and "upper shale member" to the parts of the Kirtland below and above the Farmington Sandstone. A sequence consisting of a thin locally conglomeratic basal sandstone and overlying variegated shale and soft sandstone, that lies on the upper shale member in the southwestern part of the basin was named the Naashoibito Member of the Kirtland by Baltz, Ash, and Anderson (1966, p. D–10).

Dane (1936) mapped the Fruitland and Kirtland from the area mapped by Reeside (1924) across the southern part of the Central basin and into the southern part of the present area of investigation. East of sec. 7, T. 19 N., R. 2 W., Dane (1936, p. 115, and pl. 39) combined the two formations and mapped them as the Kirtland Shale, because the basis for distinguishing the two formations becomes less evident eastward. However, because equivalents of both the Fruitland Formation and the Kirtland Shale occur in the present area of investigation, the rocks mapped as Kirtland Shale by Dane (1936) are designated in the present report as the undivided Fruitland Formation and Kirtland Shale.

EXTENT AND THICKNESS

The undivided Fruitland Formation and Kirtland Shale are present throughout the area. The Fruitland and Kirtland crop out in the southwestern and southern parts of the area, where they form low rounded hills and benches and steep slopes beneath cuestas capped by the overlying Ojo Alamo Sandstone of Paleocene age. West of the area, in T. 20 N., R. 6 W., the combined thickness of the Fruitland and Kirtland was estimated to be slightly less than 600 feet (Dane, 1936, p. 114). The sequence thins eastward; in the NW¼ sec. 25 and NE¼ sec. 26, T. 20 N., R. 2 W., the two formations are about 243 feet thick, and in the NE¼ sec. 22 and NW¼ sec. 23, T. 21 N., R. 1 W., they are about 85 feet thick (pls. 2, 6).

Dane (1936) mapped the combined formations as the Kirtland Shale from T. 19 N., R. 2 W., into T. 21 N., R. 1 W. Laterally equivalent beds from there northward were reported by Dane (1946) to be included in the Lewis Shale as far north as the southern part of T. 25 N., R. 1 E. However, detailed examination and mapping of outcrops in the San Pedro Foothills and Northern Hogback Belt by the present writer indicate that, throughout this area, the undivided Fruitland Formation and Kirtland Shale form a persistent lithologic unit which can be differentiated from the underlying

Lewis Shale and the overlying Ojo Alamo Sandstone. As previously stated, thin beds of the Pictured Cliffs Sandstone north of sec. 23, T. 21 N., R. 1 W. were mapped with the Fruitland and Kirtland by the present writer. North of sec. 4, T. 25 N., R. 1 E., the thin silty, shaly beds equivalent to the Pictured Cliffs were mapped with the Lewis Shale.

In the San Pedro Foothills the Fruitland and Kirtland dip very steeply west, or locally are vertical or overturned slightly, and form a narrow, discontinously exposed belt of soft rounded sandstone ledges with intervening thin to thick beds of soft dark-gray and olive-green shale and some carbonaceous shale. In the Northern Hogback Belt the sequence dips steeply west and forms low ridges and slopes west of the slopes and valleys cut in the Lewis Shale. The thickness of the sequence is varied because of slight angular discordance and erosional unconformity with the overlying Ojo Alamo Sandstone; probably there is also an unconformity within the map unit (pl. 6). In the NW¼SE¼ sec. 11, T. 21 N., R. 1 W., the sequence is about 128 feet thick, including at the base 27 feet of sandstone and shale equivalent to the Pictured Cliffs Sandstone. On the north side of San Jose Creek in the SW¼NE¼ sec. 34, T. 23 N., R. 1 W., the sequence is about 220 feet thick, including about 31 feet of sandstone and shale equivalent to the Pictured Cliffs. South of Almagre Arroyo in the NE¼ sec. 2, T. 23 N., R. 1 W., the sequence is about 84 feet thick, including 33 feet of poorly exposed sandstone and shale equivalent to the Pictured Cliffs.

North of sec. 20, T. 24 N., R. 1 E., the undivided Fruitland and Kirtland thicken, and near the center of sec. 8, T. 24 N., R. 1 E., they are about 200 feet thick, including 46 feet of poorly exposed sandstone and shale equivalent to the Pictured Cliffs. North of here the sequence alternately thickens and thins. It is about 280–300 feet thick, including 35 feet of poorly exposed beds equivalent to the Pictured Cliffs, in the NE¼NW¼ sec. 29 and NE¼ sec. 17, T. 25 N., R. 1 E. Farther north in T. 26 N., R. 1 E., the sequence is less than half this thickness, because upper beds are cut out by an unconformity at the base of the overlying Ojo Alamo Sandstone.

In the subsurface east of the Continental Divide, the thickness of the undivided Fruitland Formation and Kirtland Shale varies as it does in the outcrops. In the subsurface west of the divide, the sequence thickens irregularly westward. In the northwestern part of the area, it is about 450 feet thick at the Northwest Production 1–7 Jicarilla 152 well in sec. 7, T. 26 N., R. 5 W. (pl. 5). In the subsurface of the southwestern part of the area, the sequence is 300–400 feet thick (pl. 3).

The rocks of the undivided Fruitland Formation and Kirtland Shale consist of varied proportions of dark- to light-gray and olive-green clay shale, bentonitic clay, sandy shale and siltstone, and interbedded white, buff, brown, and greenish-gray fine-grained to very coarse grained sandstone. Carbonaceous to coaly shale is present, and coal beds are common in the lower part of the sequence in the subsurface of much of the area. There are a few coal beds at the surface in the southern part of the area. The sequence consists of two distinguishable lithologic units, called A and B in this report (fig. 8, and pls. 2–6). These units correlate generally with parts of the Fruitland Formation and the Kirtland Shale as mapped by Dane (1936) southwest of the area of the present report. Because the stratigraphy of these rocks is complex, the units are described in considerable detail in the following pages.

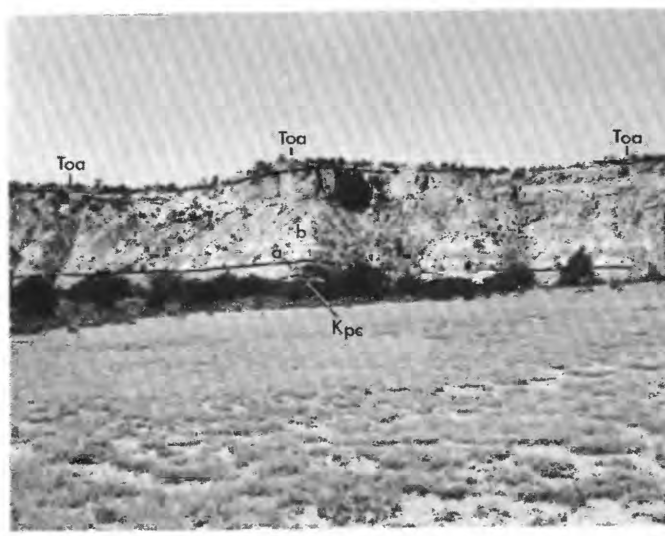


FIGURE 8.—Undivided Fruitland Formation and Kirtland Shale capped by Ojo Alamo Sandstone, east side of Mesa Portales, SW¼ sec. 35, T. 20 N., R. 2 W. Gentle slope in foreground is alluvium on Lewis Shale. Kpc, Pictured Cliffs Sandstone; a, unit A of Fruitland and Kirtland; b, unit B of Fruitland and Kirtland; Toa, Ojo Alamo Sandstone. Note the thickening of the upper sandstone of unit B near the center of the photograph. South (left) of the photograph the ledge-forming sandstones of the upper part of unit B wedge out into shale. (See pl. 6.)

LITHOLOGY

UNIT A

The lower unit, which is equivalent to part of the Fruitland Formation, is here called unit A. In most of the area unit A is easily distinguished from the underlying Pictured Cliffs Sandstone because the lower beds of unit A at most places consist of dark-gray carbonaceous shale or coaly material. The Pictured Cliffs locally contains slightly carbonaceous shale and lignitized plant fragments, but these rocks are not as carbonaceous as the lower beds of unit A. At outcrops along the entire eastern margin of the area, unit A is overlain by fine-grained to very coarse grained locally conglomeratic sandstone which is the basal part of unit B. This sandstone forms the soft light-colored bluffs at the base of unit B shown in figure 8.

At the surface in the southeastern part of the area, unit A consists of dark-gray carbonaceous silty clay shale with interbedded thin sandstone and siltstone and a few thin lenses and persistent beds of impure coal near the base. Unit A is a little more than 50 feet thick in the stratigraphic section measured by Dane (1936, p. 116, beds 3–12 from the base) in the SE¼ sec. 7, T. 19 N., R. 2 W. (pls. 2, 6). On the outlying butte in the SW¼ sec. 25, T. 20 N., R. 2 W., unit A is about 28 feet thick. In the NW¼ sec. 20, T. 20 N., R. 1 W., unit A is about 15.5 feet thick. Here it consists of lower beds of sandy gray clay, carbonaceous shale, and thin sandstone, and an upper bed of carbonaceous sandy shale that contains marine pelecypods and *Ophiomorpha.*

In the San Pedro Foothills, unit A is present but thin at some places and absent at other places (pl. 6). The unit is composed of sandy silty gray shale, carbonaceous shale, and interbedded thin sandstone. In the SW¼ NE¼ sec. 27, T. 23 N., R. 1 W., beds of unit A are exposed on a low hill in the valley. Here unit A includes a thin bed of concretionary-weathering fine-grained sandstone that contains the marine pelecypod *Inoceramus* sp. This sandstone probably correlates with thick sandstone in unit A farther north. Similar thin rounded-weathering buff fine-grained sandstone beds interbedded in slightly carbonaceous shale are present at outcrops on the abandoned Gallina highway in the center of sec. 22, T. 23 N., R. 1 W., where unit A is a little more than 60 feet thick and rests on soft sandstone and sandy shale equivalent to the Pictured Cliffs Sandstone (but mapped with the Fruitland and Kirtland).

Farther north, in the Northern Hogback Belt, unit A is thinner than this at most places, but it thickens locally in the NE¼ sec. 36, T. 24 N., R. 1 W., where it contains a thin fine-grained sandstone. The unit thins to 10–30 feet in secs. 29 and 30, T. 24 N., R. 1 E. In this vicinity it is represented mostly by soft yellowish fine-to medium-grained sandstone underlain by ironstone-bearing dark-gray carbonaceous shale that rests on rocks equivalent to the Pictured Cliffs Sandstone. The sandstone is overlain unconformably at many places by coarse-grained sandstone of unit B.

North of the center of sec. 20, T. 24 N., R. 1 E., unit A thickens. At the center of sec. 8, T. 24 N., R. 1 E., it is about 200 feet thick. The lower part of unit A consists of silty olive-gray shale about 25 feet thick, and the overlying sandstone, which forms rusty-weathering ledges, has thickened to about 60 feet. The upper part of unit A is covered. Farther north, in T. 25 N., R. 1 E., unit A is thinner, and the sandstone is overlain by coarse-grained sandstone of unit B.

In the NW¼ sec. 29, T. 25 N., R. 1 E., unit A is about 128 feet thick. Here it consists of beds of silty shale overlain by the thick sandstone, which is poorly exposed but is probably about 60 feet thick. The upper part of the sandstone has an olive-green cast and weathers to rusty ledges that crop out about a quarter of a mile northeast of Llaves Post Office. The sandstone contains some coarse grains and contains casts of *Ophiomorpha.* This marine sandstone is overlain by dark-gray to olive-green carbonaceous shale overlain in turn by coarse-grained sandstone of unit B. The rocks of unit A at this locality were considered by Dane (1946, strat. section 7) to be in the upper part of the Lewis Shale, but they are assigned here to the lower part of the undivided Fruitland and Kirtland.

The stratigraphic sequence of unit A is about the same at exposures on the ridge in the SE¼NE¼ sec. 17, T. 25 N., R. 1 E., where there are two thick beds of sandstone separated by a bed of silty shale. The sandstone weathers brown to light olive and contains *Ophiomorpha.* The total thickness of the two sandstone beds and included shale is about 85 feet. The sandstones are overlain by olive-green and gray shale with thin interbedded sandstone. Some of the sandstone is coarse grained. This upper shaly part of unit A is about 86 feet thick and is overlain by a hard-ledge-forming light-tan sandstone at the base of unit B. The thin sandstones in the upper shale of unit A thicken rapidly to the north from the point of measurement, and within a few hundred feet, most of the upper 86 feet of unit A consists of massive ledge-forming medium- to coarse-grained cross-bedded sandstone (pls. 2, 6). This sandstone, and the overlying hard, ledge-forming sandstone of unit B, were included by Dane (1946, strat. section 8) in the lower part of the Animas Formation of Late Cretaceous and Paleocene age.

The sandstone of the upper part of unit A and the basal sandstone of unit B, combined, form a prominent ledge, 60–100 feet thick, as far north as the center of sec. 4, T. 25 N., R. 1 E., where shale of the upper part of unit B is cut out by the Ojo Alamo Sandstone, which then rests uncomformably on the sandstone beds of units A and B. From here north to the northern edge of the area, the massive sandstone on the cuestas above the Lewis Shale is composed of combined sandstone beds of the upper part of unit A, the lower part of unit B, and the Ojo Alamo.

The *Ophiomorpha*-bearing marine sandstone of the lower part of unit A is concealed or very poorly exposed for almost 2 miles north of sec. 17, T. 25 N., R. 1 E. In the NW¼NE¼ sec. 4, T. 25 N., R. 1 E., the upper part of the Lewis Shale and the overlying cliff-forming sandstones are well exposed in a landslide scar (fig. 9). Here beds equivalent to the Pictured Cliffs Sandstone are represented by several very thin sandstone beds intercalated with thick shale. Above this is a slope-forming greenish-gray soft silty shaly sandstone about 35 feet thick, which is probably the lower *Ophiomorpha*-bearing sandstone. This is overlain by sandy clay shale about 20 feet thick, in turn overlain by a bed of fine-grained sandstone 3.5 feet thick, which may be part of the upper *Ophiomorpha*-bearing sandstone. These beds are overlain by coarse-grained sandstone of the upper part of unit A, which seems to rest on the marine sandstone with slight erosional unconformity at this place. The soft sandy beds of the lower part of unit A were traced by their greenish color along the base of the overlying cliff-forming sandstones to the north edge of the area.

UNIT B

A sequence of rocks that is equivalent to the upper part of the Fruitland Formation and is probably equivalent to part of the Kirtland Shale rests on unit A at outcrops in the eastern part of the area. This sequence of rocks is here informally called unit B of the undivided Fruitland Formation and Kirtland Shale. The basal part of unit B is a fine-grained to very coarse grained sandstone, usually light yellowish gray or buff, and crossbedded, which contains at places large masses of gray and white silicified wood. This basal sandstone is composed mainly of angular to well-rounded quartz sand and granules, but at most places it also contains grains of weathered pink and white feldspar and fragments of pink and green rock. Locally, the sandstone contains small rounded gray, white, and red siliceous pebbles. At places the sandstone is slightly argillaceous and weathers to smooth rounded ledges or bluffs (fig. 8). However, at other places the lower part, or the entire sandstone, has hard siliceous cement and forms resistant ledges and ribs (fig. 4). The thickness of the sandstone varies considerably, ranging from only a few feet to as much as 75 feet. The basal sandstone of unit B seems to be mainly a series of overlapping or coalescing stream deposits that rest with slight erosional and, possibly, angular unconformity on older rocks at outcrops in the eastern part of the area (pl. 6).

Above the basal sandstone, the rocks of unit B consist mainly of light- to dark-gray, olive-green, and olive-gray shale with lesser amounts of interbedded white, buff, and yellow fine-grained to very coarse grained lenticular sandstone. Much of the clay is silty and sandy, and the sandstone and clay beds intergrade both vertically and horizontally. Some of the clay beds weather to purplish or reddish streaks. Gray bentonitic clay is common, particularly in the beds immediately above the basal sandstone. The swelling of this clay during weathering causes the characteristic hummocky, cracked, and fissured outcrops of parts of unit B. The aspect of the somber shale and sandstone of unit B (fig. 8) is similar to that of the lower part of the Nacimiento Formation in the southern and southeastern parts of the area. In the southeastern and southern parts of the area the upper part of unit B contains thick lenticular beds of ledge-forming fine- to coarse-grained sandstone interbedded in dark-gray, olive-green, and purplish-weathering shale (fig. 8). Some of these sandstone beds are similar in lithology and topographic expression to the Ojo Alamo Sandstone, which rests uncomformably on unit B, but they are generally more evenly bedded and finer grained than the Ojo Alamo, and they grade laterally into shale. Unit B varies in thickness because of an erosional surface at the top of the unit (pl. 6).

At the south side of Mesa Portales, south of the area of the present report, in the section measured by Dane (1936, p. 116) in the SE¼ sec. 7, T. 19 N., R. 2 W. (pl. 2), the upper 143 feet of beds assigned to the Kirtland Shale by Dane is correlated with unit B. The ledge-forming sandstone assigned to the Ojo Alamo in this section by Dane wedges out into shale of unit B east and west of the locality of Dane's section. This sandstone and the overlying shale beds are about 75 feet thick, and they are assigned to the upper part of unit B by the present writer. Thus, unit B is about 218 feet thick at the south side of Mesa Portales. Unit B is overlain with erosional unconformity by the persistent Ojo Alamo Sandstone, which is more than 50 feet thick and caps Mesa Portales.

Farther west, in the southern part of the area, resistant standstones in the upper part of unit B are present at many places. The individual sandstones are lenticular, and they wedge out laterally along the outcrop into shale, but the zone of resistant sandstones and interbedded shale is persistent across the southern part of the area beneath the Ojo Alamo Sandstone. In the physiographically dissected mesas in the southern part of the area many of the individual sandstones of the upper part of unit B are stream-laid deposits that are lenticular in cross section but are persistent in a generally northwest direction.

In a composite section measured on the outlying butte in the SW¼ sec. 25 and on the topographic spur in the NW¼ sec. 25 and NE¼ sec. 26, T. 20 N., R. 2 W., unit B is about 215 feet thick (pl. 2). The basal sandstone, about 20 feet thick, consists of fine- to coarse-grained pebble-bearing crossbedded sandstone containing silicified wood. The lower part of the sandstone is silicified and resistant. Above this, the middle part of unit B consists of soft white sandstone and dark-gray to olive-gray bentonitic shale with some soft sandstone interbedded. In the NE¼ sec. 26, T. 20 N., R. 2 W., the ledge-forming sandstones and interbedded shales of the upper part of unit B are well exposed on an eastward-projecting spur of Mesa Portales. Two resistant sandstones separated by shale cap two prominent topographic benches. The upper sandstone is overlain by slope-forming shale which is overlain with erosional unconformity by the Ojo Alamo Sandstone. On the spur the sandstones and shales of the upper part of unit B are about 90 feet thick. On the south side of the spur the lower sandstone wedges out and the upper sandstone becomes very thin, but the upper sandstone thickens again farther south on the east side of Mesa Portales. Lenses equivalent to the lower sandstone also are present farther south. Although the ledge-forming sandstones of the upper part of unit B are persistent for considerable distances on the east side of Mesa Portales, they are erratic in thickness, and locally they grade laterally into shale. At several places on the east face of Mesa Portales—notably in the NE¼NW¼ and the SW¼ sec. 35, T. 20 N., R. 2 W. (fig. 8)—the upper sandstone thickens abruptly, because of channeling at its base. This sandstone wedges out southward into shale near the southeast edge of the mesa (pl. 6).

East of Rio Puerco in the northwest part of T. 20 N., R. 1 W., and southeast part of T. 21 N., R. 1 W., the lithology of unit B is similar to that described above. The unit thins from about 187 feet in the NW¼ sec. 20, T. 20 N., R. 1 W., to about 130 feet in the NE¼ sec. 8 and NW¼ sec. 9, T. 20 N., R. 1 W., and to about 85 feet in the NE¼ sec. 22, T. 21 N., R. 1 W. The basal sandstone ranges from about 12 feet to nearly 30 feet in thickness and from fine grained to very coarse grained. Here, and in the San Pedro Foothills, most of the underlying unit A seems to be missing, probably because of erosion prior to deposition of unit B. North and northeast of Mesa Portales, on both sides of the Rio Puerco, the two ledge-forming sandstone beds of the upper part of unit B form topographic benches below the Ojo Alamo. In the NW¼ sec. 20, T. 20 N., R. 1 W., the lower sandstone is about 40 feet thick, but its thickness varies considerably along the outcrop because its base is a channeled erosion surface. The lower sandstone is overlain by shale and soft sandstone almost 55 feet thick. The upper sandstone is about 25 feet thick and locally forms a ledge beneath the Ojo Alamo. The thickness of the upper sandstone varies considerably because locally it grades laterally into shale. At some places the upper sandstone is overlain by olive-gray shale, but at other places the shale is cut out by an erosional surface at the base of the Ojo Alamo. The ledge-forming sandstones of the upper part of unit B are truncated by the Ojo Alamo Sandstone in the eastern part of sec. 8, T. 20 N., R. 1 W., where the total thickness of unit B is about 130 feet, in contrast with a thickness of 215 feet west of the Rio Puerco (pl. 6).

In the San Pedro Foothills unit B is discontinuously exposed, but it seems to be continuously distributed. The basal sandstone and the gray bentonitic shales and overlying olive-gray sandy shales are exposed in many places. Ridge-forming sandstone in the upper part of unit B is exposed on the north side of the valley of upper San Jose Creek in sec. 34, T. 23 N., R. 1 W. The thickness of unit B ranges from about 98 feet near the center of sec. 11, T. 21 N., R. 1 W., to about 188 feet in the SW¼SE¼ sec. 34, T. 23 N., R. 1 W. Unit B is overlain unconformably by the Ojo Alamo Sandstone in the San Pedro Foothills and in the Northern Hogback Belt.

In the Northern Hogback Belt, unit B is relatively thin as far north as the southern part of T. 24 N., R. 1 E. In exposures on the abandoned Gallina highway near the center of sec. 22, T. 23 N., R. 1 W., unit B rests on rocks assigned to unit A. The basal sandstone of unit B is tentatively identified as the crossbedded sandstone that is about 43 feet thick and lies about 95 feet above the top of the Lewis Shale. Above this is olive-green to olive-gray shale about 31 feet thick, which in turn is overlain by poorly exposed sandstone more than 3 feet thick. The upper part of unit B is concealed, as is the Ojo Alamo Sandstone. Mr. R. L. Reed reported that a water well penetrated coarse conglomeratic sandstone about where the Ojo Alamo should be expected beneath the alluvium in the valley southwest of the exposures of the Fruitland and Kirtland. Poor exposures of soft coarse sandstone assigned to Ojo Alamo were observed at the edge of a small alluviated valley north of the abandoned Gallina highway.

Near the corner common to secs. 10, 11, and 15, T. 23 N., R. 1 W., the basal sandstone of unit B forms a prominent, nearly vertical hogback or rib rising above the valley (fig. 4). This is a white sandstone composed of crossbedded well-cemented fine to coarse sand, containing numerous silicified logs. The basal sandstone of unit B at this locality is strikingly similar to the basal sandstone in sec. 25, T. 20 N., R. 1 W. It is apparently a stream-channel deposit, thickest (about 40 ft) in the SW¼ sec. 11, and it rests unconformably on a thin remnant of unit A. This sandstone was assigned to the Ojo Alamo by Dane (1946, strat. section 2); however, the present writer found that the sandstone is overlain by gray shale and interbedded sandstone similar to unit B farther south. On the lower slope of the hill west of the rib, soft coarse-grained conglomeratic sandstone assigned in this report to the Ojo Alamo is poorly exposed.

The Fruitland and Kirtland and the overlying Ojo Alamo Sandstone are well exposed along the ridge in sec. 2, T. 23 N., R. 1 W. In the NE¼ sec. 2, unit B is a little more than 60 feet thick. The basal sandstone forms a low ridge of fine- to coarse-grained sandstone about 9 feet thick. This is overlain by light- to dark-gray and olive-green silty clay shale and bentonitic shale containing lenticular sandstone, all about 42 feet thick. The shale of unit B is overlain by medium- to coarse-grained ledge-forming sandstone containing lenses of pebble conglomerate at the base. This conglomeratic sandstone, about 94 feet thick, is assigned to the Ojo Alamo. To the north in sec. 36, T. 24 N., R. 1 W., near the south end of the long ridge north of Almagre Arroyo, the Fruitland, Kirtland, and Ojo Alamo sequence is similar to that described above.

At exposures in the SE¼NW¼ sec. 30, T. 24 N., R. 1 E., south of a ranchhouse, the basal sandstone of unit B is tentatively identified as a hard brown-weathering sandstone 3 feet thick, which rests unconformably on an irregular surface cut in the softer sandstone of unit A. The beds overlying the hard sandstone are poorly exposed dark-gray sandy clay shale about 30 feet thick. These beds are overlain by poorly exposed pebble-bearing sandstone of the Ojo Alamo.

On the ridge in secs. 20 and 17, T. 24 N., R. 1 E., a poorly exposed pebble-bearing coarse-grained sandstone containing silicified wood is probably the basal sandstone of unit B. In the center of sec. 20 this sandstone seems to be resting on fine- to medium-grained soft sandstone of unit A, but exposures are too poor to be certain. To the north, in sec. 17, unit A thickens, and the basal sandstone of unit B rests on shale and interbedded sandstone of the upper part of unit A. Possibly, the sandstone here called the basal sandstone of unit B is a part of the Ojo Alamo, but the basal sandstone is overlain by gray sandy shale, which is in turn overlain by a thick soft sandstone assigned to the Ojo Alamo which crops out sporadically. Conclusions drawn from the poor and discontinuous outcrops are not certain, but the relations as described seem to be correct.

Near the center of sec. 8, T. 24 N., R. 1 E., a ledge-forming light-yellowish-gray medium-grained sandstone that contains silicified wood probably is the basal sandstone of unit B. It is about 74 feet thick. The upper part of this sandstone is poorly exposed and overlying beds are concealed at the point of measurement. However, the area immediately west of this sandstone is a low, rounded hill, which is probably underlain by the Ojo Alamo Sandstone. The exposed thick sandstone assigned to unit B seems to correlate with a westward-thinning sandstone beneath the Ojo Alamo in the subsurface farther west (pl. 4).

On the ridges between Arroyo Blanco and Canoncito de las Yeguas, the undivided Fruitland Formation and Kirtland Shale are exposed better than to the south, but the outcrops are discontinuous. In sec. 5, T. 24 N., R. 1 E., rocks equivalent to the Pictured Cliffs Sandstone and unit A are well exposed. Here the upper marine sandstone of unit A is overlain directly by fine- to coarse-grained ledge-forming sandstone containing silicified wood. These combined sandstone beds are about 100 feet thick, and no sharp contact was observed between the lower part, which is fine to medium grained, and the upper part, which contains coarse grains and silicified wood. Probably the upper part is the basal sandstone of unit B, and the contact with the underlying sandstone of unit A is obscured because of reworking. The coarse-grained sandstone, which contains silicified wood, is overlain by poorly exposed olive-green and dark-gray shale assigned also to unit B. Low sandy hills west of this shale are probably underlain by the Ojo Alamo Sandstone. Exposures are similar in the NW¼ sec. 32, T. 25 N., R. 1 E. Here the upper ledge-forming part of a sandstone, on which an Indian ruin is situated, seems to be the basal sandstone of unit B. Softer fine-grained sandstone below the resistant sandstone is probably part of unit A.

In the NW¼ sec. 29, T. 25 N., R. 1 E., the basal sandstone of unit B forms a ledge about 20 feet thick and consists of light-tan fine to coarse sand. The upper part of this sandstone is concealed, as is the 50 feet of rocks that overlie it. West of this is a low sandy hill probably underlain by the Ojo Alamo Sandstone. The sequence in the NE¼ sec. 17, T. 25 N., R. 1 E., is similar. Here the basal sandstone of unit B contains silicified logs and has a strong siliceous cement locally. The sandstone is about 14 feet thick and forms a resistant ledge above shale of the upper part of unit A. Dane (1946) tentatively correlated this sandstone with the Ojo Alamo. Northward, sandstone beds of the upper part of unit A thicken and, with the overlying basal sandstone of unit B, form a massive ledge 60–100 feet thick. These rocks were assigned to the Animas Formation by Dane (1946, strat. section 8). In the SE¼SE¼ sec. 8, T. 25 N., R. 1 E., the basal sandstone of unit B is overlain by poorly exposed gray and olive-green shale and interbedded thin sandstone that are estimated to be about 100 feet thick. These shale beds are the upper part of unit B and are overlain by a thick ridge-forming coarse-grained pebble-bearing sandstone correlated with the Ojo Alamo.

Near the center of sec. 4, T. 25 N., R. 1 E., the upper shale of unit B is cut out by a slightly angular erosional unconformity, and the Ojo Alamo Sandstone thickens and rests on the combined sandstones of units B and A from here to the north edge of the area (fig. 9).

FIGURE 9.—Ojo Alamo Sandstone capping cuesta in sec. 33, T. 26 N., R. 1 E. Kl, Lewis Shale, including thin beds of sandstone equivalent to Pictured Cliffs Sandstone; Kkf, sandstone of unit A (soft) and unit B (ledge) of the undivided Fruitland and Kirtland; Too, Ojo Alamo Sandstone. Northernmost stratigraphic section shown on plate 2 was measured at scar near center of photograph.

Locally, as in the SW¼ sec. 21, T. 26 N., R. 1 E., thin remnants of the upper shale of unit B intervene between the Ojo Alamo and the combined sandstones of units A and B, and the presence of the shale of unit B facilitates the mapping of the upper contact of the Fruitland and Kirtland. Elsewhere the contact is drawn within the combined sandstones of the Ojo Alamo and units A and B, at a topographic notch 60–100 feet above the base of the Fruitland and Kirtland sandstone beds. This contact is only approximate at most places. Reconnaissance of the region to the north indicates that units A and B thicken north of the Puerto Chiquito anticlinal nose in the area west and southwest of Stinking Lake in Ts. 27 and 28 N., R. 1 W. In this region units A and B are similar in thickness and lithology to units A and B in sec. 17, T. 25 N., R. 1 E.

SUBSURFACE CORRELATIONS

Units A and B of the undivided Fruitland Formation and Kirtland Shale can be recognized in the subsurface of the area investigated. In most of the area unit A consists mainly of silty shale, which contains numerous beds of coal that are as much as 30 feet thick. On the correlation diagrams (pls. 3, 4, 5) the basal coal beds and a few other beds are shown individually, but most of the coal beds are included in a zone (crosshatched) of shale and interbedded coal. This zone includes, at some places, as many as seven beds of coal interbedded in shale. In the subsurface of the southwestern part of the area (pl. 3), unit A contains a basal coal, but the stratigraphically higher coals are not present, and unit A was not subdivided from unit B.

In the north-central and northeastern parts of the area (pls. 3, 4, respectively), thin beds of siltstone and shaly sandstone in unit A thicken gradually northeastward and finally form a unit of sandstone 60–80 feet thick. This sandstone probably correlates with the *Ophiomorpha*-bearing marine sandstone of unit A that crops out in the Northern Hogback Belt (pl. 4). The coal zone of unit A thins northeastward as the individual coal beds grade into shale and die out between sandstones. The coal beds also thin eastward (pls. 4, 5), as shown by the logs of wells east of the Continental Divide, and the stratigraphic interval of most of the coal zone is represented by sandstone, shale, and carbonaceous shale at outcrops in the Northern Hogback Belt and San Pedro Foothills. In the San Pedro Foothills most of unit A is absent because of the local unconformity with unit B. A basal coal of unit A is present at outcrops on the east side of Mesa Portales in the southeastern part of the area (pl. 6).

Unit B consists of shale, sandy shale, shaly sandstone, sandstone, and a few beds of coal in the subsurface. The basal sandstone of unit B is as much as 70 feet thick at some wells east of the Continental Divide and in the north-central part of the area. However, the basal sandstone thins and wedges out southwestward and westward away from the outcrops in the eastern part of the San Juan Basin. In the southeastern part of the area (pl. 5), the basal sandstone seems to truncate much of unit A toward the outcrop areas. Subsurface data are not sufficient to determine whether the distal (western) part of the basal sandstone interfingers with the upper coals of unit A, or whether it rests in channels cut in the coal. In the north-central part of the area (pl. 3), and in the northeastern part of the area (pl. 4), the distal parts of the basal sandstone of unit B seem to be conformable with unit A. This observation and the outcrop data (pl. 6) lead to the conclusion that units A and B are unconformable only near the east margin of the San Juan Basin, and that slight folding occurred here during deposition of the Fruitland and Kirtland. This episode of folding seems to have been the first stage in the development of the system of north-northwest-plunging anticlines that now characterizes the eastern margin of the Central basin. (See structure contours, pl. 1.)

The zone of ledge-forming lenticular sandstones that occurs at outcrops of the upper part of unit B in the southern part of the area seems to be persistent in the subsurface of the southern half of the area (pls. 3, 5). The correlated sandstones shown on the diagrams are probably not continuous sheets but instead are probably numerous stream deposits occurring at about the same stratigraphic position throughout a wide area, as are the sandstones that crop out. The zone of sandstones grades northward into shaly sandstone and siltstone interbedded in shale. Stratigraphically higher beds of sandstone and shaly sandstone interbedded with shale occur in unit B in the northwestern part of the area (pl. 5).

GENERAL DISCUSSION

The sediments of unit A probably were deposited in mixed marine, lagoonal, and paludal environments, as indicated by their generally fine-grained even-bedded nature and by the marine fossils and coal they contain. The "Lewis Shale" florule and faunule of Anderson (1960, p. 8) was collected in the NE¼ sec. 4, T. 25 N., R. 1 E., from rocks which the present writer assigns to the middle part of unit A of the Fruitland and Kirtland. On the basis of contained spores, pollen, foraminifers, dinoflagellates, and hystrichosperids, Anderson concluded that the sediments were deposited in brackish water. *Ophiomorpha* which is common in the sandstones of unit A in the northeastern part of the area, is of uncertain biological affinities, but it has been reported only from marine rocks. The marine pelecypod *Inoceramus* sp. also occurs at some places in these sandstones. The lower part of the Fruitland Formation in other parts of the basin is known to have been deposited in a mixed marine-terrestrial environment because it contains coal, intertongues with the Pictured Cliffs Sandstone, and contains brackish-water fossils (Stanton, 1916).

The basal sandstone of unit B in outcrop areas has the general lithologic characteristics of a stream-channel deposit and contains abundant fossil wood, indicating a terrestrial environment of deposition. The carbonaceous bentonitic shale and fine-grained sandstone of the upper part of unit B indicate deposition in still water in swampy or lacustrine environments. The Kirtland Shale florule of Anderson (1960, p. 5) was collected in the east-central part of sec. 8, T. 20 N., R. 1 W., from rocks assigned to unit B. According to Anderson the florule consists of spores and pollen of vegetation of the immediate area deposited in a swampy environment. The ledge-forming sandstones and interbedded shales of the upper part of unit B were deposited in stream-channel and flood-plain environments.

Sandstone beds of the undivided Fruitland Formation and Kirtland Shale range in grain size from very fine to very coarse and contain small pebbles at places. Some of the fine to medium sand consists of well-rounded grains of quartz possibly derived from the source areas to the southwest which supplied the sediment of older Cretaceous rocks, and which supplied the sediments of the Fruitland and Kirtland in the southwestern and western parts of the Central basin. However, much of this sand might also have been derived from erosion and reworking of older Cretaceous rocks in newly uplifted areas.

The lithology of many of the sandstone beds of the Fruitland and Kirtland is dissimilar to the lithology of the underlying Pictured Cliffs Sandstone and Mesaverde Group. This fact suggests that part of the source terranes of the Fruitland and Kirtland were different from those of most of the older Cretaceous rocks. The *Ophiomorpha*-bearing marine sandstone of unit A is composed mainly of fine to medium sand but contains beds of coarse sand in the northeastern part of the area. This sandstone also contains more biotite and other ferromagnesian minerals than the Pictured Cliffs Sandstone; possibly the source terrane was composed of volcanic or metamorphic rocks. Much of the sand of unit B is coarse-grained to granule-size angular to subangular quartz, pink and green chert and rock fragments, and pink and white feldspar fragments. Small pebbles of quartz, quartzite, chert, and volcanic rock are present at places. The stratigraphically highest rocks of the Colorado Plateau region from which materials of this type could have been derived are the Dakota Sandstone of Early and Late Cretaceous age. The Morrison Formation (Upper Jurassic) also contains material of this type. The feldspar fragments in the Fruitland and Kirtland sandstones do not necessarily indicate a source of terrane of Precambrian granitic rocks, inasmuch as arkosic rocks occur in the Chinle Formation (Upper Triassic), the Cutler Formation and equivalent rocks (Permian), and the Madera and Sandia Formation of the Magdalena Group and equivalent rocks (Pennsylvanian) in uplifts bounding the San Juan Basin.

The bentonitic clay shale of unit B is considerably different from the shale of underlying Cretaceous formations. The bentonitic shale might be altered volcanic ash. To generalize, the lithology and stratigraphy of the Fruitland and Kirtland sequence seem to reflect tectonic changes in the San Juan Basin and adjacent regions, and they provide the oldest direct evidence of Laramide deformation in this region.

The changes in thickness and grain size of the rocks of the Fruitland and Kirtland give evidence of the directions from which their sediments were derived. As previously stated, the distribution of the Pictured Cliffs Sandstone in the San Juan Basin indicates that late in Pictured Cliffs time a part of the Cretaceous sea was restricted to form an embayment (fig. 7) in the eastern part of the region that is now the Colorado Plateau. The lower shale and coals of unit A in the southeastern part of the present area of investigation were deposited in lagoonal and paludal environments on the south margin of the embayment of the Cretaceous sea. Similar rocks of the Fruitland Formation were deposited on the north edge of the embayment (Zapp, 1949; G. H. Wood, Jr., and others, 1948; Dane, 1946). During deposition of these rocks, the region of the Central basin seems to have subsided and the marine water to have deepened and spread laterally in the embayment. The *Ophiomorpha*-bearing marine sandstone of unit A thickens and coarsens northeastward. Similar *Ophiomorpha*-bearing marine sandstones occur in the lower part of the Fruitland Formation above the Pictured Cliffs Sandstone southwest of Dulce, N. Mex. in the northeastern part of the basin. The general distribution and stratigraphic relations indicate that the sediments of the marine sandstone probably were derived from a highland rising northeast of the marine embayment.

During or slightly after the deposition of the extensive coal and shale beds of the upper part of unit A, the east margin of the San Juan Basin was uplifted slightly, and rocks of unit A were eroded slightly on the margin of the basin. The basin may have been tilted slightly to the west at this time, as postulated by Silver (1950, p. 112, 119–121, and figs. 3, 7). Deposits of unit B then were laid down on unit A. These deposits seem to be mainly terrestrial at outcrops on the east and south margins of the present area of investigation. However, the sandstones of unit B in the northeastern and eastern parts of the area grade laterally into thin beds of shaly sandstone and siltstone enclosed in thick shale in the subsurface. This gradation takes place both westward and southward, indicating that the source areas of these sands were east and northeast of the present San Juan Basin. The distal (western) parts of sandstone zones of unit B are so shaly and so persistent in the subsurface that they might have been deposited in a marine or lacustrine environment. Possibly this environment was a remnant of the former embayment of the Cretaceous sea isolated (or nearly isolated) from the eastward-retreating sea because of downwarping of the depositional basin and rise of the highlands east of the area of the present report. The ledge-forming sandstones of the upper part of unit B also thin and become shaly in the subsurface away from outcrops in the southeastern and southern parts of the area. This seems to indicate that source areas of some of the sediments of unit B were south and southeast of the report area. Facies relations on the west side of the San Juan Basin indicate that sediments for the Fruitland and Kirtland of that region were derived from the southwest and west. The facies relationships for the entire San Juan Basin seem to indicate a drainage system that was centripetal to the depositional basin.

CONTACTS

The undivided Fruitland Formation and Kirtland Shale are conformable on the Pictured Cliffs Sandstone in most of the area. Locally in the San Pedro Foothills the basal sandstone of unit B cuts out all of unit A and rests with slight erosional unconformity on rocks equivalent to the Pictured Cliffs.

The contact of the undivided Fruitland Formation and Kirtland Shale with the overlying Ojo Alamo Sandstone is unconformable. At all localities where the contact was observed it is a channeled erosional surface.

AGE AND CORRELATION

Other than unidentified fossil wood, the only fossils that the writer found in the undivided Fruitland Formation and Kirtland Shale in the report area are *Ophiomorpha*—a fossil which may be a marine fucoid alga or a fossil burrow of a marine organism—and *Inoceramus* sp., a marine pelecypod. Both of these forms indicate Cretaceous age.

Vertebrate, invertebrate, and plant fossils were collected from the Fruitland Formation and Kirtland Shale in the southwestern and western parts of the Central basin by several workers. Gilmore (1916, p. 279–281; 1919, p. 8–9; 1935, p. 186–187) discussed the vertebrate fossils, which include remains of dinosaurs, turtles, crocodiles, and fish, and concluded that the Fruitland and Kirtland (and the Ojo Alamo Sandstone as then defined) are older than the uppermost Cretaceous rocks (Lance Formation) of Wyoming and Montana. Stanton (1916, p. 309–310) discussed Cretaceous invertebrates from the Fruitland Formation. He concluded that both brackish-water and fresh-water forms occur and that the Fruitland Formation is older than the Lance Formation. In a discussion of the flora of the Fruitland and Kirtland, Knowlton (1916, p.

329–331) concluded that these formations are of Montana age. Reeside (1924, p. 24) summarized the evidence provided by fossils and concluded that the Fruitland Formation and Kirtland Shale contain closely related floras and faunas and that both are of late Montana age, possibly equivalent to part of the Pierre Shale and the Fox Hills Sandstone east of the Rocky Mountains. Baltz, Ash, and Anderson (1966, p. D–12, D–13) reviewed the evidence of age of the dinosaur fauna of the Naashoibito Member of the Kirtland and concluded that it is of Montana age and older than the Lance Formation. The Fruitland and Kirtland, then, are Late, but not latest, Cretaceous age.

The coaly beds, shale, and sandstone of unit A are equivalent to part of the Fruitland Formation of the western and northwestern parts of the Central basin, as shown by the previous mapping of Dane (1936) and Reeside (1924) and by correlations of subsurface data by many petroleum geologists. However, the other lithologic units of the Fruitland and Kirtland in the report area cannot now be correlated with certainty with units of the Fruitland and Kirtland in other parts of the Central basin. Some correlations, as discussed in the following paragraphs, are suggested because of lithologic similarities, but these correlations have not been established by detailed work.

The southwest-thinning *Ophiomorpha*-bearing marine sandstone of unit A is probably a part of the subsurface rocks called the northeast lobe of the Pictured Cliffs Sandstone by Silver (1950, p. 112). However, the marine sandstone of unit A and the overlying beds of the lower part of unit B are similar to sandstone in the upper part of the Fruitland Formation, and to beds of shale and fine- to coarse-grained even-bedded sandstone assigned by Wood, Kelley, and MacAlpin (1948) to the Kirtland Shale and the lower part of the Animas Formation ("zone of intertonguing between Kirtland and Animas") in the northern part of the San Juan Basin, southwest of Pagosa Springs, Colo. Outcrops of the *Ophiomorpha*-bearing sandstone were examined northward along the eastern side of the San Juan Basin in a reconnaissance from the area of this report to the vicinity of Dulce, N. Mex. The sandstone seems to be equivalent to the thick olive and brownish sandstone and shale of the Fruitland Formation that rest on the southward-thinning massive Pictured Cliffs Sandstone southwest of Dulce. Thus, the marine sandstone of unit A seems to be younger than the northern part of the Pictured Cliffs, which is probably about the same age as the Pictured Cliffs in the area of this report.

Unit B is probably equivalent mainly to the lower member of the Kirtland Shale, as indicated by comparison with Dane's (1936, p. 113–116) description of the Kirtland of the southern part of the Central basin. The sandstone beds of part of unit B in the report area grade westward in the subsurface into rocks which might be marine or brackish-water deposits. Dilworth (1960, p. 25) reported that foraminifera occur near the middle of the Farmington Sandstone Member of the Kirtland Shale. The presence of these fossils may indicate that the lower member of the Kirtland Shale and part of the Farmington are of marine, or at least brackish-water, origin in the western part of the Central basin. The upper sandstones of unit B are very similar to beds of the Farmington Sandstone Member.

The bentonitic shale beds in unit B are possibly altered volcanic ash, and this suggests a correlation with volcanic rocks of the McDermott Member of the Animas Formation (Barnes and others, 1954; see also Reeside, 1924, p. 24–28) of northwestern San Juan Basin. However, the writer and R. B. O'Sullivan found cobbles of andesitic rock in the Farmington Sandstone Member of the Kirtland Shale northwest of Farmington; thus, the presence of volcanic material does not necessarily indicate equivalence to the McDermott, which lies above the Kirtland Shale. Also, the presence of siliceous pebbles in unit B does not necessarily indicate equivalence to pebble-bearing rocks of the McDermott (see Reeside, 1924, p. 26), because siliceous pebbles occur also in sandstone included in the upper part of the Kirtland by Barnes, Baltz, and Hayes (1954), and in sandstones included in the upper part of the Kirtland by Reeside (1924, pl. 1) and Hayes and Zapp (1955) west of Pinyon Mesa northwest of Farmington.

The lithology of unit B is similar to that of the Naashoibito Member of the Kirtland (Baltz and others, 1966), which is the uppermost member of the Kirtland Shale in the southwestern part of the Central basin. However, regional stratigraphic relations seem to indicate that the upper part of the Kirtland is absent from the eastern part of the basin because of a regionally angular unconformity at the base of the overlying Ojo Alamo Sandstone.

ROCKS OF TERTIARY AGE

OJO ALAMO SANDSTONE

DEFINITION

Above the undivided Fruitland Formation and Kirtland Shale throughout the area is a persistent fine- to coarse-grained locally conglomeratic sandstone of varied thickness. This sandstone was first mapped as the lower part of the Puerco Formation by Gardner (1909, pl. 1; 1910, pl. 2). Renick (1931, p. 52) also mapped the thick sandstone as the lower part of the Puerco Formation. Dane (1936, p. 117) mapped the

Ojo Alamo Sandstone (as mapped by Reeside, 1924) across the south side of the Central basin from T. 22 N., R. 8 W., eastward to the Rio Puerco; he found that this is the sandstone that had been mapped by Gardner and by Renick as the lower part of the Puerco Formation.

The type locality of the Ojo Alamo Sandstone is on Ojo Alamo Arroyo in the northwest part of T. 24 N., R. 11 W., in the southwestern part of the Central basin near the abandoned Ojo Alamo store (Baltz and others, 1966) Dinosaur-bearing shale and sandstone exposed along Ojo Alamo Arroyo were first called the Ojo Alamo Beds by Brown (1910). Sinclair and Granger (1914) found dinosaur remains in rocks above Brown's Ojo Alamo Beds, and defined their Ojo Alamo Beds to include, in ascending order, the following units: (1) "shales with dinosaurs, lower horizon" (Brown's Ojo Alamo Beds); (2) lower conglomerate; (3) "shales with dinosaurs, upper horizon"; (4) conglomeratic sandstone with fossil logs. Unit 4 is overlain by shale and sandstone assigned to the Puerco Formation (now called the Nacimiento Formation) by Sinclair and Granger. Bauer (1916, p. 276) assigned the "shales with dinosaurs, lower horizon" to the upper part of the Kirtland Shale and defined the Ojo Alamo Sandstone to include the lower conglomerate, a medial unit of shale and soft sandstone (the "shales with dinosaurs, upper horizon"), and the upper conglomeratic sandstone.

Baltz, Ash, and Anderson (1966) restudied the type locality of the Ojo Alamo and found that the upper conglomerate of Bauer's Ojo Alamo intertongues with the overlying Nacimiento Formation and rests unconformably on a deeply channeled erosion surface cut in the dinosaur-bearing medial shale unit of Bauer's Ojo Alamo. They restricted the Ojo Alamo Sandstone to include only the upper conglomerate of Bauer's Ojo Alamo, and they assigned the restricted Ojo Alamo to the Tertiary because it intertongues with the Paleocene Nacimiento Formation. They named and defined the Naashoibito Member of the Kirtland Shale to include the medial shale unit and lower conglomerate of Bauer's Ojo Alamo. The Naashoibito was assigned to the Kirtland because of the faunal and lithologic similarities of the Naashoibito and the underlying upper shale member of the Kirtland.

Reeside (1924, p. 28 and pl. 1) indicated that the unit he mapped as Ojo Alamo on the west and southwest margins of the Central basin was the same as Bauer's Ojo Alamo; however, it is clear that except near Hunter Wash, Ojo Alamo, and Barrel Spring Arroyo, Reeside's mapped Ojo Alamo included only the upper conglomerate of Bauer (Baltz and others, 1966, p. D9, D14). Thus the unit mapped as Ojo Alamo Sandstone by Reeside (1924, pl. 1) southeast of Coal Creek (T. 24 N., R. 11 W.) and the unit mapped as Ojo Alamo by Dane (1936, pl. 39) in the southeastern part of the Central basin are generally the same as the restricted Ojo Alamo Sandstone of Baltz, Ash, and Anderson.

The Ojo Alamo Sandstone of the area of the present report is the restricted Ojo Alamo of Baltz, Ash, and Anderson (1966) and is mapped in the southern part of the area generally in accordance with the Ojo Alamo of Dane (1936, p. 116–121, and pl. 39). The Ojo Alamo of Hinds (1966) in the south-central part of the report area is also the Ojo Alamo of the present report. Dane (1936, pl. 39) included, in the lower part of his Ojo Alamo at the south and northeast sides of Mesa Portales, a few lenticular sandstone beds and shale which the present writer assigns to the upper part of unit B of the undivided Fruitland Formation and Kirtland shale. Fassett (1966) also included the lenticular sandstones and shale of the upper part of unit B in his Ojo Alamo at the east and northeast sides of Mesa Portales.

EXTENT AND THICKNESS

The Ojo Alamo Sandstone crops out in an irregular band above the undivided Fruitland Formation and Kirtland Shale almost continuously across the southern tier of townships (T. 20 N., Rs. 1–5 W.) of the report area, where it caps northward-sloping cuestas. The rocks dip in northerly directions, and the Ojo Alamo forms steep cliffs facing south, southeast, and southwest. According to Dane (1936, p. 121), the thickness of the Ojo Alamo is about 170 feet just west of San Ysidro Wash (Arroyo San Ysidro on pl. 1 of the present report). In this vicinity (southwest corner T. 20 N., R. 3 W., and northeastern part T. 19 N., R. 4 W.), at the south side of Mesa Aguila, the Ojo Alamo includes, as its lower part, a thick local channel sandstone that wedges out both east and west. East and west of the channel sandstone, the Ojo Alamo is 80–100 feet thick. Farther east the Ojo Alamo thickens and thins irregularly because of channeling at its base. In a composite section measured in the NE¼NE¼ sec. 23, T. 20 N., R. 2 W., the Ojo Alamo is about 70 feet thick. East of the Rio Puerco, the Ojo Alamo strikes northeast and forms northwest-sloping cuestas. In the S½NE¼ sec. 22, T. 21 N., R. 1 W., the Ojo Alamo is 91 feet thick.

In the San Pedro Foothills the Ojo Alamo Sandstone dips steeply west, and in places it is vertical or slightly overturned. Here the Ojo Alamo forms low rounded ridges exposed in the walls of the canyons that drain San Pedro Mountain. In the SE¼SW¼ sec. 11, T. 21 N., R. 1 W., the Ojo Alamo is 113 feet thick. The Ojo Alamo is well exposed along an abandoned irrigation ditch on the north side of San Jose Creek in the SW¼ NE¼ sec. 34, T. 23 N., R. 1 W., where it is about 90 feet thick.

In the Northern Hogback Belt, the Ojo Alamo is soft and poorly exposed or covered at many places, but there are a sufficient number of outcrops to establish its identity and persistence. In secs. 10 and 15, T. 23 N., R. 1 W., the pebble-bearing Ojo Alamo is poorly exposed on the slopes west of the high rib of the basal sandstone of unit B of the Fruitland and Kirtland. The Ojo Alamo forms low, northwest-dipping ridges of conglomeratic sandstone in the northeastern part of T. 23 N., R. 1 W., and near the southeastern corner of T. 24 N., R. 1 W. In the NE¼ sec. 2, T. 23 N., R. 1 W., the Ojo Alamo is about 110 feet thick.

In sec. 30, T. 24 N., R. 1 E., the Ojo Alamo forms a poorly exposed low ridge of pebble-bearing sandstone just east of a ranchhouse. In the SE¼ sec. 20, T. 24 N., R. 1 E., the Ojo Alamo is tentatively identified as a poorly exposed yellowish sandstone lying just west of the ranch road. A light-gray sandstone containing silicified wood on the low ridge just east of the road is similar in lithology to the Ojo Alamo but is apparently the basal sandstone of unit B of the Fruitland and Kirtland. North of here, in sec. 17 of the same township, the Ojo Alamo is poorly exposed, forms a low ridge, and rests on dark-gray and black shale assigned to the Fruitland and Kirtland. The basal sandstone of unit B contains fossil wood and a few small pebbles; it crops out on the wooded ridge east of the Ojo Alamo. Northward from here to the northern part of T. 25 N., R. 1 E., the Ojo Alamo is very poorly exposed but crops out at places, where it forms low hills largely masked by sand and sandy soil. The presence of the sandstone was determined by digging holes several feet deep through the sandy soil in the NW¼ sec. 29, and the NW¼ sec. 32, T. 25 N., R. 1 E.

Along the Forest Service road in the SE¼ sec. 8, T. 25 N., R. 1 E., a thick sandstone correlated with the Ojo Alamo rests on dark-gray and olive shale of the upper part of unit B of the Fruitland and Kirtland. The ridge-forming sandstone containing silicified wood in the NE¼ sec. 17, T. 25 N., R. 1 E., that Dane (1946, strat. section 8) specified as being about 100 feet above the base of the Animas Formation and correlated doubtfully with the Ojo Alamo is correlated with the basal sandstone of unit B by the present writer. North of here the Ojo Alamo is more resistant to erosion and forms low west-sloping ridges. It caps a high cuesta in T. 26 N., R. 1 E., where it rests directly on sandstone of the Fruitland and Kirtland. In the SW¼SE¼ sec. 33, T. 26 N., R. 1 E. (fig. 8), the Ojo Alamo is nearly 200 feet thick and rests unconformably on sandstone, about 53 feet thick, of unit B of the Fruitland and Kirtland. These combined sandstones were classified as the basal sandstone of the Animas Formation by Dane (1946, 1948), who used the terminology of the northern San Juan Basin in this region. The Ojo Alamo caps the high cuestas from here to the north edge of the area and at most places, rests on sandstone of the Fruitland and Kirtland. The exact position of the contact is difficult to distinguish, as was previously discussed.

In the subsurface the Ojo Alamo is disturbed continuously throughout the area. In the southern part of the area the Ojo Alamo ranges in thickness from 80 to 100 feet and thickens gradually to the north or northeast, as it does at the surface. The thickening takes place as sandstone tongues in the lower part of the Nacimiento Formation thicken northward and merge with the underlying Ojo Alamo Sandstone (pls. 3–5). In the northern part of the area the Ojo Alamo Sandstone ranges in thickness from about 180 feet to about 200 feet.

LITHOLOGY

The Ojo Alamo Sandstone is composed of several beds of buff, tan, and brown medium-grained to very coarse grained sandstone that contain lenses of olive-green to gray shale at places. The sand grains are mostly angular to subangular and consist mostly of quartz. Other common constituents are grains and granules of red, gray, and green chert and other rock fragments. Sand and granule-size cleavage fragments of pink feldspar are common also. Pebbles ranging in size from half an inch to several inches in diameter are scattered through the sandstone at many places, and, locally, the lower few inches to several feet of the formation is pebble-to-cobble conglomerate. Most of the pebbles and cobbles are well-rounded gray and white quartz and quartzite, but red, yellow, and green siliceous pebbles as well as sandstone and shale pebbles also are present. Some of the pebbles contain Paleozoic marine fossils and appear to be siliceous replacements of pebbles that were formerly limestone. Pebbles are most common in the Ojo Alamo in the southern part of the area and are scarce in the San Pedro Foothills. In the Northern Hogback Belt, in sec. 36, T. 24 N., R. 1 W., the lower part of the Ojo Alamo is a conglomerate that contains numerous 2- to 3-inch pebbles of volcanic rock, including a distinctive pink rhyolite porphyry. Farther north in the Northern Hogback Belt, pebbles are present sporadically in the Ojo Alamo. Logs replaced by silica or limonite are common in the Ojo Alamo at many localities. Some of the logs are as much as 2½ feet in diameter and 20 feet or more in length. These are similar to smaller silicified logs in sandstone of the Fruitland and Kirtland.

In outcrops the Ojo Alamo Sandstone is moderately indurated and cemented by silica, clay, and ferruginous compounds. Some hard thin beds are highly ferruginous and rusty weathering. At some places, however, the sandstone several inches beneath the weathered surface is much more friable than it is at the surface. Probably the Ojo Alamo is cemented better at the surface than where it is buried beneath younger rocks because mineral-bearing water "bleeds" out of the sandstone, evaporates at and near the surface, and deposits mineral matter between the grains. This view is supported by reports of water-well drillers that in places the Ojo Alamo behaves like quicksand during drilling.

Tangential crossbedding characterizes the formation, but at most places the several beds of sandstone tend to weather as massive units. In the southern part of the area, the lower half of the Ojo Alamo forms a massive cliff. The upper half is more highly crossbedded and less resistant and forms rounded slopes and ledges set back from the cliffs of the lower half. Locally, lenticular units of gray and olive-green shale intervene between some of the sandstone beds of the Ojo Alamo.

The sandstone and conglomerate of the Ojo Alamo are mainly overlapping stream-channel deposits. Silver (1950, p. 121) postulated that the Ojo Alamo was deposited as pediment gravel. Some of the upper beds of the Ojo Alamo show bedding that is characteristic of dune sand. Sinclair and Granger (1914, p. 301) suggested that the upper conglomeratic sandstone of their Ojo Alamo Beds (the restricted Ojo Alamo of Baltz and others, 1966) "seems to represent material swept into the basin of accumulation by floods, perhaps during an interval of crustal uplift which stimulated the streams to carry down the gravels which had accumulated in their banks, destroying the large trees growing there. Some of the drift logs are two or three feet across and over 50 feet long. The branches and bark have been stripped off * * *."

The sandstone of the Ojo Alamo is similar to the coarse-grained sandstone in parts of the Fruitland and Kirtland of the area of this report. Generally, the Ojo Alamo is much thicker and coarser grained and more arkosic, and the pebbles it contains are larger than those found at places in the Fruitland and Kirtland.

The lithologies of the Ojo Alamo and the coarse sandstone of the Fruitland and Kirtland are similar enough to suggest common source areas. The Ojo Alamo Sandstone thickens northward; thus, a highland northeast of the present San Juan Basin may have been a major source area (fig. 7). Dane (1936, p. 118) observed that in the southern part of the area the grain size of the Ojo Alamo increases toward the east. The coarsest gravel observed in the Ojo Alamo in the report area is in the northeastern part of T. 23 N., R. 1 W., the southeastern part of T. 24 N., R. 1 W., and in the southwestern part of T. 24 N., R. 1 E., evidence also favoring a postulated source area to the east or northeast. Probably this source area was in the vicinity of the present Brazos uplift.

Reeside (1924, p. 29–30) suggested that the Ojo Alamo of the western side of the basin was derived from the east or south. However, the writer and R. B. O'Sullivan measured the strikes of numerous channel edges and the dips and strikes of foreset beds and laminae in the Ojo Alamo near Farmington, and these measurements indicate that in this part of the basin the Ojo Alamo was deposited by streams flowing from the west-northwest and the northwest, probably from a highland in the position of the western part of the present San Juan Mountains. Probably the Ojo Alamo was laid down as pediment deposits by streams flowing into the basin from several sides after downwarping of the basin, or uplift of highlands in the surrounding region.

CONTACTS

The Ojo Alamo Sandstone rests with erosional unconformity on the undivided Fruitland Formation and Kirtland Shale in the area of this report. Evidence of scouring and deep channeling at the base of the Ojo Alamo can be seen at many places. Baltz, Ash, and Anderson (1966, p. D18–D19) found that the restricted Ojo Alamo in the southwestern part of the Central basin rests on a highly irregular erosional surface cut in the rocks they assigned to the Kirtland Shale. The writer and S. R. Ash traced the Ojo Alamo across most of the southern margin of the Central basin between the type locality and Cuba, and they found that the lower contact of the sandstone is an irregular erosion surface at all the localities where it was observed.

Dane (1936, p. 118–121) reasoned that the erosion surface he observed at the base of the Ojo Alamo at places in the southern part of the basin is no more than the result of scouring and channeling by streams competent enough to transport and deposit coarse sediment. Also, according to Dane (1936, p. 119), at places between Alamo Arroyo and the Rio Puerco, the base of the Ojo Alamo is not at the same stratigraphic position at points a few hundred feet apart. He believed that although there was a relatively sudden change in conditions of deposition when the Ojo Alamo was deposited, the evidence shows that this change did not occur everywhere at the same time, and that at places there was a transitional change in sedimentation. Dane (1936, p. 120–121) suggested that the eastward thinning of the underlying Kirtland Shale is the result of a lesser amount of deposition toward the southeast, and that there is no hiatus between the Ojo Alamo and the Kirtland Shale.

In the opinion of the present writer, however, the evidence of erosional unconformity and slight regional angular unconformity is clear in the area of investigation as well as in the western part of the basin. The variations of thickness of the undivided Fruitland Formation and Kirtland Shale in the San Pedro Foothills and Northern Hogback Belt indicate that slight folding and erosion occurred there before deposition of the Ojo Alamo. The contact mapped by the present writer in the southern part of the area is one of strong erosional unconformity. Locally the Ojo Alamo thickens abruptly (as in the southern parts of Mesa Aguila and Mesa Portales) and the erosion surface at its base cuts out lenticular sandstone and shale beds of the upper part of unit B of the Fruitland and Kirtland. Where the Ojo Alamo rests on sandstone beds of unit B this unconformity can be recognized only by tracing individual beds, because the lithology and topographic expression of the finer grained parts of the Ojo Alamo are similar to those of the lenticular sandstones of the upper part of unit B.

Dane (1936, p. 119) pointed out the problem of differentiating the Ojo Alamo from locally present sandstones of the upper part of the Kirtland Shale in the southern part of the area, stating:

> In many places also the upper part of the Kirtland shale is very sandy; in several places it contains beds of sandstone 5 to 10 feet thick that are lithologically similar to or identical with the finer-grained sandstone phases of the Ojo Alamo, and at a few places the upper 50 feet or more of the Kirtland is a white or gray fine-grained cross-bedded sandstone that can be separated from the overlying [Ojo Alamo] sandstone only on the basis of continuous tracing of the stratigraphic position of the contact elsewhere.

In the subsurface the undivided Fruitland Formation and Kirtland Shale are as much as 450 feet thick in the western part of the area. In the eastern part of the area these rocks are less than half that thickness. Correlations of electric logs of wells suggest that individual beds within the Fruitland and Kirtland do not thin eastward, as would be expected if the overall thinning was the result of a lesser amount of deposition to the east. In fact, some units thicken eastward and northeastward (pls. 4, 5). It appears that from west to east successively lower beds of the Fruitland and Kirtland are truncated by the Ojo Alamo in the western part of the area. This would seem to indicate that, prior to deposition of the Ojo Alamo, the rocks of the eastern part of the San Juan Basin were tilted to the west, and part of the Kirtland was eroded from the eastern part of the basin. This view is much the same as the conclusion of Silver (1950, p. 112), who reported that the relief on the top of the Kirtland in the subsurface of the Gavilan area is 100–200 feet in 10 miles. The combined thickness of the Fruitland Formation and Kirtland Shale on the west side of the Central basin near Farmington is more than 1,600 feet; thus it is possible that as much as 1,400 feet of Fruitland and Kirtland rocks was eroded from the eastern part of the basin prior to deposition of the Ojo Alamo. As previously stated, however, there is evidence of local uplift and erosion in the eastern part of the basin during deposition of the Fruitland and Kirtland, and these rocks may never have been as thick on the east side of the Central basin as they are on the west side.

R. B. O'Sullivan and the writer found that, northwest of Farmington, the Ojo Alamo Sandstone rests with erosional unconformity on reddish shale and interbedded pebbly sandstone 180–200 feet thick that were assigned by Reeside (1924, pl. 1) to the McDermott Formation (the McDermott Member of the Animas Formation, as redefined by Barnes and others, 1954) between Barker Arroyo and Pinyon Mesa. Along the west side of Pinyon Mesa a well-exposed channeled surface at the base of the Ojo Alamo Sandstone cuts out at least 150 feet of the underlying McDermott; and on the east side of La Plata River east of Pinyon Mesa, the Ojo Alamo truncates the southward-thinning McDermott. The McDermott is absent south of T. 30 N., R. 13 W., along the west side of the Central basin. (See O'Sullivan and Beikman, 1963. The McDermott Member is shown as the lower part of the Animas Formation on their map.)

On the basis of stratigraphic relations observed in the report area and the regional stratigraphic relations described by Baltz, Ash, and Anderson (1966, p. D18–D19), there is an erosional unconformity and probably a regionally angular unconformity at the base of the restricted Ojo Alamo Sandstone in the eastern, southern, and western parts of the Central basin. The dinosaur-bearing shales assigned to the Naashoibito Member of the Kirtland Shale at the type locality of the Ojo Alamo (Baltz and others, 1966) are of Montana (Late, but not latest) Cretaceous age and are overlain with erosional unconformity by the Ojo Alamo. Dinosaur-bearing rocks assigned to the McDermott Member of the Animas Formation, which lies on the upper part of the Kirtland in the western part of the San Juan Basin, also are overlain with erosional unconformity by the Ojo Alamo. *Triceratops*, which characterizes terrestrial rocks of latest Cretaceous (Lance) age, has not been found in the San Juan Basin.

The Ojo Alamo Sandstone is conformable with and transitional into the overlying Nacimiento Formation of Paleocene age in the area. No evidence of unconformity was observed in outcrops, and subsurface data seem to indicate that the Ojo Alamo is conformable with the Nacimiento and intertongues with it. In the southwestern part of the basin the intertonguing of the Ojo Alamo and the Nacimiento can be seen in outcrops (Baltz and others, 1966). The Ojo Alamo intertongues with the Nacimiento Formation also in the western part of the basin, near Farmington (O'Sullivan and Beikman, 1963), and grades northward into the lower part of the Nacimiento northwest of Farmington (Hayes and Zapp, 1955).

AGE AND CORRELATION

Baltz, Ash, and Anderson (1966, p. D15–D18) assigned the restricted Ojo Alamo Sandstone to the Paleocene because it intertongues with the overlying Nacimiento Formation and because it contains a pollen and spore flora of probable Paleocene age.

The "Ojo Alamo 1" pollen and spore flora of Anderson (1960, p. 5) was collected in the southeastern part of the area in sec. 5, T. 20 N., R. 1 W., from rocks which Anderson considered to be at the base of the Ojo Alamo. Anderson (1960, p. 9) reported that this flora is very different from his Kirtland Shale flora and has a "Tertiary ecologic aspect," but is not necessarily Tertiary on the basis of common forms. The significance of the "Ojo Alamo 1" flora is not clear because the rocks might contain pollens reworked from underlying beds.

The "Ojo Alamo 2" pollen and spore flora of Anderson (1960, p. 5) was collected from the middle of the Ojo Alamo Sandstone in sec. 13, T. 21 N., R. 1 W. This flora is closely related to floras from the overlying Nacimiento Formation, which is early Paleocene (Anderson, 1960, p. 8). Baltz, Ash, and Anderson (1966, p. D17) found that at Barrel Spring Arroyo the restricted Ojo Alamo and the lower part of the Nacimiento contain pollen and spore floras that are similar. The flora from the Nacimiento was found in the lower part of the beds that contain the Puerco mammal fauna of early Paleocene age. The Ojo Alamo and Nacimiento floras from Barrel Spring Arroyo are similar to Anderson's "Ojo Alamo 2" and Nacimiento floras from the report area and are unlike a flora from the Kirtland Shale at Ojo Alamo Arroyo.

The only other fossils found in the restricted Ojo Alamo Sandstone are also plants. The petrified logs that are common in the Ojo Alamo (and also at places in the Fruitland, Kirtland, and Nacimiento) are not reported to have a determinable stratigraphic significance. The fossil leaves that Knowlton (in Reeside, 1924, p. 31–32) said suggest Tertiary age were collected in the western part of the Central basin from rocks that are probably equivalent to the restricted Ojo Alamo Sandstone.

The dinosaur-bearing rocks that Bauer (1916) defined as being the middle unit of the Ojo Alamo were reassigned as the Naashoibito Member of the Kirtland Shale (Baltz and others, 1966), and no dinosaur remains are known to occur in the restricted Ojo Alamo Sandstone.

The correlation of the Ojo Alamo Sandstone with possibly equivalent rocks in the upper member of the Animas Formation of the northwestern and northern parts of the basin cannot be established without further detailed work on the outcrops and the subsurface geology of that region. Reconnaissance along the northeast side of the San Juan Basin indicates that the rocks mapped as Ojo Alamo in the northeastern part of the report area persist as far north as Dulce, N. Mex.

NACIMIENTO FORMATION

DEFINITION

Tertiary rocks in the valley of the Rio Puerco southwest of Cuba were named the Puerco Marls by Cope (1875, p. 1008–1017). Paleocene fossils from the Puerco of Cope (collected 50 miles west of the Rio Puerco) were studied by Matthew (1897, p. 259–261), who found two distinctly different faunas. He restricted the name Puerco Formation to the rocks containing the older fauna and proposed the name Torrejon Formation for the rocks containing the younger fauna. Matthew credited the name Torrejon Formation to J. L. Wortman, who had distinguished the different stratigraphic positions of the two faunas in the field. The name was taken from arroyos considered to be the heads of Arroyo Torrejon. These arroyos, in the southwestern part of the present area, are forks of what is now called Encino Wash, a tributary of Arroyo Torrejon (spelled Torreon on some maps), which lies south of the report area.

Gardner (1909) mapped the (then unnamed) Ojo Alamo Sandstone and overlying beds, including the thick sandstones capping Mesa de Cuba, as the Puerco Formation. Subsequently, Gardner (1910, p. 713) proposed the term Nacimiento Group to include both the Puerco and the Torrejon Formations, specifying (p. 717) that along the Rio Puerco south and west of Nacimiento (now known as Cuba) the Puerco is 558 feet thick and the overlying Torrejon is 276 feet thick. The lower limit of the Puerco Formation described in Gardner's later text (1910, p. 717) does not correspond to the lower limit on his map (1910 pl. 2), as will be discussed. Also, most of Gardner's (1910, p. 717) Torrejon Formation at the type locality of the Nacimiento

Group consists of sandstone beds which Cope (1875) specifically placed above his Puerco Marls and seems to have correlated with the "sandstones of the Eocene" at the "portals of Canoncita de las Vegas" (Canoncito de las Yeguas on pl. 1 of the present report). Renick (1931, p. 51–53) mapped the Puerco and Torrejon Formations as an undivided unit having about the same upper and lower stratigraphic boundaries as the map unit called the Puerco Formation in Gardner's earlier (1909) paper and the rocks described as Puerco and Torrejon Formations in Gardner's later (1910) paper.

Sinclair and Granger (1914) and Dane (1932) found that Gardner (1910) had defined the Nacimiento Group incorrectly, and that he had included some of the rocks containing Torrejon fossils in his Puerco Formation, and the lower beds of the Wasatch Formation in his Torrejon Formation. Dane (1936) mapped a restricted unit as the Puerco(?) and Torrejon Formations. The lower part of Gardner's (1909, pl. 2; 1910, pl. 2) Puerco Formation was mapped by Dane as the Ojo Alamo Sandstone. The sandstone beds capping Mesa de Cuba and other mesas to the west had been mapped by Gardner in the Torrejon Formation; these were mapped by Dane as part of the Wasatch Formation (now classified as the San Jose Formation of Eocene age). Wood and Northrop (1946) mapped the Puerco and Torrejon Formations as the same undivided unit mapped by Dane (1936). In a later work, Dane (1946) used the name Nacimiento Formation for the rocks he had mapped earlier as the Puerco(?) and Torrejon. Simpson (1948, p. 272–273) agreed with this usage and proposed that Puerco and Torrejon be considered only as names of faunal zones in the Nacimiento Formation, since no one had succeeded in mapping as separate lithologic units the beds containing the Puerco and Torrejon fossils. (See also Simpson, 1959.)

Dane (1946) traced the Nacimiento Formation from the vicinity of Cuba northward along the east edge of the San Juan Basin; he found that it is equivalent generally to rocks mapped as the Animas Formation of Cretaceous and Paleocene age by investigators in Colorado. For this reason, he restricted the use of the name Nacimiento Formation to the area south of Canoncito de las Yeguas in T. 25 N., R. 1 E., and applied the name Animas Formation to approximately the same rocks north of Canoncito de las Yeguas. The Animas Formation (Reeside, 1924, p. 32–33) has been traced eastward from its type locality on the Animas River near Durango, Colo., around the northern part of the Central basin (Zapp, 1949; Barnes, 1953; G. H. Wood, Jr., and others, 1948; Dane, 1946, 1948) to the northern part of the report area. However, the rocks classified as Animas Formation in the report area by Dane (1946, 1948) are lithologically more similar to those of the typical Nacimiento Formation than to typical Animas rocks. A lithologic division between the Animas and Nacimiento facies can be made on the northwest side of the Central basin in Colorado (Baltz, 1953, p. 45–46).

In the southern and southeastern parts of the present report area, the Nacimiento Formation of this report is approximately the same as the unit mapped as the undivided Puerco(?) and Torrejon Formations by Dane (1936) and by Wood and Northrop (1946). However, north of Canoncito de las Yeguas, rocks classified by Dane (1946, 1948) as being in the lower part of the Animas Formation are correlated by the present writer with the upper part of the undivided Fruitland Formation and Kirtland Shale, and the Ojo Alamo Sandstone. Beds above the Ojo Alamo Sandstone in the northern part of the area that were designated as the Animas Formation by Dane are designated by the present writer as the Nacimiento Formation, and the name Animas Formation is not used for rocks in the report area.

TYPE LOCALITY

Although Gardner (1910, p. 717) did not specify the exact place of measurement of the type locality of the Nacimiento Group, most workers have assumed that his section was measured at the south end of Mesa de Cuba in the northwestern part of T. 20 N., R. 2 W. Comparison of Gardner's section with sections measured by Simpson (1959, p. 4) and by the present writer (fig. 10) indicates that Gardner did measure the part of his section which he designated as the Puerco Formation at the south tip of Mesa de Cuba. The lower 170 feet of Gardner's Torrejon Formation consists mostly of sandstone beds that are the massive sandstones that cap Mesa de Cuba. These sandstones are now classified as part of the Eocene San Jose Formation. The shale and thin sandstone composing the upper 106 feet of Gardner's Torrejon Formation must have been measured elsewhere, because only the massive sandstones are preserved at the south end of Mesa de Cuba (fig. 11).

Gardner's (1909, 1910) maps included with the Nacimiento Group the sandstone now classified as the Ojo Alamo. Renick (1931, p. 51–52), Dane (1932), and Simpson (1959, p. 16–19) supposed that Gardner's section of the Puerco Formation included at the base rocks now called the Fruitland and Kirtland, and that the fourth unit above the base—a sandstone 40 feet thick—is the Ojo Alamo. However, Gardner's section (except the shaly upper part of his Torrejon) was measured probably near the locality of measurement (1d on pl. 1) of the upper part of the present writer's composite section of the Nacimiento Formation (described at the end of this report) north of the Torreon

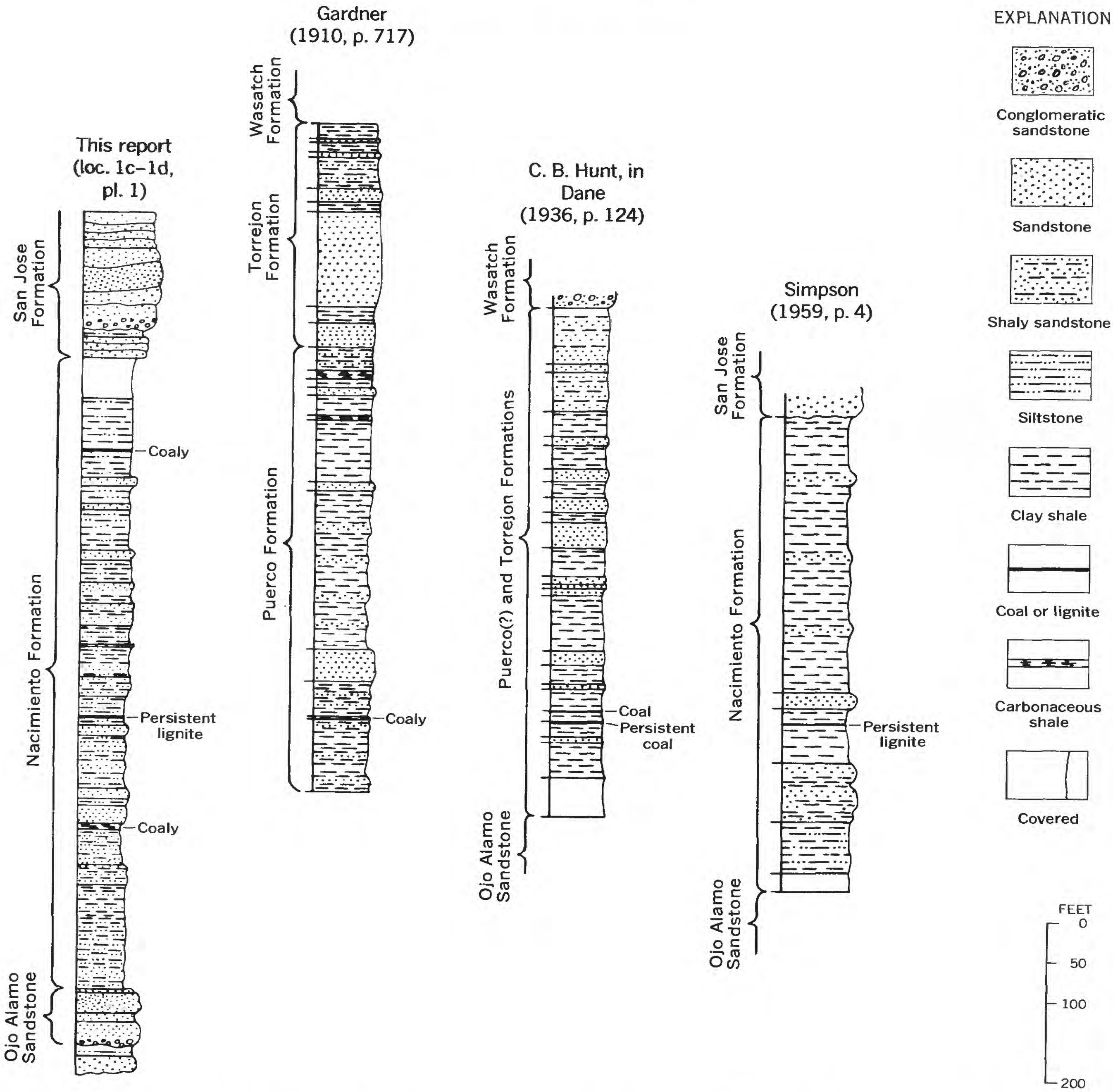


Figure 10.—Comparison of stratigraphic sections of exposures at type locality of Nacimiento Formation, south end of Mesa de Cuba.

road in sec. 11, T. 20 N., R. 2 W. If this is correct, the second unit from the base of Gardner's section ("Shale, very dark, local coal streaks") is a prominent and persistent band of lignite above a small bench, and about 90–140 feet above the valley floor. This lignite is unit 71 of the present writer's stratigraphic section. Thus, the base of Gardner's section is about 250 feet stratigraphically above the Ojo Alamo Sandstone. The lignite is probably the "persistent lignite" shown in the third unit above the base of Simpson's (1959, p. 4) section, and the fifth unit above the base of Hunt's section (in Dane, 1936, p. 124). Hunt's section indicates that the Puerco(?) and Torrejon Formations are about 633 feet thick. Simpson's (1959, p. 19) measurement of the thickness of the same rocks, now called the Nacimiento Formation, is about 600 feet, based on approximate altitudes from a barometric altimeter. However, the composite section measured by the pres-

FIGURE 11.—Type locality of Nacimiento Formation, south end of Mesa de Cuba, sec. 11, T. 20 N., R. 2 W. Alluvium in foreground rests on lower part of Nacimiento Formation. c, coaly shale (unit 60 of the stratigraphic section measured at loc. 1d). Persistent lignite bed (unit 71) is about 140 feet above c, and cannot be seen clearly in this view. Tsc, lower part of Cuba Mesa Member of San Jose Formation.

ent writer is about 800 feet thick, and this thickness accords fairly well with a thickness of about 860 feet for the Nacimiento Formation at the Sun Oil 1 McElvain well in sec. 23, T. 21 N., R. 2 W. (See pl. 5.) Since the base of the Nacimiento Formation is the top of the Ojo Alamo Sandstone, there is almost 200 feet of shale and thin sandstone beds in the lower part of the Nacimiento that has not been previously described at the type locality. These rocks are well exposed on the hills north of Arroyo Chijuilla in secs. 13 and 14, T. 20 N., R. 2 W. (loc. 1c on pl. 1); they are described in a stratigraphic section at the end of the present report and are shown graphically on plate 2.

EXTENT AND THICKNESS

The Nacimiento Formation is present above the Ojo Alamo Sandstone throughout the area. The Nacimiento crops out in the Penistaja Cuestas sector across the southern part of the area, where it forms low rounded hills of drab clay, siltstone, and soft sandstone. Thin resistant sandstones in the upper third of the formation form low benches and small northward-sloping cuestas. In the southwestern part of the area at the Shell Oil 1 Pool Four well in the SE¼ sec. 22, T. 21 N., R. 5 W., the Nacimiento is about 850 feet thick. The composite stratigraphic section measured in the SE¼ SE¼ sec. 14, and at the south end of Mesa de Cuba in sec. 11, T. 20 N., R. 2 W., indicates that the Nacimiento is about 800 feet thick west of the Rio Puerco.

In the San Pedro Foothills the Nacimiento Formation is discontinuously exposed in the walls of the canyons and sides of valleys, where its beds of somber clay and thin sandstone dip steeply west, or are vertical to slightly overturned. The thickness is varied (pl. 2), perhaps partly because of squeezing of the shale in the belt of sharp folding, but mainly because of angular and erosional unconformity with overlying rocks of the San Jose Formation. Near the center of sec. 11, T. 21 N., R. 1 W., the Nacimiento is 537 feet thick. Farther north in T. 22 N., the Nacimiento is thinner, but the formation is estimated to be about 1,000 feet thick north of San Jose Creek in sec. 34, T. 23 N., R. 1 W. The formation seems to be thinner to the north in sec. 15, T. 23 N., R. 1 W.

In the southern part of the Northern Hogback Belt the steeply west-dipping rocks of the Nacimiento Formation are poorly exposed in discontinuous low ridges separated by alluvial valleys. In sec. 20, T. 24 N., R. 1 E., the Nacimiento is about 550 feet thick, or possibly slightly more; owing to poor exposures, the base of the formation was not determined with certainty. In the W½ sec. 8, T. 24 N., R. 1 E., the base was not determined with certainty, but the Nacimiento Formation is at least 1,250 feet thick. Farther north it is better exposed as the west dip of the beds becomes less steep. North of Canoncito de las Yeguas, sandstones of the Nacimiento form ridges and spurs west of the Ojo Alamo cuesta. Near the centerlines of secs. 17 and 18, T. 25 N., R. 1 E., the Nacimiento is almost 1,400 feet thick. The base is not exposed at the point of measurement.

Although the thickness is irregular in the outcrops along the east edge of the area, the Nacimiento thickens generally northward. In the subsurface a similar but more regular northward thickening takes place (pl. 3). The formation is 800–850 feet thick in the southern part of the area and is as much as 1,750 feet thick near the north edge of the area. Well data indicate also that the Nacimiento thins irregularly eastward in the subsurface near the east edge of the Central basin.

LITHOLOGY

The Nacimiento Formation consists of shale and interbedded soft to resistant sandstone. These rocks are of two different lithologic facies in the northern and southern parts of the area; however, the lateral change in facies takes place so gradually and exposures are so discontinuous on the east side of the area that it is impossible to map any logical lithologic boundary between facies. The Nacimiento of the southern part of the area is a facies consisting mainly of clay shale and sandy shale that contain some soft sandstone and a few resistant sandstone beds. In the northern part of the area the Nacimiento contains a greater proportion of sandstone and, near the north edge of the area, more than half of the formation is sandstone.

In the vicinity of the southern part of Mesa de Cuba, the Nacimiento consists of four more or less distinguishable units. The lowest unit is soft, gray to light-olive-gray clay shale with purplish bands that contain numerous thin beds of lenticular soft siltstone and shaly fine- to coarse-grained sandstone, all about 130–150 feet thick in sec. 14, T. 20 N., R. 2 W. Above this is a unit of gray clay and interbedded soft highly lenticular fine-grained to very coarse-grained white-weathering sandstone containing one or two thin beds of impure coal, all about 120 feet thick in sec. 12, T. 20 N., R. 2 W. Next above is a unit of soft, olive-green and gray clay and siltstone containing several beds of lenticular soft fine- to coarse-grained argillaceous sandstone, and near the top, a conspicuous bed of black to dark-brown lignite (equivalent to the previously mentioned lower lignite in the sections of Gardner, Hunt, and Simpson). This unit is about 115 feet thick in sec. 11, T. 20 N., R. 2 W., where it forms rounded topographic spurs near the foot of Mesa de Cuba.

The highest unit of the Nacimiento Formation consists of variegated light-purple, gray, and olive-green clay and siltstone containing lenticular yellow and white argillaceous soft sandstone and several thick ledge-forming buff to brown sandstone beds. The unit is about 425 feet thick in sec. 11, T. 20 N., R. 2 W., and forms steep ledgy slopes below the caprock of Mesa de Cuba. The prominent, lenticular, ledge-forming sandstones are interbedded in the shale of the lower two-thirds of the highest unit of the Nacimiento. These sandstones, or sandstones laterally equivalent to them, cap small cuestas at many places farther west in the southern part of the area. The upper third of the highest unit consists mainly of shale but contains two or three beds of lignitic shale that form conspicuous outcrop bands associated with manganiferous sandstones at places across the southern part of the area. These sandstones and carbonaceous beds are lenticular, but they are good stratigraphic markers not far below the top of the Nacimiento Formation in much of the southern part of the area. The four units of the Nacimiento were not mapped; however, they persist across the southern part of the area and also for some distance to the north into the San Pedro Foothills.

In the San Pedro Foothills northward from the northern part of T. 22 N., R. 1 W., the proportion of sandstone in the Nacimiento Formation increases. Here and there the lower part of the formation contains thick fine- to coarse-grained sandstone and interbedded olive-green and gray carbonaceous shale. The middle part of the formation is poorly exposed, but it seems to consist mainly of gray to olive-green shale and interbedded lenticular sandstone. The upper part of the Nacimiento consists of several beds of ridge-forming conglomeratic coarse-grained arkosic sandstone interbedded with dark-gray and olive-green shale and shaly sandstone. The upper sandstones of the Nacimiento are lithologically similar to the overlying sandstone of the San Jose Formation; but the sandstones of the Nacimiento are generally thinner, and the dark-gray and olive-green shale with which they are interbedded is unlike the variegated shale of the San Jose. In the San Pedro Foothills between the north fork of the Rio Puerco and the upper part of Arroyo Naranjo, these upper arkosic sandstones of the Nacimiento are cut out by the unconformity at the base of the San Jose. The upper sandstones are present locally in sec. 16 and part of sec. 20, T. 21 N., R. 1 W., where they form low ridges in and west of the Rio Puerco valley, but they seem to be cut out by the unconformity farther south and are not present in the southern part of the area.

The above-described general lithologic character of the Nacimiento Formation seems to persist in the Northern Hogback Belt as far as the north edge of the area. However, where the lower part of the Nacimiento was observed it contains a smaller proportion of sandstone north of the central part of T. 24 N., R. 1 E., than south of there. The zone of the upper conglomeratic arkosic sandstones of the Nacimiento is varied in thickness, and these sandstones are absent locally, as in sec. 20, T. 24 N., R. 1 E., where the upper part of the Nacimiento is cut out because of angular unconformity with the San Jose Formation. North of there the upper conglomeratic arkosic sandstones of the Nacimiento are persistent and are overlain by dark-gray and olive-green sandy shale upon which the San Jose Formation rests at outcrops and in the subsurface of the northern part of the area.

In the subsurface, the lithology of the Nacimiento is similar to that at the surface. In the southern part of the area the Nacimiento consists mainly of shale, but the proportion of sandstone increases northward. The upper conglomeratic arkosic sandstones exposed in the Northern Hogback Belt are fairly persistent in the subsurface in a northwest-southeast direction, but to the south and southwest the sandstones thin and become discontinuous lenticular deposits enclosed in beds which are predominantly shale. Intraformational thickening occurs beneath the zone of the upper conglomeratic arkosic sandstones of the Nacimiento, and these might be locally unconformable on the part of the Nacimiento beneath them. Near the outcrops in the southern part of the area the rocks equivalent to the zone of upper conglomeratic sandstones are cut out by the angular unconformity at the base of the overlying San Jose Formation (pls. 3, 5).

The sandstone beds of the Nacimiento Formation in the Northern Hogback Belt contain much fresh angular orthoclase feldspar and other detritus that indicate a source terrane of Precambrian rocks. Most of the pebbles scattered through the sandstones are quartz and quartzite, but a few pebbles of volcanic rocks were observed in the northeastern part of the area. Thick beds of volcanic conglomerate, tuffaceous sandstone, and weathered tuff, such as characterize the Animas Formation on the northern side of the Central basin in Colorado, were not observed in the Nacimiento Formation. However, many of the sandstone beds contain ferromagnesian minerals, and beds of olive-green chloritic shale are common. The sediments for these rocks might have been derived from the erosion of weathered Upper Cretaceous or Paleocene volcanic rocks that were present in the San Juan Mountains region, or they might have been derived from Precambrian rocks. Beds of bentonitic shale are present at places in the Nacimiento.

Much of the Nacimiento Formation consists of shale, siltstone, and fine- to medium-grained sandstone similar to the Cretaceous rocks of nearby regions and presumably derived by erosion from these rocks. In the southern part of the area there is, at places, an almost chaotic intergrading of soft argillaceous sandstone, siltstone, and clay shale in the lower part of the Nacimiento. Sandstones in the lower part of the Nacimiento contain mixtures of coarse angular grains and fine to medium well-rounded sand containing scattered pebbles. These poorly sorted sediments seem to be a mixture of first-cycle material derived from Precambrian rocks and second- or third-cycle material derived from Cretaceous and older sedimentary rocks that were dumped into a subsiding basin of deposition. Sediments of the middle and upper parts of the Nacimiento are better sorted and more evenly bedded.

The size and shape of the basin of deposition of the Nacimiento Formation and equivalent parts of the Animas Formation of Colorado can be inferred partly from outcrops of these rocks. The Nacimiento Formation and the Animas Formation are preserved only in the Central basin and at places on the southern side of the San Juan Mountains north of the Archuleta anticlinorium (Cross and Larsen, 1935; G. H. Wood, Jr., and others, 1948; Larsen and Cross, 1956). Baltz (1953, p. 44–45) found that angular unconformities and oversteps occur within the Animas Formation and between rocks mapped as the Animas Formation and the Nacimiento Formation along the Hogback monocline south of Durango, Colo. (See fig. 5 in Baltz and others, 1966.) R. B. O'Sullivan and the writer observed similar unconformable relations between the Nacimiento Formation and rocks probably equivalent to the lower part of the Animas and to the Ojo Alamo along the Hogback monocline near the State line north of Farmington, N. Mex. These relations in Colorado and New Mexico indicate that the lower part of the Animas Formation and the Ojo Alamo Sandstone were distributed on at least part of the Four Corners platform, on the flanks of the San Juan dome, and in the Central basin before the major episodes of folding on the west side of the Central basin. However, much of the Animas and Nacimiento Formations in the northwestern part of the basin consists of sediments reworked from Cretaceous rocks and from lower beds of the Animas Formation that were on the Four Corners platform before the folding began. Chaotic bedding and poor sorting of rocks in the Nacimiento and Animas Formations in the basin adjacent to the Hogback monocline near the New Mexico–Colorado line north of Farmington are the result of dumping of sediments eroded from the soft Cretaceous rocks on the Four Corners platform. The poorly sorted rocks seem to have been deposited as fans at the mouths of sediment-laden streams debouching into the Central basin during Paleocene time. Probably, most of the rocks of the upper part of the Animas and Nacimiento Formations were not deposited very far west of the Hogback monocline, because the overstepping relations of these rocks in the basin near the Hogback indicate several periods of uplift and erosion of the Four Corners platform during deposition in the basin.

The northern limit of the early Tertiary (Nacimiento and Animas) depositional basin is not known with certainty, since no unconformities have been reported within Animas rocks on the northern and northeastern edges of the Central basin. North of the San Juan Basin the Animas is overlain with angular unconformity by the Blanco Basin Formation of Oligocene(?) age (Larsen and Cross, 1956, p. 61), which laps onto Cretaceous and older rocks in the southeastern San Juan Mountains. The Blanco Basin Formation is overlain by the middle and upper Tertiary volcanic rocks which compose much of the present San Juan Mountains.

The main volcanic facies of the Animas Formation is in the northwestern and north-central parts of the Central basin. The McDermott Member (Baltz, 1953, p. 37–41; Barnes and others, 1954) of the Animas is Cretaceous in age and seems to have been erupted from centers in the vicinity of the laccolithic domes of the La Plata Mountains northwest of Durango, Colo., as indicated by the directions of coarsening and thickening of the volcanic breccia of the member. Larsen and Cross (1956, p. 57) suggested that the volcanic sediments of the main part of the Animas are about the same age as some of the older Tertiary intrusive centers in the northern and northwestern parts of the San Juan Mountains. The abundant granitic and metamorphic detritus in the Animas must have been derived from Precambrian rocks, probably from the San Juan dome and the Brazos uplift. The Brazos uplift was probably part of a geanticline (fig. 7) that included the Sangre de Cristo uplift prior to the formation of the Rio Grande trough in Miocene time (Baltz, 1965, p. 2065–2066, 2072). The Sangre de Cristo uplift shed detritus into the Raton basin east of the uplift in Paleocene time (Johnson and Wood, 1956); probably, therefore, the geanticline was the northeast boundary of the Animas and Nacimiento depositional basin. The southeast edge of the basin is unknown. The writer found no evidence that would indicate that the Nacimiento uplift was tectonically active during deposition of the Nacimiento Formation (and equivalent rocks of the Animas Formation), and these rocks may have been distributed across this region prior to early Eocene time.

The southern margin of the Nacimiento and Animas depositional basin also is unknown. Possibly the Zuni and Defiance uplifts were tectonically active and defined a southern and southwestern limit of the depositional basin. The angular unconformity between the Nacimiento and the overlying Eocene San Jose Formation (pl. 3) in the report area indicates that, by the end of the Paleocene at least, the southern limb of the San Juan Basin was being formed, thus probably indicating that the Chaco slope and Zuni uplift were active. In the Datil Mountains of west-central New Mexico, south of the Zuni uplift, the Mesaverde Group is overlain with angular unconformity by the Baca Formation of probable Eocene age (Wilpolt and others, 1946; Bachman and others, 1958), evidence that also may indicate that the region southwest of the San Juan Basin was not a part of the Paleocene basin of deposition.

To summarize, the two sedimentary facies of the Nacimiento Formation in the report area appear to have been deposited in slightly different environments, and the shale facies in the southern part of the area probably was derived mainly from different source areas than the coarse sandstone facies of the northern part of the area. The coarse sandstone facies of the Nacimiento Formation and equivalent rocks of the Animas Formation are part of a huge apron of volcanic and orogenic debris that was derived from rising highlands lying north and northeast of the San Juan Basin and was spread to the southwest into the basin. The shaly facies of the Nacimiento, which is present across the southwest third of the Central basin, is composed partly of finer grained material deposited at the distal edges of the apron, but the shaly facies consists in large part of reworked Cretaceous sediments eroded from the Four Corners platform and probably from the southern part of the Chaco slope.

The lithology and vertebrate fossils of the Nacimiento Formation indicate that the sediments were deposited in a terrestrial environment. The lenticular sandstones are stream-channel deposits, and the clay and siltstone were deposited on floodplains and alluvial fans, and in ephemeral lakes. The basin of deposition may have been poorly drained and swampy. The shaly facies in particular seems to have been deposited in a paludal and lacustrine environment; some of the rocks are highly carbonaceous in places, and they contain not only fossil mammals but also fossil fish and a reptilian fauna characterized by crocodiles, the aquatic lizard *Champsosaurus*, and many genera and species of turtles (Gilmore, 1919; see also Sinclair and Granger, 1914, p. 309–310, 313). The pollen and spore flora of the Nacimiento (Anderson, 1960, p. 8) also indicates deposition in a lowland environment not far from temperate upland environments.

CONTACTS

Where the contact of the Nacimiento Formation and underlying Ojo Alamo Sandstone was observed, no evidence of unconformity was discovered. The contact seems to be gradational through a few inches to several feet of sandy shale. Evidence of intertonguing in the subsurface was presented in the discussion of the Ojo Alamo.

The contact of the Nacimiento and the overlying San Jose Formation is one of angular and erosional unconformity throughout most of the area. The erosional nature of the contact is apparent at most exposures, and at many places coarse-grained pebble-bearing sandstone of the San Jose rests in channels cut in the upper part of the Nacimiento.

In a branch canyon of one of the tributaries of the upper Rio Puerco in the SW¼NE¼SW¼ sec. 11, T. 21 N., R. 1 W., the angular nature of the contact between the San Jose and Nacimiento Formations is apparent. Here beds of the Nacimiento are only 537 feet thick. They are overturned and dip about 85° E. The basal sandstone of the San Jose dips about 69° W. at the contact. About 75 feet west of the contact, the dip of the San Jose flattens abruptly to about 10° W. On the north wall of the deep canyon just north of these exposures, the steeply dipping basal sandstone of the San Jose cuts out almost 200 feet of beds of the Nacimiento Formation between the bottom of the canyon and the top of the north wall of the canyon.

In the SE¼SW¼ sec. 23, T. 22 N., R. 1 W., faulted fossil-bearing shale and sandstone of the San Jose rest unconformably on rocks as old as the Lewis Shale. These outcrops were first observed and their significance was recognized in 1955 by R. L. Koogle, who kindly showed them to the writer.

Farther north, exposures are such that the unconformable relations cannot be observed directly. However, the irregular thickening and thinning and the absence of the upper conglomeratic, arkosic sandstone unit of the Nacimiento at places in the San Pedro Foothills and Northern Hogback Belt (pl. 2) indicate that folding and erosion occurred here after deposition of the Nacimiento. Near the center of sec. 20, T. 24 N., R. 1 E. (and in the subsurface at the Reading and Bates 1 Duff well, sec. 24, T. 24 N., R. 1 W.), the Nacimiento is only about 600 feet thick, and the upper conglomeratic, arkosic sandstones of the Nacimiento are not present beneath the San Jose, apparently because of angular unconformity. These upper beds of the Nacimiento are present, however, in secs. 7 and 8, T. 24 N., R. 1 E., where the Nacimiento is at least 1,250 feet thick. North of Arroyo Blanco, the contact of the San Jose and the Nacimiento is one of erosional unconformity, but no discordance of dip was observed. The north-northwest-plunging anticlinal noses on the eastern margin of the basin seem to have been formed mainly in late Paleocene time after the deposition of the Nacimiento Formation, as shown by the angular unconformity with the overlying San Jose Formation of early Eocene age. Further folding occurred also during and after the deposition of the San Jose.

In the subsurface the southward thinning of the Nacimiento Formation is partly intraformational thinning. However, correlation of lithologic units, penetrated in deep wells shows that the basal sandstone of the San Jose Formation bevels successively younger rocks of the Nacimiento from north to south, and the contact is thus one of erosion and slight angular unconformity. (See pls. 3, 5.) This indicates that the southwest limb of the Central basin began to be formed in late Paleocene time.

AGE AND CORRELATION

The Nacimiento Formation, of Paleocene age, contains several of the classic terrestrial vertebrate faunas of that epoch of the Tertiary Period. The history of the discovery and identification of these faunas has been discussed by Gardner (1910, p. 703–713), Sinclair and Granger (1914, p. 298), Matthew (1937), and Simpson (1959, p. 1–3).

The first fossil mammals found in the Puerco Marls of Cope (1875) were collected by David Baldwin west of the present area and were described as lowest Eocene by Cope (1881). Gardner (1910) referred the Nacimiento Group to the Eocene also. Sinclair and Granger (1914, p. 313) stated that both the Puerco and Torrejon Formations had been referred to as basal Eocene, but that "more recently, Paleocene seems to be growing in favor." Matthew (1914, p. 381–382) discussed the use of the term "Paleocene," stating, "The typical and best known Paleocene fauna is that of the Puerco and Torrejon formations, Nacimiento terrane, of New Mexico." He indicated that the Puerco was of earliest Tertiary age. Apparently, Matthew (1921, p. 220) changed his mind later and decided the Paleocene was Cretaceous rather than being part of the Tertiary. Bauer (1916, pls. 64, 69) assigned the Puerco and Torrejon to the Tertiary, as shown by his map symbol, but he did not express a direct opinion in the text of his paper. Gilmore (1919, p. 9) considered the faunas to be "basal Eocene." Reeside (1924, p. 43–44) reviewed the fossil evidence and concluded that the Puerco and Torrejon were early Tertiary in age and assigned them to the Eocene. Dane (1936, p. 122) also assigned the Puerco (?) and Torrejon to the Eocene, but in his later (1946) work he assigned the Nacimiento Formation to the Paleocene and Cretaceous (?).

The Puerco and Torrejon faunas are now accepted by most paleontologists as the standards of reference for North American terrestrial faunas of early and (part of) middle Paleocene age, respectively. H. E. Wood and his collaborators (1941) proposed that the Puercan and Torrejonian be designated as provincial ages of the early and middle parts of the Paleocene Epoch of the Tertiary Period. Late Paleocene fossils occur in the northern part of the Central basin southeast of Durango, Colo. in beds mapped as the Wasatch Formation by Reeside (1924), and Cross and Larsen (1935). The rocks containing the fossils were called the Tiffany Beds by Granger (1917, p. 829). The Tiffany fauna was described by Granger (1917), by Matthew and Granger (1921), and by Simpson (1935a, b, c). Tiffanian now designates a provincial age of the late Paleocene (H. E. Wood and others, 1941; Simpson, 1948, p. 275–276).

Torrejon fossils have been found in the upper part of the Nacimiento Formation in Encino Wash (a tributary of Arroyo Torrejon, which is also called Torreon Arroyo on some maps) and upper Arroyo San Ysidro in the southern part of the area. However, until recently no fossils had been reported from the Nacimiento Formation at its type locality at the southern end of Mesa de Cuba. Recently Simpson (1959) reported Torrejon fossils west of Arroyo Chihuila (Arroyo Chijuilla on pl. 1), several miles west of the south end of Mesa de Cuba and also northeast of Cuba. These fossils are distributed vertically from near the top of the Nacimiento to within 100–125 feet of what Simpson considered to be the base of the formation. Puerco mammal fossils have not been found in the area of the present report, nor have Tiffany fossils been found. Thus, on the basis of the positive evidence presented by mammal fossils, the Nacimiento Formation of the present area can be dated only as middle Paleocene.

The base of the Nacimiento (and top of the Ojo Alamo) is probably below the level indicated by Simpson in his section at the type locality of the Nacimiento, and beds totaling more than 200 feet in thickness in the lower part of the type Nacimiento have not yielded fossils. The lithology of the lower part of these beds is very similar to that of the beds in the lower 75 feet of the Nacimiento which contain Puerco fossils at Kimbetoh Arroyo and Ojo Alamo Arroyo west of the report area (Sinclair and Granger, 1914, especially fig. 2). Thus it seems probable that beds of Puerco (early Paleocene) age are present in the lower part of the Nacimiento in the vicinity of the Rio Puerco and elsewhere in the area of this report. This is supported by the fact that the "Ojo Alamo 2" and "Nacimiento 1" pollen and spore floras collected by Anderson (1960) near the type locality of the Nacimiento, are similar to floras collected from rocks containing Puerco mammals near the type locality of the Ojo Alamo Sandstone (Baltz and others, 1966, p. D17).

Dane (1946) expressed the opinion that the rocks mapped as the Wasatch Formation in the northeastern part of the San Juan Basin include beds laterally equivalent to the Tiffany Beds of late Paleocene age. He pointed out that the Tiffany fauna has not been found in New Mexico but stated that vertebrate faunas of Eocene age have not been reported from the lowest 500 feet or more of the Wasatch Formation in the southeastern part of the basin, and the age of these beds is undetermined. However, Simpson (1948, p. 377) postulated that there is a hiatus between the Nacimiento Formation and the San Jose Formation (Wasatch of Dane and previous authors), reasoning that the Nacimiento is probably no younger than middle Paleocene. He reported that he had found Eocene fossils within 50 feet of the base of the San Jose Formation. In 1959 Simpson confirmed his earlier (1948) statement concerning the age of the upper part of the Nacimiento in the southern part of the report area. The present writer found good evidence of an angular unconformity between the Nacimiento and San Jose in the area between secs. 7 and 20, T. 24 N., R. 1 E. The sandstone mapped as the basal part of the San Jose by the writer is also the unit judged to be the base of the San Jose by Simpson (oral commun., 1959). After tracing and mapping the base of the San Jose, the writer believes that the sandstone beds at the base of the San Jose at the type locality of the Nacimiento are at about the same stratigraphic position as those in sec. 20, T. 24 N., R. 1 E., where Eocene fossils are present near the base of the San Jose. This conclusion is supported also by subsurface correlations of the San Jose. These correlations also show a southward beveling of the upper part of the Nacimiento by the San Jose. Angular unconformity was observed at the base of the San Jose in sec. 11, T. 21 N., R. 1 W. Thus, it seems probable that the Nacimiento Formation exposed in most of the area is of early and middle Paleocene age and is overlain unconformably by lower Eocene beds of the San Jose as suggested by Simpson (1948).

In the northern part of the area the Nacimiento is locally almost 1,800 feet thick. This is more than twice as thick as the Nacimiento exposed in the southern part of the area where Torrejon fossils are present near the top of the formation. Thus, the upper beds of the Nacimiento Formation in the northern part of the report area may be of Tiffany (late Paleocene) age. The upper arkosic conglomeratic sandstones of the Nacimiento are lithologically similar to some of the beds containing the Tiffany fauna at the Mason quarry north of Tiffany Station in Colorado (fig. 1). The Tiffany Beds in Colorado contain large quantities of tuffaceous material and olive-green shale more similar to the Animas Formation than to typical San Jose rocks. The rocks several hundred feet above the beds containing the Tiffany fauna are more similar to typical San Jose rocks than are the Tiffany Beds. Barnes (1953) mapped (as bed "d") the rocks specified by Reeside (1924, p. 55–56) to be the basal arkose of the Wasatch at the northern end of the H–D Hills about 12 miles north-northeast of the Mason quarry. Reeside had specified that Tiffany fossils occurred in the lower part of the beds he mapped as Wasatch. However, Barnes found that the base of the Wasatch (bed "d" of Barnes) as shown by Reeside's stratigraphic section could be traced southward to the south end of the H–D Hills, and that the Mason quarry with its Tiffany fossils is about 280 feet below the position of rocks mapped by Reeside as basal part of the Wasatch at the north end of the H–D Hills. Thus, Reeside's (1924, pl. 1) lower contact of the Wasatch in the valley of Los Pinos River north of Ignacio, Colo., is considerably lower stratigraphically than it is at the north end of the H–D Hills, and Reeside included in the Wasatch the Tiffany Beds, whose lateral equivalents he excluded from the Wasatch elsewhere. Reconnaissance tracing of the base of the San Jose Formation in much of the western and northern parts of the basin seems to indicate that the Tiffany Beds should be included in the Animas Formation and that they probably are below the stratigraphic position of the base of the typical San Jose. Further detailed tracing of beds to supplement the observations of Barnes (1953) would probably solve this problem.

To summarize, rocks mapped as the Nacimiento Formation in the report area are of middle (Torrejon) and probably early (Puerco) Paleocene age at the surface of the southern part of the area. The upper part of the Nacimiento north of Arroyo Blanco in the Northern Hogback Belt might be of late (Tiffany) Paleocene age because the Nacimiento Formation is so much thicker in the northern part of the area than in the southern part. The Nacimiento Formation of the report area correlates with most of the Animas Formation in Colorado, but in the northeastern part of the San Juan Basin the lower beds of the Animas of Dane (1946, 1948) are equivalent to parts of the Ojo Alamo Sandstone, and in places they may be equivalent to parts of the unit mapped as undivided Fruitland Formation and Kirtland Shale in the report area.

SAN JOSE FORMATION

DEFINITION

Resting on the Nacimiento Formation with erosional and angular unconformity throughout the area is a sequence of sandstone and shale mapped by previous investigators as the Wasatch Formation. Originally, the names Green River and Wasatch, were applied to these rocks by Cope (1875, 1877), who did not map the area but found Eocene fossils similar to those of the Wasatch Formation of Wyoming. Cope (1875) found the Eocene fossils in two horseshoe-shaped areas of badlands south of "Canoncita de las Vegas" (now known as Canoncito de las Yeguas) in the northeastern part of the report area. In his excellent summary of the history of the terminology of the Eocene rocks of the San Juan Basin, Simpson (1948, p. 262) identified the horseshoe-shaped badlands tentatively as the upper parts of Arroyo Blanco, and Arroyo Almagre (Almagre Arroyo on pl. 1 of the present report).

In his first (1875) description of the rocks which he later (1877) called "Wahsatch," Cope described fossiliferous "variegated marls" lying above the massive sandstones in which "Canoncita de las Vegas" (Canoncito de las Yeguas) is cut. He pointed out that the variegated beds closely resemble the Wasatch beds of Bear River, Wyo. These variegated beds he definitely intended to include in the "Wahsatch formation," but it is not certain that he intended to include the underlying massive sandstones also in the "Wahsatch." The massive sandstones are underlain by rocks described by Cope as being "marls" of "mixed black and green colors" (the Nacimiento Formation) which, he stated, are the lowest beds of the Eocene. Cope traced these beds southward for "40 miles" (actually about 25 miles) to the vicinity of Nacimiento (present-day Cuba). To these rocks he applied the name "Puerco marls," and he seems to have considered the overlying thick sandstone (in turn overlain by the "variegated marls") west of the Rio Puerco as being the same as the sandstone beneath the variegated beds at "Canoncita de las Vegas." At any rate, by implication the sandstones were included with the "Wahsatch" variegated beds, and they definitely were not included with the underlying beds described as the "Puerco marls." This terminology (emended to Wasatch) was generally accepted and perpetuated by most later workers in the San Juan Basin, although several revisions of nomenclature were proposed, mainly by C. R. Keyes. (See Simpson, 1948, p. 269–271, 273–280, for detailed discussion of the history of the terminology.)

Although the name Wasatch Formation was used by later investigators for rocks in the report area, different investigators included different rocks in the formation. Gardner (1909, pl. 2) mapped the thick variegated shales and interbedded sandstones (the "variegated marls" described by Cope) lying north of Mesa de Cuba as the Wasatch Formation. The thick sandstones at Canoncito de las Yeguas were excluded from the Wasatch by Gardner (1910, pl. 2), although in quoting Cope (1875), he (1910, p. 703–705) inserted the name Wasatch in brackets after Cope's description of the sandstones at Canoncito de las Yeguas. The thick conglomeratic sandstones of Mesa de Cuba (fig. 11) and other mesas and cuestas farther west were mapped as the upper part of the Puerco Formation by Gardner (1909), and he later (1910) specified them to be the Torrejon Formation. Renick (1931, p. 52) accepted Gardner's classification of the Torrejon and Puerco and included the sandstones of Mesa de Cuba in the Torrejon. Renick (1931, pl. 1) mapped the base of the Wasatch at about the same stratigraphic position north of Cuba as Gardner did (1909, pl. 2). However, Renick (1931, p. 55, pl. 1) showed that Gardner's reconnaissance mapping of the base of the Wasatch along the foot of San Pedro Mountain was largely incorrect.

Dane (1936, p. 125, and pl. 39) mapped the Wasatch to include not only the variegated shale mapped as Wasatch by Gardner and by Renick, but also to include the thick sandstones capping Mesa de Cuba and the mesas and cuestas to the west that Gardner and Renick had included in the Torrejon Formation. Dane (1946, 1948), and Wood and Northrop (1946) placed the lower contact of the Wasatch at the base of thick arkosic sandstone lying under the variegated shales in the San Pedro Foothills and Northern Hogback Belt.

Simpson (1948, p. 277–280) proposed that the name Wasatch be replaced in the San Juan Basin by a new name, San Jose Formation, stating that these rocks were deposited in an entirely different sedimentary basin from that of the type Wasatch in Wyoming and Utah, and that the age spans, although overlapping, were not the same for the two formations. A specific locality of the San Jose Formation was designated (Simpson, 1948, p. 281) as the badlands area in the drainage of San Jose Creek along and near the Continental Divide about 1 mile northwest of Regina, N. Mex., in sec. 29, T. 22 N., R. 1 W. He also designated a type region, which is the eastern part of the report area between Canoncito de las Yeguas and Cuba, where the San Jose consists of several major intergrading lithologic facies. These were recognized by Dane (1946) and by Simpson (1948), both of whom described the stratigraphic relations but did not map the facies of the formation. Simpson (1948, p. 367–374) designated the facies as the "sandstone facies of Yeguas Canyon," and the "Almagre" and "Largo clay facies." The Almagre and Largo clay facies of Simpson are the beds containing the early Eocene Almagre and Largo vertebrate faunas named by Granger (1914, p. 205–207).

The San Jose Formation of the present report is the San Jose as defined by Simpson (1948). The lower contact is the same as that specified by Simpson (1948, p. 367; also, oral commun., 1959) in sec. 20, T. 24 N., R. 1 E., and mapping indicates that this contact is equivalent to the contact at the base of the sandstones capping Mesa de Cuba, and smaller mesas about 1 mile northwest of Cuba. The sandstones capping Mesa de Cuba were specified by Simpson (1948, p. 367) to be within the San Jose; thus the San Jose is the same unit as the Wasatch mapped by Dane (1936) and by Wood and Northrop (1946). The San Jose of Fassett (1966) on Mesa de Cuba is the San Jose of the present report. However, west of Arroyo Chijuilla, Fassett (1966) and Hinds (1966) mapped the base of their San Jose at the base of a ledge-forming sandstone which is locally 200–250 feet stratigraphically above the base of the San Jose of the present report. In the northeastern part of the area, the base of the San Jose, as mapped for the present report, is the base of the Wasatch mapped by Dane (1948) in the northeastern part of the San Juan Basin.

During the present investigation four lithologic units were distinguished and mapped as members of the San Jose Formation. Throughout the area the lower part of the San Jose consists mostly of conglomeratic sandstone here named the Cuba Mesa Member. In most of the southern two-thirds of the area, the Cuba Mesa Member is overlain by drab-colored variegated shale and interbedded soft to hard sandstone here named the Regina Member of the San Jose Formation. In the northern part of the area, the Cuba Mesa Member is overlain by a thick sequence of sandstone which is here named the Llaves (pronounced yah′-ves) Member of the San Jose Formation. The lower part of the Llaves Member intertongues with and grades southward into the Regina Member. Near the Continental Divide in the northeastern part of the area, the upper part of the Llaves Member grades southward and westward into red shale and interbedded sandstone which are here named the Tapicitos Member of the San Jose Formation. A persistent medial sandstone unit of the Llaves Member separates the Regina Member from the Tapicitos Member on the northern part of the Tapicitos Plateau. North of the report area an unnamed member has been recognized but not mapped.

EXTENT AND THICKNESS

The San Jose Formation is the surface formation in most of the Central basin of the San Juan Basin and is at the surface in most of the present area of investigation. The San Jose has been eroded deeply, and the differential resistance to erosion of its units of sandstone and shale produced a varied and, in places, rugged physiography. Because of this physiography, the thickness of the preserved parts of the San Jose varies considerably.

In the Penistaja Cuestas the thickness of the San Jose Formation ranges from less than 200 feet at the south to about 750 feet at the high mesa on the Continental Divide in the north-central part of T. 20 N., R. 4 W. This thickness is estimated partly on information from the Skelly Oil 1 White well in sec. 8, T. 21 N., R. 4 W. North of Mesa de Cuba, the composite thickness of the San Jose is about 1,430 feet along State Highway 44 between sec. 20, T. 21 N., R. 1 W., and the high mesa on the Continental Divide in sec. 28, T. 22 N., R. 2 W. The San Jose is estimated to be about 800 feet thick in the valley of San Jose Creek near the southwest corner of T. 22 N., R. 1 W. In the San Pedro Foothills in the SW¼ sec. 2 and SW¼ sec. 3, T. 21 N., R. 1 W., the preserved part of the San Jose is about 865 feet thick. In the Yeguas Mesas region the San Jose is about 1,650 feet thick, as determined from composite sections.

In the north-central part of the area, on the Tapicitos Plateau, the San Jose Formation is 1,700–1,800 feet thick, as determined from logs of wells in T. 26 N., R. 2 W. Farther south on the Tapicitos Plateau the base of the San Jose rises structurally, and its upper beds have been eroded. The thickness of the San Jose in the southern part of T. 24 N., R. 2 W., is 1,300 feet or less.

In the Largo Plains more than half the San Jose Formation has been removed by erosion. The formation is thinnest along Canon Largo and the western parts of its tributaries, where the Cuba Mesa Member is exposed because overlying beds have been stripped away by erosion. Near Otero Ranch in the southwestern part of T. 24 N., R. 5 W., the San Jose ranges in thickness from a little less than 200 feet to about 300 feet as determined from logs of wells. In the broad washes south of Canon Largo the San Jose is 200–400 feet thick. In the eastern part of the Largo Plains, in the northern part of T. 22 N., R. 3 W., the San Jose is 800–900 feet thick.

LITHOLOGY

CUBA MESA MEMBER

Throughout the area, and elsewhere in the San Juan Basin, the lower part of the San Jose Formation consists of conglomeratic arkosic sandstone containing lenticular reddish, green, and gray shale. These rocks are here named the Cuba Mesa Member of the San Jose Formation for exposures on the upper slopes and top of Mesa de Cuba (known also as Cuba Mesa) west of the Rio Puerco in T. 21 N., Rs. 1 and 2 W. The type section of the member was measured along State Highway 44 northwest of Cuba. The base of the section is in the NE¼NW¼ sec. 20 (fig. 12), and the section was measured westward across secs. 17, 8, 7, and 6, T. 21 N., R. 1 W., and secs. 1 and 2, T. 21 N., R. 2 W. The locality (2) of measurement of the type section is shown on the geologic map (pl. 1), a detailed description is given at the end of this report, and the section is shown graphically on plate 2.

At the type section the Cuba Mesa Member is about 782 feet thick; it consists mainly of buff and yellow, rusty-weathering tangentially crossbedded arkosic coarse-grained conglomeratic sandstone. The lower part contains several thin lenses of gray and purplish-gray sandy shale. The upper third of the member is split by two tongues of the Regina Member (pls. 1, 2). These tongues, which consist of gray and pale-red soft shale containing thin beds of soft sandstone, wedge out into the Cuba Mesa Member south of State Highway 44. The Cuba Mesa Member is overlain by the main part of the Regina Member, which is composed of variegated shale and soft sandstone and contains several interbedded thick sandstones similar to those of the Cuba Mesa Member. The Cuba Mesa Member

FIGURE 12.—Typical exposures of sandstone of lower part of Cuba Mesa Member of San Jose Formation, NW¼ sec. 20, T. 21 N., R. 1 W. Banded shale on slope beneath Cuba Mesa Member is Nacimiento Formation.

intertongues with the Regina Member at many other places in the area as shown on plates 1 and 2.

The Cuba Mesa Member is much thicker at the north end of Mesa de Cuba and in the subsurface northwest of the mesa (pl. 5) than elsewhere in the area. In the southern part of the area near Arroyo Chijuilla, the upper half of the Cuba Mesa Member is split into two tongues which wedge out westward into the Regina Member near the southwest corner of T. 21 N., R. 2 W. (strat. section, pl. 2).

The lower half of the Cuba Mesa Member persists to the west and is estimated to be about 300 feet thick in sec. 33, T. 21 N., R. 2 W. West of there it is split into two persistent units of sandstone separated by a thick unit of variegated shale mapped as a tongue of the Regina Member (pl. 2). The lower sandstone unit of the Cuba Mesa Member is locally as much as 50–75 feet thick, contains a few pebbles and some silicified logs, and forms a low ledge or weak cliff above the Nacimiento Formation. In the south-central part of the area the lower sandstone unit locally contains interbedded shale and is soft and poorly exposed; there are, however, sufficient outcrops to determine its persistence. Westward from Arroyo Chijuilla, the lower sandstone unit maintains about the same stratigraphic position relative to the conspicuous zones of lignitic shale and manganiferous sandstones of the upper part of the Nacimiento Formation. The base of the lower sandstone unit of the Cuba Mesa Member is a channeled erosion surface which can be observed at many places. The irregular base accounts partly for the variations in thickness of the unit. The upper sandstone unit of the Cuba Mesa in the south-central part of the area forms a prominent escarpment above the tongue of the Regina Member and is more than 60 feet thick. At places the base of this sandstone is a channeled erosion surface. In sec. 25, T. 21 N., R. 5 W., the tongue of the Regina Member wedges out, and the two sandstone units of the Cuba Mesa Member merge.

A ledge-forming coarse-grained sandstone tongue of the Cuba Mesa Member is interbedded in the lower part of the Regina Member in parts of T. 21 N., Rs. 3 and 4 W., in the south-central part of the area (pl. 1). In sec. 34, T. 21 N., R. 4 W., this sandstone also merges with the underlying main part of the Cuba Mesa Member as an intervening tongue of the Regina Member wedges out. West of here this tongue of shale of the Regina Member is present locally, but it wedges out in sec. 19, T. 21 N., R. 4 W., and farther northwest the Cuba Mesa Member is a massive unit of cliff-forming thick-bedded sandstone about 300 feet thick that contains very little shale except near the base. Lenticular sandstones lithologically similar to those of the Cuba Mesa Member occur in the lower part of the overlying Regina Member.

Northeastward from the type section at the north end of Mesa de Cuba, the two sandstone tongues of the upper third of the Cuba Mesa Member wedge out into the sandy variegated shale of the Regina Member. The lower part of the Cuba Mesa Member, about 490 feet thick, is split into two units of sandstone by a tongue of variegated shale of the Regina Member. Both units of sandstone persist as far north as the SW¼ sec. 2, T. 21 N., R. 1 W. (pl. 2) where the lower sandstone, containing several beds of shale, is 152 feet thick, the tongue of the Regina Member is about 200 feet thick, and the overlying sandstone of the Cuba Mesa Member is only 37 feet thick. North of here the upper of the two sandstones of the Cuba Mesa Member either wedges out or is represented by thin soft lenticular sandstone included with the Regina Member. The lower sandstone unit of the Cuba Mesa persists to the north in the San Pedro Foothills and the Northern Hogback Belt. This unit, probably equivalent to only the lower 150–200 feet of the Cuba Mesa Member at the type section, is folded sharply in the San Pedro Foothills and dips steeply west or is vertical. Northward from sec. 20, T. 24 N., R. 1 W., the dip of the Cuba Mesa Member becomes less steep.

In the eastern part of the area the thickness of the Cuba Mesa Member varies because of the erosional and angular unconformity at its base. In the San Pedro Foothills this relationship is well exposed in the north wall of the canyon in the SW¼ sec. 11, T. 21 N., R. 1 W. Here the lower unit of sandstone of the Cuba Mesa Member is about 180 feet thick at the bottom of the canyon; updip at the top of the ridge, however, it is about half as thick. The thickness of the Cuba Mesa Member is difficult to measure in the San Pedro Foothills and southern part of the Northern Hogback Belt, but in much of these sectors it is probably less than 150 feet thick.

In T. 24 N., R. 1 E., the Cuba Mesa Member consists of three sandstone units separated by tongues of variegated shale of the Regina Member (pl. 2). The medial and upper sandstone units are tongues that wedge out southward into the Regina Member, but the upper unit persists farther south than the medial unit. In the SW¼NE¼ sec. 1, T. 25 N., R. 1 E., the persistent lower sandstone of the Cuba Mesa Member is 27 feet thick, the lower shale tongue of the Regina is 51 feet thick, the medial sandstone unit of the Cuba Mesa is 61 feet thick, the upper tongue of the Regina is 144 feet thick, and the upper sandstone unit of the Cuba Mesa, containing thin shale beds, is 65 feet thick. Logs of wells in the vicinity of Arroyo Blanco indicate that the three sandstone units of the Cuba Mesa Member persist from some distance to the west in the subsurface and then merge into a thick unit that is mainly sandstone. At the surface, in sec. 30, T. 25 N., R. 1 E., the shale tongues of the Regina Member become thin, and the three sandstone units of the Cuba Mesa Member merge northward to form a unit that is mostly sandstone and is 335 feet thick in the SW¼NE¼ sec. 18, T. 25 N., R. 1 E. (fig. 14).

At the east side of the Yeguas Mesas north of Canoncito de las Yeguas, the Cuba Mesa Member is overlain by the Llaves Member, which consists mainly of sandstone. The upper contact of the Cuba Mesa Member is distinguishable, however, and this was mapped at the base of a unit of red shaly sandstone and sandy shale which is the lower part of the Llaves Member.

In the western part of the area, the Cuba Mesa Member crops out along Canon Largo and the western parts of its tributary canyons, where it forms massive cliffs of sandstone. The average thickness of the Cuba Mesa Member is about 200 feet, as estimated from well logs. The contact of the Cuba Mesa Member and the underlying Nacimiento Formation is not exposed in the western part of the area, but it is exposed in Canon Largo west of the Jicarilla Apache Indian Reservation. Near Otero Ranch the Cuba Mesa Member is overlain by a thin unit of light-gray and variegated shale assigned to the Regina Member. To the north this lowest shale unit of the Regina is replaced laterally by sandstone, and along Tapicitos Creek in the southwestern part of T. 26 N., R. 5 W., the Cuba Mesa Member is overlain by lenticular sandstone and shale equivalent to the lower shale unit of the Regina Member that rests on the Cuba Mesa Member near Otero Ranch.

Rocks assigned to the Cuba Mesa Member are 200–250 feet thick in the subsurface of most of the area. Locally, the lower part of the overlying Regina Member contains thick lenticular sandstone similar to the Cuba Mesa Member, but separated from it by units of shale. The thick upper tongues of sandstone of the Cuba Mesa Member persist northwestward in the subsurface for 8–10 miles from the northern part of Mesa de Cuba, but the sandstones are separated by westward-thickening tongues of shale of the Regina Member, and the sandstones become thin and lenticular as they do at the surface. Where the sandstones seem to be lenticular, they are assigned to the Regina Member (pl. 5). In the subsurface of the northern part of the area, the Cuba Mesa Member thickens northward as the result of merging with northward-thickening tongues of sandstone in the lower part of the Regina Member, as it does at the surface in the northeastern part of the area. Rocks assigned to the Cuba Mesa Member in the subsurface of the northern part of the area (pl. 3) are arbitrarily distinguished from the overlying Llaves Member on the basis of their thickness (about 350 ft), which is comparable with the thickness (335 ft) of the Cuba Mesa Member at the surface north of Canoncito de las Yeguas.

The sandstone of the Cuba Mesa Member is coarse grained to very coarse grained and contains granules, pebbles, and cobbles. The coarsest part of the Cuba Mesa Member is in the northeastern part of the area. Most of the sand grains are angular to subangular, but the pebbles are commonly well rounded. The sand is mainly quartz, but fragments of feldspar and chert are common at all localities. Most of the pebbles are gray quartzite and quartz, but pebbles of granite, pink quartzite, and pink, red, gray, and buff chert are common also. A few pebbles of volcanic rock were observed. At most places the sandstone beds are tangentially crosbedded, and they seem to be stream-channel deposits. Silicified and carbonized logs are common in the sandstone at some places. The Cuba Mesa Member was probably deposited by streams flowing to the west and southwest from highlands east and northeast of the present San Juan Basin, as indicated by eastward coarsening of the rocks. These highlands must have been composed mainly of granite and metamorphic rocks of Precambrian age. The locally very thick sandstones of the Cuba Mesa Member at the type locality, and also a short distance west of the report area, are stream deposits that may have been derived from source areas southeast of the basin also. The source areas for most of the Cuba Mesa Member were probably the same as those for part of the Nacimiento Formation, that is, the Laramide geanticline (fig. 7) that included the Brazos and Sangre de Cristo uplifts (Baltz, 1965, p. 2065–2066, 2072), and perhaps part of the San Juan dome. The numerous quartzite pebbles and cobbles in the northeastern part of the area could have been derived from the extensive Precambrian quartzite terranes of the Brazos uplift described by Just (1937).

REGINA MEMBER

In the southern two-thirds of the area, the Cuba Mesa Member is overlain by a thick sequence of clay shale and siltstone containing interbedded soft sandstone and some hard ledge-forming sandstone. These rocks are here named the Regina Member of the San Jose Formation for exposures near the town of Regina. The rocks are best exposed east of the Continental Divide in the badlands of the drainage basin of Arroyo Blanco in T. 24 N., R. 1 E. and R. 1 W. The Regina Member consists partly of the rocks described in stratigraphic sections 2 and 3 of Simpson (1948, p. 371–374), which are part of his composite section of the San Jose Formation. Simpson measured these sections on the southern rim of Arroyo Blanco and near the Continental Divide in sec. 8, T. 23 N., R. 1 W. Simpson's stratigraphic sections (shown graphically on pl. 2) do not include the lower part of the San Jose, which he estimated (1948, p. 374) to be 200–300 feet below the base of his stratigraphic section 3. However, the results of the present investigation indicate that the base of Simpson's lowest stratigraphic section may be 700–800 feet above the base of the San Jose. For this reason the type section of the Regina Member is here specified to be in the badlands and steep slopes to the west in the SW¼ sec. 31, T. 25 N., R. 1 E., and the SE¼ sec. 36, T. 25 N., R. 1 W. The locality of measurement (3b) is shown on the geologic map (pl. 1), a detailed description of the stratigraphic section is given at the end of this report, and the section is shown graphically on plate 2.

At the type section, the main part of the Regina Member is about 575 feet thick, and it rests conformably on pebble- and cobble-bearing coarse-grained arkosic sandstone of the Cuba Mesa Member. The total thickness of the Regina Member, including the thickness of the two tongues of the Cuba Mesa Member measured at locality 3a (SW¼NE¼ sec. 31, T. 25 N., R. 1 E.), is about 900 feet in the vicinity of the type section (fig. 13).

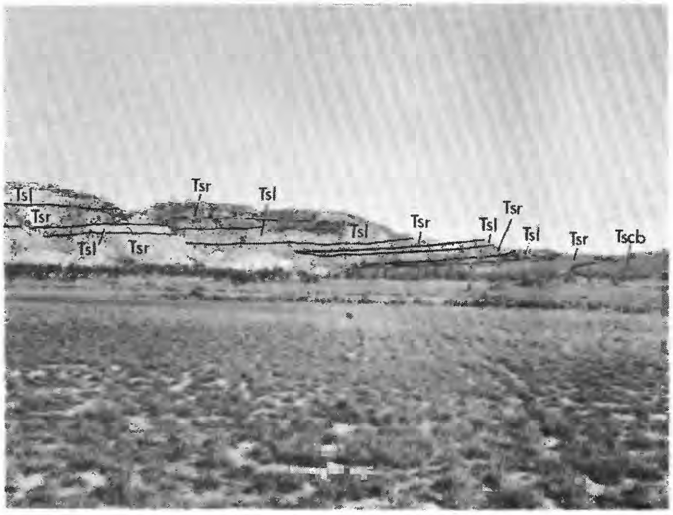


FIGURE 13.—Type section of the Regina Member of San Jose Formation, sec. 36, T. 25 N., R. 1 W., and sec. 31, T. 25 N., R. 1 E. Tscb upper tongue of Cuba Mesa Member; Tsr, Regina Member; Tsl, Llaves Member. Barren slopes on the left are mostly shale. To the north (away from observer), much of the shale of the Regina Member is replaced by sandstone tongues of Llaves Member that form prominent ledges, right of the center.

The Regina Member throughout the area consists mainly of soft beds of clay shale, siltstone, mudstone, shaly sandstone and sandy shale, but also contains numerous beds of soft fine- to coarse-grained argillaceous sandstone and a few beds of resistant conglomeratic arkosic cliff-forming sandstone. Most of the shaly beds are light gray, tan, or olive gray, but bands of dull purple, maroon, and green shale are common and are typical of the member. Pale-red to maroon shale is most common in the upper fourth of the member throughout the area. Sandstones range in color from white to buff, gray, and brown. The Regina Member includes the Almagre facies of Simpson (1948, p. 368) and the red shale and sandstone along the Continental Divide north of Regina that were specified by Simpson (1948, p. 369–371) to be the lower part of the overlying Largo facies. No persistent, mappable lithologic boundary was found to separate the beds of the Almagre facies from the lower beds of the Largo facies, although a gross distinction, based mainly on differences of color, can be made.

At the type section, the Regina Member contains, near the middle and near the top, several beds of resistant conglomeratic sandstone. These sandstones are tongues of the Llaves Member, and they wedge out to the south or become soft discontinuous lenses enclosed in shale of the Regina Member. The sandstone tongues of the Llaves thicken northward as the intervening shale units of the Regina thin, or grade laterally into shaly sandstone (pl. 2; fig. 13). North of sec. 19, T. 25 N., R. 1 E., the rocks laterally equivalent to the Regina Member are mostly standstone and shaly sandstone which are assigned to the Llaves Member. This transitional relationship was first recognized by Dane (1946), who described it generally but did not subdivide the rocks he assigned to the Wasatch. In the subsurface of the northern part of the area the Regina Member intertongues with and grades northward into the lower part of the Llaves Member, as it does at the surface in the eastern part of the area (pl. 3).

At the type section, the Regina Member is overlain by a ledge-forming conglomeratic sandstone of the Llaves Member. This sandstone and several stratigraphically higher sandstone beds of the Llaves Member wedge out to the southwest between southward-thickening tongues of the Regina Member (pl. 1). Because of this relationship, the upper contact of the Regina Member is stratigraphically higher to the south than it is at the type section, and the Regina is thicker to the south. The highest thick beds of sandstone of the Llaves Member on the ridge above the type section of the Regina are at about the same stratigraphic position as the persistent medial sandstone unit of the Llaves Member, which rests on the Regina Member in the northern part of the Tapicitos Plateau.

Thick ledge-forming lenticular beds of sandstone interbedded with red and variegated shale occur near the top of the Regina Member at places along the Continental Divide nearly as far south as Cuba and in the southern part of the Tapicitos Plateau south of Canada Larga. Thick lenticular sandstone beds are present in the upper part of the Regina in the Tapicitos Plateau in the northwestern part of the area. Relatively persistent, resistant sandstones interbedded in thick shale are fairly common locally in the lower third of the member as well as in the upper part.

The highest thick sandstone capping the mesa on the Continental Divide north of Regina in secs. 16 and 21, T. 23 N., R. 1 W., is probably equivalent to the medial sandstone of the Llaves Member. The highest beds of persistent thick sandstone on the narrow mesas along the Continental Divide in secs. 21 and 28, T. 22 N., R. 2 W., also are probably equivalent to the medial sandstone of the Llaves Member. At places south of Canada Larga the persistent medial sandstone of the Llaves Member is difficult to differentiate from the sandstone beds in the upper part of the Regina Member except by continuous tracing of beds.

The lithology of parts of the Regina Member in the San Pedro Foothills is not typical of the member elsewhere. Beds of greenish-gray clay shale and siltstone, similar to Cretaceous rocks, are interbedded with thin conglomeratic sandstones which contain numerous pebbles of sandstone, shale, and limestone. Cretaceous shark teeth, as well as Tertiary mammal teeth, occur in these beds. Much of the sedimentary detritus composing these beds probably was eroded from Cretaceous and older sedimentary rocks of the Nacimiento uplift, which seems to have been tectonically active during the deposition of the Regina Member. The uppermost beds of the Regina Member, preserved at a few places in the southern part of the San Pedro Foothills, overlap the Cuba Mesa Member and also rocks as old as the Mesaverde Group; the beds contain pebbles of limestone and sandstone similar to those of the Triassic rocks exposed on the Nacimiento uplift. The stratigraphic relations of these overlapping rocks are discussed later.

Because of intertonguing relationships of the Regina Member with the Cuba Mesa and Llaves Members, and because the San Jose Formation has been eroded deeply, the thickness of the Regina Member varies greatly in different parts of the area. In the subsurface of the northern part of the Tapicitos Plateau, the Regina is about 1,040 feet thick at the Humble Oil and Refining 1 Jicarilla M well in sec. 23, T. 25 N., R. 4 W. To the northeast most of the Regina is replaced laterally by thick sandstone beds of the Llaves Member (pl. 3).

The Regina Member has been eroded deeply in the southern part of the Northern Hogback Belt, and in the San Pedro Foothills. The preserved lower part of the member ranges in thickness from a few feet to 800 feet. Most of the Regina Member is preserved in the high hills just west of the Continental Divide west of Arroyo Blanco, and at the Abraham 1 Abraham well in sec. 17, T. 24 N., R. 1 W. (pl. 4), the Regina Member is about 1,640 feet thick. This is almost twice the total thickness of the member at the type section (localities 3a, 3b, pl. 2). The southward thickening is partly the result of the southward stratigraphic rise of the upper contact of the Regina Member because of the intertonguing relationship with the overlying Llaves Member. However, the thickening is due also to southward thickening of rocks within the Regina Member, and the member is thickest near the axis of the San Juan Basin.

The part of the Regina Member that is preserved along the Continental Divide in most of the Penistaja Cuestas is no more than 500–600 feet thick. In the western part of the Largo Plains the preserved part of the Regina Member is only 100–300 feet thick, but the thickness is greater to the north and northeast because the land surface rises toward the Tapicitos Plateau. The Regina Member is about 1,100 feet thick at the U.S. Smelting, Mining, and Refining 2–2 Jicarilla 137 well (sec. 2, T. 23 N., R. 4 W.).

LLAVES MEMBER

In the Yeguas Mesas, in the drainage of Canoncito de las Yeguas, most of the San Jose Formation is a unit composed mainly of massive beds of resistant arkosic conglomeratic sandstone that rests conformably on the Cuba Mesa Member. The sandstone unit contains also thin beds of red and variegated shale and shaly sandstone. This unit is here named the Llaves (pronounced yah′-ves) Member of the San Jose Formation for exposures near the mouth of Canoncito de las Yeguas about 1¼ miles northwest of Llaves Post Office (fig. 14). The stratigraphic section of the lower part of the Llaves Member was measured up the eastward-projecting spur of the mesa in the N½ of sec. 18, T. 25

FIGURE 14.—Typical exposures of lower part of Llaves Member (Tsl) of San Jose Formation near mouth of Canoncito de las Yeguas (at left), sec. 18, T. 25 N., R. 1 E. Tn, Nacimiento Formation; Tsc, Cuba Mesa Member of San Jose Formation.

N., R. 1 E. (loc. 4, pl. 1). At this locality the lower part of the Llaves Member is almost 700 feet thick; it rests on sandstone of the Cuba Mesa Member which is about 335 feet thick. Because the beds of the Llaves Member dip west, stratigraphically higher beds are preserved farther west. The highest beds of the Llaves Member (out of view in fig. 14) that were measured on the mesa near the mouth of Canoncito de las Yeguas are probably stratigraphically slightly lower than a thick sandstone exposed at the base of the north wall of the canyon in the SW¼ sec. 4, T. 25 N., R. 1 W. Between the bottom of the canyon in this section, and the top of the ridge in sec. 33, T. 26 N., R. 1 W. (loc. 5, pl. 1), approximately 450 feet of the upper beds of the Llaves Member is present and constitutes the upper part of the measured type section. These rocks consist of yellow and buff arkosic conglomeratic sandstone and interbedded red sandstone and some red and gray shale.

Similar stratigraphically higher beds, estimated to be about 150 feet thick, are present farther west near the Continental Divide and assigned also to the Llaves Member; thus, the Llaves Member is about 1,300 feet thick in the Yeguas Mesas area. A description of the stratigraphic sections is given at the end of this report, and the stratigraphic section of the lower part of the member is shown graphically on plate 2.

The Llaves Member is composed mostly of very coarse grained conglomeratic sandstone. The sand is angular to subangular and consists mainly of quartz and quartzite grains, but fragments of pink to gray feldspar are abundant. Most beds contain pebbles and cobbles, and some beds are very gravelly. The pebbles and cobbles are rounded and stream worn, and most of them are white to gray and purplish metaquartzite. At some places, pebbles and cobbles of granite are common, and a few fragments of gneiss and schist were observed. Pebbles of red and gray chert, volcanic rock, sandstone, and shale also were observed. The sandstones are highly crossbedded and range in thickness from less than 10 feet to almost 100 feet. The sandstones are characteristically light tan, buff, or gray, and they commonly weather to a brownish hue, which has led to their being described as copper colored (Dane, 1946; Simpson, 1948, p. 366).

The Llaves Member contains numerous thin beds of clay shale and mudstone that are predominantly maroon but are also green and gray. Also common are thin beds of red sandstone, sandy shale, and shaly sandstone, and at places, especially in the upper 500 feet of the member, rocks of this type form units as much as 60 feet thick. Reddish sandstone with red shaly partings forms the basal unit, about 85 feet thick, of the Llaves Member on the east side of the Yeguas Mesas.

The lower part of the Llaves Member tongues out to the south into the Regina Member at the surface and in the subsurface. North of the area the lower part of the Llaves Member tongues out northward into an unnamed sequence of shale and sandstone that is similar in lithology and stratigraphic position to the Regina Member. However, the lower part of the Llaves Member is persistent to the northwest in the subsurface (pl. 3), where it is 300–700 feet thick. A persistent unit of sandstone, which contains a few beds of shale at places and generally ranges in thickness from about 50 to 100 feet, extends southward and westward from the main body of sandstone of the Llaves Member and rests on the Regina Member in much of the northern part of the area. This persistent sandstone unit is equivalent to beds above the top of the stratigraphic section of the lower part of the Llaves Member that was measured at the mouth of Canoncito de las Yeguas. Thus, the persistent unit is 700–800 feet above the base of the Llaves Member and is stratigraphically near the middle of the member. Remnants of sandstone that are probably equivalent to the persistent medial sandstone of the Llaves Member cap high isolated buttes on the Continental Divide north of Regina and on and near the divide in the southern part of T. 22 N., R. 2 W.

The upper part of the Llaves Member, above the position of the persistent medial sandstone, is present only in the Yeguas Mesas. The beds of the upper part of the Llaves thin to the south and west and are split by tongues of red shale, which are assigned to the Tapicitos Member of the San Jose Formation. The details of the intertonguing in the western part of T. 25 N., R. 1 W., are complex, and the relationships shown on the geologic map have been generalized slightly. The units mapped as tongues of the Llaves Member are sandstone beds which are persistent and can be traced into the massive sandstones of the Llaves. The units mapped as tongues of the Tapicitos Member are mostly red shale. However, they also contain lenticular sandstone beds similar to those of the Llaves Member, but not merging into it. Thick beds of sandstone which seem to have been lenticular stream-channel deposits cap several mesas and buttes on the Continental Divide in T. 25 N., R. 1 W., and farther to the northwest. Some of these sandstone beds are stratigraphically equivalent to sandstone beds in the Llaves Member but do not now connect with the Llaves. Therefore, these isolated sandstones were mapped with the Tapicitos Member. A similar philosophy of mapping was applied in delineating the Llaves and Tapicitos Members along the western side of the Yeguas Mesas.

The sediments that form the rocks of the Llaves Member are coarsest in the northeastern part of the area near the type section, and the grain size decreases westward. The coarse-grained quartzose and arkosic sand that makes up the Llaves Member appears to be mainly first-cycle sediment derived from a terrane of Precambrian granite and metamorphic rocks. The cobbles and pebbles of the Llaves Member are mostly bluish and gray metaquartzite similar to the widespread metaquartzites of the Brazos uplift (Just, 1937). Many of the granite pebbles and cobbles are unlike the dense reddish-brown granite of the Nacimiento uplift but are similar to granite in the Brazos uplift and western side of the Sangre de Cristo uplift, from which they possibly were derived. The red sandstone and shale of the Llaves Member are similar to rocks of the Cutler Formation (Permian) and Chinle Formation (Triassic), which probably were exposed in the Brazos uplift and probably in the Nacimiento uplift at the time when the sediments of the Llaves Member were deposited. Much of the red sediment that makes up these beds was probably second-cycle material derived from the Permian and Triassic rocks of the uplifts bounding the basin.

As determined by reconnaissance in other parts of the basin, the Llaves Member seems to be a large narrow northwest-trending fan of coarse detritus dumped near the structurally deepest part of the Central basin by streams flowing northwestward from a Precambrian terrane in the position of the present Brazos and Sangre de Cristo uplifts. The Nacimiento uplift stood as low hills of Paleozoic and Mesozoic rocks from which sediment was eroded; this is indicated by the lithology and overlaps of the Regina Member near the uplift. The uplift probably deflected west-flowing streams so that some of them were directed around the north end of the uplift and into the basin near the site of the present Yeguas Mesas. The northeastward thinning of the Regina Member of the San Jose Formation across T. 24 N., R. 1 W., indicates that at the time of deposition of stratigraphically equivalent rocks of the lower part of the Llaves Member, the San Juan Basin was being downwarped and the monocline on the west side of the French Mesa–Gallina uplift was being formed. The large northwest-trending anticlines of the Archuleta anticlinorium also may have stood as topographic highs. If this is so, the west-flowing streams carrying coarse detritus from the Brazos–Sangre de Cristo region across the Chama basin were probably channeled around the southern part of the Archuleta anticlinorium and entered the newly forming San Juan Basin near the position of Canoncito de las Yeguas. Detritus eroded from sedimentary rocks on the Nacimiento uplift and Chaco slope was deposited in the southern part of the basin as the Regina Member, and these deposits interfingered with the southern edge of coarse material of the Llaves Member. Detritus, probably eroded from sedimentary rocks on the San Juan dome, was deposited north of the present area as a facies similar to the Regina Member, but on the northern side of the Llaves fan.

TAPICITOS MEMBER

Above the persistent medial sandstone of the Llaves Member, on the northern part of the Tapicitos Plateau in the area of this report, is a unit composed of maroon and variegated shale and intercalated lenticular sandstone that are (along with stratigraphically equivalent beds of the upper part of the Llaves Member) the youngest rocks of the San Jose Formation. This unit is here named the Tapicitos Member of the San Jose Formation, for exposures in the upper drainage of Tapicitos Creek and near Tapicitos Post Office. The Tapicitos Member is well exposed also in the upper drainage of Gavilan Creek above Gavilan, in the cliffs and badlands just west of the Continental Divide in the eastern part of T. 25 N., R. 2 W., and in the western part of T. 25 N., R. 1 W.

Exposures along State Highway 95 east of upper Gavilan Creek in secs. 1, 2, and 11, T. 25 N., R. 2 W., are considered to be the type section of the Tapicitos Member, although a detailed stratigraphic section was not measured. Along State Highway 95 the Tapicitos Member rests on the persistent medial sandstone of the Llaves Member and is estimated to be about 450 feet thick. The lower part of the Tapicitos Member is about 300 feet thick and consists mostly of slope-forming pale-red to maroon clay shale, siltstone, and mudstone and some variegated white, gray, and purplish beds. The shale contains lenticular soft white and yellow sandstone and some beds of hard gray sandstone. The lower part of the Tapicitos Member is overlain by a tongue of the Llaves Member that consists of several beds of hard coarse-grained sandstone of varied thickness. This sandstone tongue, 20–30 feet thick, forms cliffs and small benches, and farther west the tongue changes laterally into lenticular beds of sandstone included in the Tapicitos Member. The upper part of the Tapicitos Member, above the sandstone tongue of the Llaves, consists of slope-forming red clay shale, siltstone, and interbedded sandy shale and thin sandstone. The upper part of the Tapicitos Member is estimated to be about 120 feet thick. The Tapicitos Member is overlain by a tongue of thick cliff-forming sandstone of the Llaves Member which caps the highest mesas on the Continental Divide to the north. The Tapicitos Member, as here defined, is equivalent to most of the Largo facies of Simpson (1948, p. 369), although the lowest beds of the Largo facies are included in the Regina Member. A stratigraphic section of the Largo facies was measured by Simpson (1948, p. 370–371) near the head of the north branch of Oso Arroyo. The exact locality of measurement was not specified by Simpson, but it probably was in sec. 30, T. 25 N., R. 1 W. A modified description of this section is included at the end of this report. The base of Simpson's stratigraphic section is probably about 25–50 feet above the base of the Tapicitos Member, and the highest beds described by Simpson are probably nearly equivalent stratigraphically to the tongue of the Llaves Member separating the lower and upper parts of the Tapicitos Member north of Simpson's locality of measurement.

The Tapicitos Member on the Tapicitos Plateau consists mainly of reddish to maroon shale, but at all places it contains beds of thin to thick lenticular sandstone. Some of the sandstone beds are persistent for several miles along the outcrop and locally form resistant ledges. These sandstones are brown to yellowish buff, coarse grained, locally conglomeratic, and crossbedded. They are lithologically similar to sandstone of the Llaves Member. Other sandstone beds are white, buff, or red, fine to coarse grained and argillaceous, and thin and nonpersistent; they are lithologically similar to some sandstones of the Regina Member. The thickness of the Tapicitos Member varies considerably because its upper surface has been eroded deeply. The maximum thickness is about 500 feet, and at most places the preserved part of the member is no more than 300 feet thick.

In the western and southern parts of the Yeguas Mesas the Tapicitos Member grades laterally eastward and northward, respectively, into the upper part of the Llaves Member. Thick tongues of red shale of the Tapicitos Member grade laterally into red shaly sandstone or are replaced laterally by yellowish-buff sandstone of the Llaves Member. Some of the units of reddish sandstone and sandy shale can be traced for considerable distances within the Llaves Member; however, where they are predominantly sandstone and sandy shale, they are mapped arbitrarily with the Llaves Member. The lower part of the Tapicitos Member interfingers locally with the upper part of the persistent medial sandstone unit of the Llaves Member.

The Tapicitos Member seems to have been formed of flood-plain and stream-channel deposits. The upper part of the Llaves Member is probably a part of the main fan of coarse detritus dumped where major streams flowing from the highlands at the east entered the San Juan Basin; however, this upper part is smaller in extent than the lower part of the Llaves Member. Either the competence of the streams which deposited the upper part of the Llaves Member was less than that of the earlier streams, or the neighboring highlands were worn down and did not contribute as much coarse sediment as they had earlier. The thick coarse-grained lenticular sandstones of the Tapicitos Member were probably deposited in the main channels of streams flowing westward from the fan. Because the Tapicitos Member and its probable equivalents farther to the north and northwest are preserved only in relatively small areas in the axial part of the Central basin, it is impossible to infer more than a general picture of its original distribution and facies relationships. Probably the Central basin was tectonically quiescent and was filled by sediments of the Tapicitos Member, which lapped out across the folded margins of the basin onto the surrounding platforms and slopes. This is indicated by the fact that the highest rocks assigned to the upper part of the Regina Member overlap steeply tilted older rocks in the San Pedro Foothills near La Jara Creek and in the northeastern part of T. 21 N., R. 1 W. Coarse-grained sandstone and red shale, similar in lithology and stratigraphic position to the Tapicitos Member, overstep older Tertiary and Cretaceous rocks on the Hogback monocline on Bridge Timber Mountain in the northwestern part of the basin (Baltz, 1953, p. 52–53; Barnes and others, 1954; Baltz and others, 1966, fig. 5).

The environments of deposition of the drab shales, which characterize the Regina Member, and of the maroon shales, which characterize the Tapicitos Member, were discussed briefly by Simpson (1948), who referred to these rocks as the Almagre facies and Largo facies, respectively. Simpson quoted the conclusions of Van Houten (1945, p. 442–444) concerning the interpretation of alternate banding of red and pale clays common in continental deposits of early Tertiary age. Van Houten concluded that the gray and drab-colored sediments were deposited in swampy lowland areas, whereas red beds were deposited under drier conditions on savannahs. Simpson (1948, p. 380–382) inferred that the Almagre facies (included in the Regina Member of the present report) was deposited in a swampy environment and that the Largo facies (included in the uppermost part of the Regina Member, and in the Tapicitos Member of the present report) was deposited in savannahlike conditions. Although this inference seems to be correct in the light of ecological evidence deduced from the faunas of the two facies, the present writer believes that the main reason for the difference in color of the lower and upper parts of the San Jose must be the difference in color of the older sedimentary rocks from which most of the Eocene sediments were derived. The Cretaceous rocks, which seem to have provided much of the sediment of the Regina Member, are drab-colored rocks which were deposited originally in marine environments or in swampy lowland areas. Sediments eroded from Cretaceous rocks in Eocene time were deposited in the San Juan Basin after being transported for only moderately short distances; they were probably buried rapidly, thus retaining part of their original character. Red beds of Jurassic, Triassic, and Permian age, which were exposed after stripping of Cretaceous rocks from the uplifts surrounding the San Juan Basin, were already oxidized, and sediments derived from these rocks were deposited as second- or third-cycle red beds of the upper part of the Regina Member and the Tapicitos Member. The lithology of some beds of the Llaves and Tapicitos Members is strikingly similar to that of the Chinle and Cutler Formations.

The above conclusions are partly supported by the nature of Quaternary and Recent sediments on the eastern margin of the San Juan Basin. These sediments strongly reflect the lithology and color of their parent rocks on the adjacent Nacimiento uplift.

CONTACTS

The San Jose Formation rests on the Nacimiento Formation with erosional and angular unconformity in the east-central part of the San Juan Basin. In the subsurface, part of the southward thinning of the Nacimiento takes place within the formation (pl. 3); however, the Cuba Mesa Member of the San Jose Formation truncates successively lower beds of the Nacimiento from north to south. The angularity between the Cuba Mesa Member and the Nacimiento Formation is less than 1° regionally; only about 600 feet of rocks of the Nacimiento is truncated in more than 30 miles. The angular unconformity reflects gentle northeast tilting of the southwest limb of the San Juan Basin in late Paleocene time.

On the east side of the Central basin, the thickness of the Nacimiento Formation varies considerably in short distances, and the angular unconformity at the base of the San Jose Formation in the eastern part of the area (previously described in the discussion of the Nacimiento Formation) represents relatively sharp local folding rather than broad regional tilting. Excellent exposures of the angular unconformity between the Cuba Mesa Member and the Nacimiento Formation can be seen in sec. 11, T. 21 N., R. 1 W., where the difference between the angles of dip of these units is about 30°.

In the same vicinity, thin erosional remnants of shale and sandstone tentatively assigned to the Regina Member occur as outliers near the tops of the narrow divides between the deep canyons. These rocks dip about 10° W. They are overlain with erosional unconformity by high-level terrace deposits of pinkish-orange boulder conglomerate of probable late Tertiary or Quaternary age. The best exposed and thickest outlier of shale and sandstone of the Regina is near the top of a steep cliff in the south-central part of sec. 2, T. 21 N., R. 1 W. At this place the rocks assigned to the Regina Member are about 130 feet thick, and they consist, in ascending order, of the following: White to gray conglomeratic channel sandstone; coaly shale; gray, olive-green, and maroon shale; and red sandstone containing pebbles of chert and limestone. These rocks are cut out entirely a short distance to the west by a channel deposit of the overlying Tertiary or Quaternary high-level terrace gravel. The lowest beds assigned to the Regina Member rest with marked angular unconformity on overturned beds of the Nacimiento Formation, Ojo Alamo Sandstone, Fruitland and Kirtland Formations, and Lewis Shale. Poorly exposed remnants of reddish shale and sandstone assigned to the Regina Member rest on the Lewis Shale to the east, and remnants are preserved at the tops of the narrow ridges in sec. 11, T. 21 N., R. 1 W. The stratigraphic position of the overlapping rocks was not determined with certainty; they are younger than the Cuba Mesa Member, however, and they are lithologically most similar to the upper part of the Regina Member of the San Jose or to parts of the Tapicitos Member. The overlapping rocks were assigned tentatively to the upper part of the Regina Member. This angular unconformity indicates that part of the San Jose Formation overlapped the steeply folded older rocks along the east-central margin of the San Juan Basin in Eocene time.

Lithologically similar faulted rocks that were assigned to the Regina Member rest unconformably on the Lewis Shale in the valley of La Jara Creek in sec. 23, T. 22 N., R. 1 W. These rocks overlap the Cuba Mesa Member of the San Jose as well as the older rocks and dip west at angles as steep as 45°. The overlapping rocks of the Regina Member at this locality contain teeth of *Hyracotherium* (formerly called *Eohippus*) (G. G. Simpson, oral commun., 1959) and thus are definitely of Eocene age. These rocks are topographically lower than the overlapping rocks of the Regina farther south and were folded and faulted down after their deposition.

The stratigraphic relations of the Cuba Mesa and Regina Members indicate at least three stages of deformation. The first stage of deformation and erosion occurred in late Paleocene or early Eocene time and resulted in the regional unconformity between the Nacimiento Formation and the Cuba Mesa Member of the San Jose Formation. This first stage resulted also in sharp folding of the north-northwest-plunging anticlines in the eastern part of the area, and the attendant locally sharp angular unconformities between the Cuba Mesa Member and the Nacimiento near the east margin of the Central basin. The second stage of deformation occurred in early Eocene time during deposition of the Regina Member and resulted in a local intraformational unconformity along the east margin of the area. During the second stage, the lower part of the Regina Member, the Cuba Mesa Member, and the older rocks on the east margin of the area were steeply tilted west and were eroded and then overlapped by the youngest part of the Regina Member. The third stage of deformation occurred after the deposition of the San Jose Formation. During the third stage, the overlapping beds of the Regina Member and the older rocks along the east margin of the area were tilted west and faulted, and the San Jose Formation on the southwest limb of the Central basin was tilted gently northeast.

Gardner's cross section "*A–A*" (1910, pl. 2) was drawn through the vicinity of the overlapping rocks of the Regina Member in sec. 2, T. 21 N., R. 1 W. Gardner indicated that the Wasatch (the San Jose Formation of this report) rests with pronounced angular unconformity on rocks ranging from the Nacimiento Formation to the Mancos Shale and is overlain by "Recent Bowlders." He (1910, p. 721) concluded that the Wasatch overlapped older rocks and rested against Precambrian rocks at the foot of San Pedro Mountain. His mapping (1909, 1910) of the base of the Wasatch along the front of San Pedro Mountain is largely incorrect. However, the observations of R. L. Koogle (oral commun., 1955) and the present writer confirm that Gardner was at least partly right, and that part of the San Jose Formation does overlap older rocks at a few places along the front of San Pedro Mountain. Because the Tertiary or Quaternary high-level terrace gravels conceal underlying rocks, it was not determined whether the remnants of the Regina Member lap onto the Precambrian granite of San Pedro Mountain, as stated by Gardner. In the San Pedro Foothills, however, the Regina Member does not contain abundant granite detritus that would indicate that the Precambrian core of the Nacimiento uplift was exposed to erosion during the deposition of the San Jose Formation. The Regina Member does, however, contain Cretaceous shark teeth, abundant fragments of Cretaceous rocks, and detritus probably derived from Jurassic and Triassic rocks. This seems to indicate that the Mesozoic and Paleozoic rocks were not completely stripped from the Nacimiento uplift until after the deposition of the San Jose Formation.

Church and Hack (1939) found remnants of a peculiar and distinctive bluish-gray chert resting on Precambrian rocks on San Pedro Mountain. They correlated this chert with a unit of chert lying beneath the Abiquiu Tuff of H. T. U. Smith (1938) on Pedernal Peak at the northeast side of the Nacimiento uplift. The chert of both areas was named the Pedernal Chert Member of the Abiquiu by Church and Hack (1939, p. 618), who said that the chert rests on a widespread erosion surface. In the northeastern part of the Nacimiento uplift and in the Brazos uplift, the Abiquiu Tuff rests on the El Rito Formation of H. T. U. Smith (1938), which is of Eocene(?) age. The Abiquiu is older than the Santa Fe Group of Miocene, Pliocene, and Pleistocene(?) age and might be as old as Oligocene. This relation would seem to indicate that Precambrian rocks of the Nacimiento uplift were exposed to erosion in Eocene or Oligocene time, prior to the deposition of the Pedernal Chert. However, part of the Pedernal Chert Member might be a silicified zone caused by deposition of silica leached from the Abiquiu Tuff by ground water and deposited at the base of the formation. Thus the Pedernal Chert might not be a stratigraphic unit. Also, the description of the Pedernal Chert and interbedded limestone resting on Precambrian rocks at scattered outcrops on San Pedro Mountain (Church and Hack, 1939, p. 620) is very similar to the description of the fossiliferous chertified limestone in the upper part of the Arroyo Penasco Formation of Mississippian age (Armstrong, 1955), which rests on the Precambrian at places in the Nacimiento uplift. Fitzsimmons, Armstrong, and Gordon (1956) and Hutson (1958, p. 9) found remnants of the Arroyo Penasco near the north end of San Pedro Mountain. For these reasons, the stratigraphic evidence of the rocks called the Pedernal Chert on San Pedro Mountain by Church and Hack does not show conclusively that the Precambrian rocks were exposed to erosion on the Nacimiento uplift in early Tertiary time, during deposition of the San Jose Formation. The extensive erosion surface cut on Precambrian rocks on the Nacimiento uplift is partly an exhumed erosion surface that is older than Mississippian. The stripping of part of the sedimentary rocks from this surface probably occurred in middle and late Teritary time during the formation of the Rio Grande trough east of the Nacimiento uplift, as shown by the fact that the El Rito Formation, the Abiquiu Tuff, and the Santa Fe Group are all beveled by erosion surfaces and wedge out westward on the uplift beneath the Bandelier Tuff of Pleistocene and, possibly, Pliocene age.

AGE AND CORRELATION

The San Jose Formation in the east-central part of the San Juan Basin is early Eocene in age and contains the early Eocene Almagre and Largo faunas of Granger (1914, p. 205–207). According to Simpson (1948, p. 382–383), the San Jose was deposited probably during early and middle Wasatch time. The San Jose of the type locality correlates with most of the rocks in the San Juan Basin that were called Wasatch by other writers. The major problem of correlation is the placement of the lower boundary of the San Jose Formation at different locations in the San Juan Basin.

The lower contact of the San Jose Formation was traced across the southern part of the area to the west side of the drainage divide west of Lybrooks (fig. 1) in T. 23 N., R. 7 W , west of the area of the present report. The contact of the San Jose was traced northward from Lybrooks to the vicinity of Cedar Hill, N. Mex., on the Animas River near the Colorado boundary by P. T. Hayes (oral commun., 1956). (See Dane and Bachman, 1957.) This contact is similar in general, but not in all details, to the base of the Wasatch mapped by Reeside (1924, pl. 1). In the vicinity of Cedar Hill and to the north in Colorado, the Nacimiento Formation contains thick beds of coarse-grained sandstone similar to the basal part of the San Jose. The base of the San Jose (Wasatch) was mapped by Reeside (1924, p. 40–41) as the base of a thick, persistent sandstone in this area. Reeside found that the sandstone beds of the Nacimiento (his Torrejon) Formation are lenticular. The basal sandstone of the Wasatch in the vicinity of the Colorado boundary near Cedar Hill was said by Reeside to be equivalent to the upper Paleocene Tiffany Beds. However, as pointed out by Barnes (1953), it is impossible to trace precisely the contact northward to the quarries in the southern part of the H–D Hills in Colorado (fig. 1) where the Tiffany fossils were found. Barnes expressed uncertainty about correlating the basal rocks of the Wasatch from the Animas River to the southern part of the H–D Hills; however, reconnaissance of this area by R. B. O'Sullivan and the writer determined that Barnes' "bed d" above the Tiffany Beds in the southern part of the H–D Hills is equivalent, or nearly so, to "bed a" of Barnes, which is the base of the Wasatch as mapped by Reeside (1924, pl. 1) in the canyon of the Animas River near the Colorado boundary. Thus, the San Jose Formation is probably entirely Eocene in the northwestern part of the San Juan Basin, as it is in the present area of investigation. As pointed out earlier in this report, the Tiffany Beds probably should be included with the Nacimiento and Animas Formations.

The basal part of the San Jose Formation is conglomeratic arkosic sandstone throughout the Central basin of the San Juan Basin, except locally south of Durango, Colo. (Baltz, 1953, p. 61–62; Reeside, 1924, p. 40–41). This sandstone, or zone of sandstones, in most of the basin is probably equivalent to the Cuba Mesa Member. The Regina Member is preserved across much of the central part of the basin as far west as the lower part of Canon Largo (west of the report area).

The Regina Member tongues out northward into the lower part of the Llaves Member, which is present in a northwest-trending belt from the vicinity of Canoncito de las Yeguas to the Mesa Mountains and southern part of Bridge Timber Mountain in Colorado (fig. 1). The bold cliffs of sandstone of the San Jose east of Aztec, N. Mex. and in the canyon of the Animas River on both sides of the Colorado–New Mexico boundary are composed of rocks probably equivalent to both the Cuba Mesa and Llaves Members.

In the northern third of the Central basin in New Mexico and Colorado, an unnamed member that is mainly shale is stratigraphically equivalent to the lower part of the Llaves Member and to the Regina Member. This northern unit has not been studied in detail, but it seems to persist across the northern part of the Central basin, where it is underlain at most places by sandstone that is equivalent to the Cuba Mesa Member. Rocks probably, or nearly, equivalent to the persistent medial sandstone of the Llaves Member lie on the northern shale unit at many places in the northern part of the basin. The sandstone capping Carracas Mesa east of the San Juan River near the Colorado boundary, and the highest sandstones capping the Mesa Mountains and H–D Hills southeast and east of Durango, Colo., may also be equivalent to the medial sandstone of the Llaves Member, as may be a persistent sandstone occurring near the top of Bridge Timber Mountain southwest of Durango. This sandstone and the overlying rocks, predominantly red shale, overlap Cretaceous rocks on the Hogback monocline (Baltz, 1953; Barnes and others, 1954; Baltz and others, 1966, fig. 5).

The Tapicitos Member is preserved in a large area on the Tapicitos Plateau in the east-central part of the Central basin. The highest red beds of the San Jose on Bridge Timber Mountain in the northwest part of the basin are probably equivalent to the Tapicitos Member.

In view of the rapid variations in lithology of the continental deposits of the San Jose Formation and the unconformities at various places, the above-suggested regional correlations of the members are only tentative. Detailed mapping in parts of the basin will be necessary to determine with assurance the distribution and relations of all the members of the San Jose Formation.

The possible correlation of the San Jose with the Blanco Basin Formation of the southern San Juan Mountains has been suggested. Cross and Larsen (1935, p. 48–50) named and described the Blanco Basin Formation and assigned a questionable Oligocene age to it because of its stratigraphic position unconformably above rocks ranging in age from Tertiary (Animas Formation) to Precambrian, and below volcanic rocks of questionable Miocene age. Cross and Larsen correlated the Blanco Basin with the Telluride Conglomerate of the western San Juan Mountains. Several writers have suggested that the Blanco Basin is equivalent to the San Jose (Wasatch) Formation (Baltz, 1953, p. 76–77; Van Houten, 1957; Kelley, 1957, p. 157; Muehlberger and others, 1960, p. 99). Although lithologic similarity makes this correlation reasonable, no fossils have been reported from the Blanco Basin Formation, and structural considerations cast some doubt on the correlation. The Blanco Basin in the San Juan Mountains is at higher altitudes than the San Jose Formation in the San Juan Basin, and this might indicate that it is younger than the San Jose. The Blanco Basin Formation may have been deposited in areas where rocks equivalent to the San Jose were never present, or from which they had been stripped by erosion before deposition of the Blanco Basin. On the other hand, some of the younger rocks of the San Jose overlap older Tertiary and Cretaceous rocks at places on the Hogback monocline and at the foot of San Pedro Mountain. The overlaps probably indicate that the Central basin was filled with sediments in Eocene time, and that the youngest sediments of the San Jose were deposited outside the margins of the Central basin as well as within it. The fact that the overlapping rocks of the San Jose are tilted suggests that depression of the basin or elevation of surrounding uplifts (or both) occurred after deposition of the youngest rocks of the San Jose. If the Blanco Basin is equivalent to the youngest rocks of the San Jose, the post-San Jose folding would explain the difference in altitude of the two formations.

Similar arguments may be applied to the correlation of the San Jose Formation and the El Rito Formation of H. T. U. Smith (1938), which is of probable Eocene age and occurs in the Brazos uplift and in the northeastern part of the Nacimiento uplift. Muehlberger, Adams, Longood, and St. John (1960, p. 99) stated that the Blanco Basin Formation interfingers with the El Rito Formation and grades southward into it. The coarse debris of the El Rito was deposited by streams flowing southwestward and westward from Precambrian terranes of the Laramide geanticline that included the Brazos uplift, and the north-south distribution of the coarse conglomerates of the El Rito is similar to the north-south distribution of the conglomeratic sandstones of the Llaves Member of the San Jose Formation. Both of these factors as well as the general lithologic similarities favor correlation of the San Jose and El Rito Formations. However, the El Rito is at higher altitudes (except where it has been faulted or tilted down toward the Rio Grande trough) than the San Jose Formation.

The Blanco Basin and El Rito Formations are probably equivalent to the youngest rocks of the San Jose Formation, or possibly to slightly younger rocks that were part of the same depositional sequence but are not preserved in the San Juan Basin. The Blanco Basin and El Rito Formations probably were deposited during the closing phases of Eocene sedimentation, when the structural basin was nearly filled and the sediments began to lap onto the worn-down highlands that were the source terranes of older Eocene sediments. The last-deposited sediments may have been as young as Oligocene. Redbeds of the Vallejo Formation of probable early Tertiary age (Upson, 1941) occur in the San Luis basin on the margin of the Sangre de Cristo uplift in Colorado. Redbeds in the lower part of the Tertiary Picuris Tuff of Cabot (1938) rest on Precambrian and Pennsylvanian rocks in the Sangre de Cristo uplift in New Mexico (Montgomery, 1953).

The San Jose Formation is equivalent, in part at least, to other lower Tertiary rocks in the Southern Rocky Mountain region. The Cuchara and Huerfano Formations in the northern Raton basin east of the Sangre de Cristo Mountains are early and middle Eocene in age (Johnson and Wood, 1956), and their facies is similar to that of the San Jose Formation. Part of the Eocene and Oligocene(?) Galisteo Formation of the Galisteo basin, east of the Rio Grande and southeast of the Nacimiento uplift, is similar lithologically to the San Jose Formation and may have been related genetically to the San Jose, although deposited in a different basin. Stearns (1943, p. 310–311) found late Eocene (Duchesnean provincial age) fossils in the upper part of the Galisteo, which is as much as 4,500 feet thick. Fossils have not been found in the middle and lower parts of the Galisteo. The lower part of the Galisteo contains rocks lithologically similar to the Nacimiento Formation and the Ojo Alamo Sandstone; thus, the lower part of the Galisteo might be Paleocene.

IGNEOUS ROCKS

Three dikes of igneous rock occur along joints in the Tapicitos Member of the San Jose Formation on the Tapicitos Plateau. The southernmost dike is in secs. 24 and 25, T. 26 N., R. 3 W. It is about 1½ miles long and trends approximately N. 8° E. Another dike to the north in sec. 24 is about three-quarters of a mile long and trends N. 27° E. North and east of the short dike is another dike that begins in the southern part of sec. 18, T. 26 N., R. 2 W., and extends northward past the north boundary of the report area. This dike trends N. 8° E. and is about 6 miles long, including the part north of the area mapped. None of the dikes appears to be more than 50 feet wide, and all are nearly vertical. The dike rock is harder than the enclosing sedimentary rocks, and the dikes form narrow ribs rising above hills eroded on the sandstone and shale of the Tapicitos Member.

The petrography of the dike rocks was not studied. The rock consists of phenocrysts of plagioclase and pyroxene in a dense matrix and at places contains stoped material, much of which is recognizable as altered wallrock of the San Jose Formation. The wallrock is baked for several feet on either side of the dikes.

The dikes have vertical and horizontal joints at places. In the vicinity of Tapicitos Creek, some of the horizontal joints can be traced into bedding planes in the adjacent sandstone and shale of the Tapicitos Member, and the horizontal joints appear to be related in some manner to the bedding of the sedimentary rocks into which the magma of the dike rock was intruded. At places the vertical and horizontal jointing gives the dikes the appearance of walls of large masonry blocks, probably accounting for the name of Tapicitos Creek (tapicitos, in colloquial Spanish, means "little walls").

The dikes are similar in lithologic character, structure, and alinement to those that form a broad swarm a few miles to the north. The north-northeast-trending lamprophyre dikes of the swarm were mapped by Dane (1948), who discussed their relations to the volcanic rocks of the northeastern part of the San Juan Basin and the adjacent San Juan Mountains. He concluded that the dikes are probably of Miocene age. By analogy, the dikes in the report area are classified as Miocene(?).

DEPOSITS OF TERTIARY OR QUATERNARY AGE—HIGH-TERRACE GRAVEL

Gravel of late Tertiary or Quaternary age caps small west-sloping high-level terraces at the foot of San Pedro Mountain (fig. 3 and pl. 1). The pebbles, cobbles, and boulders which compose the gravel are mostly pink to reddish-brown and purplish-brown coarse-grained dense hard granite, identical in appearance with the Precambrian granite of the core of San Pedro Mountain, from which the gravel must have been derived. The high-level gravel deposits consist of local remnants of gravel 50–100 feet thick that are preserved at altitudes ranging from about 8,000 to 8,400 feet. The gravel was deposited on a west-sloping erosional surface that beveled the folded and faulted rocks of the eastern part of the San Pedro Foothills. The only remnants of this erosional surface in the San Pedro Foothills are preserved beneath the gravel deposits. The highest erosional surface in the Yeguas Mesas may be equivalent to this surface.

Remnants of gravel deposits consisting mainly of fragments of sedimentary rocks are present also in the higher parts of the foothills just north of San Pedro Mountain (east of the mapped area). The gravel deposits lie on remnants of an erosion surface that bevels the folded Mesozoic and Paleozoic rocks. These gravel deposits are at altitudes similar to those of the high-level deposits west of San Pedro Mountain and are probably equivalent to them. The remnants of the erosion surface beneath the high-level gravel at the northern end of San Pedro Mountain were correlated by Bryan and McCann (1936, p. 156) with the Ortiz surface, of the Rio Grande region, that is said to be of Pliocene or Pleistocene age.

A study of topographic maps of the northern part of the San Juan Basin indicates that the erosional surface on which the high-level gravel was deposited at the western and northern sides of San Pedro Mountain may have been part of a formerly widespread erosional surface. This surface might be equivalent to the erosional surface on which the Bridgetimber Gravel was deposited southwest of Durango, Colo. The top of Bridge Timber Mountain is at an altitude of about 8,270 feet. Atwood and Mather (1932, p. 89 and pl. 2) considered the surface beneath the Bridgetimber Gravel to be part of the San Juan peneplane of late Pliocene age, and considered the Bridgetimber Gravel to be preglaciation, and thus of Pliocene or early Pleistocene age. For all these reasons the high-level gravel deposits along the western side of San Pedro Mountain are assigned a Pliocene or Pleistocene age. They probably were deposited as parts of alluvial fans on a west-sloping pediment cut at the base of San Pedro Mountain.

DEPOSITS OF QUATERNARY AGE

TERRACE GRAVEL, COLLUVIUM, AND STREAM-CHANNEL GRAVEL

Terrace gravel, colluvium, and stream-channel gravel of Pleistocene and Recent age occur in the San Pedro Foothills at lower topographic levels than the Tertiary or Quaternary gravel. The terrace gravel consists mainly of pebbles, cobbles, and boulders of granite derived from rocks of Precambrian age, but some of the fragments are sandstone and limestone derived from the Paleozoic and Mesozoic rocks exposed along the west side of San Pedro Mountain. The gravel caps terraces at several topographic levels. Slope wash on the walls of canyons and the sides of valleys consists of colluvium weathered from the underlying bedrock and gravel slumped from the terraces. Stream-channel gravel occurs in the upper parts of some streams. The gravel and colluvium contain clay and sand reworked from Mesozoic and Paleozoic rocks. The various gravel and colluvial deposits of Pleistocene and Recent age that were laid down during the several stages of cutting and filling in the San Pedro Foothills were not mapped separately (pl. 1).

Patches of gravel consisting mainly of pebbles, cobbles, and boulders of granite cap low-level terraces along San Jose Creek and the western side of the Rio Puerco, near Rito Leche east of Cuba, and in sec. 33, T. 20 N., R. 1 E. The erosional surfaces preserved beneath the gravels were said by Bryan and McCann (1936, p. 164) to have been parts of the Rito Leche pediment, which these writers defined as a widespread erosional level graded to a stage of the Rio Puerco younger than the "La Jara pediment" but older than the present stage of the Puerco, as previously discussed in the section on land forms. The present writer found boulders of granite littering the slopes of a narrow west-trending hill of rocks of the Nacimiento Formation in sec. 14, T. 20 N., R. 2 W. This hill was formerly capped by terrace gravel, which may have been part of the Rito Leche pediment. This may indicate that the upper part of the Rio Puerco formerly flowed to the west for an unknown distance. The present southerly course of the Rio Puerco in the southern part of the area may be the result of stream capture during the destruction of the Rito Leche pediment by recent headward cutting of the lower part of the Rio Puerco.

Small patches of colluvium, colluvial boulders, and pebble and cobble gravel occur on east-facing slopes cut mainly on the Lewis Shale in Ts. 25 and 26 N., R. 1 E. The deposits lying on the slopes in T. 25 N., R. 1 E., are mostly sandy colluvium containing large sandstone boulders slumped from the cliffs formed by the Fruitland and Kirtland Formations and Ojo Alamo Sandstone. Small patches of gravel lying on the Nacimiento Formation, Ojo Alamo Sandstone, and the Fruitland and Kirtland Formations in secs. 4, 8, and 17, T. 25 N., R. 1 E., are composed of pebbles and cobbles of granite, quartzite, and sandstone washed from the cliffs of the San Jose Formation at the west.

ALLUVIUM

Alluvium consisting of sand, silt, and clay and minor amounts of gravel occurs in the valleys of all the major streams in the area. The alluvium is of Pleistocene and Recent age. Most of the deposits of alluvium are being eroded at present, and the stream channels are entrenched in arroyos cut recently in the alluvium. Sparse data indicate that at most places the alluvium is less than 100 feet and commonly less than 50 feet thick.

GEOLOGIC STRUCTURE

REGIONAL SETTING

The area mapped for this report is in the east-central part of the San Juan Basin, a large Laramide structural basin in northwestern New Mexico and southwestern Colorado (fig 5). The east-west width of the San Juan Basin is about 135 miles, and the north-south length is about 180 miles.

The tectonic elements of the basin were first defined by Kelley (1950, p. 103–104), who also defined the boundaries of the basin. In later works, Kelley (1955, 1957a, b; also Kelley and Clinton, 1960) slightly modified the terminology and selected slightly different boundaries for several units. Traditionally, the term San Juan Basin has been used by many geologists to include the Four Corners platform, Central basin, Chaco slope, and parts of the Gallup and Acoma sags. The San Juan Basin as used in the present report is the large feature defined in Kelley's earlier (1950, p. 101) work. The terminology used for the structural elements shown in figure 5 is that of Kelley (1955, p. 23 and fig. 2), with a few modifications by the present writer.

The Central basin is asymmetrical, the structurally deepest part being much nearer the north edge of the basin than the south edge. The Central basin is bounded along part of the northeast, northwest, and west sides by monoclinal structures. It is bordered on the northwest by the gently inward-dipping Four Corners structural platform and on the south by the gently inward-dipping Chaco structural slope. The east-central structural boundary is the north-trending Nacimiento fault. This fault separates the basin from the Nacimiento uplift, of which Sierra Nacimiento and San Pedro Mountain are parts. The rocks of the basin and the adjacent part of the uplift have been folded sharply in a narrow belt along the Nacimiento fault.

North of the Nacimiento uplift, the boundary of the Central basin jogs to the east, and the east margin of the basin is a curving monoclinal flexure on the west side of the faulted French Mesa-Gallina uplift (Kelley and Clinton, 1960, p. 50). North of this uplift is a broad arcuate system of faulted anticlines and synclines that was called the Archuleta anticlinorium by Wood, Kelley, and MacAlpin (1948). The Archuleta anticlinorium is the northeastern boundary of the Central basin.

East of the French Mesa-Gallina uplift and the Archuleta anticlinorium is a shallow structural basin. This has been called the Chama basin by Kelley (1955, p. 23) and by Budding, Pitrat, and Smith (1960, p. 78). The west limb of the Chama basin merges into the uplift and the anticlinorium, and the east limb merges into a faulted monocline along the west side of the Brazos uplift. Although the Chama basin has the configuration of a shallow syncline, it is structurally considerably higher than the San Juan Basin.

The area mapped for this report is in the southeastern part of the Central basin (fig. 5). The eastern part of the area includes part of the belt of sharply folded rocks west of the Nacimiento fault and the Nacimiento uplift, and includes also a segment of the monocline on the western side of the French Mesa-Gallina uplift.

DESCRIPTION OF STRUCTURE

STRUCTURE CONTOURS

The general structure of most of the area is portrayed on plate 1 by structure contour lines. The base of the Ojo Alamo Sandstone was chosen as the contour datum because the Ojo Alamo is persistent throughout the area, and because its base is easily determined and correlated by means of the electric logs of most wells drilled for oil and gas in the region. The position of the base of the Ojo Alamo on a few logs was uncertain, but on most of these logs the questionable stratigraphic interval is less than 50 feet, and thus is less than half the contour interval. The contours do not depict the exact structure of rocks older than the Ojo Alamo, because there is an unconformity at the base of the Ojo Alamo; however, the structure of the older rocks is not much different from that of the Ojo Alamo except near the eastern margin of the area. Also, the contours do not show the exact structure of the San Jose Formation, which is somewhat different from that of the Ojo Alamo because there is an unconformity at the base of the San Jose.

FOLDS

Most of the area lies within the Central basin of the San Juan Basin, and its geologic structure is simple. The structural axis of the San Juan Basin extends southeast diagonally across the northeastern part of the area from T. 26 N., R. 3 W., to the southeastern part of T. 24 N., R. 1 W., where the axis terminates in the sharply folded rocks at the east side of the basin (pl. 1; fig. 5).

Most of the area is southwest of the axis of the San Juan Basin, and the rocks in this part of the area dip gently northeast on a broad structural slope. At most places on this structural slope the dip is 1° or less. In the northern part of T. 20 N., Rs. 2–4 W., and in the southern part of T. 21 N., R. 5 W., near the outcrop of the Cuba Mesa Member of the San Jose Formation, the northeast dip is as much as 5° locally, where a narrow northwest-trending belt of steeper dips interrupts the homoclinal structural slope. In the southwestern part of the area, south of this belt of steeper dips, the regional dip is 1°–2° NE.

In the southeastern part of the area, the structure contours bend northeastward through a series of broad low north-northwest-plunging anticlinal noses and anticlinal bends, and the regional dip is northwest. The regional dip is locally more than 10° in this part of the area but is progressively less to the northwest toward the interior of the basin. The anticlinal noses are in part older than the San Jose Formation, as shown by the angular unconformity between the Nacimiento and San Jose Formation on some of the folds. However, the San Jose Formation is folded also, and most of the major anticlinal and synclinal structures involving rocks of the San Jose Formation seem to be rejuvenated older folds. Some of the folds were formed after the deposition of the Cuba Mesa Member and during or after the deposition of the Regina Member. In general, the anticlinal noses are asymmetrical, having comparatively steep west limbs and gently dipping east limbs. In places, their symmetry is nearly that of monoclines or structural terraces. The broad curving anticlinal nose (here called the Johnson anticline) at the west side of Mesa Portales has a slightly steeper east limb locally and is an exception to the generalization. The low anticlinal nose crossing Mesa Portales in the eastern part of T. 20 N., R. 2 W., is asymmetrical to the west. This nose may be a northern extension of the La Ventana anticline (pl. 7). The anticline that plunges north-northwest across T. 20 N., R. 1 W., and the western part of T. 21 N., R. 1 W., is here called the San Pablo anticline. The anticlinal nose in the central part of T. 21 N., R. 1 W., east and northeast of Cuba, is here called the Rito Leche anticlinal nose. South of Rito Leche the southeastern part of this fold has been tilted into a west-sloping anticlinal bend, and farther south the southwest limb of the fold is overturned. The bend in the outcrop belt of the Mesaverde Group near Senorito probably represents the overturned west limb of this older fold, which was tilted west during the main elevation of the Nacimiento uplift in San Jose time and later. The southeastern part of the San Pablo anticline also has been tilted west to form an anticlinal bend south of the report area (Wood and Northrop, 1946, structure section *E–E′*; see also geologic section *DD–D′D′*, pl. 8 of the present report).

In the western part of the San Pedro Foothills the rocks dip 2°–20° W., and the contours trend north regionally. However, the contours are deflected locally by several north-northwest-plunging subsurface anticlinical noses. The noses north of the Rio Leche anticlinal nose are represented only weakly in the San Jose Formation at the surface, presumably because they were formed mainly in late Paleocene time before deposition of the San Jose, as indicated by the unconformity at the base of the formation. Only slight additional rejuvenation of the anticlines occurred after deposition of the San Jose. The positions of contours on the noses are determined mainly from surface stratigraphic relations in the San Pedro Foothills that indicate thickening and thinning of the Nacimiento Formation beneath the unconformity (pl. 2). Subsurface data also determine the contours depicting the position (pl. 1) of the buried anticlinal nose in the southern part of T.

24 N., R. 1 W., and the northern part of T. 23 N., R. 1 W. The position of the nose in the eastern part of T. 24 N., R. 1 W., is determined in part by subsurface data and in part by surface data, which indicate a considerable thinning of the Nacimiento Formation on this structural feature. The nose shown in the east-central part of T. 22 N., R. 1 W., is an interpretation based mainly on the observed thinning of the Nacimiento Formation beneath the Cuba Mesa Member of the San Jose Formation in the southern part of the San Pedro Foothills, and also on surface dips in the San Jose which indicate a flanking shallow syncline near the Continental Divide north of Regina. Well data also indicate the presence of this syncline.

In the eastern part of the San Pedro Foothills, the rocks are folded sharply along a major north-trending synclinal bend. The surface trace of the east-dipping axial plane of the synclinal bend is, at most places, near the east edge of the outcrop belt of the Regina Member of the San Jose Formation. At most places in the San Pedro Foothills, the rocks just west of the trace of the axial plane dip 10°–30° W., whereas just east of the trace the dip ranges from 60° W. to vertical. South of the upper part of San Jose Creek, the Nacimiento Formation and older rocks on the east limb of the synclinal bend are overturned at many places and dip east at angles ranging from 50° to nearly vertical. Generally, the greatest overturning occurs in the beds preserved on the highest parts of the ridges, and the beds exposed in the bottoms of the deep canyons are nearly vertical or dip steeply west. The synclinal bend is younger than the north-northwest-trending pre-San Jose anticlinal noses, as shown partly by the fact that the synclinal bend cuts across them. The older part of the San Jose Formation is sharply folded along the synclinal bend, but the angular unconformity between the Regina Member and older rocks in secs. 2 and 11, T. 21 N., R. 1 W., and sec. 23, T. 22 N., R. 1 W., indicates that the synclinal bend was formed partly during deposition of the San Jose Formation. The tilting and faulting of the overlapping beds of the Regina Member indicate that there was further deformation along the synclinal bend after the deposition of the San Jose Formation.

North of San Pedro Mountain, the Cretaceous and Tertiary rocks of the Northern Hogback Belt dip west on a west-facing monoclinal flexure and are bent eastward around a low northeast-trending anticline, which lies north of the Nacimiento uplift in the northwestern part of T. 23 N., R. 1 E. In the west-central part of T. 24 N., R. 1 W., the west-dipping rocks are bent into a sinuous but generally north trend along a monoclinal flexure that forms the west side of the French Mesa-Gallina uplift, which lies just east of the northeastern part of the area (pl. 7). The dip of rocks on the west limb of the monoclinal flexure becomes progressively less northward from T. 24 N., R. 1 E. In T. 26 N., R. 1 E., the rocks of the monocline strike north-northwest along the west flank of a northwest-plunging anticlinal nose. As judged from the outcrop pattern of the Mesaverde Group, the trace of the axial plane of this nose trends diagonally through sec. 2, T. 26 N., R. 1 E. The fold, here called the Puerto Chiquito anticlinal nose, is on the west flank of the north-trending French Mesa-Gallina uplift.

The synclinal bend extends northward from the San Pedro Foothills and marks the foot of the monocline in the Northern Hogback Belt. In the southeastern part of T. 24 N., R. 1 W., and adjacent parts of T. 24 N., R. 1 E. and T. 23 N., R. 1 W., a shallow northeast-trending syncline and the parallel narrow sharply folded Schmitz anticline lie west of a northeast-trending segment of steeply dipping beds on the monocline. Beds of the Regina Member of the San Jose Formation are the folded rocks at the surface. The contours showing the subsurface structure of the Ojo Alamo Sandstone on plate 1 are based on interpretation of cross sections constructed from measurements of the dips of rocks of the San Jose at the surface (fig. 15). However, the Schmitz anticline may be mainly a shallow feature within the San Jose Formation, and the fold may die out with depth. The anticline in the San Jose could have been caused by crowding and crumpling near the southeast-dipping axial plane of the major synclinal bend at the foot of the monocline. Fitter (1958) interpreted the structure as being the result of faulting rather than folding. However, the present writer carefully traced individual beds of the Regina

FIGURE 15.—Variegated shale of Regina Member of San Jose Formation, SW¼ sec. 35, T. 24 N., R. 1 W. Steeply dipping beds on left side of the hill are on southeast limb of the Schmitz anticline.

Member across several parts of the structure and found no evidence of faulting.

FAULTS

At places in the southeastern and eastern parts of the mapped area (pl. 1), the rocks are broken by normal faults. In secs. 24 and 25, T. 20 N., R. 3 W., the Ojo Alamo Sandstone near the crest of the Johnson anticline is displaced along a north-northeast-trending normal fault downthrown to the west. The vertical separation on this fault is probably 50 feet or less, and the fault seems to die out rapidly to the north. A similar fault, downthrown to the east, is concealed by alluvium in Arroyo San Ysidro, but its presence is indicated by an offset of the Ojo Alamo Sandstone across the Arroyo. Two northwest-trending normal faults, downthrown to the west, displace the Mancos Shale, Mesaverde Group, and Lewis Shale near the crest of the San Pablo anticline.

In the NE¼SW¼ sec. 11, T. 21 N., R. 1 W., the overturned beds of the Fruitland Formation and Kirtland Shale, Ojo Alamo Sandstone, and Nacimiento Formation are displaced horizontally about 50 feet along an east-dipping low-angle fault that is overthrust to the west. This fault dies out in a short distance into folded rocks of the Nacimiento Formation. A high-angle fault, downthrown to the west, occurs in the central part of sec. 23, T. 21 N., R. 1 W., where the upper part of the Lewis Shale is thrown against the Fruitland and Kirtland. A similar high-angle fault throws the Lewis Shale against the Nacimiento Formation in the NW¼ sec. 23, T. 22 N., R. 1 W.

The overlapping beds of the Regina Member of the San Jose Formation and the steeply dipping older rocks in sec. 20, T. 22 N., R. 1 W., are displaced along several normal faults. The rocks are downthrown to the northeast on all the faults. The vertical separation of the Regina Member along each of these faults is probably less than 200 feet.

Farther north in the San Pedro Foothills, the Mesaverde Group and younger rocks dip west much less steeply near San Jose Creek than they do north and south of it. The local area of gentler dips may be the sharply tilted eastern part of a northwest-plunging pre-San Jose syncline. The rocks east of the Mesaverde Group are displaced along several normal faults. (See also Wood and Northrop, 1946.)

Rocks in the Northern Hogback Belt are displaced at several localities along faults that are transverse to the strike of the beds. Steeply dipping rocks of the undivided Fruitland and Kirtland Formations and the Ojo Alamo Sandstone are displaced along three faults of this type in parts of secs. 10, 11, and 15, T. 23 N., R. 1 W. Steeply dipping rocks of the Mesaverde Group are displaced along similar faults on the sharp bend in the monocline in secs. 21, 29, and 32, T. 24 N., R. 1 E. On all these faults the horizontal separation is left lateral, and the block south of each fault is offset to the east relative to the block north of the fault. The rocks south of the fault in sec. 32, T. 24 N., R. 1 E., dip much less steeply than the rocks north of the fault, indicating that segments of the monocline have slumped eastward slightly. A north-trending normal fault displaces the Mesaverde Group and adjacent rocks along Archuleta Arroyo near the center of T. 26 N., R. 1 E. The fault is downthrown to the east, and parallel to the fault the horizontal separation is left lateral.

The north-trending Nacimiento fault and associated smaller faults (pl. 7) which define the boundary between the San Juan Basin and the Nacimiento uplift (Kelley and Clinton, 1960, p. 50–51) are east of the Mesaverde Group and were not mapped by the present writer, although they were observed at places. Judging by the structure sections of Wood and Northrop (1946) and those constructed by the writer (pl. 8), the maximum vertical separation on the Nacimiento fault may be more than 10,000 feet. Renick (1931) and Wood and Northrop (1946) indicated that the Nacimiento fault dips east and the Precambrian rocks of the Nacimiento uplift were elevated along it and overthrust toward the west. According to Renick (1931, p. 73), the westward movement on the fault was from one-half to 1 mile. The evidence for otherthrusting is open to other interpretation, as will be made clear in a later section of this report. The vertical throw on the Nacimiento fault diminishes at the north end of San Pedro Mountain (pl. 8), and the fault passes northward into the Gallina fault (pl. 7). Near the Nacimiento uplift the Gallina fault trends northeast, is nearly vertical, and is downthrown to the west. The fault cuts across the structurally high part of the French Mesa–Gallina uplift and terminates north of the Puerto Chiquito anticlinal nose.

JOINTS

Joints were observed at many places but were not mapped or studied for the present report. Kelley and Clinton (1960, fig. 2 and p. 19–22) portrayed and described joint systems of the San Juan Basin, including the area of the present report. Within the report area, prominent joint sets trend N. 10° E., N. 75° W., and N. 35° E.–N. 60° E., according to Kelley and Clinton. Sets trending about S. 60° W. are especially persistent near Lindrith, and sets trending S. 65° E., S. 65° W., and S. 25° W. are prominent west of the north end of the Nacimiento uplift.

Joint sets trending N. 8°–25° E. have the most conspicuous topographic expression. In places, the country has a marked "grain" that follows the trend of these joints. This grain is particularly noticeable in the north-central part of the area north of Canada Larga. Here many of the tributaries of the major westward-draining canyons follow north-northeast (or south-southwest) courses, and the dikes of igneous rock on Tapicitos Creek follow the north-northeast trend. North-northeast-oriented faults, joints, and dikes are common features along the entire eastern side of the San Juan Basin from the Lucero uplift northward into Colorado. In the northern part of the basin, north of the report area, joints of the north-northeast set have been intruded by a great swarm of Miocene(?) lamprophyre dikes (Dane, 1948).

ANALYSIS OF REGIONAL LARAMIDE STRUCTURE

GENERAL PROBLEMS

The San Juan Basin and its bounding uplifts (fig. 5) show the two major regional structural trends that characterize much of the east half of the Colorado Plateau (Kelley and Clinton, 1960, p. 13, fig. 7). The Zuni uplift at the south side of the basin is alined northwest, and the Archuleta anticlinorium and San Juan dome at the north side form a northwest-alined arc that is roughly parallel to the northwest trending trough of the basin. The Defiance uplift at the west side of the basin and the Nacimiento and French Mesa–Gallina uplifts at the east side are alined northward. Thus, the shape of the basin that is partly included within these uplifts approaches the symmetry of a parallelogram or an oval whose long dimension is oriented northwest, roughly parallel to the general orientation of the trough of the basin. Upon this shape is superimposed the semicircle of the west, north, and east rim of the Central basin. The shape of the rim is largely the result of the curved northeast trend of the Hogback monocline and the curved northwest trend of the monocline that links the French Mesa–Gallina uplift and the Archuleta anticlinorium along the east side of the basin.

Kelley and Clinton (1960, p. 95–97) discussed the problem of analyzing the forces that produced the northwest-trending and the north- to northeast-trending Laramide structures of the Colorado Plateau. They stated that it does not appear possible that both of these trends could have been formed by the same regional stress system, especially if the maximum stress was horizontal or nearly so. They postulated two, or possibly more, periods of Laramide orogeny, "each of a different direction of activation". According to their hypothesis, the north- and northeast-trending monoclines were formed first, and the northwest-trending anticlines, synclines, and uplifts such as the Zuni and Uncompahgre uplifts were formed last.

In the San Juan Basin, however, this sequence of events does not appear to be correct, as is shown by the stratigraphic relations of the latest Cretaceous and the Tertiary rocks in the area mapped for this report (pl. 1). The northwest-trending trough of the San Juan Basin began to form in Late Cretaceous (Montana) time. The eastward thinning of the Fruitland Formation and Kirtland Shale seems to indicate that the north-trending structures of the eastern margin of the San Juan Basin had begun to be uplifted before the end of the Cretaceous. The northwest-trending anticlines on the eastern margin of the basin may have begun to form before the deposition of the Paleocene Ojo Alamo Sandstone. The unconformable relation of the Nacimiento and San Jose Formation indicates that these anticlines were largely formed by the end of Paleocene time. The unconformities and overlaps within the San Jose Formation near the synclinal bend at the margin of the basin indicate that the north-trending Nacimento uplift and the northeast-trending French Mesa–Gallina uplift (pl. 7) were elevated in Eocene time, mainly after the formation of the northwest-trending anticlines, but during continued depression of the San Juan Basin. Most of the movement on the Nacimiento fault occurred during the final stages of depression of the basin and elevation of the uplift, after the deposition of the San Jose Formation. A similar timing of deformational events is recorded in the latest Cretaceous and Tertiary rocks on the northeast-trending Hogback monocline in Colorado (Baltz, 1953). A major problem, then, is that of determining how the different structural trends (which might be the products of differently oriented forces) could have formed contemporaneously, or at least during overlapping periods of time.

Kelley (1955, p. 66–67) suggested that the eastern part of the Colorado Plateau has been shortened in a northeasterly direction. The shortening was said to be effected in the Zuni uplift, the San Juan Basin, and the Eastern Rockies, as well as in other basins and uplifts farther west. Kelley suggested further that the crustal shortening would have necessitated right shift between the plateau and the Nacimiento uplift, and he cited the staggered folds at the base of the Nacimiento uplift as evidence suggesting right shift. The entire plateau is said to have been under compression during Laramide deformation (Kelley, 1955, p. 74).

It is difficult to prove, however, that the geometry of the Zuni uplift, the San Juan Basin, and the adjacent uplifts to the north and east necessarily indicates crustal shortening. In a recent discussion of the origin of the Zuni uplift, Kelley and Clinton (1960, p. 48) stated: "For the most part there does not appear to be anything about the fracture pattern that could not have been formed by a predominantly vertical pressure. * * * Origin by a dominant lateral stress, on the other hand, is favored by overturned and thrust structures that are common bordering the Plateau." These statements might be applied to most other parts of the eastern sector of the plateau. Structural features that clearly indicate horizontal compressional stress during Laramide orogeny are not common in the eastern part of the Colorado Plateau, although such features are present in some of the bounding uplifts.

Consideration of the paleogeography and the geologic history of the eastern part of the Colorado Plateau and the adjacent mountainous regions suggests another possible mechanism for the production of the Laramide uplifts and basins—an isostatic response to vertical principal forces. Most of the present uplifts that surround the San Juan Basin are on more ancient highlands or on areas of thin pre-Cretaceous sedimentary rocks, whereas the San Juan Basin contains a relatively thick sequence of pre-Cretaceous rocks. The Defiance, Zuni, and Nacimiento uplifts were positive areas in Pennsylvanian and early Permian time (Read and Wood, 1947). Rocks of Triassic and Jurassic ages thin southward and change facies in the area of the Zuni uplift; this indicates that the Zuni uplift was structurally slightly higher than the San Juan Basin in those times, also. The ancient Upcompahgre–San Luis uplift of Colorado and north-central New Mexico (Read and Wood, 1947; Kelley, 1955, fig. 13; King, 1959, p. 104–105; Baltz 1965, p. 2044) was a positive area in late Paleozoic, Triassic, and Jurassic time, and was the source of a tremendous amount of sediment, at least in Paleozoic time. The Brazos uplift, part of the Archuleta anticlinorium, and part of the San Juan dome were apparently parts of this ancient positive area (Read and others, 1949). During the Cretaceous submergence of the Rocky Mountain geosyncline, the San Juan Basin apparently subsided more than the positive areas. Differential subsidence is indicated by the fact that the Cretaceous rocks are not as thick at the north edge of the San Juan Basin in Colorado as they are in the Central basin in New Mexico (Silver, 1951, fig. 4, p. 110). Dane (1960b, p. 67) indicated that the sources of some of the sediments for the Dakota Sandstone were the Precambrian rocks in the area of the present Brazos uplift. Dane (1960a, figs. 2, 3, p. 49, 51) showed also that there are unconformities within the Mancos Shale at places on and near the Archuleta anticlinorium and also on the northwest side of the San Juan Basin. During Laramide orogeny the southern part of the ancient Uncompahgre–San Luis positive area was elevated and transformed into the complex San Luis–Sangre de Cristo uplift (fig. 7) which was a source for much of the sediment that formed the thick latest Cretaceous and Tertiary rocks of the San Juan Basin and the Raton basin east of the uplift (Baltz, 1965, p. 2065–2066, 2072–2073).

The San Juan Basin and the bounding Laramide uplifts do not coincide in all details with the ancient basin and positive areas. Nevertheless, it is notable that over a long span of time and through several distinct episodes of deformation these areas have maintained their respective general negative and positive tectonic characters. The recognition of this fact, however, does not indicate whether the various deformations were caused by vertical forces or by tangential compressional (horizontal) principal forces. If the San Juan Basin was formed by a vertical principal force, it has been lengthened or stretched; whereas, if the basin was formed by a tangential compressional principal force, it has been shortened. Therefore, the problem of the nature of the force could be partly solved if it could be determined whether lengthening or shortening occurred.

The stratigraphic and structural relations determined by the study of the report area (pl. 1) are important new data for analyzing the Laramide structure of the San Juan Basin and its eastern bounding uplifts. The data provide a fairly clear sequential framework to relate the conclusions derived from analyzing the geometries of individual structures in attempting to interpret the structure of the eastern Colorado Plateau.

NACIMIENTO FAULT

For almost 50 miles north of the Puerco fault belt the eastern boundary of the San Juan Basin is the north-trending Nacimiento fault, along which the basin is depressed relative to the Nacimiento uplift (pl. 7). The northwest trending folds of the basin terminate abruptly against the fault that transects them, and the folds are tilted west along the persistent major synclinal bend west of the fault. The synclinal bend, which is alined with the fault and the uplift, is superimposed across the northwest-trending folds, and the stratigraphy of the San Jose Formation shows that the synclinal bend is mainly younger than the northwest trending folds.

Renick (1931, p. 71–74) was the first to map the Nacimiento fault in detail; he called it the "Sierra Nacimiento overthrust." According to Renick (p. 71), "Most of the fault planes in this zone dip toward the east, showing that the mountain mass has been overthrust to the west, toward the San Juan Basin. This overthrust is not a single fault, but in several places the movement has taken place along several planes of shear."

On most of his structure sections Renick (pl. 1), showed the Nacimiento fault (or faults) as relatively steep and dipping east at about the same angle as the surface dips of beds west of the fault. Renick (p. 72 and pl. 2) described the most complex structure as being on the northern flank of San Pedro Mountain (east of the Nacimiento fault and north of the San Pedro Mountain fault, pl. 7). Here, according to Renick, a series of fault plates overthrust from east to west, repeat the Precambrian rocks and the lower beds of the Magdalena Group of Pennsylvanian age. The planes of the faults were said to dip east at a relatively flat angle. In a more recent investigation, however, Hutson (1958, p. 37–38) found only northeast-dipping interbedded limestone and clastic rocks of the Madera Limestone of the Magdalena Group in this area, and concluded that Renick was mistaken in his interpretation of low-angle thrust plates of Precambrian rocks east of the main Nacimiento fault.

G. H. Wood, Jr., and S. A. Northrop (1946) also interpreted the Nacimiento fault as an overthrust from east to west, but apparently for partly different reasons than Renick. Renick's map (1931, pl. 1) shows the Senorito Sandstone Lentil (Poleo Sandstone Lentil of current usage) of the Chinle Formation of Triassic age resting on the Mancos Shale of Cretaceous age in a manner suggesting a low-angle overthrust plate in the W½ sec. 13, T. 21 N., R. 1 W. However, Wood and Northrop (1946) indicated that this overthrust plate is not present. Wood and Northrop (1946) indicated that Renick's interpretation (pl. 1, structure section *F–F′*) of the supposed plate of Poleo Sandstone Lentil of the Chinle Formation thrust across stratigraphically higher beds of the Chinle father south near the northwest corner of T. 17 N., R. 1 E., was incorrect. The observations of the present writer suggest that the red beds shown by Wood and Northrop (1946) as Chinle Formation thrown against Mancos Shale (in a manner suggesting a low-angle thrust plate) in the E½ sec. 11, T. 21 N., R. 1 W., are probably overlapping beds of the Regina Member of the San Jose that are poorly exposed beneath the Tertiary or Quaternary terrace gravel. (See pl. 1 of the present report.)

It appears that none of the investigations to date have disclosed direct evidence that low-angle thrust plates occur along the Nacimiento fault. Because exposures are generally poor at most places, there is very little direct evidence of the attitude of the plane of the Nacimiento fault. Where the writer has seen exposures of the fault zone near the south end of the Nacimiento uplift, the plane appears to be high angle, either vertical or dipping very steeply east. Huston (1958, p. 37–38) found that near the north end of the Nacimiento uplift the Nacimiento fault dips about 83° E. Although the fault curves slightly at many places, it is remarkably straight for its entire length of almost 50 miles This quality also suggests that the fault plane dips very steeply.

OVERTURNED BEDS

The main evidence for overthrusting from the east is the overturned east dip of rocks at some places east and west of the Nacimiento fault. (See Renick's structure sections, 1931, pl. 1; Wood and Northrop, 1946.) On the downthrown western side of the fault, the main area of overturned beds extends from the northeastern part of T. 22 N., R. 1 W., to the east-central part of T. 20 N., R. 1 W. (Renick, 1931; Wood and Northrop, 1946). The greatest overturning occurs in the east-central part of T. 21 N., R. 1 W.; in the southeastern part of T. 22 N., R. 1 W.; and locally in the northeastern part of T. 20 N., R. 1 W. At a few places the overturned beds dip east at angles as low as 40°, but at most places the dips are much steeper. Where sedimentary rocks are preserved on the upthrown east side of the fault, the beds are overturned and dip east at a few places, but generally the beds dip west at angles ranging from nearly vertical to less than 45°.

Near the north end of the Nacimiento fault, the rocks west of the fault dip west at angles ranging from 70° to nearly vertical, whereas east of the fault the rocks dip northeast at angles ranging from 20° to 50°. Along the southern third of the fault the beds are not overturned on either side of the fault, the west dips are considerably less than 45° at many places, and, locally, rocks on either side of the fault dip toward each other. Near the south end of the fault the rocks on both sides dip east.

In the area mapped for this report (pl. 1), the localities of sharpest overturning at the foot of San Pedro Mountain are those where the stratigraphy shows that the northwest-plunging pre-San Jose anticlinal noses intersect the major north-trending synclinal bend west of the Nacimiento fault. The sharp overturning in the hogbacks near Senorito in the northeastern part of T. 21 N., R. 1 W., is near the intersection of the synclinal bend and the west-tilted southern part of the Rito Leche anticlinal nose. Steeply inclined beds occur adjacent to the Nacimiento fault farther south, where the west-tilted southern part of the San Pablo anticline is crossed by the synclinal bend (pl. 8). Similar relations are seen farther south on other anticlines, although overturning does not occur near the southern part of the fault.

Several areas of gently west-dipping beds west of the fault appear to be titled pre-San Jose synclines. Immediately north of upper San Jose Creek in the southeastern part of T. 23 N., R. 1 W., the rocks east and west of the fault are not overturned but dip west at angles ranging from nearly vertical at the outcrop of the Dakota Sandstone to about 45° at the outcrop of the Mesaverde Group and about 64° at the outcrop of the Ojo Alamo Sandstone. The dips of the Nacimiento Formation and the Cuba Mesa Member of the San Jose Formation are steeper than dips of the beds to the east, and the Cuba Mesa Member may be nearly vertical, although the exposures are too poor for certain determination. Here the Nacimiento Formation is thicker than it is in adjacent areas to the north and south. To the south, as the dip of the Nacimiento Formation becomes steeper (and the Mesaverde Group is overturned), the Cuba Mesa Member of the San Jose Formation rests on stratigraphically lower beds of the Nacimiento Formation. Most of this thinning of the Nacimiento Formation can be demonstrated to be stratigraphic.

The overturned beds along parts of the Nacimiento fault could have reached their present structural attitudes as the result of west tilting either on a monocline or on a drag fold (synclinal bend) along a high-angle fault. The geometry of this concept is illustrated in pl. 8. Section *AA–A′A′* illustrates the northwestern parts of a pre-San Jose anticline and a flanking syncline in the subsurface near the east edge of the Central basin. Section *BB–B′B′* illustrates the structural conditions farther south along upper San Jose Creek, where the axial plane of the synclinal bend is west of the axis of the pre-San Jose syncline. Section *CC–C′C′* represents the structural conditions farther to the south in sec. 11, T. 21 N., R. 1 W., where the axial plane of the synclinal bend lies west of the axis of the pre-San Jose anticline, as shown by the southwestward thickening of the Nacimiento Formation. Section *DD–D′D′* represents the structural conditions still farther south, where the axial plane of the synclinal bend lies west of the tilted southern part of the San Pablo anticline.

The amount of folding during the main stage of formation of the major synclinal bend (during deposition of the Regina Member of the San Jose) is shown by the attitude of the base of the San Jose Formation in section *CC–C′C′* where upper beds of the Regina Member overlaps the older rocks. The southwest limbs of the pre-San Jose anticlines are folded more than the base of the San Jose Formation because these limbs were already inclined to the southwest (as much as 30° at section *CC–C′C′*) before the folding of the San Jose began. Evidence for this is the well-exposed angular unconformity between the west-dipping San Jose and the overturned Nacimiento Formation in sec. 11, T. 21 N., R. 1 W. Thus, where the axial plane of the synclinal bend lies west of the pre-San Jose anticlines, the southwest limbs of the anticlines had reached overturned positions before the base of the San Jose Formation was folded into a vertical attitude on the east limb of the synclinal bend. Conversely, where the axial plane of the major synclinal bend lies west of the axis of a pre-San Jose syncline, the base of the San Jose dips west more steeply than the southwest limb of the sycline because the limb of the syncline was inclined northeast before the San Jose Formation was folded. The geometry of these concepts is shown diagrammatically in figure 16.

From these considerations the writer concludes that the local areas of overturned pre-San Jose rocks west of the Nacimiento fault do not necessarily indicate westward thrusting on the fault. Rather, the overturned rocks are the tilted and steepened southwest limbs of the northwest-plunging pre-San Jose anticlines, where the southeastern parts of these folds lie east of the axial plane of the major synclinal bend.

SYNCLINAL BEND

The geometry of the synclinal bend, as reflected by the base of the San Jose Formation, might be taken to indicate east-west crustal shortening along an east-dipping overthrust fault. As shown in figure 17*A*, a point on an undeformed bed is displaced through a horizontal distance (x–x') as well as a vertical distance (x'–y) when the bed is folded concentrically. This kind of horizontal shortening may be accomplished also by parallel folding and thrusting (fig. 17*B*).

On the other hand, as a result of vertical movement only, plastic deformation can be accomplished in such a manner that the limb of a fold is stretched and thinned, and a point on the deformed bed is moved through only the vertical component x–y (fig. 17*C*). Also, as the result of vertical movement only, the effect of thinning can be accomplished by cleavage folding (shear cleavage), as shown diagramatically in figure 17*D*. Thus, the formation of a synclinal bend or a monocline can be attended by horizontal shortening (fig. 17*A*, *B*), by vertical stretching and lengthening of the limb of the fold (fig. 17*C*, *D*), or by both.

Figure 17*E* illustrates the structural features observed in deformed models in which a plastic material rests on a relatively competent basement material which has folded slightly and has then ruptured in response to

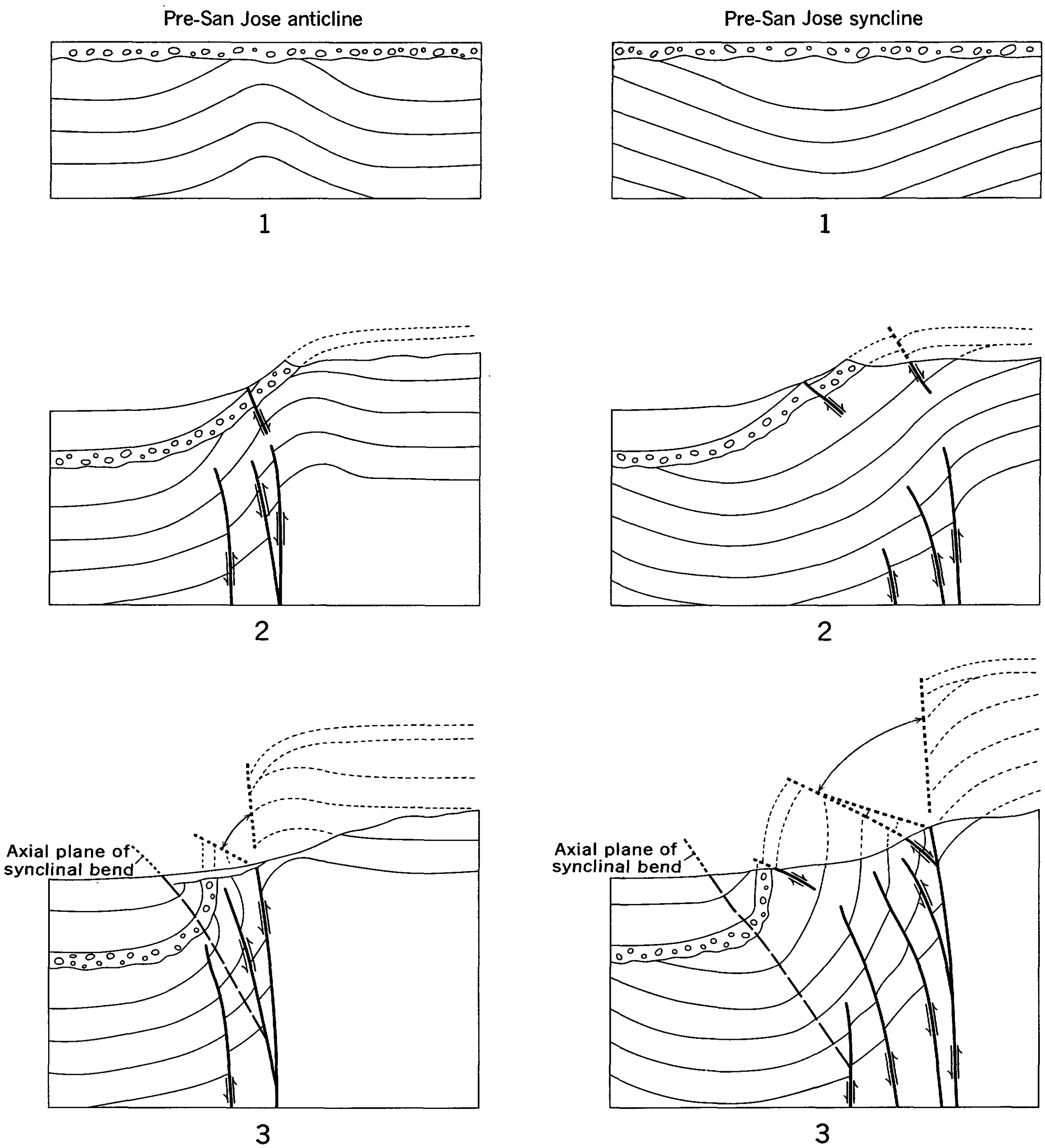
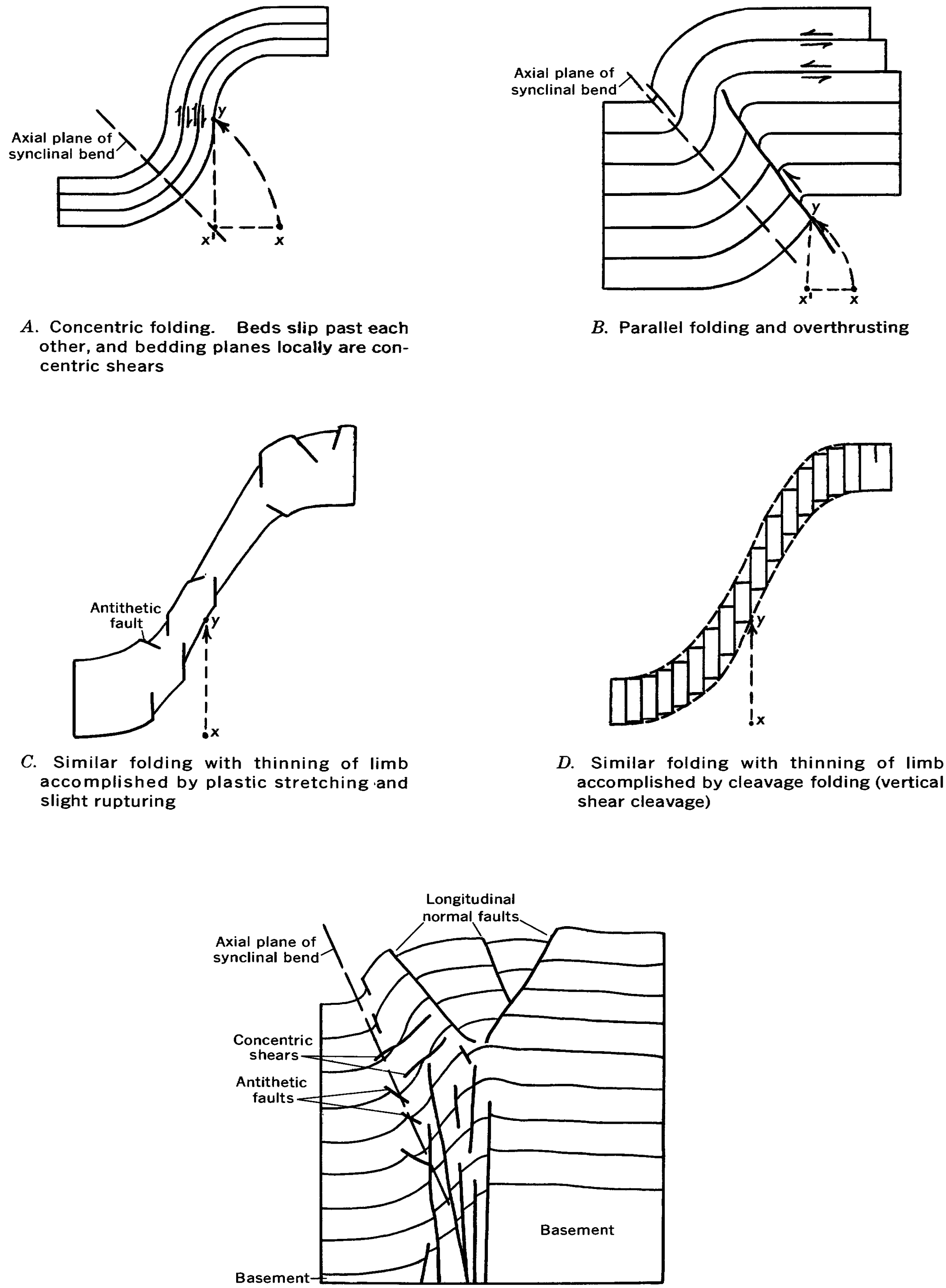


FIGURE 16.—Diagrammatic sections showing possible stages of development of steeply dipping and overturned beds adjacent to a high-angle fault.

vertical uplift of the basement of one side of the model. In the deeper part of the fold, lengthening of the monoclinal limb is accomplished by movements along steeply inclined shears; whereas in the upper part of the fold, lengthening is accomplished by a combination of plastic stretching, concentric shearing, antithetic faulting, and grabening along longitudinal normal faults. Beds in the upper part of the monoclinal fold are steeply inclined because of crowding near the axial plane of the synclinal bend. This crowding is caused by crimping that occurs as the left side of the model is depressed by steps along several planes of shear in the deeper part of the fold and because there is a component of gravitational stress directed toward the basin in the upper part of the fold. Although the mechanical elements of concentric folding, parallel folding, and plastic stretching all can be observed in the less competent upper part of the model, the fold is, in effect, a shear fold produced by shear cleavage of the competent basement in response to vertical movements.



A. Concentric folding. Beds slip past each other, and bedding planes locally are concentric shears

B. Parallel folding and overthrusting

C. Similar folding with thinning of limb accomplished by plastic stretching and slight rupturing

D. Similar folding with thinning of limb accomplished by cleavage folding (vertical shear cleavage)

E. Folded and faulted beds draped across a shear fold in a relatively rigid basement. Movement of basement is predominantly vertical

FIGURE 17.—Diagrammatic sections of several types of folds.

Hafner (1951) made theoretical studies of the internal stress distributions produced when several systems of external boundary forces acted on parts of the earth's crust, and he calculated the probable attitudes of faults likely to be associated with these systems. In the case of differential vertical uplift and depression of adjacent belts or blocks, Hafner (1951, p. 391–396, pl. 1*D*) showed that the internal stress distribution in the deeper rocks near the common margins of the blocks tends to produce reverse faults that dip steeply toward the uplifted block. These faults curve in the shallower rocks and become steep thrusts that also dip toward the uplifted block. The faults observed in the simple model portrayed in figure 17*E* tend to follow the theoretical configurations determined by Hafner for the case of differential vertical uplift, and some of the faults in the less competent upper part of the fold dip toward the uplifted block.

The concept of shear folding in the basement (fig. 17*E*) was used in constructing the diagrams in figure 16 and the sections in plate 8 because it best satisfies the geometric requirements in the deeper parts of the folds where sharp folding of the basement might otherwise be required. It is highly unlikely that the massive granite which forms the basement in the Nacimiento uplift, and probably also in the adjacent part of the San Juan Basin, could have been folded sharply. This is indicated by outcrops on the uplift where sharp folding of the sedimentary rocks was accompanied by faulting both in the sedimentary rocks and in the basement (pl. 7). The writer did not map the rocks east of the Mesaverde Group and, consequently, has little direct evidence of possible high-angle faults in the sedimentary rocks near the Nacimiento fault other than the faults mapped by Wood and Northrop (1946) and Hutson (1958). However, in the mapped area, the high-angle fault along which the steeply dipping beds of the Lewis Shale are thrown against the less steeply inclined Fruitland and Kirtland Formations in sec. 23, T. 21 N., R. 1 W., is similar to the high-angle faults illustrated in stage 3 of figure 16 and in figure 17*E*. Another fault of this type throws the Lewis Shale against the Nacimiento Formation in the NW¼ sec. 23, T. 22 N., R. 1 W. Dane (1936, p. 100–101, 109, 132) suggested that local thinning of units of the Mesaverde Group in T. 19 N., R. 1 W., near Senorito is the result of strike faulting. He pointed out that the Mancos Shale is not thinned but suggested that the position of the Mesaverde may have been favorable for steep thrusts, and that such faults may exist, although none were observed by him. The antithetic faults downthrown to the east in sec. 23, T. 22 N., R. 1 W., could have been formed in response to local tensional forces set up by slight stretching of the east limb of the synclinal bend, and they are interpreted as being analogous to the antithetic faults shown in figure 17*E*.

Stretching and thinning of the steep limb of the synclinal bend west of the Nacimiento uplift as the result of plastic deformation or shear cleavage (or both) would be favored by the thick units of shale in the Chinle, Mancos, Lewis, and Nacimiento Formations. The plastic stretching of any particular unit of shale need not have been excessive, for the tensile strength of shale is low, and the thinning could have resulted from movements on small high-angle normal faults and innumerable small shears in all the units. Furthermore, the stratigraphically higher units might not have been stretched and thinned appreciably, because, as shown by the lithology and the overlapping relations of the Regina Member of the San Jose Formation (pl. 8, section *CC–C′C′*), erosion undoubtedly attended the folding. The erosion of the upper part of the fold would obviate the geometric necessity of stretching (or faulting and rotating) indicated by the arrows in the reconstructed parts of the folds in stage 3 (fig. 16) and the grabening shown in figure 17*E*. Also, during the formation of the synclinal bend, the eastern part of the San Juan Basin probably was shortened slightly in a northeasterly direction because the basin was crowded toward the Nacimiento uplift, and this crowding probably reduced the tensional stresses in the synclinal bend. Evidence of crowding is the slight rejuvenation of some of the northwest-trending pre-San Jose folds during and after the deposition of the San Jose Formation.

The synclinal bend extends north of the Nacimiento fault (pl. 7), where the axial plane of the bend marks the foot of the large monocline on the western flank of the French Mesa–Gallina uplift. The synclinal bend probably marked the foot of a southern extension of the monocline along the west side of the Nacimiento uplift in early Eocene time. This conclusion is suggested by the overlap of the gently tilted beds of the Regina Member of the San Jose Formation across sharply folded Paleocene and Cretaceous rocks in the southern part of the San Pedro Foothills (pl. 8, section *CC–C′C′*). These overlapping beds consist largely of reworked Mesozoic sedimentary rocks and do not contain any large quantities of granitic debris that would indicate that the core of the Nacimiento uplift was exposed to erosion during deposition of the Regina Member. Much of the present vertical separation on the Nacimiento fault seems to have occurred after the synclinal bend (and the monocline to the north) was largely formed—that is, after the deposition of the San Jose Formation. Some further tilting of the synclinal bend must have accompanied the later stages of movement on the Nacimiento fault, because the overlapping beds are tilted west and have been folded down and faulted north and south of Rito de los Pinos.

From these hypothetical and factual considerations, the writer concludes that the major synclinal bend west of the Nacimiento fault does not indicate that, by geometric necessity, the fault must be an overthrust dipping east at a low angle, as Renick (1931) and Wood and Northrop (1946) indicated. Most of the structural features along the fault could have been produced by nearly vertical displacements along several shear planes, one of which became the main Nacimiento fault during the later stages of deformation. The relative straightness of the Nacimiento fault and the dip of the fault plane observed at a few places indicate a steeply dipping reverse fault. The southern part of the fault may be nearly vertical.

EVIDENCE OF STRIKE-SLIP MOVEMENT

The staggered arrangement of the northwest-trending pre-San Jose anticlines (pls. 1, 7) suggests that they were formed by crumpling resulting from right shift along the Nacimiento fault in an early stage of its development, before there was much structural relief between the San Juan Basin and the Nacimiento uplift and before the fault had ruptured the sedimentary rocks lying on the more rigid Precambrian basement rocks. Several northwest-trending features on the uplift might have developed as parts or counterparts of the folds in the basin. Some of the west-dipping patches of sedimentary rocks on the west limb of the uplift (east of the Nacimiento fault) could be parts of synclinal troughs tilted during the formation of a monocline and faulted from the tilted synclines that now lie in the basin west of the fault. However, the folds in the basin are truncated by the fault, and there is no obvious correspondence of the immediately adjacent structural features of the basin and the uplift. Dislocation because of horizontal shift during the major movement on the Nacimiento fault seems indicated.

Immediately north of the Nacimiento uplift there is a similar lack of correspondence of immediately adjacent features east and west of the Gallina fault. However, the buried anticlinal nose west of the curving segment of monocline in the northern part of T. 23 N., R. 1 W., and the southern part of T. 24 N., R. 1 W., might correspond to the highest part of the granitic core of San Pedro Mountain, which trends northwest. Also, the sharp synclinal fold north of the Rito Leche anticlinal nose in the northeastern part of T. 21 N., R. 1 W., might correspond to the Bluebird Mesa on the Nacimiento uplift (pl. 7). If these correspondences are more than coincidental, a right shift of perhaps as much as 3 miles is indicated along the northern part of the Nacimiento fault, and the Nacimiento fault is a wrench.

To check the general validity of the mechanics discussed above, a simple model was constructed (fig. 18). The model consisted of two flat plates of cardboard laid together flush and partly covered with a viscous batter of flour and water. Dry flour was sifted on the batter to form a crust. The cardboard plate representing the San Juan Basin was moved slightly so as to produce right shift, and a series of echelon folds began to form in the batter across the joint between the cardboard plates. As the right shifting was continued, and the "basin" was depressed relative to the "uplift," a monocline formed in the batter above the joint between the plates. During this stage of deformation, the parts of the echelon anticlines in the "basin" adjacent to the area of greatest relief on the monocline were overturned (fig. 18, section *A–A′*). The anticlines adjacent to the area of least relief on the monocline were tilted west (fig. 18, section *B–B′*). During continued right shift and depression of the "basin," the batter began to rupture, and discontinuous high-angle faults formed along the monocline above the joint between the cardboard plates. As the faults began to form, the development of the echelon folds ceased. By a very slight underthrusting of the "basin," the "uplift" was caused to bulge upward near the fault (fig. 18, section *A–A′*).

Although there was no attempt to construct this inelegant model to scale with respect to strength of materials, the experiment indicates that the sequence of events postulated for the Nacimiento fault is mechanically possible with right shift along a high-angle reverse fault. The echelon folds in the "basin" part of the model are shallow seated, and, by analogy, the actual folds in the San Juan Basin may be shallow seated also. Near the "uplift" the amplitudes of the folds of the model are much greater, in accord with the postulation that the local patches of sedimentary rocks at the western edge of the Nacimiento uplift are tilted synclinal troughs faulted from the tilted synclines of the San Juan Basin.

The vertical displacement of the Nacimiento fault becomes greater from south to north. The greatest amount of vertical displacement is northeast of Cuba, where the vertical separation may be as much as 10,000 feet (pl. 8). The axis of the San Juan Basin lies just a few miles north of the north end of the Nacimiento uplift, and the top of the Precambrian rocks on the uplift is 16,000–18,000 feet higher than the top of the Precambrian rocks in the trough of the adjacent parts of the San Juan Basin. Figure 19*A* shows generalized structural profiles of the top of the Precambrian rocks on the Nacimiento and French Mesa–Gallina uplifts and in the San Juan Basin west of the uplifts. If both profiles were straightened or flattened, the profile of the basin would be longer than the profile of the uplifts.

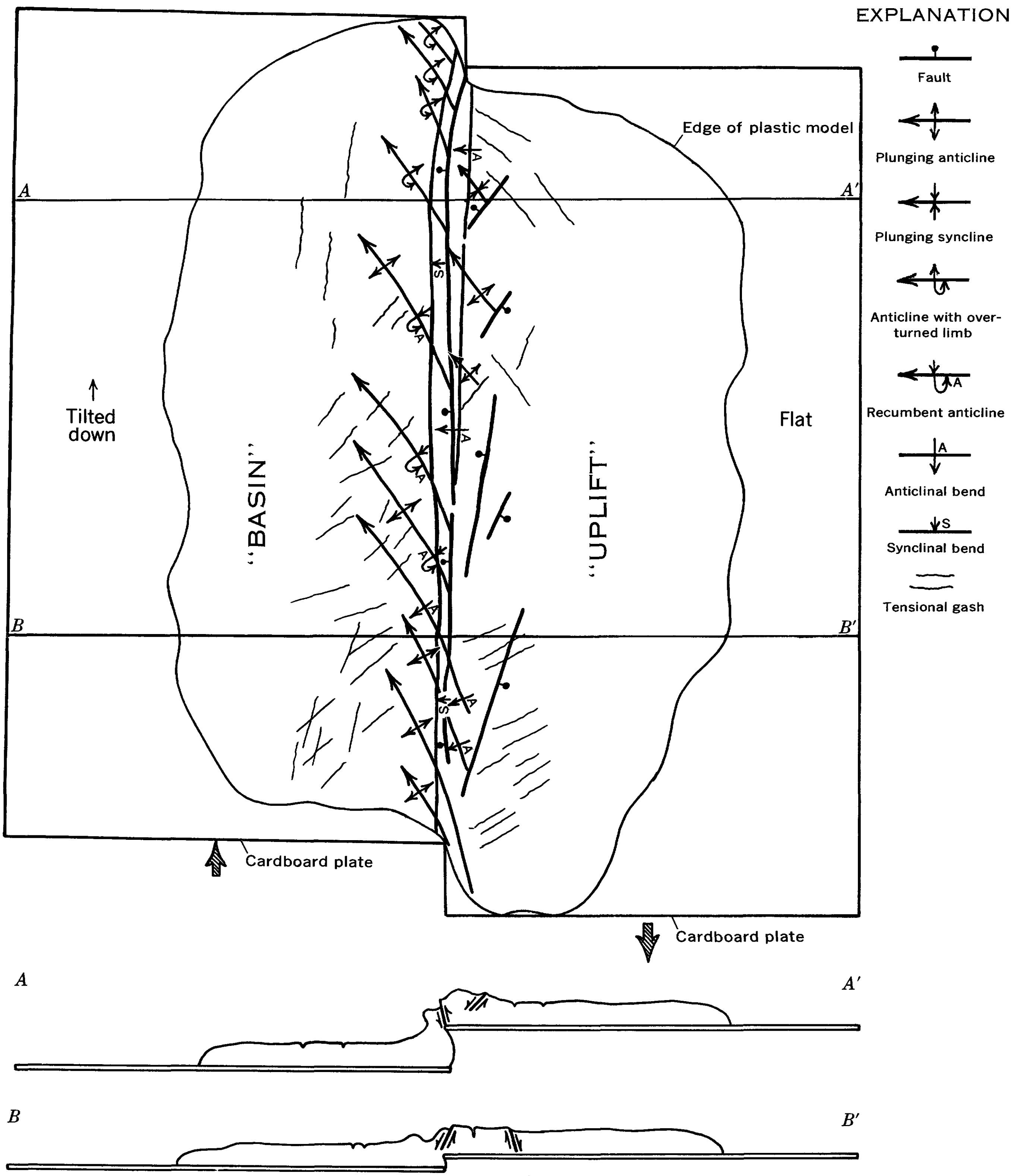
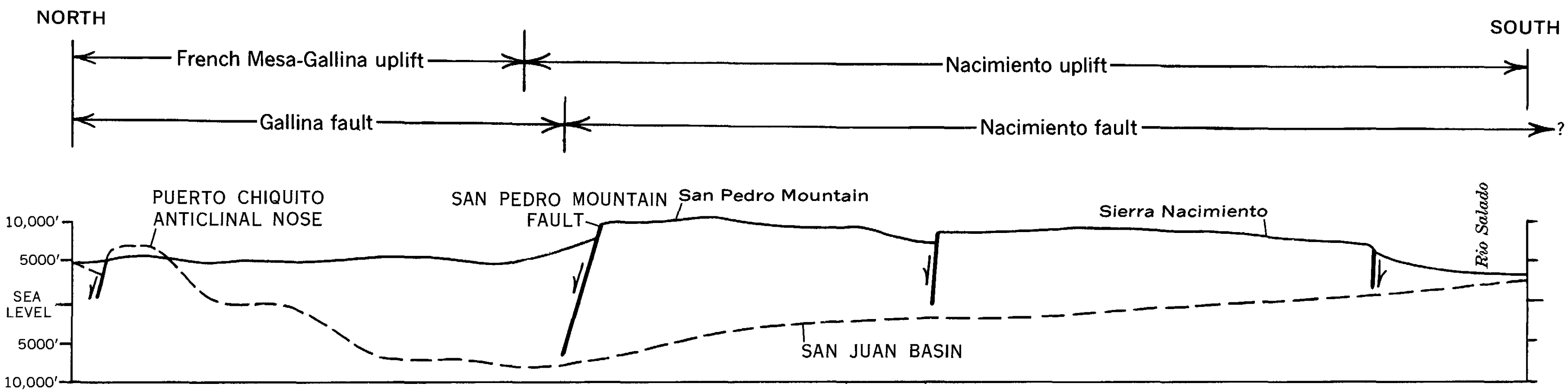


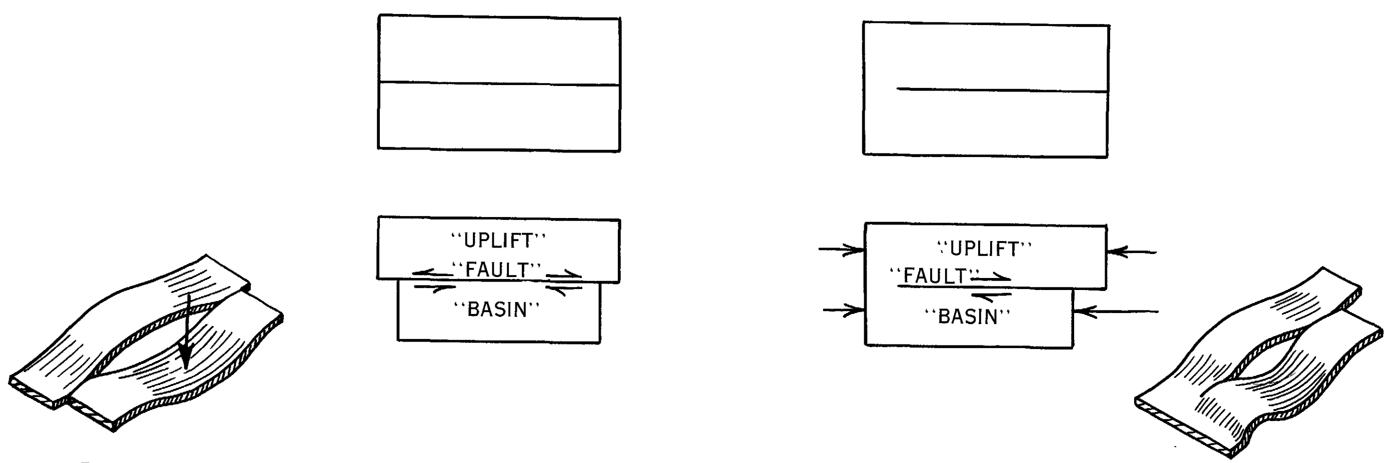
Figure 18.—Sketch of plan and sections of plastic model showing deformation resulting from right shift and tilting of rigid plate beneath model.

Because the vertical scale of figure 19*A* is greatly exaggerated, the difference in length between the straightened profiles would be exaggerated, but even the actual lengths of the profiles would be appreciably different.



Length of profiles: 70 miles

A. Structural profiles of top of Precambrian rocks of the French Mesa-Gallina and Nacimiento uplifts (solid line), and the eastern part of the San Juan Basin (dashed line). Profiles are drawn through the areas of maximum structural relief east and west of the Gallina and Nacimiento faults



B. Diagrams showing relative shift between basin and uplift as the result of a vertical force only

C. Diagrams showing relative shift between basin and uplift as the result of a tangential compressional force

FIGURE 19.—Structural profiles and diagrams showing possible directions of shift of the San Juan Basin relative to the French Mesa-Gallina and Nacimiento uplifts.

At this point in the discussion, the large-scale geometry of basin formation should be considered, in order to determine whether the San Juan Basin has been shortened horizontally relative to the Nacimiento and French Mesa–Gallina uplifts, or whether the basement rocks of the basin have been stretched and lengthened. The slight amount of earth curvature was not plotted in constructing the profiles of figure 19*A*, but curvature should be considered in constructing and interpreting geologic sections. The regional geometrical aspects of basin formation were discussed by Dallmus (1958), who pointed out that curvature should be taken into account because the earth has finite dimensions and mass, and volume changes that result from the compression of rocks are limited. In mathematical treatments these finite dimensions should be considered instead of the infinite planes, areas, and volumes that are implied when the surface of the earth is considered as a straight line or plane in construction of conventional geologic sections.

In the sections shown in figure 20, arc *ACB* represents the general curvature of the earth, line *ADB* represents a chord of the arc *ACB*, and line *CO* represents a segment of the radius of the arc *ACB* whose center is the center of the earth. Points *A* and *B* represent the edges of a segment of the earth's crust that has subsided because of a vertical force.

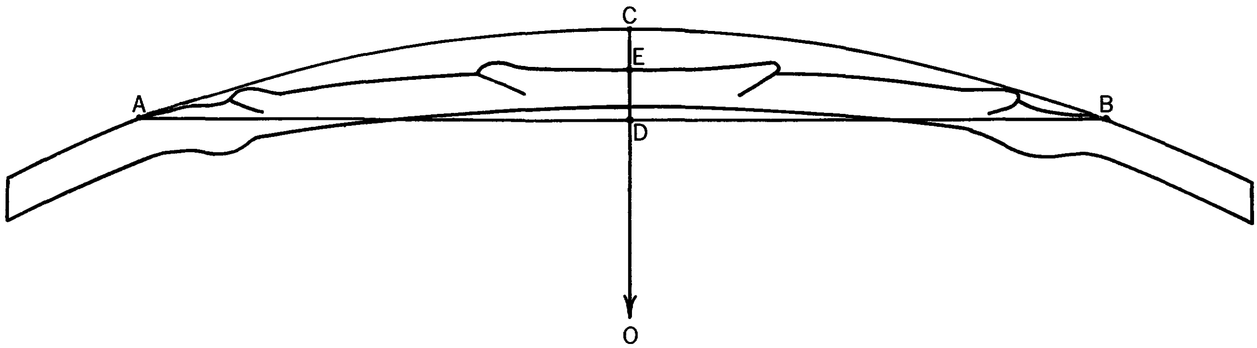
In figure 20*A*, line *AEB* represents the general configuration of the upper surface of a structural basin that has subsided vertically through a distance *CE*. Distance *AEB* is shorter than arc *ACB*; thus, if points *A* and *B* have not changed position relative to each other and to the center of the earth, the horizontal dimension of the basin has been decreased. Since the volume of the subsiding segment of the crust has not changed, the segment has been compressed. The generated stresses are related directly to the amount of subsidence *CE* for a given length of the chord *ADB*.

Actually, in subsidence of this kind, part of the compressional stress would be relieved by a slight lessening of volume as the result of bulk compaction of the rocks and perhaps by a slight flowage from the edges of the basin. However, the volume change would be relatively small, and most of the stress would be relieved by folding or thrust faulting, which would, in effect, locally change the vertical shape or the vertical dimension (thickness) of the crustal segment. The folding and faulting might occur at the margins of the basin, within the basin, or in both places. Probably the crust outside the basin at points *A* and *B* would be buckled or faulted also, or the diameter of the basin might be increased. However, for simplicity, it is assumed that points *A* and *B* do not change position with respect to each other or to the center of the earth.

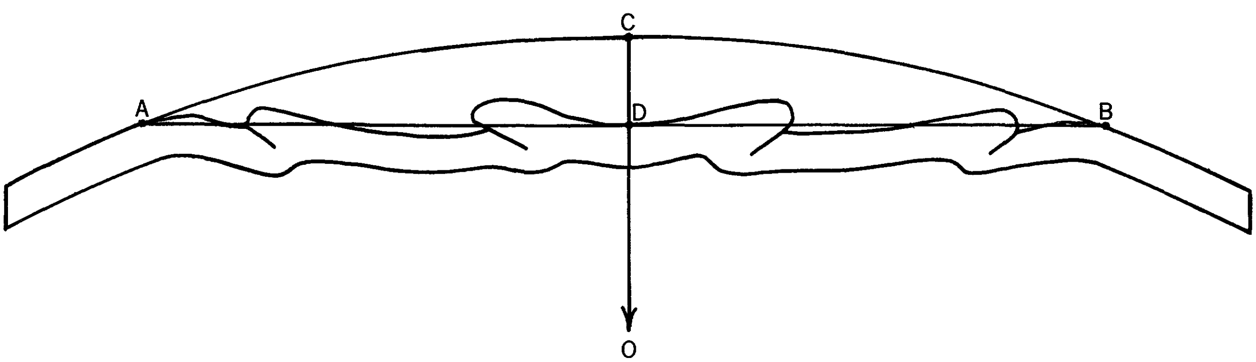
The maximum amount of shortening would occur when the basin subsided through the distance *CD*, and the basin would then be the same length as the chord *ADB* (fig. 20*B*). If nearly all the compressional stress was relieved by folding and faulting, further subsidence would relieve any residual compressional stress and would bring the limbs of the basin into tension. However, if the deformation was entirely elastic, which is unlikely, the limbs of the basin would not be stretched to generate a tensional stress in the crustal segment until the basin had subsided through a distance greater than *CF* (fig. 20*C*). In figure 20*C* the upper surface of the basin (*AFB*) is the same length as arc *ACB*, and *CD* equals *DF*. Thus, a basin that subsides because of a predominantly vertical force (caused by loading at the top of the crust, or withdrawal of subcrustal material) is first shortened and undergoes compression as a result of the shortening; then, if the basin continues to subside, the compressional stress is released, and eventually the rocks of the basin are stretched and undergo tension. However, if the basin subsides owing to a vertical force in a regional tensional stress field it is not compressed, but is lengthened as it subsides through distance *CD*. This lengthening of course, requires that points *A* and *B* are displaced away from each other by the stretching force, so that the crustal segment remains the same length as line *ACB*. Further subsidence stretches the rocks of the basin or causes the formation of a graben or half graben.

Dallmus (1958, table 1, p. 888) calculated the length of the chords (corresponding to line *ADB*) and the median heights of arcs (corresponding to line *CD*) above the chords for great circle arcs ranging from 1° to 5°. For an arc of 1° the distance *CD* is about 777 feet. The length of the profile of the Central basin of the San Juan Basin shown in figure 19*A* is less than 1° of the earth's circumference; however, the amount of subsidence of the basin relative to the ends of the profile is more than six times the greatest amount of subsidence (*CF*=approximately 1,500 ft) necessary to bring the limbs of the basin into tension (fig. 20*C*) and stretch them if the subsidence were caused by a predominantly vertical force (fig. 19*B*).

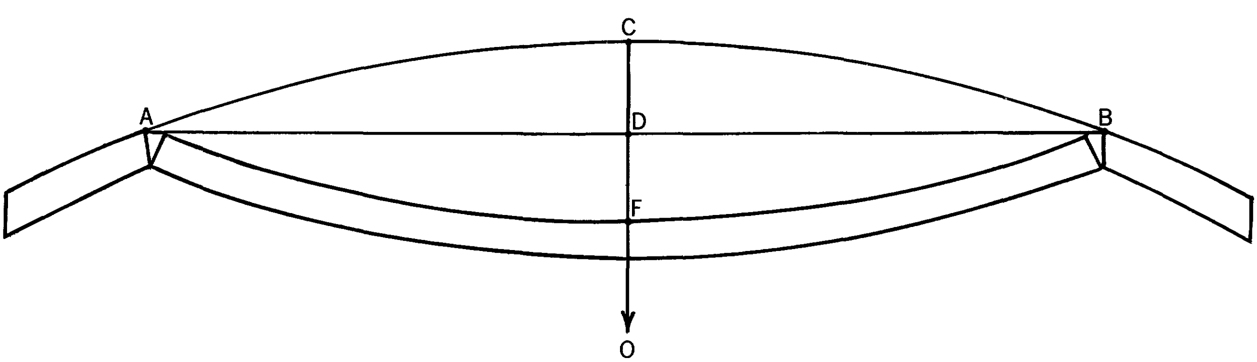
Of course, the profile shown in figure 19*A* represents only the eastern part of the Central basin. Even so, the amount of Laramide subsidence of the San Juan Basin as a whole was apparently great enough to lengthen the entire basin, if the subsidence occurred in response to a predominantly vertical force. The lengthening is likely even if (as in the extreme case represented by fig. 20*C*) there is no permanent deformation of the basin or its margins during a compressional phase (fig. 20*A*, *B*) of subsidence. For example, con-



A. Early compressional phase of subsidence



B. Maximum compressional phase of subsidence. Further subsidence will relax compressional stress and bring the basin into tension



C. Maximum amount of subsidence necessary to bring basin into tension if preceding deformation had not been permanent

FIGURE 20.—Compressional and tension phases of subsidence of a segment of the earth's crust.

sider a northeast-southwest profile across the maximum dimension of the basin from the vicinity of Gallup, N. Mex., to Pagosa Springs, Colo. (fig. 5)—an arc of a little more than 2¼°. South of Gallup the top of the Cretaceous Dakota Sandstone is at an average altitude between 5,000 and 6,000 feet. On the Archuleta anticlinorium southwest of Pagosa Springs, the Dakota Sandstone is at an average altitude between 6,000 and 7,000 feet. In the deepest part of the Central basin the top of the Dakota is more than 2,000 feet below sea level. Therefore, the structural relief of the basin is 7,000–9,000 feet, depending on where one considers the opposite edges of the basin to be. If the maximum dimension is taken from the southwestern part of the Gallup sag to the crest of the Archuleta anticlinorium, the horizontal dimension of the basin is about 2½°. From the lengths of chords of great circle arcs given by Dallmus (1958, table 1, p. 888), the writer calculated that the median height (*CD*) of a 2½° arc is about 4,970 feet. Thus, the 7,000–9,000 feet of relief is near the greatest amount of subsidence (*CF*=9,940 ft for a 2½° arc) necessary to bring the southwest and northeast limbs of the basin into tension, even if the previous deformation was entirely elastic (fig. 20*C*). If the Zuni uplift or its northeastern flank is considered to be the southwestern edge of the basin, a shorter arc is measured, and the greatest amount of subsidence necessary to bring the limbs into tension is even less than that (*CF*=9,940 ft) for the 2½° arc.

A northwest-southeast profile of the Dakota Sandstone between the French Mesa anticline and the Hogback monocline near the Colorado line extends about 1½°. The average structural relief of the profile is more than 6,000 feet, indicating an amount of subsidence that is more than sufficient to bring the northwest and southeast limbs into tension. Thus, during the late stages of Laramide orogeny, the entire basin would have been lengthened, or the limbs would have been stretched, if the subsidence were caused by a predominantly vertical force within the basin.

It can be seen from these considerations that the geometry of the basinal fold shown in figure 19*A* necessitates the conclusion that the southwest limb of the Central basin was stretched (or lengthened), or that it moved toward the axis of the basin along a horizontal component. The right shift indicated by the staggered folds along the Nacimiento fault implies that the southwest limb has not been stretched appreciably, but has moved toward the axis of the basin; thus the Central basin has been shortened relative to the Nacimiento and French Mesa–Gallina uplifts. The nature of this horizontal component of movement is not indicated, however. The movement would have been necessary whether the basinal trough subsided owing to a vertical force and "pulled" the southwest limb toward it, or whether the southwest limb was "shoved" toward the axis by horizontal compressional forces causing downbuckling of the basin.

Right shift along the Nacimiento fault could have been caused by differential yielding of the basin and the Nacimiento uplift to a vertical principal force, as illustrated in figure 19*B*, or to local vertical forces (downbuckling of the basin) produced by nearly horizontal regional compression, as illustrated in figure 19*C*. The direction of shift on the Gallina fault provides a clue to the forces.

GALLINA FAULT

Near the north end of the Nacimiento uplift, the Nacimiento fault passes into the northeast-trending Gallina fault (pl. 7). Here the Gallina fault is downthrown to the west, like the Nacimiento fault, but the vertical separation on the Gallina fault is less than 1,000 feet, whereas the vertical separation is more than 9,000 feet on the Nacimiento fault near the north end of the uplift (pl. 8, sections *AA–A′A′* and *BB–B′B′*). The work of Hutson (1958), Fitter (1958), and Lookingbill (1953) shows that the Gallina fault cuts obliquely across part of the monocline north of the Nacimiento uplift, persists north-northeastward on the French Mesa-Gallina uplift for almost 25 miles from the Nacimiento fault, and dies out north of the Gallina anticline (pl. 7).

The apparent throw on the Gallina fault is down to the west between the Nacimiento uplift and the northern end of the French Mesa anticline. Farther north the apparent throw is down to the east on the Gallina and Rio Gallina anticlines, but the throw is down to the west near the termination of the fault. Along the Gallina anticline the fault is high-angle reverse, and the fault plane dips west (Lookingbill, 1953). These differences in apparent throw seem to be a result of strike-slip movement that caused juxtaposition of folds that were not formed together originally. The movement allowed some folds, such as the Puerto Chiquito anticlinal nose and the syncline to the north, to develop independently from the features on the other side of the fault. The folds west of the fault indicate that the San Juan Basin adjacent to the fault has been shortened relative to the part of the French Mesa–Gallina uplift that is east of the fault. This shortening indicates right shift on the fault, and part of the northeastward shift on the west (basin) side of the fault seems to have been "taken up" geometrically by the northwest-plunging Puerto Chiquito anticlinal nose (fig. 19*A*), which is strongly asymmetrical, having a steep northeast limb and a bordering faulted syncline at the northeast. The Gallina fault dies out north of this syncline. The axes of the Rio Gallina and Gallina Mountain anticlines parallel the Gallina fault; they may be secondary vertical drag structures that are related to the fault. The amount of right shift on the Gallina fault is less than that on the Nacimiento fault, mainly because the Gallina fault is near the trough of the San Juan Basin, where the greatest amount of vertical movement occurred. Also, the alinement of the Gallina fault more closely approaches the northeast-southwest direction of shortening of the San Juan Basin than does the alinement of the Nacimiento fault, and this factor tends to decrease the amount of shift necessary to accomplish shortening of the basin along the Gallina fault.

If the trough of the San Juan Basin had subsided (relative to the French Mesa–Gallina uplift) in response to a regional vertical force within the basin, the northeast limb of the basin would have been stretched and the Puerto Chiquito nose and other folds west of the fault would not have developed; or the northeast limb would have been "pulled" southwestward toward the trough during the late stages of basin formation, and the lateral shift on the Gallina fault would have been left instead of right (fig. 19*B*). The right shift on the Gallina fault indicates that the basin was downbuckled as it shifted northeast, encroaching on the Archuleta anticlinorium (fig. 19*C*). The shift that accompanied the major movements on the Nacimiento and Gallina faults in post-San Jose time seems to have been the last major stage of deformation. Most of the shift occurred after the stage of deformation (fig. 20*B*). during which compressional forces could possibly be attributed to the shortening and crowding within the basin and along its margin, if the basin had subsided in response to a dominantly vertical regional force located within it. Therefore, the right shift on the Gallina fault seems to be good evidence that the force which produced the northwest-trending axis of the San Juan Basin was a regional tangential compressional force directed toward the basin.

SAN PEDRO MOUNTAIN FAULT

Along the north side of San Pedro Mountain, the northern part of the Nacimiento uplift is tilted steeply to the north and dropped along a northwest-trending normal fault (pl. 7), which was called the San Pedro Mountain fault by Hutson (1958, p. 33). According to Hutson, the fault plane dips 63° NE. in the SW¼ sec. 1, T. 22 N., R. 1 W. At the northwest this fault intersects the Nacimiento fault near the upper part of San Jose Creek in sec. 1, T. 22 N., R. 1 W. (south of the position of intersection shown by G. H. Wood, Jr., and S. A. Northrop, 1946), and the fault extends with a curved trace for about 10 miles to the southeast, where it dies out. The dropping and northward tilting of the block north of the San Pedro Mountain fault causes the vertical separation on the southern part of the Gallina fault to be much less than the vertical separation on the Nacimiento fault (pl. 8, sections *AA–A′A′*, *BB–B′B′*).

Wood and Northrop (1946) indicated left shift along the (then unnamed) San Pedro Mountain fault on their geologic map and indicated that the fault terminates at the Nacimiento fault. Hutson (1958, p. 37 and fig. 5) indicated that the block south of the San Pedro Mountain fault has shifted west (right shift), and that the fault extends west of the Nacimiento fault into the belt of steeply dipping beds along the major synclinal bend west of the Nacimiento fault. Hutson's (1958, fig. 5) map shows the San Pedro Mountain fault extending west into the basin along San Jose Creek in sec. 34, T. 23 N., R. 1 W., and indicates that the Mesaverde Group and younger rocks south of San Jose Creek are offset to the west (right shift) relative to the same rocks north of San Jose Creek. However, Hutson seems to have mistaken the Cuba Mesa Member of the San Jose Formation for the Ojo Alamo Sandstone in sec. 3, T. 22 N., R. 1 W., south of San Jose Creek, and thus, he mistakenly mapped the poorly exposed Nacimiento Formation, Ojo Alamo Sandstone, and undivided Fruitland Formation and Kirtland Shale as the Lewis Shale in this vicinity. There are no exposures in the broad gravel- and alluvium-filled valley of San Jose Creek to support an assumption of right-lateral offsets of the Mesaverde Group and younger rocks along a northwest extension of the San Pedro Mountain fault.

The outcrops of the Dakota Sandstone and lower part of the Mancos Shale west of the Nacimiento fault in sec. 35, T. 23 N., R. 1 W., are offset sharply to the east relative to outcrops farther south in sec. 2, T. 22 N., R. 1 W., as shown by Wood and Northrop (1946). However, this offset seems to be mainly the result of right shift on an east-trending fault in the basin west of the Nacimiento fault in the southern part of sec. 35, T. 23 N., R. 1 W. This fault seems to terminate at the Nacimiento fault; and if it is part of the San Pedro Mountain fault, it has been offset to the north from the San Pedro Mountain fault (located on the uplift by Hutson in the SW¼ sec. 1, T. 22 N., R. 1 W.) because of right shift along the Nacimiento fault. The present writer concludes there is no particular evidence that indicates the San Pedro Mountain fault does not terminate at the Nacimiento fault, and there is no evidence that indicates a major strike-slip component of movement along the San Pedro Mountain fault.

The San Pedro Mountain fault at the northern end of the Nacimiento uplift is near the area of maximum structural relief between the uplift and the San Juan Basin; the fault might be a tensional fault formed mainly in response to dominantly vertical local forces. However, the 63° NE. dip of the fault plane indicates that the block north of the fault also had a horizontal component of movement as it moved down, a movement which accomplished some lengthening of the north end of the uplift. This lengthening occurred in a north-northeasterly direction almost parallel to the general trend of the Gallina fault (pl. 7). If the San Juan

Basin shifted northward along the Nacimiento fault and north-northeastward along the Gallina fault, as seems to be indicated, local horizontal tensional stresses, as well as vertical stresses, were set up in the vicinity of the junction of the faults near the north end of San Pedro Mountain. The geometry of this concept was not taken into account in the illustration of the general case (fig. 19*C*), where the Nacimiento and Gallina faults are considered to be segments of a straight line, but the situation is shown in figure 21. In the simplest case, if the basin is moved northward along the Nacimiento fault, a gap appears along the Gallina fault (fig. 21*B*) as the basin is pulled away from the uplift and the southern part of the French Mesa–Gallina uplift. A segment of the monocline near the axis of the San Juan Basin and west of the Gallina fault is then unsupported along its eastern side, and the northern part of the Nacimiento uplift is partly unsupported because of a gaping fissure at its northern end. Of course, there is no fissure now along the southern part of the Gallina fault, and there is no evidence that one ever existed. However, the slumping and north-northeastward lengthening of the northern part of the Nacimiento uplift that are implied by the geometry of the San Pedro Mountain fault are consistent with the idea that local horizontal tensional stresses as well as vertical forces produced the San Pedro Mountain fault. Furthermore, the left shift on the transverse faults that cut the Mesaverde Group in the Northern Hogback Belt in the SW¼ T. 24 N., R. 1 E. (pls. 1, 7) indicates that the segment of monocline just west of Canon de Chavez slumped and was tilted toward the southern part of the Gallina fault. The southern edge of this tilted segment seems to have been the right-lateral transverse fault that offsets the Dakota Sandstone in sec. 35, T. 23 N., R. 1 W.

All these facts indicate that the San Pedro Mountain fault is probably a rotational normal fault hinged at the southeast end. The fault was produced probably by local vertical and horizontal tensional forces during downbuckling and north-northeastward shift of the San Juan Basin along the Nacimiento and Gallina faults. The dropping and slight northeastward movement of the block north of the San Pedro Mountain fault slightly decreased the amount of right shift on the Gallina fault.

The angular unconformity between Pennsylvanian and Permian rocks on the block north of the San Pedro Mountain fault (Hutson, 1958, p. 11–12) might indicate that the fault is a rejuvenated ancient structural feature or that it is superimposed on an ancient feature. The relations of the San Pedro Mountain, Nacimiento,

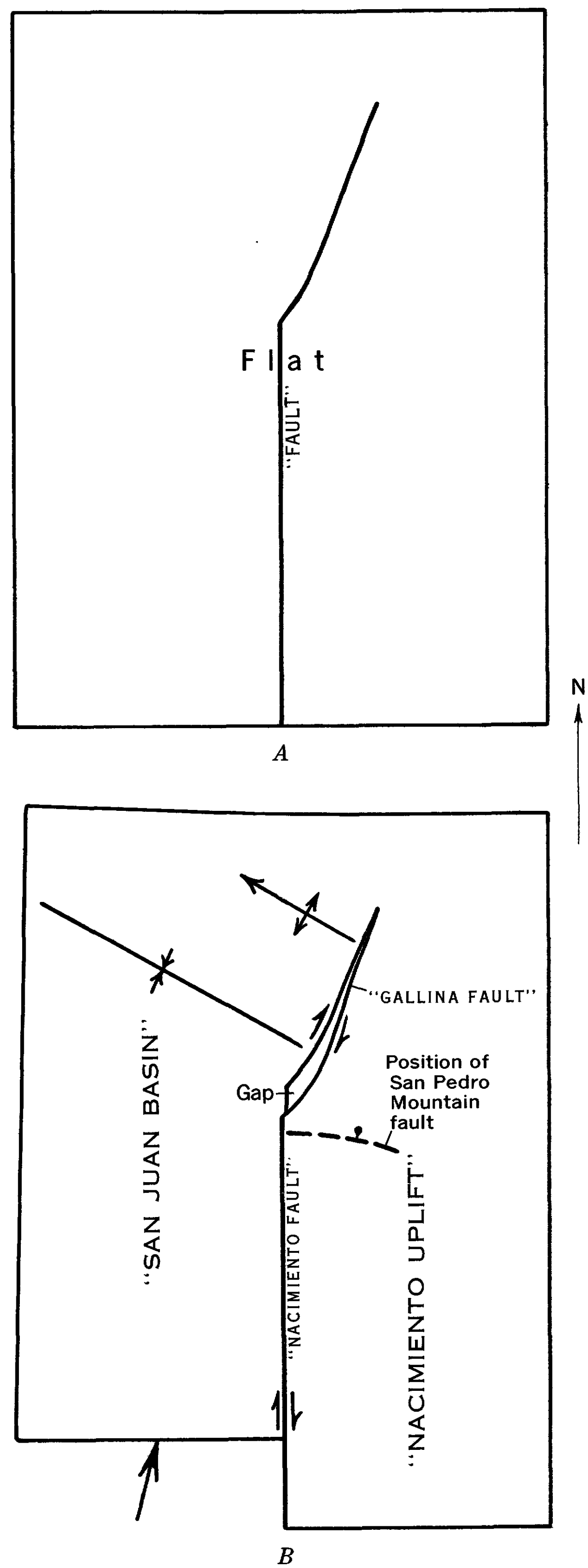


FIGURE 21.—Model showing area of horizontal tensional stress (gap) that develops during right shift on a fault having differently oriented segments.

and Gallina faults are shown in three dimensions in figure 22.

ARCHULETA ANTICLINORIUM

The northwest-trending Archuleta anticlinorium lies along the northeast edge of the San Juan Basin north of the French Mesa-Gallina uplift. The anticlinorium is an interbasinal structural divide that separates the San Juan Basin from the Chama basin, and from the San Juan sag of Kelly (1955, fig. 5, p. 23), which is a northwestern extension of the Chama basin in Colorado (fig. 5). The anticlinorium is basically a wrinkled and faulted arch, and this was emphasized by Kelley and Clinton (1960, p. 49–50), who referred to the structure as the Archuleta arch. However, the present writer prefers the term Archuleta anticlinorium, as originally used by Wood, Kelley, and MacAlpin (1948), and by Kelley (1955), because it emphasizes the complex nature of the arch.

The axes of most of the folds of the anticlinorium trend northwest, as do many of the faults. A few fold axes and a few faults trend north or northeast. The crest of the anticlinorium is marked by local structural highs and sags, most of which are slightly oblique to the general trend of the anticlinorium. The structurally highest part of the anticlinorium is on the Horse Lake and Willow Creek anticlines near the southeastern end of the anticlinorium. (See structure contours: Dane, 1948; G. H. Wood, Jr., and others, 1948.) The part of the anticlinorium that is in New Mexico plunges southeast into the Chama basin (fig. 23).

The peculiar system of faulted folds in the Cretaceous rocks on the Archuleta anticlinorium north of El Vado (fig. 23) was interpreted differently by Muehlberger (1960) and by Dane (1948). Muehlberger (1960, p. 109) interpreted the Horse Lake and Willow Creek anticlines, and other folds on the anticlinorium, as having been formed by shallow-seated decollement folding. The Dakota Sandstone and overlying rocks supposedly glided westward over older sedimentary rocks and were folded because of the driving force provided by the weight of the Cretaceous sedimentary rocks tilted up on the western flank of the Brazos uplift. However, wells drilled to the Precambrian basement rocks on the Horse Lake and Willow Creek anticlines and on South

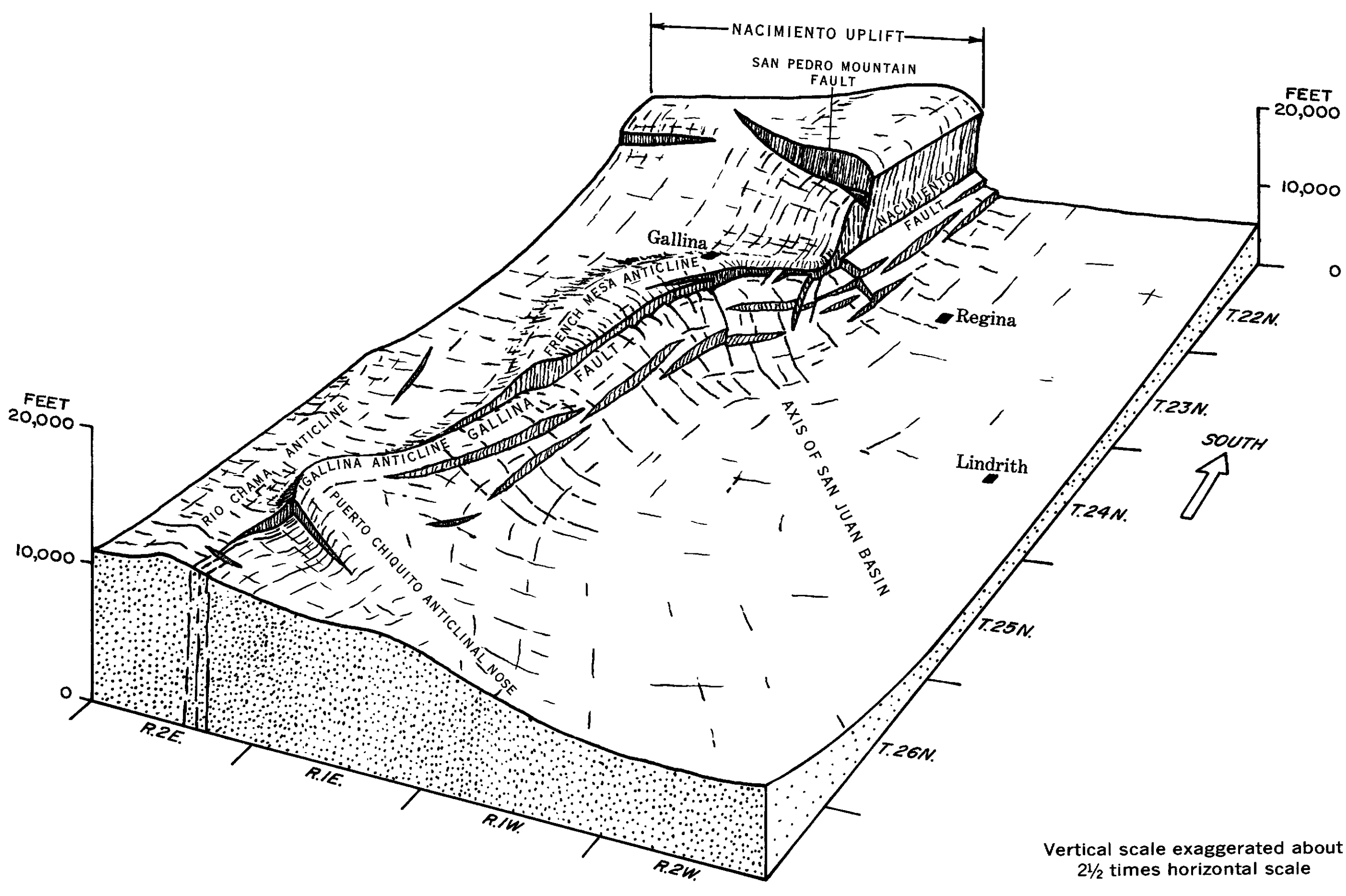


FIGURE 22.—Probable general configuration of Precambrian basement rocks of Nacimiento uplift (northern part), French Mesa–Gallina uplift, and adjacent part of the San Juan Basin. Upper surface of Precambrian rocks is partly restored on higher part of Nacimiento uplift.

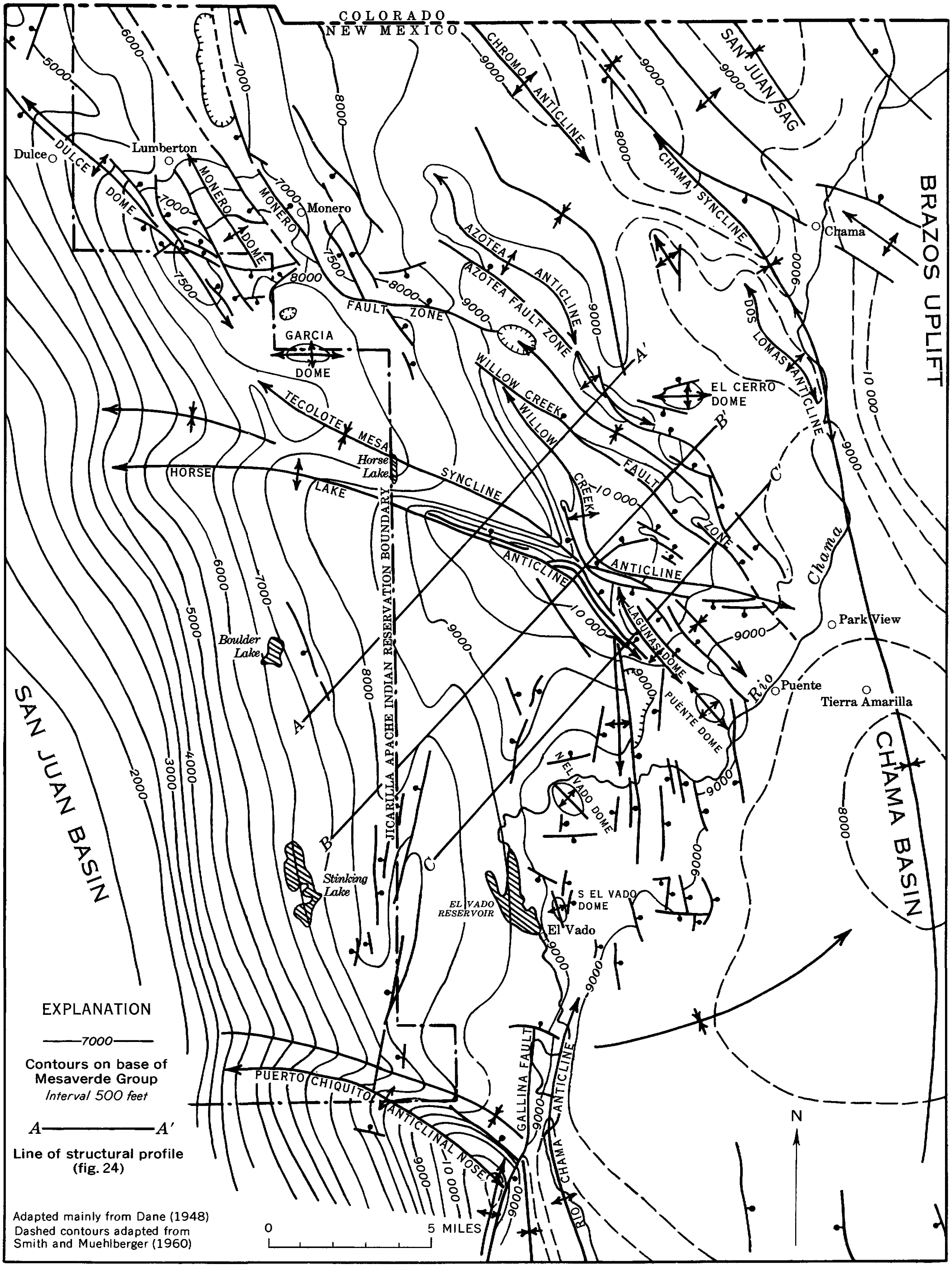


FIGURE 23.—Structure-contour map of southeastern part of Archuleta anticlinorium and adjacent parts of San Juan and Chama basins.

El Vado dome show that the basement is uplifted and that rocks beneath the Dakota are folded or faulted up in apparent concordance with the structure of the Dakota. The contact of the Dakota and the underlying Morrison Formation, where it is exposed in the canyon of the Rio Chama east of North El Vado dome, is a sedimentary contact, and there is no evidence of shearing along the contact. Furthermore, it is unlikely that a thick sequence of Cretaceous shale and sandstone ever stood on the narrow western flank of the Brazos uplift to provide the driving force for a decollement sheet, because erosion must have attended the uplift of these rocks, as shown by the fact that the Blanco Basin and El Rito Formations of early Tertiary age bevel the Cretaceous and older rocks on the eastern edge of the Chama basin and the Brazos uplift (Smith and Muehlberger, 1960).

According to Dane (1948), the folds were caused by horizontal compression, possibly with some vertically applied uplifting force. Dane explained the northwesterly trend of the Horse Lake anticline and the northerly trend of the Willow Creek anticline as having resulted from the wedging together of two blocks, one of which had a northwesterly trend and the other a northerly trend. The wedging together is said to have produced the (Tecolote Mesa) syncline between the two blocks. Dane postulated that the compressional stress was oriented northeast-southwest in the northern part of the anticlinorium and east-west in the southern part of the anticlinorium.

The configurations of the Horse Lake and Willow Creek anticlines and the pattern of the fold axes and faults (fig. 23) shed some light on the origin of these structures. The asymmetrical Horse Lake and Willow Creek anticlines are basically faulted blocks tilted in opposite directions (fig. 24). Between them lie two wedge-shaped slices that are also tilted in opposite directions. The southeast wedge has been dropped slightly and folded to form Lagunas and Puente domes and adjacent faulted synclines (fig. 23). The northwest wedge is dropped to form the Tecolote Mesa syncline. The overall configuration of the Horse Lake and Willow Creek anticlines and the intervening wedges is that of a faulted northwest-elongated dome that has been tilted slightly toward the San Juan Basin. The southeast and northwest wedges are the dropped axial parts of the dome.

The axes of the northwestern part of the Horse Lake anticline and the southern part of the Willow Creek anticline trend generally N. 70°–80° W., whereas the axes of the southern part of the Horse Lake anticline and the northwestern part of the Willow Creek anticline trend N. 10°–30° W. The faults on the opposed steep limbs of the anticlines are generally parallel to the adjacent segments of the axes of each fold. The angle between these two main sets of folds and faults is between 50° and 60°, and this is suggestive of the angle between genetically related sets of shear fractures. In a general way, the large normal faults of the Willow Creek fault zone and the faults parallel to Lagunas and Puente domes trend in a northwesterly direction which bisects the angle between the trends of the major fold axes and their related faults. If the northwest-trending faults are related genetically to the folds and faults trending N. 70°–80° W., and N. 10°–30° W., the northwest-trending faults might have originated as longitudinal faults parallel to the axis of an elongate dome.

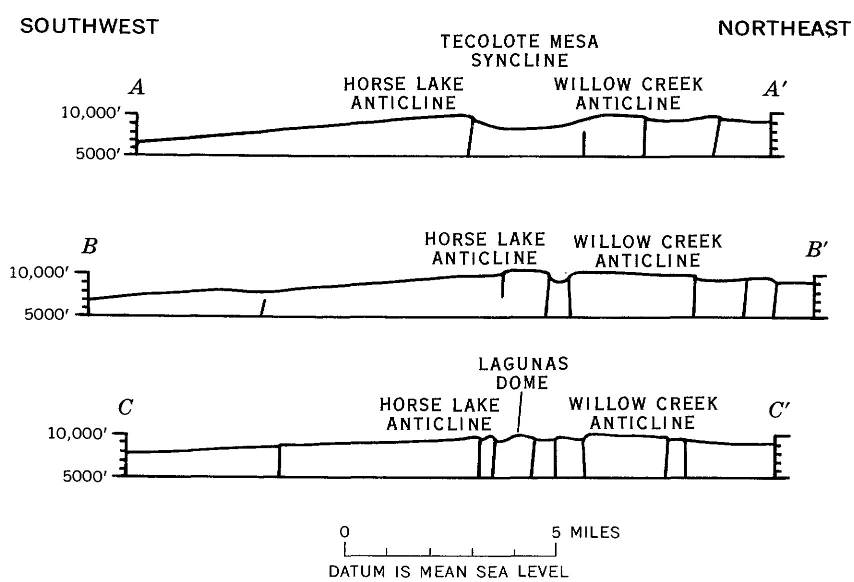


FIGURE 24.—Structural profiles of Horse Lake and Willow Creek anticlines.

The overall pattern of fold axes and faults is similar to the pattern of faults that might be expected to form on an elongate dome or doubly plunging anticline because of longitudinal and transverse stretching of the upper part of the fold as it was uplifted (De Sitter, 1956, p. 201–211). Longitudinal faults form parallel to the axis because of stretching at right angles to the axis. Shear faults form at acute angles to the axis because the fold is stretched parallel to the axis as well as at right angles, and the shears allow relief of the tensional forces in a component between the two main directions of tensional stress. In the terminology of De Sitter (1956, p. 208–211, fig. 147), the shear faults would be perianticlinal faults. The stretching of the shallow upper part of a fold causes lengthening, which is accomplished often by grabening in the crestal part of the fold.

If the major northwest-trending faults and the major faults that parallel the axes of the Horse Lake and Willow Creek anticlines originated because of tension in the upper part of a dome, the vertical displacement on the faults would become less in the deeper part of the fold because the deeper part would not have been stretched as much as the upper part. Thus, the uparched basement rocks might have been displaced only slightly on each fault. Also, the amount of vertical displacement on the faults becomes less in a horizontal direction away from the structurally high part of the dome, and the unfaulted Cretaceous rocks on the steep limbs of the northwestern parts of the Horse Lake and Willow Creek anticlines may overlie buried faults that are extensions of the faults that displace the Cretaceous rocks near the central part of the dome. Thus, the pattern made by the major faults and the curved axes of the Horse Lake and Willow Creek anticlines may have formed because of fracturing of the competent basement rocks and the overlying sedimentary rocks during doming of the southeastern part of the Archuleta anticlinorium.

The evidence for this concept is circumstantial because there is no proof that the supposed shear and longitudinal faults were formed at the same time. Also, it cannot be shown definitely at present that the first stage of Laramide orogeny produced a broad low dome on the southeastern part of the anticlinorium, although the stratigraphic relations of the Fruitland and Kirtland and the Ojo Alamo Sandstone in the San Juan Basin west of the anticlinorium might indicate this, as do unconformities within the Mancos Shale on the anticlinorium. The Cretaceous rocks might have been deformed along very ancient basement fractures of the Paleozoic uplift on which the anticlinorium is situated. The deformation probably would have proceeded selectively along those preexisting fractures that were oriented to relieve the Laramide stresses most easily. Nevertheless, the general pattern of the larger features is notably similar to the fracture pattern that can be predicted for a large elongated dome or doubly plunging anticline.

Although the southeastern part of the Archuleta anticlinorium may have originated as a broad dome, the fracture pattern itself does not indicate whether the dome was formed by predominantly vertical forces (with no attendant crustal shortening) or by generally horizontal (tangential) deep-seated compressional forces (with attendant upward bulging and crustal shortening). Also, the pattern of deformation might have been caused by lateral shift along a postulated deep-seated regional wrench zone (the "Rattlesnake lineament"), as suggested by Kelley and Clinton (1960, p. 95). However, if the southeastern part of the anticlinorium has been shortened, the structurally high part on which Horse Lake and Willow Creek anticlines are situated has been shortened more than the structurally lower part of the anticlinorium on which Dulce and Monero domes are situated. Under such circumstances, a local coupling action would result between the Horse Lake–Willow Creek and Dulce–Monero structural culminations, and this coupling action may or may not be related to deep-seated regional wrench zones.

The configurations of the individual folds of the southeastern part of the anticlinorium indicate something about the origin of the folds. Locally, on the east flank of Horse Lake anticline and the west flank of Willow Creek anticline, the sedimentary rocks are vertical and at some places may be overturned slightly. The configuration of the Tecolote Mesa syncline and the adjacent steeply dipping limbs of the anticlines seems to indicate shortening in a northeast-southwest direction, as does the configuration of the Lagunas-Puente domes wedge. The Horse Lake anticline is related to the Tecolote Mesa syncline in the same way that the Puerto Chiquito anticlinal nose is related to the syncline on its northern flank, and the alinements of the Horse Lake and Puerto Chiquito folds are similar (fig. 23); thus, possibly, all these features have a similar origin due to northeast-oriented compression.

Thus, although the general pattern of the major faults on the Horse Lake and Willow Creek anticlines seems to indicate that the faults were formed by longitudinal and transverse tensional stresses in the upper part of a broad dome, the configuration of the individual folds seems to indicate at least a small amount of shortening that would require a compressional force. These stress conditions are not necessarily incompatible, inasmuch as they could have been produced during two (or more) phases of yielding of the competent basement rocks to a northeast-oriented tangential compressional force.

A possible mechanism is illustrated by the structural profiles shown in figure 25. In figure 25*A* the hypothetical profile (at right angles to the axis of the southeastern part of the Archuleta anticlinorium) shows faults that might have formed on a low doubly plunging dome that was upwarped between the San Juan and Chama basins because of a deep-seated nearly horizontal compressional stress. Tensional (longitudinal and shear) faults would form in the higher part of the relatively competent basement rocks of the dome because of longitudinal and transverse stretching, and these faults would be extended upward into the relatively incompetent sedimentary rocks, which would be stretched more than the basement because they were higher in the fold. Once the faults had appeared in the relatively competent basement rocks, further deformation would probably proceed along these early defined zones of structural weakness.

During the post-San Jose stage of deformation, when the major right shift occurred on the Nacimiento and Gallina faults, the San Juan Basin encroached northeastward on the Archuleta anticlinorium, and the San Juan Basin was depressed more than the Chama basin. The basement rocks of the Horse Lake block were tilted toward the San Juan Basin, and this tilting probably deflected the compressional force locally (fig. 25*B*) so that some of the earlier formed normal faults became high-angle reverse faults. Strike-slip movement along the earlier formed shear faults would have allowed the Horse Lake and Willow Creek basement blocks to be shoved toward each other as the wedge-shaped Tecolote Mesa and Lagunas-Puente basement blocks were depressed and shoved slightly outward parallel to the axis of the dome. Thus, strike-slip movements on the shear faults would have accomplished transverse (northeast-southwest) shortening and slight longitudinal (northwest-southeast) lengthening of the dome. This could account for the northeast-southwest shortening implied by the geometry of the sharply folded sedimentary rocks on the opposed flanks of the Horse Lake and Willow Creek anticlines, and for the shortening implied by the configurations of Tecolote Mesa syncline and Lagunas and Puente domes. A mechanism of strike-slip as well as vertical movement between competent blocks of the unparched basement might have produced folds in the sedimentary rocks on other parts of the anticlinorium also, but it is beyond the scope of the present paper to discuss the mechanics of the other folds.

The writer concludes that the fault pattern and the symmetry of the Horse Lake and Willow Creek anticlines on the southeastern part of the Archuleta anticlinorium indicate that this part of the anticlinorium originated as a low northwest-elongated dome which was later deformed into an anticlinorium. The entire Archuleta anticlinorium seems to have been produced by

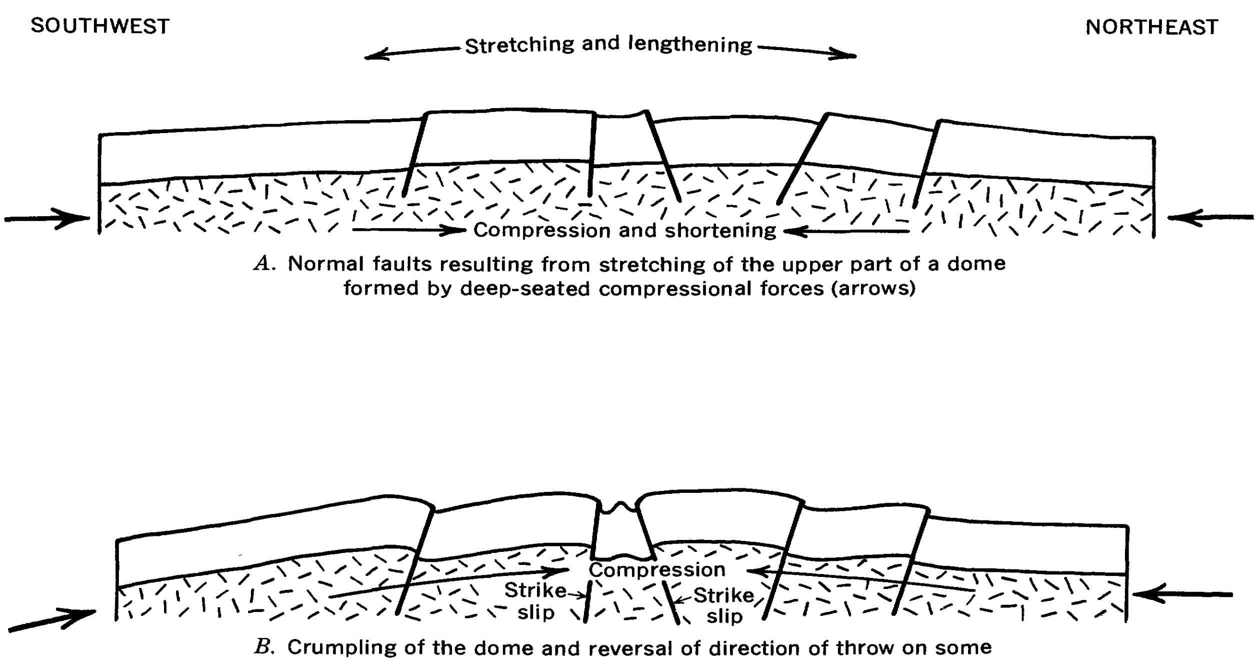


FIGURE 25.—Diagrammatic sections showing hypothetical stages of formation of an anticlinorium from an elongate dome.

the northeasterly compressional force that downbuckled the San Juan and Chama basins and caused the right shift on the Nacimiento and Gallina faults. Probably the main deformation was accomplished in two or more stages during Late Cretaceous and early Teritary time. According to Wood, Kelley, and MacAlpin (1948), sills associated with the Miocene(?) dikes in Colorado are not displaced by the major faults that offset the Cretaceous rocks; therefore, the major faults probably are Laramide. However, according to Dane (1948), a few of the faults on the anticlinorium are younger than the Miocene(?) dike swarm crossing that feature and may be of Miocene or Pliocene age. The intrusion of the dikes was probably related to stresses other than those that produced the basin and anticlinorium.

SALADO-CUMBRES STRUCTURAL DISCONTINUITY

The Nacimiento and Gallina faults and the eastern margin of the Archuleta anticlinorium mark parts of a major regional structural discontinuity. The two faults themselves are sharp and easily recognized as a discontinuity, but north of the surface termination of the Gallina fault there is no equivalent single structural feature that delineates the discontinuity. However, the patterns of deformation are considerably different on either side of a slightly curved line projected north-northeastward from the northern termination of the Gallina fault. The folds and faults of the Archuleta anticlinorium do not terminate abruptly at the north-northeast-trending stippled boundary shown (on pl. 7) as the east boundary of the anticlinorium north of the Gallina fault; nevertheless, many of the structural features do terminate very near this boundary, and the structural grain of the Chama basin at the southeast is dissimilar to that of the anticlinorium (fig. 23).

The line or band of discontinuity can be projected north-northeast past the northwest-plunging end of the Brazos uplift and the southeast end of the San Juan sag, but it is lost beneath the Tertiary rocks of the San Juan Mountains volcanic field in the vicinity of Cumbres Pass north of the Colorado boundary. The total length of the discontinuity from the vicinity of the place where the Rio Salado crosses the south end of the Nacimiento uplift to the vicinity of Cumbres Pass is almost 110 miles. The structural discontinuity is here called the Salado-Cumbres structural discontinuity.

The Salado-Cumbres discontinuity is similar in its general alinement and position to a central segment of the "Eastern Rockies trend" (of Kelley and Clinton 1960, fig. 9, p. 93)—a straight north-northeast-trending lineament drawn through the northern part of the Lucero uplift, the north end of the Nacimiento uplift, and the north end of the Brazos uplift. Possibly, the Salado-Cumbres discontinuity extends southwestward from the Nacimiento uplift along the east side of the Puerco fault belt toward the Lucero uplift. The San Juan sag and the northern part of the Brazos uplift in Colorado are buried beneath the San Juan Mountains volcanic field, and it is not known how far the discontinuity persists to the northeast from Cumbres Pass. Precambrian rocks lying directly beneath the Tertiary Potosi Volcanic Group are exposed at a few places along the Conejos River in T. 33 N., Rs. 5 and 6E. (Larsen and Cross, 1956, pl. 1), northeast of Cumbres Pass in Colorado. These Precambrian rocks may be in the buried northern part of the Laramide Brazos uplift. Therefore, the discontinuity might persist, beneath the volcanic rocks, at least as far northeast as the westernmost outcrops of Precambrian rocks on the Conejos River.

Where the Salado-Cumbres structural discontinuity is the Nacimiento and Gallina faults it is "real." Along the east side of the Archuleta anticlinorium the significance of the discontinuity is a matter of interpretation. However, the fact that the rocks are deformed differently on opposite sides of a line (or narrow band) suggests that the discontinuity may represent a real feature, such as the contact between rocks of differing structural competence, or a major zone of fracturing. This feature, if present, would have to be in the basement along the east side of the Archuleta anticlinorium, since the surface sedimentary rocks are the same on either side of the discontinuity, and at the surface there are no known faults parallel to the discontinuity.

Not only does the structural grain differ on opposite sides of the Salado-Cumbres discontinuity, but, perhaps more importantly, differing major features are opposed. Where the Nacimiento uplift is opposite the San Juan Basin, the east side is structurally highest; where the Archuleta anticlinorium is opposite the Chama basin, the west side is structurally highest; and, farther north, where the Brazos uplift is opposite the northern part of the Chama basin and the San Juan sag, the east side is again structurally highest (fig. 26).

The Salado-Cumbres structural discontinuity is oblique to the trends of the major structural features on either side. The alinement of the Nacimiento fault diverges more from the direction of shortening of the San Juan Basin and Archuleta anticlinorium that does the alinement of the Gallina fault and the northern part of the discontinuity. This obliqueness suggests a rather obvious conclusion that the basement rocks of the major structural features yielded differently during deformation, setting up local stresses which governed the formation of local structural features. The Precambrian basement rocks of the Nacimiento uplift are

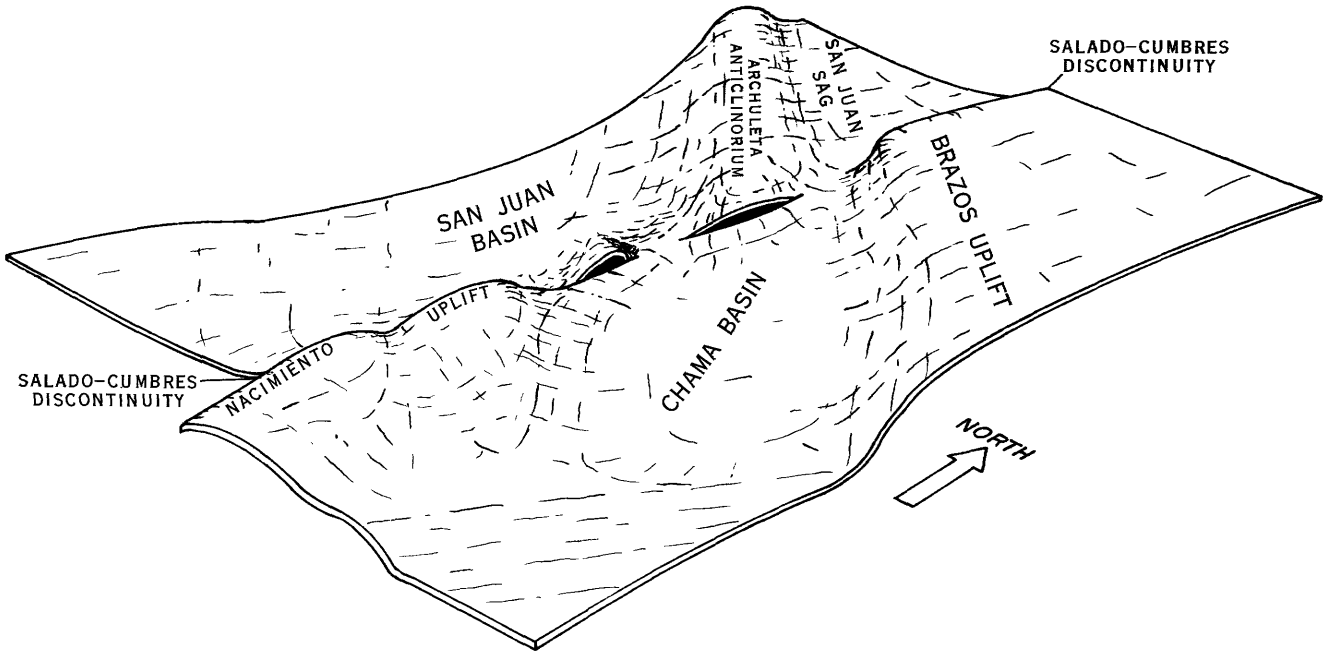


FIGURE 26.—Generalized model of major features along Salado–Cumbres structural discontinuity.

mostly granite, whereas the Precambrian rocks of the Brazos uplift are mainly metasedimentary and metavolcanic. Unfortunately, almost nothing is known about the basement rocks of the Archuleta anticlinorium and the San Juan and Chama basins. The major structural uplifts on either side of the discontinuity seem to be generally distinct structural blocks whose general outlines and orientations were determined, at least partly, by pre-Laramide events. The northerly alinement of the Nacimiento uplift is as old as Pennsylvanian or Permian (Renick, 1931, p. 14–19; Wood and Northrop, 1946; Read and Wood, 1947, p. 226, 232–234), and the northwesterly alinements of the Archuleta anticlinorium and Brazos uplift also are as old as Pennsylvanian or Permian (Dane, 1948; Read and others, 1949). Although Pennsylvanian rocks are absent from much of the anticlinorium and parts of the uplifts, deep wells have shown that these rocks are present in the San Juan and Chama basins.

The differences in amount of shortening between the northwest-alined San Juan Basin and the north-alined Nacimiento and French Mesa–Gallina uplifts were accommodated mainly by right shift on the Nacimiento and Gallina faults. The folding and crumpling of the Archuleta anticlinorium that caused a small amount of shortening in a northeasterly direction seem to imply some right shift between the anticlinorium and the Chama basin. If the shift took place along a deep-seated shear zone in the basement rocks, the overlying sedimentary blanket would have been twisted and dragged above the shear zone. The bend and increase in amplitude of the northern part of the Rio Chama anticline (fig. 23) and the southerly trend of some of the large faults northeast of El Vado might indicate twisting, but the evidence is not conclusive. The Archuleta anticlinorium and the Chama basin are complementary features. The amount of northeast-southwest shortening of the upbuckled anticlinorium is of the same general magnitude as the amount of shortening of the downbuckled Chama basin; thus, there is no geometric necessity for a large amount of lateral shift along the structural discontinuity north of the Gallina fault.

CONCLUSIONS

The general oval or parallelogram shape of the San Juan Basin cannot be attributed to outward-directed compressional forces arising entirely from shortening and crowding within the basin as it subsided. The amount of subsidence was such that outward-directed compressional forces in the basement could have acted only during the early phases of Laramide subsidence. During the remainder of the subsidence the Central basin would have been stretched or would have subsided as a graben if it had not been under compression by a force directed toward the basin. The stratigraphy and structure of the San Jose Formation on the east margin of the basin indicate that shortening in a northeast direction occurred also during the later (San Jose and post-San Jose) phases of subsidence. Therefore, this shortening seems to require that the subsidence was caused by northeast-directed regional tangential compression. This force probably produced both the basin and the surrounding uplifts.

The north-trending Nacimiento fault and the northeast-trending Gallina fault are high-angle wrenches along which right shift occurred during downbuckling and shortening of the San Juan Basin in a northeast direction. The southeastern part of the Archuleta anticlinorium has been upwarped and also shortened in a northeast direction. The Nacimiento and Gallina faults and the southeast margin of the Archuleta anticlinorium mark the Salado-Cumbres structural discontinuity—a major north-northeast-trending structural discontinuity along which differing major features are opposed. The variations in structure on either side of the discontinuity seem to be the result of differential yielding to the regional compressional force by crustal blocks whose alinements and structural competence are different.

According to Dallmus (1958, p. 907), the average stress in a subsiding crustal segment is midway between the center and the ends of the chord of the segment. Thus, the central part of a large depressed segment of the crust should be a favored location for intrabasinal and interbasinal arches and uplifts. The positions of the arches are governed, of course, by the positions of preexisting zones of crustal weakness as well as by the positions of maximum stress within a basin. The interbasinal San Juan dome and Archuleta anticlinorium lie partly on an ancient northwest-trending uplift, and they are probably near the central part of the northwest-trending Late Cretaceous basin whose northeast margin was marked by the San Luis–Sangre de Cristo geanticline (fig. 7). Thus, the anticlinorium and part of the dome might have originated as an intrabasinal arch in the area of maximum compressional stress in the subsiding basin. Stratigraphic relations of the San Jose Formation and its probable equivalents, the Telluride Conglomerate and Blanco Basin Formation in the San Juan Mountains, indicate that the San Juan dome was upwarped as the Central basin was depressed, and the compensating effect of the early Tertiary radial expansion of the dome must have played a part in defining the curved northern rim of the basin. Presumably, part of the uplifting of the dome was related also to the middle Tertiary volcanism and, perhaps, to deep intrusion of magma in that region. Part of the doming of the San Juan Mountains occurred after the San Juan peneplain was formed in Pliocene or early Pleistocene time (Atwood and Mather, 1932; Larsen and Cross, 1956). The origin of the late Tertiary and Quaternary forces is not known.

Although an analysis of the Laramide structure of the east side of the San Juan Basin and adjacent uplifts indicates that the basin and uplifts were produced by regional tangential compression, the analysis does not determine whether or not this stress might ultimately have been the result of a regional vertical principal force which caused the subsidence of a very large segment of the earth's crust. Conceivably, this segment might have been as wide as the entire Cretaceous Rocky Mountain geosyncline.

Another origin is suggested, however, by the fact that the linear uplifts and basins east and north of the San Juan Basin conform to a regional pattern of curving uplifts concave to the southwest. On the east side of the Laramide San Luis–Sangre de Cristo geanticline, the Sangre de Cristo Mountains were the site of reverse faulting and of overthrusting in Paleocene and Eocene time (Burbank and Goddard, 1937; Baltz and Bachman, 1956; Wanek and Read, 1956; Johnson and others, 1958; Johnson, 1959). The northern part of the Sangre de Cristo uplift bends northwestward and merges, generally, with the northwest-trending uplifts, such as the Gunnison and Uncompahgre uplifts in the northeastern part of the Colorado Plateau. These relations suggest that a segment of the earth's crust including the Colorado Plateau might have been shifted north-northeastward by a regional tangential force that folded, uplifted, and crumpled the margins of the segment and wrinkled its interior.

SUMMARY OF DEPOSITIONAL AND TECTONIC HISTORY

On the basis of stratigraphic relations determined in the mapped area and elsewhere in northwestern New Mexico and southwestern Colorado (fig. 27), the general history of latest Cretaceous and early Tertiary sedimentation can be interpreted, and some of the stages of Laramide deformation of the San Juan Basin and some of the adjacent uplifts can be dated. In late Montana time, during deposition of the Pictured Cliffs Sandstone and the Fruitland and Kirtland Formations, the San Luis–Sangre de Cristo geanticlinal uplift (fig. 7) rose to define the northeast limb of a northwest-trending basin that included the area of the present San Juan Basin but was larger. The area of the Nacimiento uplift may have been a shoal at this time, as indicated by the lithology of the Pictured Cliffs and by a local unconformity in the Fruitland and Kirtland. Near the end of Cretaceous time, the San Juan Basin began to form. Prior to deposition of the Ojo Alamo Sandstone, low folds began to form in the adjacent parts of the present San Juan Basin and the Nacimiento uplift, as shown by the erosional and angular unconformity at the base of the Ojo Alamo. This folding may indicate a small amount of horizontal shift between the newly forming San Juan Basin and the Nacimiento up-

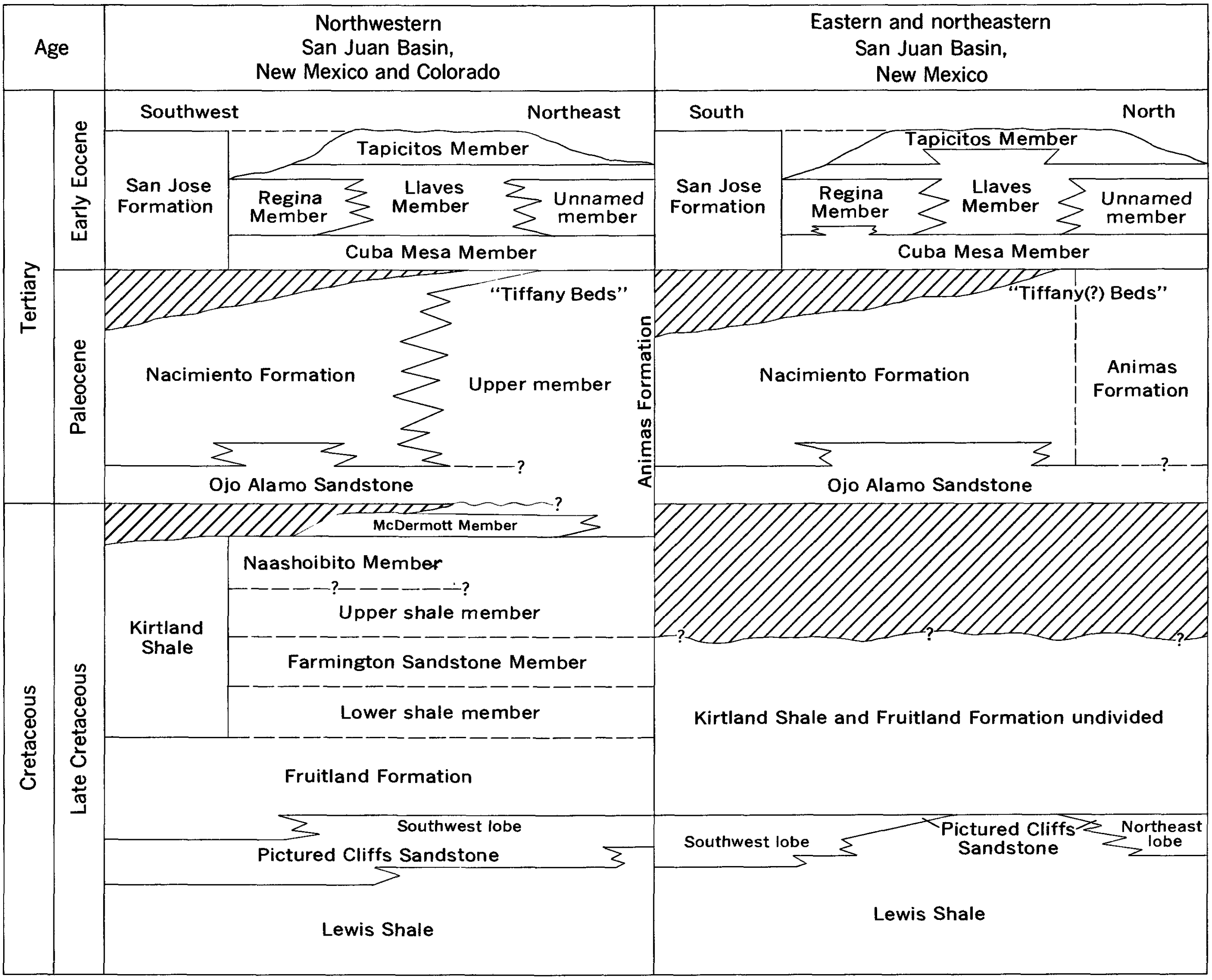


FIGURE 27.—Nomenclature and probable correlations of part of Upper Cretaceous rocks and of lower Tertiary rocks, San Juan Basin.

lift, but the structural relief between the two was small. The Archuleta anticlinorium probably began to form during deposition of the Mancos Shale, and before the end of Cretaceous time it was uplifted slightly to form an intrabasinal arch, thus beginning the delineation of the San Juan Basin and the San Juan sag. The Hogback monocline of the northwest side of the Central basin began to form prior to deposition of the Ojo Alamo.

During Paleocene time the San Luis–Sangre de Cristo geanticline (including part of the Brazos uplift) contributed a large amount of orogenic and volcanic detritus to the San Juan Basin region. Large amounts of volcanic detritus were contributed from the area of the San Juan dome. The Nacimiento uplift, the Archuleta anticlinorium, and the Chama basin may have undergone some deformation, but they were parts of the same depositional basin in which the Ojo Alamo Sandstone and the Nacimiento and Animas Formations accumulated. The Animas Formation is present in the San Juan sag in the southern part of the San Juan Mountains and seems to have been deposited across the Archuleta anticlinorium. No unconformities were found within the Nacimiento Formation along the east margin of the basin, and the Nacimiento and Animas Formations were deposited, probably, across the region of the Chama basin and Nacimiento uplift. Parts of the Nacimiento and Animas Formations were deposited on the Four Corners platform west of the Central basin, but intraformational unconformities indicate that folding continued episodically along the Hogback monocline during early and middle Paleocene time. In latest

Paleocene or earliest Eocene time the entire Central basin was downwarped, and the northwest-trending anticlines at the east side of the basin and the adjacent part of the Nacimiento uplift were folded sharply, as shown by the local variations in thickness of the Nacimiento Formation on the margin of the basin. The basin probably was depressed slightly relative to the Nacimiento uplift during the right shift that produced the folds.

In early Eocene time the San Luis–Sangre de Cristo geanticline contributed a large amount of arkosic detritus to the San Juan Basin region. These sediments of the Cuba Mesa Member of the San Jose Formation rest with angular unconformity on the Nacimiento Formation in the western, southern, and eastern parts of the Central basin; but the San Jose and Nacimiento may be conformable in the interior and northern part of the Central basin, where the Nacimiento is thickest and contains beds of late Paleocene age. During deposition of the Regina Member of the San Jose Formation, differential vertical movements defined the east edge of the Central basin as the basin was depressed relative to the Nacimiento and French Mesa–Gallina uplifts. The first stage of deformation was the production of a west-facing monocline along the west side of the uplifts. Cretaceous and older sedimentary rocks were eroded from the Nacimiento uplift, but the Precambrian core apparently was not exposed at this time. Probably the Paleocene and uppermost Cretaceous rocks were eroded also from the main part of the Archuleta anticlinorium and the rising San Juan dome, and the detritus was deposited in the northern part of the San Juan Basin as an unnamed member of the San Jose Formation. The Precambrian terrane of the Brazos uplift contributed a large volume of coarse detritus (Llaves Member of the San Jose Formation) to the deeper part of the San Juan Basin. Folding continued episodically on the Hogback monocline on the northwest side of the Central basin in early Eocene time. During a period of relative tectonic quiescence the San Juan Basin was filled by sediments of the San Jose Formation which lapped out of the basin and onto the flanks of the adjacent uplifts (Telluride Conglomerate and Blanco Basin and El Rito Formations) as the source areas were worn down by erosion. Evidence for this conclusion are the overlapping relation of the San Jose on the Hogback monocline in the northwestern part of the basin and the newly discovered overlap in the mapped area on the east-central margin at the basin.

Post-San Jose (probably Eocene or Oligocene) deformation was attended by wrenching movements along the Nacimiento and Gallina faults during further depression and northeastward shift of the Central basin and further elevation of the Nacimiento uplift. The San Jose Formation was tilted inward along the margins of the entire Central basin. The San Jose Formation and older rocks were uplifted and tilted along the west side of the Archuleta anticlinorium. The northeast limb of the basin was defined in its present position as the arch was deformed into an anticlinorium. This compressional final phase of Laramide orogeny completed the delineation of the major structures along the Salado-Cumbres discontinuity.

The Brazos uplift and the eastern part of the Nacimiento uplift were tilted eastward after Oligocene or early Miocene time, as shown by the fact that the El Rito and Abiquiu Formations of Smith (1938) in the Brazos uplift and in the northeastern part of the Nacimiento uplift are tilted eastward. This tilting occurred in Miocene and Pliocene time and was accompanied by strong faulting along the east margins of the uplifts during the formation of the Rio Grande trough and the consequent disruption of the Laramide San Luis-Sangre de Cristo geanticline (Baltz, 1965, p. 2072–2073). The eastward tilting of the uplifts east of the San Juan Basin might have caused slight stretching in the basin, and this stretching may have selectively opened earlier formed fractures. In Miocene(?) time these reopened fractures were intruded by a swarm of lamprophyre dikes in the northeastern part of the basin, on the Archuleta anticlinorium, and in the Puerco fault belt and southeastern part of the basin.

Structural adjustments have taken place in the southeastern part of the Nacimiento uplift as recently as Recent time, as shown by the fact that the Bandelier Tuff has been broken by normal faults (Wood and Northrop, 1946; Northrop, 1950, p. 41–42). The latest stage of uplift and doming of the San Juan Mountains region occurred after the formation of the San Juan peneplain, in Pliocene or early Pleistocene time (Atwood and Mather, 1932, p. 26–27). This deformation resulted in some further slight tilting of at least the north margin of the San Juan Basin.

DESCRIPTIONS OF TYPE SECTIONS

Sections were measured by E. H. Baltz and S.R. Ash. The specific type sections are as follows:

Localities 1a–1d—Continued

	Thickness (feet)
Kirtland Shale, etc.—Continued	
Unit B—Continued	
25. Siltstone, and interbedded very fine grained sandstone. The lower half is olive green; the upper half is banded gray, brown, and purple. Unit forms nodular-weathering notch	9
24. Shale, purple and olive; upper part is silty and grades into the overlying unit	16
23. Sandstone, light-gray, tan-weathering; composed of silt-size to very coarse particles of quartz, a few grains of black minerals and rock fragments, and a few clay pebbles. About 20 ft above the base is a dark-brown concretionary layer. Unit is crossbedded and forms a vertical ledge. On the south side of the spur this unit wedges out, but equivalent lenticular sandstone is present farther south on Mesa Portales	25
22. Sandstone, brown to white, medium-grained, argillaceous; weathers to a notch	1
21. Sandstone, olive-gray, fine- to medium-grained; forms a slope	18
20. Shale, light-olive-gray; contains plant fragments	1.5
19. Sandstone, buff, fine-grained, argillaceous; forms a small rounded ledge	3.5
18. Clay, banded olive-green and purple, slightly bentonitic; forms smooth rounded, fissured hills	8
17. Sandstone, very light brown, fine-grained to very fine grained, argillaceous and micaceous; gray shale stringer near the middle; forms a rounded ledge	11
16. Clay, similar to unit 18	34
15. Sandstone, very light gray to white, fine- to medium-grained; composed of angular to subround quartz with a trace of pink and green chert and black minerals. Forms a rounded soft slope at the eastern end of a spur	27
14. Sandstone, similar to unit 13 but softer; rests on pink sandstone equivalent to unit 13 on a small cuesta crossed by a road	11
13. Sandstone, light-gray, light-buff, and white, medium- to coarse-grained, with some granules; composed of angular to subround quartz with some rock fragments, and contains pebbles of sandstone and red and gray siliceous rocks. Much silicified wood is present, including some logs as large as 2 ft in diameter. Sandstone is strongly crossbedded; forms a strong ledge capping an isolated butte at the north end of loc. 1a	10
Unit A:	
12. Sandstone, light-olive-gray to buff, fine- to medium-grained; contains argillaceous stringers; forms a slight, rounded ledge on the butte	19

Localities 1a–1d—Continued

	Thickness (feet)
Kirtland Shale, etc.—Continued	
Unit A—Continued	
11. Sandstone, medium-gray, fine- to medium-grained, argillaceous; contains many flattened lignitized logs and a lignite band at the base. Sandstone contains stringers of gray clay with lignitized plant fragments. To the southwest this unit forms a prominent, persistent carbonaceous zone on the escarpment of Mesa Portales	9
Total thickness of Kirtland Shale and Fruitland Formation undivided	243.5
Pictured Cliffs Sandstone:	
10. Sandstone, light-gray, medium-grained; composed of angular to subangular quartz with a few pink and black grains and black mica flakes. Unit is slightly gypseous and ferruginous; forms a steep slope	15
9. Shale, fissile clay, dark-gray; poorly exposed on a slope	3
8. Sandstone, light-olive-gray, fine-grained to very fine grained. About 30 percent of unit is clay shale in beds 2–12 in. thick. Unit is poorly exposed on the slope	16.5
7. Covered. Probably shale	4
6. Sandstone, light-olive-gray, fine-grained to very fine grained. Lower part is poorly cemented and forms a soft slope. Upper part is papery-bedded brown-weathering sandstone	6
5. Shale, clay, olive-green; poorly exposed	5
4. Sandstone, light-yellowish-brown, fine-grained, soft; contains thin stringers of clay shale. Poorly exposed	4
3. Sandstone, buff, medium-grained; contains black grains; crossbedded. Weathered surface is a ferruginous brown rind ⅛ in. thick, and beds have a slightly concretionary appearance. Sandstone contains *Ophiomorpha* and pelecypods; forms small ledges capping benches. Locally forms slopes	3.5
2. Sandstone, light-yellowish-brown, fine-grained to very fine grained, silty. Upper half contains three 6-in. stringers of gray shale. Unit forms a rounded slope	7.5
Total thickness of exposed Pictured Cliffs Sandstone	64.5
Lewis Shale (in part):	
1. Shale, silty clay, light-olive-gray to gray; contains scattered tiny carbonized plant fragments. The unit is poorly exposed on a slope	15+

Locality 2

[Outcrops along State Highway 44 northwest of Cuba, N. Mex. Section measured mainly on the north side of the road. Base of section is in the NE¼NW¼ sec. 20; it was measured westward across secs. 17, 8, 7, and 6, T. 21 N., R. 1 W., and secs. 1 and 2, T. 21 N., R. 2 W. Thickness of unit 30 in secs. 28 and 33–35, T. 21 N., R. 2 W., was estimated from topographic maps]

	Thickness (feet)
San Jose Formation:	
Llaves(?) Member:	
31. Sandstone, buff, massive; caps a mesa on the Continental Divide. Top eroded	50+
Regina Member:	
30. Shale, sandy silty clay; gray with reddish, yellow, and white bands. Lenses of soft argillaceous fine- to coarse-grained buff sandstone are interbedded, and most of the unit forms soft slopes and low rounded hills. Several ledge-forming thick beds of sandstone are interbedded with variegated sandy shale. Highest part of unit exposed along the Continental Divide in secs. 28 and 29, T. 22 N., R. 2 W., is predominantly reddish shale with thick lenticular sandstone interbedded	600± (estimated)
Cuba Mesa Member (type section), upper tongue:	
29. Sandstone, rusty-brown to buff-weathering; composed of coarse-grained to granule-size angular to subrounded quartz, with some feldspar. Upper part is a hard rusty ferruginous zone. Unit thins northward but thickens southwestward and merges with unit 22 as units 23–28 wedge out	52
Regina Member, tongue; wedges out to southwest:	
28. Clay shale, silty, olive-gray, reddish-weathering	20
27. Sandstone, olive-green, fine- to medium-grained soft, argillaceous	9
26. Covered. Probably shale	7
25. Sandstone, light-orange to buff; composed of very coarse grained to granule-size quartz with some feldspar. Unit forms a slope in a roadcut	8
24. Sandstone, buff, fine- to medium-grained; caps a small hill and forms an irregular ledge	16
23. Clay shale, sandy and silty; greenish gray to olive green with purple-weathering bands	23
Cuba Mesa Member (type section), tongue:	
22. Sandstone, light-yellowish-orange; composed of fine-grained to granule-size angular to subround quartz with feldspar and rock fragments; forms a strong ledge. Lower half is composed of several stream-channel sandstones with thin interbeds of gray shale. Upper half is more massive. Unit wedges out to the northeast, but thickens to the south and merges with unit 18 as unit 19 wedges out	80
21. Covered	10

Locality 2—Continued

	Thickness (feet)
San Jose Formation—Continued	
Cuba Mesa Member, etc.—Continued	
20. Sandstone, rusty-brown, very coarse grained; gray shale interbedded	5
Regina Member, tongue; wedges out to south:	
19. Shale, gray, soft; contains thin beds of soft sandstone. Unit forms a slope on the high hill north of State Highway 44	55
Cuba Mesa Member (type section), main part:	
18. Sandstone, buff, stained yellowish-brown, coarse-grained, crossbedded. Forms smooth rounded ledges north of State Highway 44 west of Rito de los Pinos. Unit is the upper part of the lower tongue of the Cuba Mesa Member north of the locality of measurement	47
17. Sandstone, soft and shaly; carbonaceous shale is interbedded	15
16. Sandstone, yellow and buff, very coarse grained and pebbly, crossbedded; forms rounded ledges	45
15. Sandstone, gray and yellow, soft; lenses of shale are interbedded	27
14. Shale, clay; gray carbonaceous shaly sandstones are interbedded. Unit contains many silicified logs; forms a long, low slope	20
13. Sandstone, yellow and buff, very coarse grained; contains granules and small pebbles. The sand is mainly angular to subangular quartz but is arkosic and micaceous. Many large silicified logs. Unit has sweeping crossbedding; forms irregular rounded ledges	83
12. Shale, gray, carbonaceous; poorly exposed on a slope above the lowest sandstone ledge west of Rito de los Pinos	5
11. Sandstone, yellow-buff, coarse-grained to very coarse grained, arkosic; contains many silicified logs; upper 1–2 feet is ironstone. The unit caps the top of the hill north of State Highway 44 in the northern part of sec. 29, T. 21 N., R. 1 W. The top of the unit seems to be equivalent to the top of the lowest sandstone ledge west of Rito de los Pinos. This unit and underlying units are mainly equivalent to the basal part of the Cuba Mesa Member farther north	55
10. Sandstone, orange-brown, coarse-grained to very coarse grained; forms a small poorly exposed ledge	7
9. Sandstone, light-yellowish-brown, coarse-grained to very coarse grained, arkosic. Unit is similar to unit 7 and forms an irregular slope capped by a hard ferruginous band	36
8. Clay shale, olive-gray. Lower 5 ft is brown lignitic shale that weathers purplish. Unit forms a soft slope	13

Locality 3—Continued

	Thickness (feet)
San Jose Formation—Continued	
Cuba Mesa Member (main part):	
7. Sandstone, brown to yellowish-brown; contains fine-grained to granule-size quartz and quartzite and some feldspar, and scattered small quartzite pebbles. Concretionary weathering creates brown "cannonballs" up to 2 ft in diameter. Unit forms a strong persistent ledge	27
Total thickness of Cuba Mesa Member (including tongues of Regina Member)	355.5
Nacimiento Formation (in part):	
6. Clay shale, silty, sandy, light-olive-gray; forms poorly exposed slope	16
5. Sandstone, light-tan, fine- to medium-grained, thin-bedded; forms poorly exposed slope	27
4. Clay shale, silty, dark-gray, slightly bentonitic. Upper half is brown carbonaceous sandy shale. Unit forms a poorly exposed slope	26
3. Sandstone, light-tan, fine- to medium-grained, soft, poorly exposed	24
2. Sandstone, dark-rusty-brown, medium- to coarse-grained; contains stringers of quartzite granules and small pebbles, and forms a small ledge	1
1. Shale, clay, dark-gray; forms a poorly exposed slope	10+

Locality 4

[Section measured on the eastward-projecting spur of the ridge southwest of Spring Canyon in the N½ sec. 18, T. 25 N., R. 1 E.]

	Thickness (feet)
San Jose Formation:	
Llaves Member (type section of lower part):	
50. Sandstone, light-reddish-brown, coarse-grained; weathers to a massive rounded bluff capping top of narrow part of ridge	20
49. Sandstone, light-yellowish-brown; composed of medium to very coarse arkosic quartz sand containing small cobbles of gray to purplish quartzite. Unit is crossbedded and holds up a narrow ledge	50
48. Clay shale, silty, gray to olive; weathers red and contains interbedded red-weathering sandstone	35
47. Sandstone, buff; coarse grained with scattered granules and small pebbles; forms small ledge	3
46. Clay shale, silty, light-gray to olive; weathers red. Unit contains interbedded thin sandstone	14
45. Sandstone, light-brown-weathering, coarse-grained to very coarse grained; contains numerous lenses of pebbles which are as large as 2 in. in diameter. Unit forms a strong ledge	40
44. Clay shale, silty, red-weathering; contains thin sandstone beds	37

Locality 4—Continued

	Thickness (feet)
San Jose Formation—Continued	
Llaves Member, etc.—Continued	
43. Sandstone, light-pinkish-brown, fine- to coarse-grained; forms a ledge on a long narrow spur	20
42. Clay shale, silty, sandy, light-gray to light-olive-gray; contains thin sandstone beds; forms a slope	50
41. Sandstone, grayish-yellow, very coarse grained; contains numerous scattered pebbles	4.5
40. Sandstone, light-reddish-gray, fine-grained. Beds are about 6 in. thick and separated by stringers of gray shale. Entire unit weathers red; forms a retreating slope on a small bench	15
39. Sandstone, light-yellowish-brown, coarse-grained and conglomeratic. Forms a strong ledge	55
38. Clay shale, red to gray; and interbedded shaly sandstone. Unit forms a notch in cliffs	30
37. Sandstone, light-yellowish-brown, fine- to coarse-grained, arkosic; contains a lens of small-pebble conglomerate, and fossil wood impressions. Unit is crossbedded and forms a strong cliff	40
36. Sandstone, light-reddish-gray to maroon, fine- to medium-grained. Sandstone beds are about 1 ft thick and are separated by red-weathering clay shale beds. Unit forms a slope. To the north this unit grades into hard sandstone	33
35. Clay shale, silty, light-olive-gray; forms a slope	6
34. Sandstone, light-brown, medium- to coarse-grained; forms a small ledge	9
33. Shale, sandy and silty, greenish-gray, reddish-weathering	35
32. Sandstone, earthy, pale-maroon, fine- to medium-grained. 50 ft. to the south this unit becomes massive yellow coarse-grained sandstone	6
31. Clay shale; weathers pale maroon	12
30. Sandstone, yellow, coarse-grained; contains granules of quartz and feldspar, and pebbles and cobbles of quartzite. Unit is crossbedded; forms a ledge	14
29. Clay shale, silty, light-gray to olive-gray; weathers pale maroon; forms a slope	12
28. Sandstone, light-purplish-brown and red, fine- to medium-grained, earthy; forms a rounded irregular ledge	10
27. Sandstone, buff, fine- to coarse-grained; contains granules and scattered small pebbles. Unit is crossbedded and forms a strong ledge	30
26. Shale, argillaceous silt, and fine-grained sandstone, greenish-gray; weathers red and forms a slope. To the south this unit is cut out by channel sandstone of unit 27	30

Locality 4—Continued

San Jose Formation—Continued Llaves Member, etc.—Continued	Thickness (feet)
25. Sandstone, reddish-stained; interbedded thin reddish shale. Sandstone is fine- to medium-grained and contains a few small pebbles. Sandstone beds are 5–12 ft thick and form retreating ledges separated by notches weathered in shale. Bedding is irregular and the sandstones are crossbedded	85
Total thickness of preserved lower part of Llaves Member	695.5
Cuba Mesa Member:	
24. Sandstone, bluff, medium- to coarse-grained, arkosic; contains lenses of pebbles and, near the top, scattered cobbles. Forms a strong cliff	94
23. Shale, silty, argillaceous, and very fine grained sandstone. Unit weathers reddish and greenish gray, and forms a slope	16
22. Sandstone, gray to reddish-purple, medium-grained to very coarse grained, arkosic; contains large pebbles and small cobbles, which are mostly quartzite. Some pebbles are feldspar and volcanic rocks. Unit is crossbedded; forms a massive cliff	39
21. Covered	10
20. Clay shale, silty, dark-gray; forms a slope	25
19. Sandstone, gray to light-purplish-gray very coarse grained; contains pebbles and is crossbedded; forms a rounded ledge	40
18. Sandstone, olive-gray, fine- to medium-grained; forms a slope	3.5
17. Sandstone, buff, arkosic	2
16. Clay shale, gray	4
15. Sandstone, olive-green, shaly; forms a poorly exposed slope	7
14. Clay shale, siltstone, and green to pale-purplish sandstone. Forms a soft slope	19
13. Sandstone, buff to greenish-gray, thin- to shaly-bedded; forms a soft slope	7
12. Sandstone, buff; forms soft, retreating ledges	8
11. Sandstone, medium-grained; forms a small ledge	3
10. Shale, argillaceous, silty, sandy, greenish-gray; forms a slope	9
9. Sandstone, yellowish-gray, fine-grained to very coarse grained, arkosic; contains pebbles of quartz, quartzite, feldspar, and volcanic rock. Forms a ledge	18
8. Sandstone, yellowish-gray, fine-grained to very coarse grained, arkosic; contains lenses of granules and small pebbles; crossbedded. Forms a massive ledge	22
Total thickness of Cuba Mesa Member	334.5

Locality 4—Continued

Nacimiento Formation (in part):	Thickness (feet)
7. Sandstone, yellow to buff, fine-grained, argillaceous; forms a notch	8
6. Clay and siltstone, gray; forms a slope	12
5. Sandstone, olive-green, fine-grained, soft, shaly-bedded	7
4. Sandstone, olive-green, fine-grained. Base of unit is a small ledge, upper part is a soft slope	15
3. Clay shale, sandy, olive-green; forms a slope	18
2. Sandstone, similar to unit 4; forms small ledge and grades into overlying unit	9
1. Sandstone, yellowish-gray, medium-grained to very coarse grained; contains lenses of pebbles and lenses of gray clay shale. Unit is crossbedded; forms a ledge	40

Locality 5

[Section measured on a ridge on the northern side of Canoncito de las Yeguas east of Pasture Canyon, from the SW¼ sec. 4, T. 25 N., R. 1 W., to the center of sec. 33, T. 26 N., R. 1 W. Loc. 5 is shown on pl. 1, but section is not shown on pl. 2.]

San Jose Formation: Llaves Member (type section of upper part):	Thickness (feet)
Sandstone, buff, gray, brown, and red, fine-grained to very coarse grained, arkosic, conglomeratic; contains beds of red and gray silty clay shale, but is mostly sandstone. Lowest part of the unit is buff, massive, ledge-forming sandstone containing some shale, and is about 120 ft thick. Above this is red shale with thin interbeds of sandstone about 70 ft thick and mapped as a tongue of the Tapicitos Member. Above this is brown and red, thin- to thick-bedded, ledge-forming sandstone with thin interbeds of red shale. The upper part of the unit contains several thick beds of shaly soft red sandstone	450+

The lower part of the basal sandstone of this unit probably is nearly equivalent to units 49–50 of the Llaves Member at loc. 4. West of loc. 5 near the Continental Divide are more sandstone and shale beds of the Llaves Member. These highest beds of the member are estimated to be about 150 ft thick.

Locality 6

[Stratigraphic section modified slightly from the section measured by Simpson (1948, p. 370–371) near the head of the north branch of Oso Canyon (locality not shown pl. 1 and section not shown on pl. 2). Figure 3 of Simpson (1948) shows this section (No. 1) measured east of the Wayne Hatley Ranch. The locality appears to be in sec. 30, T. 25 N., R. 1 W. The rocks were considered by Simpson to be characteristic of the Largo facies of the San Jose Formation]

San Jose Formation: Tapicitos Member, lower part (typical exposures):	Thickness (feet)
13. Sandstone, buff; massive in appearance but crossbedded, hard; forms benches. Top eroded. On an adjacent peak about 50 ft more of similar beds is present. These highest beds probably are nearly equivalent to the tongue of the Llaves Member near the middle of the Tapicitos Member along State Highway 95 in sec. 2, T. 25 N., R. 2 W	15

Locality 6—Continued

San Jose Formation—Continued

Tapicitos Member, etc.—Continued	Thickness (feet)
12. Clay, banded, red	15
11. Sandstone, like unit 13	15
10. Clay and sandy clay, bright red; in regularly alternating beds	40
9. Sandstone, wedges out in a few feet laterally	2
8. Clay, red; massive but slightly banded	15
7. Sandstone, soft; wedges out laterally	5
6. Clay, red, banded; contains lenses of buff sandstone in the upper part	80
5. Sandstone, light-gray, hard, crossbedded, persistent	12
4. Clay, red, banded; bluish- or greenish-gray spots and lenses. Reddish siltstone and very fine grained sandstone are interbedded. American Museum of Natural History fossil mammal quarry, loc. 150, is 13.5 ft above base of this unit	34.5
3. Sandstone, white; soft except for occasional plates weathering hard and brown	0.5
2. Clay, variegated, mottled purplish and yellow	12
1. Clay, red	5
Total thickness of Tapicitos Member exposed at this locality	251

Base of hill; lower beds covered by slope wash. Unit 1 is about 25–50 ft above the base of the Tapicitos Member and the top of the persistent medial sandstone of the Llaves Member.

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