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Geology and ground-water resources of the southern part of the Jicarilla Apache Indian Reservation described

By

S. W. West and E. H. Baltz

N.M-55

United States
Department of the Interior
Geological Survey
Albuquerque, New Mexico

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This report has not been edited for

Geological Survey format and nomenclature

Prepared in cooperation with the

Jicarilla Apache Tribe

Open-file report

September 1962

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Abstract

The southern part of the Jicarilla Apache Indian Reservation and the adjacent areas comprise about 1,300 square miles in parts of Rio Arriba, Sandoval, and McKinley Counties, N. Mex. The area is in the eastern part of the San Juan Basin, a large structural and drainage basin in the east-central part of the Colorado Plateau physiographic province. Six physiographic sectors in the area are here named: the Penistaja Cuestas, Largo Plains, Tapicitos Plateau, Yeguas Mesas, San Pedro Foothills, and Northern Hogback Belt.

The area lies in the Central basin of the San Juan Basin and is bounded on the east by the French Mesa-Gallina uplift and the Nacimiento uplift where rocks ranging in age from Precambrian to Cretaceous crop out. Rocks of Late Cretaceous age crop out along the southern and eastern sides of the area, and rocks of Tertiary age crop out in most of the area.

The oldest rocks that were mapped are those of the Mesaverde Group of Late Cretaceous age. Other Upper Cretaceous rocks mapped include in ascending order: the Lewis Shale, the Pictured Cliffs Sandstone, the Fruitland Formation and Kirtland Shale, undivided, and the Ojo Alamo Sandstone. The Mesaverde Group ranges from 560 to about 1,700 feet thick in the area and consists of thick to thin sandstone, shale, and some coal. These rocks might yield potable water at shallow depth along the east side of the area but in most of the area they are deeply buried and contain mineralized water. The Lewis Shale is about 1,900 feet thick in the northern part of the area but thins abruptly to about 500 feet thick in the southwestern part because lower beds of the Lewis grade laterally into sandstone of the Mesaverde Group. The Lewis Shale does not yield potable water to wells. The Lewis Shale is overlain conformably by the Pictured Cliffs Sandstone, which ranges in thickness from 35 feet in the east-central part of the area to 235 feet in the subsurface in the southwestern part. No ¶

no ¶

The Pictured Cliffs does not yield potable water to wells in the area, and it contains mineralized water and natural gas at places in the subsurface.

Resting conformably on the Pictured Cliffs throughout the area is a complex sequence of sandstone and shale assigned to the undivided Fruitland Formation and Kirtland Shale. These rocks range in thickness from 60 to 100 feet in the east-central part of the area, to 450 feet in the western part of the area. Sandstone beds in the Fruitland and Kirtland might yield small amounts of water to wells at places in the southern and northeastern parts of the area, but in most of the area these rocks are not potential aquifers. In the subsurface of the northern half of the area sandstones in the lower part of the Fruitland and Kirtland contain natural gas and some mineralized water. The undivided Fruitland Formation and Kirtland Shale are overlain unconformably by the Ojo Alamo Sandstone, which ranges in thickness from 70 to 80 feet in the southern part of the area to 200 feet in the northern part. The Ojo Alamo is an important aquifer in the southern part of the area, and it is the deepest aquifer from which large amounts of potable water may be expected in most of the area.

Rocks of Tertiary age include, in ascending order, the Nacimiento Formation, the San Jose Formation, and several dikes of igneous rocks. The Nacimiento Formation of Paleocene age rests conformably on the Ojo Alamo Sandstone and ranges in thickness from 540 feet in the east-central part of the area to 1,750 feet in the subsurface in the north-central part. In the southern half of the area the Nacimiento consists mostly of shale with a few intercalated beds of sandstone, and it does not yield water to wells. In the northern half of the area the Nacimiento consists of shale and thick beds of sandstone which yield potable water to wells at a few places. These sandstone beds may be feasible sources of large supplies of water from deep wells.

The San Jose Formation of Eocene age rests unconformably on the Nacimiento Formation and crops out in most of the area. The San Jose ranges in thickness from 200 to 750 feet in the southern part of the area to 1,800 feet in the northern part. Four lithologic units were distinguished and mapped. These are here named the Cuba Mesa, the Regina, the Llaves, and the Tapicitos Members of the San Jose Formation. The Cuba Mesa Member, the basal part of the formation, is mostly conglomeratic arkosic sandstone ranging in thickness from 40 to 780 feet. The Cuba Mesa Member intertongues with the overlying Regina Member which consists of variegated shale with interbedded thick to thin sandstone. The Regina Member ranges in thickness from 400 to 800 feet in the southern part of the area to 1,640 feet in the subsurface of the east-central part. In the northern third of the area the Regina Member grades northward into the lower part of the Llaves Member which consists mainly of conglomeratic arkosic sandstone and is as much as 1,300 feet thick. A persistent medial sandstone unit of the Llaves Member overlies the Regina Member in most of the northern part of the area. The upper part of the Llaves Member grades westward into the Tapicitos Member which consists of red shale and interbedded thin to thick sandstone. The Tapicitos Member is present only in the northern third of the area. Sandstone beds in all of the members of the San Jose yield water to wells and the thick sandstones of the Cuba Mesa and Llaves Members may be practical sources of large amounts of water for deep wells in parts of the area.

Igneous rocks of Miocene(?) age occur as ~~lamprophyre~~ dikes in the north-central part of the area. These rocks do not yield water to wells, but they may locally impede the westward movement of water in the San Jose Formation and older rocks.

Unconsolidated gravel of Tertiary or Quaternary age caps several high terraces at the foot of San Pedro Mountain. Gravel of Quaternary age caps lower-level terraces and occurs in stream channels and valleys in the same part of the area. The gravel yields small supplies of potable water to wells and springs. ~~Valley-filling~~ alluvium occurs in all of the major valleys and contains small amounts of water at many places.

The northwest-trending axis of the San Juan Basin extends diagonally across the northern part of the area, and in most of the area the rocks dip gently northeast. A staggered system of northwesterly plunging anticlinal noses occurs in the eastern part of the area near the Nacimiento uplift. The angular unconformity between the San Jose and Nacimiento Formations indicates that these folds were formed mainly in late Paleocene time, possibly as the result of right shift along the Nacimiento fault which marks the boundary between the San Juan Basin and the Nacimiento uplift. Near the eastern margin of the area, adjacent to the Nacimiento uplift, the rocks dip steeply west, and at places are vertical or are overturned and dip steeply east. These steeply dipping beds form the eastern limb of a major north-trending synclinal bend which lies immediately west of the Nacimiento fault. A local angular unconformity between the Regina Member of the San Jose Formation and the older rocks indicates that the synclinal bend was formed mainly in early Eocene time, although further deformation occurred after deposition of the San Jose Formation. A sinuous, west-facing monocline lies north of the Nacimiento uplift at the eastern side of the San Juan Basin and the western side of the contiguous French Mesa-Gallina uplift. The rocks of the northeastern part of the area dip west on the monocline. The rocks are broken by faults at a few places in the eastern part of the area, but the stratigraphic displacements on the faults are 200 feet and less.

The principal sources of ground-water recharge are precipitation and streamflow on outcrops of the aquifers in the eastern and southern parts of the area, at altitudes of 7,000 to 8,000 feet. ~~These outcrops are on the eastern and southern margins of the Central basin of the San Juan Basin.~~ Most of the ground water ~~moves down dip toward the interior of the Central basin and~~ is discharged from outcrops at lower altitudes, ~~mainly in the western part of the area,~~ where the water is dissipated by evapotranspiration. Seepage investigations of the San Juan River indicate that the increment of ground-water discharge to the river in relation to the flow of the river is too small to detect. Therefore, withdrawal of ground water from the Jicarilla Reservation would not measureably affect the flow of the San Juan River.

Water in the Ojo Alamo Sandstone and the San Jose Formation varies widely in chemical quality from one unit to another, and also within a unit from one place to another. High concentrations of sodium relative to that of calcium and magnesium make some of the water undesirable for irrigation, and high concentrations of sulfate make some of the water undesirable for drinking.

Small supplies of ground water, most of which is potable, can be obtained at depths of a few feet to a few hundred feet at most places throughout the area. Deep water wells have not been drilled, but the available data indicate that the largest yield and ~~the highest~~ specific capacities of a deep wells would be expected at places where the greatest thickness of water-bearing sandstone could be tapped. The ratio of thickness of sandstone to depth of penetration is important because the depth of drilling necessary to penetrate a certain thickness of sandstone varies widely throughout the area. The total thickness of sandstone below 200 feet and above the base of the Ojo Alamo Sandstone ranges from 80 to 1,840 feet as determined from electric logs of selected wells drilled for oil and gas. The thickness of sandstone below 200 feet and above the base of the San Jose Formation ranges from 0 to 840 feet. The ratio of the total thickness of sandstone to the depth to the base of the Ojo Alamo Sandstone ranges from 0.13 to 0.54, and the ratio of the thickness of sandstone to the depth to the base of the San Jose Formation ranges from 0.17 to 0.57. The most favorable place for developing large-capacity deep wells is in T. 25 N., R. 5 W., near one of the tracts of land that was suggested as suitable for irrigation by the Bureau of Indian Affairs.

The specific capacities of 59 wells that tap sandstone aquifers in the San Juan Basin, including 8 wells in the project area, range from 0.0002 to 0.015 gpm (gallons per minute) per foot of sandstone penetrated. The average for the eight wells in the project area is 0.008. If the average specific capacity per foot of sandstone penetrated (0.008) could be applied to a well in sec. 25, T. 25 N., R. 5 W., and if 300 feet of drawdown could be tolerated, the yield of a well that tapped all the beds of sandstone to the base of the San Jose Formation would be 1,460 gpm, and the yield of a well that tapped all the beds of sandstone to the base of the Ojo Alamo Sandstone would be 3,530 gpm. The actual yield probably would be less than the calculated average. The calculated potential yield of deep wells suggests that test drilling is warranted.

Introduction

Purpose and scope

The Jicarilla Apache Indian Tribe recently began a series of studies and long-range plans for economic development of tribal lands in New Mexico (fig. 1). The economy of the Tribe at present is based

Figure 1.--Index map of northwestern New Mexico showing location (stippled) of the area investigated for this report.

on mineral leases and royalties, livestock growing, and operation of a few small farms. Farming now offers little economic stability because most of the Jicarilla Apaches live near Dulce in the northern part of the reservation, where the growing season is too short for many crops. Soil moisture commonly is deficient throughout the reservation and livestock raising is somewhat limited by a scarcity of forage. Utilization of ground-water resources, especially for irrigation or industry, would diversify the tribal economy and provide an increased measure of economic security for an increasing population. Water may be necessary also for secondary recovery of oil and gas in and near the reservation.

The Jicarilla Apache Tribal Council requested the U.S. Geological Survey to make a cooperative study ~~of part of the reservation~~ to appraise the availability and the chemical suitability of the ground water for irrigation, industrial, and domestic use. The southern part of the reservation was chosen for the study because its climate is more suitable for farming than the climate of the northern part.

The geology of the southern part of the reservation and the adjacent region to the south and east (fig. 1) was mapped and the subsurface stratigraphy was studied to define aquifers and determine their areal extent. The areas of recharge and discharge and areas of probable saturation of many aquifers were determined, and data on hydrology and chemical quality of water in potential aquifers were obtained. All the data obtained provide a basis for appraising the ground-water potential of the area.

Location and extent of area

The area investigated (figs. 1 and 5) includes approximately 1,300 square miles in parts of Rio Arriba, Sandoval, and McKinley Counties, northwestern New Mexico. The eastern boundary is along the foothills and lower slopes of Sierra Nacimiento and San Pedro Mountain in Sandoval County, and along the western margin of the irregular belt of lower mountains and mesas north of San Pedro Mountain in Rio Arriba County. The other boundaries were chosen to include the southern part of the Jicarilla Apache Indian Reservation and the area to the south where potential aquifers crop out.

Previous work

The geology of parts of the area has been mapped and described briefly in several reports. The southern and eastern parts of the area were included in reconnaissance mapping by Gardner (1909), who also described briefly the stratigraphic relations of Cretaceous and Tertiary rocks in this area (Gardner, 1910). Renick (1931) mapped 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 part of the area. Dane (1932) described briefly the latest Cretaceous and Paleocene rocks of the region, and (Dane, 1936) mapped the rocks in Tps. 20 and 21 N., Rs. 1-5W, as a part of a study of the La Ventana-Chacra Mesa coal field to the south.

Dane (1946) also published a chart and description of the latest Cretaceous and Tertiary rocks of the eastern side of the San Juan Basin, including a description of the rocks ~~in parts of~~ along a narrow belt in the eastern part of the area of the present report. Wood and Northrop (1946) mapped the Nacimiento Mountains (Sierra Nacimiento), San Pedro Mountain, and the foothills to the west, which had been mapped previously by Renick (1931). The Dulce-Chama area, which was mapped by Dane (1948) includes T. 26 N., Rs. 1 E. and 1 W.

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

Several earlier investigations were concerned with the ground-water resources in and near the Jicarilla Reservation. A brief reconnaissance study was made by G. C. Taylor, Jr. in 1939 (unpublished data) to determine the availability of potable water in the southwestern part of the reservation. Fred A. F. Berry (1957) (unpublished data) summarized briefly the ground-water potential of the reservation. S. W. West and J. R. Rapp made a reconnaissance of the geology and ground-water hydrology in and near the southern part of the reservation in 1958 (unpublished data).

Present work

Field work for this report was done from May to October 1959 and in May 1960 by E. H. Baltz, assisted by S. R. Ash. The geology (fig. 5) of the eastern part of the area was mapped in detail and stratigraphic studies were made in order to differentiate the rock units to the west. All the geologic mapping was done on aerial photographs.

Wells and springs were inventoried in the part of the area adjacent to the Jicarilla Reservation, and water levels in the wells were measured where possible. Much information on wells was supplied by the owners and other residents, and by the following well drillers: Branch Drilling Co., C. W. Dunn, L. J. Ingram, J. C. Leeper, J. G. Mathews Drilling Co., L. Messer, F. I. Northcutt, R. L. Reed, T. W. Stevenson, and Turner Drilling Co. Samples of water were obtained from wells and springs and were analyzed by the U.S. Geological Survey for their principal chemical constituents. Records of wells and springs and chemical analyses of water from the southern part of the Jicarilla Reservation had been obtained previously by G. C. Taylor, Jr., S. W. West, and J. R. Rapp.

A planimetric base map was compiled at a scale of 1:63,360 (1 inch equals 1 mile) from the La Ventana, Cuba, Llaves, and Horse Lake 15-minute quadrangle topographic maps of the U.S. Geological Survey, 30-minute quadrangle planimetric maps of the New Mexico State Highway Commission Planning Survey, and the Resources Map of the Jicarilla Indian Reservation. The geology of the eastern part of the area was plotted on the topographic maps, and transferred to the planimetric base map. The geology of the rest of the area was transferred directly from the photographs to the planimetric base map by using a Saltzman overhead projector. The locations of wells and springs were marked on aerial photographs in the field and the locations were transferred later to the base map by inspection and comparison with the geologic map.

A study of the subsurface geology of the area was done by comparing electric logs of wells drilled for oil and gas with surface stratigraphic sections measured in the field. A structure contour map (fig. 9) and stratigraphic correlation diagrams (figs. 6, 7, and 8) also were prepared to illustrate the subsurface geology.

The introductory and geologic sections of the text and the section on the general availability of ground water were written by E. H. Baltz and the rest of the section on ground water was written by S. W. West.

System of numbering wells

In this report the wells are designated mainly by location numbers, but in part by oil company lease numbers. The location number used by the U.S. Geological Survey and the State Engineer in designating water wells in New Mexico is a description of the geographic location of the well based on the federal system of subdivision of the public land. The location number consists of a series of numbers corresponding to the township, range, section, and tract within a section, respectively, as illustrated by figure 2. If a well has not been

Figure 2.--System of numbering wells in New Mexico

located within a particular tract, a zero is used for that part of the number. In an area transected by the New Mexico Principal Meridian the letter "E" or "W" is used in the second segment of the number to designate the direction (east or west) from the meridian. Springs are numbered in the same manner, except that the letter "S" precedes the number.

Physiography

Drainage

The area investigated is in the eastern part of the San Juan Basin, a shallow structural basin most of which is drained by the San Juan River and its tributaries. About two-thirds of the area is west of the Continental Divide (figs. 3 and 5), and is drained

Figure 3.--Physiographic index map of the southern part of the Jicarilla Apache Indian Reservation and adjacent region to the south and east, N. Mex.

by intermittent streams that flow westward and northwestward to Canon Largo, which discharges intermittently into the San Juan River.

The region east of the Continental Divide is drained by intermittent streams in the Rio Grande watershed. La Jara Creek and Rito de los Pinos both are perennial streams in their upper courses, but become intermittent before reaching San Jose Creek. San Jose Creek, which is intermittent for most of its length, flows 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 and southeastern parts of the area. The Rio Puerco is intermittent below Cuba. Encino Wash and Arroyo San Ysidro drain intermittently southward and, outside of the area, join Torreon Arroyo, a southeastward-flowing intermittent tributary of the Rio Puerco. Several small westward-flowing streams such as Rito Leche, Nacimiento Creek, and Senorito Creek (in Senorito Canyon) are perennial 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.

Land forms

Nearly all the San Juan Basin, including the present area of investigation, lies within the Navajo section of the Colorado Plateau physiographic province (Fenneman and Johnson, 1946). The land forms of the area are dependent directly on the geologic structure and the lithology of the Cretaceous and Tertiary rocks which consist of thick units of shale and interbedded thick to thin units of sandstone. Nearly horizontal units of sedimentary rocks have been stripped from wide areas adjacent to the major streams. Outlying mesas and buttes remain in the interstream-divide areas. Locally, the major streams have incised deeply into Cretaceous and Tertiary rocks of the San Juan Basin, and have formed steep-walled canyons. Where the rocks are tilted steeply and eroded deeply, the resistant sandstone beds form "hogback" ridges between valleys cut in shale.

Six relatively distinct physiographic sectors in the mapped area are here described and named: Penistaja Cuestas, Largo Plains, Tapicitos Plateau, Yeguas Mesas, San Pedro Foothills, and Northern Hogback Belt (fig. 3). The physiography of each sector reflects the geologic structure and stratigraphy which affect the occurrence of ground water.

Penistaja Cuestas

The land surface of the southern part of the area is characterized by several large, curved, sloping topographic benches which extend from east to west across the area and are interrupted by the valleys or canyons of southward-draining streams. This sector is here named the Penistaja Cuestas. Each major, northward-sloping topographic bench is a cuesta held up by a thick unit of sandstone, and has a steep, sinuous, erosional escarpment for its southern edge.

Each cuesta is separated from the next cuesta to the north by an intervening band of valleys and low rounded hills carved from the shale units which intervene between the cuesta-forming sandstones. Arroyos and washes that cross the shale units have broad alluviated valleys, but where the streams cross the cuesta-forming sandstone units they have narrow valleys or 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 from Regina southwestward to the northwestern part of T. 21 N., R. 4 W. From there the boundary extends northwestward to the upper part of Venado Canyon in T. 22 N., R. 5 W. Along most of the northern boundary of the Penistaja Cuestas, the land surface descends northward abruptly from a series of rugged mesas and cuestas to the Largo Plains--a region of nearly horizontal rocks and low topographic relief. The Penistaja Cuestas sector merges eastward into the San Pedro Foothills and terminates against the sharply-folded rocks at the foot of Sierra Nacimiento. The altitudes of the southernmost cuestas range from a little less than 6,600 feet near the 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, where they 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 which slope gently toward the intermittent stream. In the west-central part of the area the plains are as much as 10 miles wide. These plains, here named the Largo Plains (fig. 3), have been dissected mildly by the intermittent streams that are tributary to Canon Largo, so that the region is one of broad, low mesas separated by swales and shallow valleys. The upper part of Canon Largo is a broad alluviated valley, but in the west-central part of the area Canon Largo is a steep-walled canyon whose bottom 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.

Altitudes along Canon Largo range from about 6,600 feet near Otero Ranch to more than 7,000 feet in the southwestern part of T. 22 N., R. 3 W. Southwest of Canon Largo the plains rise gently to altitudes of about 7,000 feet. The Penistaja Cuestas rise above the southwestern margin of the plains. Northeast of Canon Largo the plains slope gently up to altitudes of 6,800 to 7,000 feet. Northeast of the plains the intricately dissected mesas of the Tapicitos Plateau rise abruptly.

The tracts of land that the Bureau of Indian Affairs suggested as being favorable for irrigation are in the Largo Plains sector where the soil locally is fairly thick and extensive.

Tapicitos Plateau

Most of the northern and central part of the area is a high plateau which has been dissected greatly by the westward-flowing intermittent streams tributary to Canon Largo. The dissected remnants of the plateau stand as broad, irregular, sandstone-capped mesas extending westward from the Continental Divide to the Largo Plains. The plateau is here called the Tapicitos Plateau for Tapicitos Creek which heads in the eastern part of the upland (fig. 3). The plateau is roughly "V"-shaped, being narrow at the south where it merges, around the eastern end of the Largo Plains, with the Penistaja Cuestas along the Continental Divide in Tps. 21-22 N., Rs. 2-4 W.

The western boundary of the Tapicitos Plateau is a sinuous erosional escarpment overlooking the Largo Plains. The eastern boundary from T. 21 N., R. 4 W. to the central part of T. 24 N., R. 1 W. is defined as the base of the steep slopes just east of the Continental Divide. North of T. 24 N., R. 1 W., the eastern boundary of the plateau is defined as the base of the slopes west of the Continental Divide. The Tapicitos Plateau extends north of the area of this 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 top of the highest mesas. The tops of many of the mesas are at altitudes between 7,400 and 7,500 feet.

Yeguas Mesas

Near the northeastern corner of the area, numerous high mesas rise about 500 feet above the general level of the Tapicitos Plateau. The mesas are long and narrow and are separated by deep, steep-walled canyons cut in thick sandstone beds by the eastward-draining 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 half a mile at some places. This area of high mesas and deep canyons is here named the Yeguas Mesas sector (fig. 3). The eastern edge of the Yeguas Mesas is a high, irregular, eastward-facing erosional escarpment overlooking the ridges and valleys of the Northern Hogback Belt.

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 eastern side of the sector where altitudes are as much as 8,500 feet. The tops of the highest western mesas along the Continental Divide are nearly 8,000 feet in altitude.

San Pedro Foothills

The foothills of San Pedro Mountain from the upper drainage of San Jose Creek to the upper drainage of the Rio Puerco are characterized by westward-sloping terraces which extend from San Pedro Mountain to San Jose Creek. The terraces are separated by westward-trending valleys which are mainly broad and shallow at the west, but narrow and deep at the east. This area is here called the San Pedro Foothills sector (fig. 3). Deposits of gravel cap terraces at several different levels and occur also in the upper valleys of the major streams. In deep canyons near the foot of San Pedro Mountain, nearly vertical beds of Cretaceous and Tertiary sedimentary rocks are exposed. These rocks are beveled by the westward-sloping terraces and their structure and lithology has only minor influence on the land forms.

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 of the tops of some of the terraces at the foot of San Pedro Mountain are almost 8,400 feet.

Northern Hogback Belt

Extending northward from the San Pedro Foothills, along the northeastern edge of the area investigated, is a belt characterized by long, narrow, north-and northeast-trending ridges separated by alluvial valleys. 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 ribs, or "hogbacks", rising above the intervening valleys. The hogbacks are breached by gaps through which the intermittent streams of the belt drain eastward to Rio Gallina. The name Northern Hogback Belt (fig. 3) is applied to this sector to distinguish it from the hogback belt parallel to the front of Sierra Nacimiento south of the area investigated. The Northern Hogback Belt is geologically a continuation of the San Pedro Foothills, but the hogback belt has been eroded more deeply and, consequently, has different land forms.

The major topographic feature of the Northern Hogback Belt is a high sandstone ridge in the eastern part of the belt. Although this hogback is cut at places by transverse gaps, it forms a mainly continuous ridge from the upper tributaries of San Jose Creek northward beyond the northern part of the area investigated. The altitude of the top of this hogback is, at places, a little more than 7,800 feet. The narrow ridge rises 400 to 600 feet above the flanking valleys. Sandstones in 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 than the eastern hogback. Also, the north-south continuity of the western hogbacks is interrupted by broad, transverse alluviated valleys and low terraces. Altitudes in most of the hogback belt west of the main hogback range from a little less than 6,900 feet to about 7,400 feet. A 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.

The upper valleys of Arroyo Blanco and Almagre Arroyo are cut in soft, gently dipping rocks of Tertiary age and they do not have the characteristic landforms of the Northern Hogback Belt. However, these valleys are at much lower altitudes than the Tapicitos Plateau west of the Continental Divide, and they are drained to the east. For these reasons they are included arbitrarily in the Northern Hogback Belt.

Climate

Precipitation has been measured at several stations in and near the southern half of the Jicarilla Apache Indian Reservation. The precipitation records of some stations are short, and the records of most stations are intermittent. The average monthly precipitation and the periods of record at six stations are listed in table 1. The average annual precipitation ranges from 11.91 inches at Otero Ranch (altitude 6,600 feet) to 16.71 inches at Gavilan (altitude 7,350). The average monthly precipitation at the six stations is least in June and greatest in July and August. According to published records of the New Mexico State Engineer (1956) the average frost-free season near the southern part of the reservation ranges from 77 days (June 25 to September 10) at Gavilan (altitude 7,350 feet) to 128 days (May 27 to October 2) at Gobernador (altitude 6,700 feet). In much of the southern part of the reservation the frost-free season is probably about 128 days owing to the similarity of altitude and terrain of this part of the reservation and the region of Gobernador.

June, July, and August constitute the major part of the growing season; hence, about one-third of the average annual precipitation is during the growing season. Because the season of greatest precipitation coincides with the growing season, the quantity of irrigation water needed per unit area is small but essential for growing crops. However, the irrigable acreage is large, and, therefore, the total amount of water needed is large.

Geology

Regional setting

The area of this report is in the east-central part of the San Juan Basin, a large shallow structural basin in northwestern New Mexico and southwestern Colorado (fig. 4). The east-west width

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Figure 4.--Structural elements of the San Juan Basin. Modified from Kelley (1951, p. 125) and Kelley and Clinton (1960, fig. 2).

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of the basin is about 135 miles, and the north-south length is about 180 miles. The structural elements of the basin were named and described by Kelley (1950, p. 101-104) and are shown in modified form on figure 4. The Central basin (a basin within the San Juan Basin), which is bounded at the west and north by monoclinal structures, is enclosed mainly by gently inward-dipping platforms or structural slopes.

The east-central structural boundary of the San Juan Basin is the Nacimiento uplift, of which Sierra Nacimiento and San Pedro Mountain are parts. The rocks of the basin have been folded sharply in a narrow belt along the Nacimiento fault, which marks the western edge of the Nacimiento uplift. North of the Nacimiento uplift the eastern margin of the Central basin is a low monoclinal flexure on the west side of the 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 area of this report is in the southeastern part of the Central basin (fig. 4). The eastern part of the area includes part of the belt of sharply folded rocks west of the Nacimiento uplift and includes also a segment of the monocline on the west side of the French Mesa-Gallina uplift.

The rocks in the Nacimiento uplift and the eastern part of the San Juan Basin range in age from Precambrian to Recent (table 2). Granite and metamorphic rocks of Precambrian age form a basement on which younger sedimentary rocks rest. The Precambrian rocks form the bulk of San Pedro Mountain and Sierra Nacimiento, and they have been encountered at depths of 13,000 feet or more in wells drilled in the eastern part of the San Juan Basin. Paleozoic rocks, which lie on the Precambrian basement rocks, consist of thick beds of limestone, shale, sandstone, and conglomerate of Mississippian, Pennsylvanian, and Permian ages. These rocks crop out on Sierra Nacimiento and San Pedro Mountain (Renick, 1931; Wood and Northrop, 1946; Fitzsimmons, Armstrong, and Gordon, 1956). The Paleozoic rocks are present also in the subsurface of the San Juan Basin, but in that region they are buried too deeply to be considered as practical sources of ground water.

The Paleozoic rocks are overlain by a thick sequence of Mesozoic rocks consisting of sandstone and shale of Triassic, Jurassic, and Cretaceous ages. Triassic rocks that are mainly red beds crop out in a structural sag between San Pedro Mountain and Sierra Nacimiento and in the belt of steeply dipping rocks along the west side of the mountains. Jurassic rocks, consisting of sandstone, variegated shale, and thin units of limestone and gypsum, also crop out in this belt. 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 of the Central basin. The Mesozoic rocks are present in the subsurface of the Central basin, also. Some of these rocks are potential sources of ground water on the southern and eastern margins of the Central basin (Renick, 1931), but in the southern part of the Jicarilla Apache Indian Reservation most of the Mesozoic rocks are at depths of more than 3,000 feet, and only the uppermost Cretaceous rocks are considered to be practical sources of ground water in that region.

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 and are the main aquifers from which potable water may be obtained in this region.

Stratigraphy

The oldest rocks mapped in the present investigation are those of the Mesaverde Group of Late Cretaceous Age. Rocks older than the Mesaverde are shown on the geologic map (fig. 5) as Cretaceous and

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Figure 5.--Geologic map of the southern part of the Jicarilla Apache Indian Reservation and adjacent region to the south and east, New Mexico.

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older rocks, undivided, and they range in age from Precambrian to Late Cretaceous, as shown in table 2.

Rocks of Cretaceous age

Mesaverde Group

Rocks in the eastern part of the San Juan Basin that were mapped as the Mesaverde Formation of Late Cretaceous age by Renick (1931), Dane (1936, 1948), and Wood and Northrop (1946) have recently been reclassified as the Mesaverde Group by Beaumont, Dane, and Sears (1956). The Mesaverde Group in the area of this report consists of the Point Lookout Sandstone, Menefee Formation, and the La Ventana Tongue of the Cliff House Sandstone, in ascending order. The Mesaverde Group was not subdivided during the mapping for this investigation, but the three formations of the group seem to be present throughout the area.

Extent and thickness.--The Mesaverde Group crops out nearly continuously from south to north along the eastern side of the area (fig. 5) and is distributed continuously in the subsurface west of the outcrops. The Mesaverde Group is about 560 feet thick in sec. 35, T. 21 N., R. 1 W. (Renick, 1931, p. 43-44). The Point Lookout Sandstone is about 180 feet thick, the Menefee Formation is 347 feet thick, and the La Ventana Tongue of the Cliff House Sandstone is 37 feet thick. In the subsurface to the west the Mesaverde Group is about 840 feet thick at the Sun Oil Co. No. 1 McElvain well in sec. 23, T. 21 N., R. 2 W., and almost 1,700 feet thick at the Shell Oil Co. No. 1 Pool Four well in sec. 22, T. 21 N., R. 5 W.

In the northeastern part of the area the Mesaverde Group is 647 feet thick at outcrops in sec. 5, T. 24 N., R. 1 E. (Fitter, 1958, p. 19 and p. 49-51). The Point Lookout Sandstone is 95 feet thick, the Menefee Formation is 375 feet thick, and the La Ventana Tongue is about 110 feet thick. In the subsurface to the southwest the Mesaverde Group is about 630 feet thick at the Reading and Bates No. 1 Duff well in sec. 24, T. 24 N., R. 1 W.

Lithology.--The point Lookout Sandstone consists of buff, gray, and tan sandstone which generally is thick to massive bedded. The sandstone is mainly medium-grained, but it contains a few beds of fine-grained sandstone and some thin beds of shale. The sandstone is relatively resistant to erosion and forms small ledges and hogbacks.

The Menefee Formation consists of shale and interbedded thin to thick sandstone and thin beds of coal. The shales are light- to dark-gray and generally carbonaceous, containing at places lenses of coal and coaly shale. The sandstones are white, gray, buff, and brown, lenticular stream-channel deposits of fine to coarse-grained quartz sand. The Menefee Formation underlies small strike valleys and steep slopes between the Point Lookout Sandstone and the La Ventana Tongue.

The La Ventana Tongue of the Cliff House Sandstone consists of gray, buff, and orange-brown, thick to thin, medium-grained sandstone and some interbedded gray shale near the top. The sandstone is relatively resistant to erosion and forms steep cliffs in areas where the rocks dip gently, and hogback ridges where the rocks dip steeply. The main hogback of the Northern Hogback Belt is held up by the La Ventana Tongue.

The Point Lookout Sandstone was deposited as beach and near-shore marine sand. The Menefee Formation was deposited in a swampy coastal-plain environment, and the La Ventana Tongue was deposited mainly in a near-shore marine environment.

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 are interbedded with thin tongues of the Mancos Shale. The contact of the La Ventana Tongue of the Cliff House Sandstone and the overlying Lewis Shale of Late Cretaceous age is gradational by intertonguing.

Water-bearing properties.--Although data are not available on the water-bearing properties of the Mesaverde Group in the area, the beds of sandstone in the Mesaverde are porous and they should be good aquifers. Renick (1931, p. 49) reported that the porosity of several rock samples analyzed ranged from 13.71 to 28.32 percent. Renick (1931, p. 49) reported also that water of good quality issues from springs in sandstone of the Mesaverde Group south of the area of this report. Areas of recharge are at outcrops on the margins of the Central basin at altitudes higher than the altitude of the Mesaverde within the basin. Thus, artesian conditions are to be expected where the Mesaverde is in the subsurface. In most of the area, except at places on the east side, the Mesaverde Group is at depths of 2,000 to 6,000 feet, and the group is not considered to be a practical source of ground water where it is deeply buried.

Deep wells in the San Juan Basin have produced oil and gas from the Mesaverde Group at places, and saline water at other places. Fresh water has encroached downdip along the margins of the basin and has replaced part of the saline water. However, the depth to which this flushing has taken place has not been determined, and it may vary because of local conditions. Potable water is to be expected in the Mesaverde near outcrops only.

Lewis Shale

Extent and thickness.--The Lewis Shale of Late Cretaceous age crops out in a north-south belt along the east side of the area (fig. 5) and is distributed continuously in the subsurface west of the outcrops. The belt of outcrop of the Lewis Shale is adjacent to and west of the Mesaverde Group, and the structural attitudes of the units are similar. The Lewis ~~Shale dips northwest and~~ crops out as low hills rising above alluviated valleys in T. 20 N., R. 1 W. In the San Pedro Foothills the Lewis Shale is vertical to overturned, and is exposed discontinuously in the walls of canyons and in valleys. In the Northern Hogback Belt the Lewis Shale dips west and crops out on low hills and slopes rising above alluviated valleys cut in the shale.

The Lewis Shale is about 1,900 feet thick at the Reading and Bates No. 1 Duff Well (24.1W.24.424) in the northeastern part of the area. The shale thins southwestward in the subsurface. It is about 1,470 feet thick at the Magnolia Petroleum Co. No. 1 Jicarilla D well (26.3W.24.); 1,530 feet thick at the Sun Oil Co. No. 1 McElvain well (21.2W.23.); and only 500 feet thick at the Shell Oil Co. No. 1 Pool Four well (21.5W.22.44 center). Much of the thinning takes place ~~over~~ in a short distance in the subsurface of the southwestern part of the area. The abrupt thinning takes place also at the surface in the southeastern part of the area where the Lewis Shale is about 1,400 feet thick in secs. 2-4, T. 20 N., R. 1 W., but is only 550 to 600 feet thick south of Mesa Piedra Lumbre (Mesa Portal on fig. 5) according to Dane (1936, p. 111). Both Renick (1931) and Dane (1936) recognized that the thinning is largely the result of a facies change. The lower part of the Lewis Shale intertongues with and grades laterally into the upper part of the La Ventana Tongue of the Cliff House Sandstone. Thus, as the Lewis Shale becomes thinner to the south, the La Ventana becomes thicker by an approximately equivalent amount.

Lithology.--The Lewis Shale is composed of light to dark-gray fissile clay shale and some interbedded siltstone, fine-grained sandstone, and nodular concretionary limestone, containing marine invertebrate fossils. At most places the lower 100 feet of the Lewis Shale contains several thin beds of sandstone which are tongues of the La Ventana. In the subsurface of the southwestern part of the area the Lewis Shale is very sandy and silty and is only 500 to 600 feet thick. These beds are believed to be stratigraphically equivalent to the clay shale of the upper part of the Lewis Shale in the northern part of the area.

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 of Late Cretaceous age also is transitional and intertonguing. In the subsurface the intertonguing causes the top of the Lewis Shale to rise stratigraphically to the northeast as the lower part of the Pictured Cliffs Sandstone wedges out in that direction (figs. 6, 7, and 8).

Figure 6.--Diagram showing correlations of rock units as interpreted from electric logs of wells along line A-A' (shown on fig. 9)

Figure 7.--Diagram showing correlations of rock units as interpreted from electric logs of wells and surface stratigraphic section along line B-B' (shown on fig. 9)

Figure 8.--Diagram showing correlations of rock units as interpreted from electric logs of wells and surface stratigraphic section along line C-C' (shown of fig. 9)

No 97 The Lewis shale and Pictured Cliffs intertongue also at the surface in the southeastern part of the area.

Water-bearing properties.--The Lewis Shale does not yield water to wells in this area, and several water wells drilled in this formation in T. 24 N., R. 1 E. were unproductive. Because the formation is composed largely of clay/ shale, it has low porosity and permeability. Some of the thin sandstones in the lower part of the formation might yield small amounts of water, but the water is probably saline.

Pictured Cliffs Sandstone

Extent and thickness.--The Pictured Cliffs Sandstone of Late Cretaceous age crops out above the Lewis Shale in the southeastern part of the area (fig. 5), and a zone of thin sandstone, siltstone, and interbedded shale that probably is equivalent to 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 Pictured Cliffs crops out along the lower part of the erosional escarpment at the east side of Mesa Portal. On the south slope of the butte in the SW$\frac{1}{4}$ sec. 25, T. 20 N., R. 2 W. the Pictured Cliffs is about 65 feet thick. The Pictured Cliffs Sandstone is present east of the Rio Puerco in secs. 17, 19, and 20, T. 20 N., R. 1 W., but its beds are thin, shaly, and poorly exposed at places. In the NW$\frac{1}{4}$ sec. 20, T. 20 N., R. 1 W. the formation is about 75 feet thick. Between sec. 17, T. 20 N., R. 1 W. and the center of sec. 23, T. 21 N., R. 1 W. the shale and sandstone mapped as the Pictured Cliffs are about 45 feet in average thickness.

In the San Pedro Foothills and in the Northern Hogback Belt, the rocks that are probably equivalent to the Pictured Cliffs are exposed at many places and were found at other places by digging through a thin soil cover. In this region the thickness of the Pictured Cliffs varies, but it averages about 35 feet. North of sec. 23, T. 21 N., R. 1 W. the outcrop belt of the Pictured Cliffs is very narrow and the formation was not mapped as a separate unit, but was included with the overlying undivided Fruitland Formation and Kirtland Shale of Late Cretaceous age as far north as sec. 4, T. 25 N., R. 1 E. In a landslide scar in the NE$\frac{1}{4}$ sec. 4, T. 25 N., R. 1 E. shaly rocks equivalent to the Pictured Cliffs are about 58 feet thick. North of here the shaly beds were excluded from the undivided Fruitland Formation and Kirtland Shale and were mapped with the Lewis Shale.

The Pictured Cliffs Sandstone is widely distributed in the subsurface of the area, as determined by a study of electric logs of wells drilled for oil and gas (figs. 6, 7, and 8). The formation is about 235 feet thick at the J. D. Hancock No. 1 Brown well (21.5W.33.332). The thickness diminishes northeastward because of the wedge-out of the lower part of the Pictured Cliffs into the upper part of the Lewis Shale and also because of depositional thinning of the Pictured Cliffs. At the Magnolia Petroleum Co. No. 1 Cheney-Federal well (26.2W.8.223), a zone of interbedded shaly sandstone, siltstone, and interbedded silty and 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 north, as it does in outcrops, but a thin zone of sandy shale and shaly sandstone persists to the north, as it does in the outcrops. Because of the exaggerated vertical scale of the correlation diagrams (figs. 6, 7, and 8), the Pictured Cliffs is not combined with the undivided Fruitland Formation and Kirtland Shale on the diagrams. The thickness of the Pictured Cliffs Sandstone in the subsurface tends to be more or less constant across the area in a north-northwest direction. The formation thins to the east-northeast.

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 it contains beds of siltstone, and shale. The Pictured Cliffs thins northeastward and, as judged by interpretation of electric logs of wells, the thinning is accompanied by a gradual change from a predominantly sandstone facies to a facies of thin, argillaceous, fine-grained sandstone, siltstone, and interbedded shale.

At outcrops west of the Rio Puerco the Pictured Cliffs Sandstone is composed mainly of very fine grained to medium-grained sandstone. In the SW$\frac{1}{4}$ 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 this sandstone is tangentially cross-bedded and it forms rusty-weathering ledges. Above the sandstone is olive-colored soft clay shale about 5 feet thick. The shale is 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 bed of gray clay shale 3 feet thick.

East of th Rio Puerco in the southeastern part of the area the sandstone beds of the lower part of the Pictured Cliffs are very thin, fine grained, and somewhat concretionary. The sandstone at the base of the formation in the NW$\frac{1}{4}$ sec. 20, T. 20 N., R. 1 W. is about 2.5 feet thick and at places, it forms brown-weathering concretions. Light to dark gray sandy shale, about 35 feet thick, containing thin concretionary siltstone and thin, fine-grained sandstone beds overlies the basal sandstone. The upper part of the Pictured Cliffs is about 38 feet thick, and it consists of three beds of fine- to medium-grained sandstone interbedded with shale. The highest bed of the Pictured Cliffs at this locality is about 5 feet thick, and it consists of olive-gray, very sandy clay shale containing marine fossils.

At most places in the San Pedro Foothills and Northern Hogback Belt, rocks equivalent to the Pictured Cliffs Sandstone (but mapped with the Fruitland and Kirtland) consist of a lower unit that is 20-25 feet thick and consists of shale with interbedded thin rusty-weathering concretionary sandstone, and an upper unit that is 15-20 feet thick and consists of two or more soft, fine-grained, shaly sandstone beds. In sec. 4, T. 25 N., R. 1 E., rocks equivalent to the Pictured Cliffs consist of shale with several very thin beds of siltstone and fine-grained sandstone containing plant fragments. North of this locality these rocks were mapped with the Lewis Shale.

Many of the beds of the Pictured Cliffs Sandstone contain lignitized fragments of fossil plants scattered through the rocks and forming thin mats on bedding planes. The carbonaceous material is associated with marine invertebrate fossils and characterizes the Pictured Cliffs of the eastern part of the area.

Contacts.--The Pictured Cliffs Sandstone rests conformably on the Lewis Shale and intertongues with it. In the subsurface and 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 beds of thin sandstone and siltstone which are the basal parts of the undivided Fruitland Formation and Kirtland Shale. Also, at many places in the northern Hogback Belt, north of sec. 20, T. 24 N., R. 1 E., rocks equivalent to the Pictured Cliffs are overlain conformably by sandy carbonaceous shale, 15-30 feet thick, containing silicified fossil wood and thin, rusty-weathering siltstone and fine-grained sandstone beds. The carbonaceous shale beds seem to be absent at most places where the Fruitland Formation and Kirtland Shale are exposed in the San Pedro Foothills. At many of these places rocks equivalent to the Pictured Cliffs are overlain with slight erosional unconformity by thin to thick, coarse-grained sandstone whose stratigraphic position in the undivided Fruitland Formation and Kirtland Shale is higher than the stratigraphic position of the carbonaceous shale. Locally, the upper part of the rocks equivalent to the Pictured Cliffs is thin or absent. These relations may be the result of slight local unconformity caused by scouring or channeling, and they seem to indicate that there was slight uplift or folding in the San Pedro Mountain area not long after deposition of the Pictured Cliffs Sandstone.

Water-bearing properties.--The Pictured Cliffs Sandstone does not yield potable water to wells in this area. In much of the area the sandstones are thin, fine-grained and clayey, and they appear to have low porosity and permeability. The sandstone in the ~~in the~~ subsurface of the southern part of the area is thicker and more porous, but interpretation of electric logs of wells in this part of the area indicates that the water probably is highly saline. In the area investigated, and elsewhere in the San Juan Basin, deep wells have produced natural gas or highly saline water from the Pictured Cliffs.

Fruitland Formation and Kirtland Shale, undivided

A thin but stratigraphically complex sequence of shale, siltstone and sandstone lies on the Pictured Cliffs Sandstone throughout the area. Gardner (1909, p. 1) and Renick (1931) apparently included part of these rocks with the Lewis Shale and part of them with overlying rocks which they assigned to the Puerco Formation. Dane (1936) found that the sequence of shale, siltstone, and sandstone is equivalent to rocks mapped on the west side of the Central basin by Bauer and Reeside (1921) and Reeside (1924) as the Fruitland Formation and the overlying Kirtland Shale, both of Late Cretaceous Age. Dane (1936, p. 115, and pl. 39) arbitrarily combined the two formations east of sec. 7, T. 19 N., R. 2 W. and mapped them as the Kirtland Shale , because the basis for distinguishing the two formations was said to become less evident eastward. However, because rocks probably equivalent to both the Fruitland Formation and the Kirtland Shale occur in the present area of investigation, these rocks are designated in this report as the undivided Fruitland Formation and Kirtland Shale.

Extent and thickness.--The undivided Fruitland Formation and Kirtland Shale are present above the Pictured Cliffs Sandstone at the surface and in the subsurface throughout the area. The Fruitland and Kirtland Formations crop out in the southwestern and southern parts of the area (fig. 5) where they form low rounded hills and benches, and steep slopes beneath cuestas held up by the overlying Ojo Alamo Sandstone of Late Cretaceous age. North of T. 21 N., R. 1 W. beds laterally equivalent to the Fruitland Formation and Kirtland Shale ~~(of Dane, 1936)~~ were said 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 in the San Pedro Foothills and Northern Hogback Belt indicate that, throughout this area, the undivided Fruitland Formation and Kirtland Shale (and the Pictured Cliffs Sandstone) form a persistent lithologic unit which can be differentiated from the Lewis Shale. Judging from Dane's (1946) stratigraphic sections measured in Tps. 23-24 N., R. 1 W. and Tps. 24-26 N., R. 1 E., beds which he included at different places in the upper part of the Lewis Shale, in the Ojo Alamo Sandstone, and in the lowest parts of the Nacimiento Formation of Tertiary age and the Animas Formation of Late Cretaceous and Tertiary age are equivalent to the undivided Fruitland Formation and Kirtland Shale of this report.

West of the area of this report, in T. 20 N., R.6 W., the combined thickness of the Fruitland and Kirtland formations was estimated to be slightly less than 600 feet (Dane, 1936, p. 114). The sequence thins eastward, and in the NW$\frac{1}{4}$ sec. 25, and NE$\frac{1}{4}$ sec. 26, T. 20 N., R. 2 W. the Fruitland and Kirtland Formations are 246 feet thick (see fig. 8). In the SE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 8, and SW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 9, T. 20 N., R. 1 W., the sequence is 126 feet thick.

In the San Pedro Foothills and the Northern Hogback Belt the Fruitland and Kirtland formations dip steeply and form a narrow, discontinuous belt of soft shale and rounded sandstone ledges, and the thickness of the sequence is varied. In the NW$\frac{1}{4}$SE$\frac{1}{4}$ 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. In the SW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 34, T. 23 N., R. 1 W. the sequence is about 220 feet thick, including 31 feet of the Pictured Cliffs. South of Almagre Arroyo in the NE$\frac{1}{4}$ sec. 2, T. 23 N., R. 1 W. the undivided Fruitland and Kirtland Formations are 84 feet thick, including 33 feet of poorly exposed sandstone and shale equivalent to the Pictured Cliffs.

The Fruitland and Kirtland ~~Formations~~ thicken north of sec. 20, T. 24 N., R. 1 E. and near the center of sec. 8, T. 24 N., R. 1 E. they are about 200 feet thick, including 46 feet of the Pictured Cliffs. The thickness is varied to the north and is about 280-300 feet, including 35 feet of the Pictured Cliffs, in the $NE\frac{1}{4}NW\frac{1}{4}$ sec. 29 and the $NE\frac{1}{4}$ sec. 17, T. 25 N., R. 1 E. The sequence is less than half as thick in T. 26 N., R. 1 E.

In the subsurface east of the Continental Divide the thickness of the Fruitland and Kirtland ~~formations~~ is varied as it is in the outcrops. However, in the subsurface west of the divide, the sequence thickens irregularly westward. In the northwestern part of the area the Fruitland and Kirtland ~~sequence~~ ~~is~~ are about 450 feet thick at the Northwest Production Co. No. 1-7 Jicarilla 152 well (26.5W.7.332). In the subsurface of the southwestern part of the area Fruitland and Kirtland are ~~the sequence is~~ 300-400 feet thick (fig. 6).

Lithology.--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 to very coarse grained sandstone.

The lower part of the sequence consists of light to dark-gray, sandy, carbonaceous shale containing thin beds of rusty-weathering siltstone and fine-grained sandstone, and at places, silicified wood. Thin beds of impure coal are present near the base of the Fruitland and Kirtland Formations in the southern part of the area. This basal unit ranges in thickness from 0 to 30 feet and is present in the southeastern part of the area and most of the Northern Hogback Belt. In the San Pedro Foothills it is present locally but is absent at many places. The basal unit seems to be present in the subsurface of most of the area.

In the subsurface of the southern part of the area the basal unit is overlain by shale and interbedded thin siltstone. Some of these siltstones thicken northward and grade into a unit of sandstone about 80 feet thick in the subsurface of the northern part of the area (fig. 6). At the surface in the Northern Hogback Belt the basal unit of the Fruitland and Kirtland ~~formations~~ is overlain by several beds of soft fine-grained sandstone and interbedded shale. The sandstone beds contain marine fossils and thicken northward. In the SE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 17, T. 25 N., R. 1 E. this unit is 85 feet thick and consists of two beds of fine to coarse-grained, olive-gray-weathering, *Halymenites*-bearing sandstone. The *Halymenites*-bearing sandstone correlates with the northward-thickening sandstone unit in the subsurface. At outcrops north of sec. 4, T. 25 N., R. 1 E. most of the *Halymenites*-bearing sandstone unit seems to be absent because of slight erosional unconformity with sandstone higher in the Fruitland and Kirtland Formations sequence.

At outcrops in the southeastern part of the area and in the San Pedro Foothills the basal unit of the Fruitland and Kirtland Formations is overlain by a medial unit composed of sandstone and shale. The sandstone at the base of the medial unit is brown to nearly white, fine-grained to very coarse-grained, cross-bedded, and ranges from a few feet to 70 feet thick. This sandstone is overlain by soft, dark-gray bentonitic shale and interbedded olive-green shale and soft sandstone, all 30 to 100 feet thick. At many places in the area the sandstone at the base of the medial unit contains fossil wood which has been replaced by silica and limonite. Small siliceous pebbles of several ~~types~~ Kinds were found in the sandstone on a butte in the $SW\frac{1}{4}$ sec. 25 and on a hill in the $NW\frac{1}{4}$ sec. 25 T. 20 N., R. 2 W. The sandstone is composed mainly of fine-to medium-grained quartz sand, but it also contains much angular coarse-grained to granule-size quartz, pink and green chert fragments, and weathered pink and white feldspar fragments. The sandstone seems to be a series of overlapping or coalescing stream-channel deposits resting unconformably on older rocks in the eastern part of the area. The shale of the medial unit at most places contains several beds of carbonaceous bentonitic clay which swells during weathering to produce a characteristic hummocky, cracked outcrop.

The medial unit persists northward in the San Pedro Foothills and Northern Hogback Belt. The thickness of the basal sandstone varies considerably. In sec. 10, T. 23 N., R. 1 W., south of State Highway 96, the basal sandstone is as much as 70 feet thick and forms a resistant "rib" of sandstone which contains much silicified wood. At other places the basal sandstone consists of granule-bearing sandstone several feet thick. A ridge-forming, fine to coarse-grained sandstone as much as 50-70 feet thick in outcrops between Arroyo Blanco and Canoncito de Las Yeguas resembles the Ojo Alamo Sandstone. However, the sandstone seems to correlate with a westward-thinning sandstone beneath the Ojo Alamo in the subsurface (fig. 7), and it is correlated with the basal sandstone of the medial unit of the Fruitland and Kirtland ~~formations~~. At this locality the Ojo Alamo seems to be represented at the surface by poorly-exposed, soft conglomeratic sandstone that holds up discontinuous low hills west of the Fruitland and Kirtland outcrops.

In the $NE\frac{1}{4}$ sec. 17, T. 25 N., R. 1 E., the ridge above the Halymenites-bearing sandstone of the Fruitland and Kirtland is capped by a hard, ledge-forming sandstone 14 feet thick, containing small pebbles and silicified wood. This hard sandstone was correlated tentatively with the Ojo Alamo Sandstone by Dane (1946). However, the sandstone and an overlying poorly exposed unit of shale about 80 feet thick are assigned, in this report, to the medial unit of the undivided Fruitland Formation and Kirtland Shale. The shale is overlain by a coarse-grained conglomeratic sandstone assigned to the Ojo Alamo in this report. Thin sandstone beds in the shale below the hard sandstone of the medial unit of the Fruitland and Kirtland thicken abruptly to the north and merge with the hard sandstone to form a massive ledge of cross-bedded sandstone as much as 60-100 feet thick. Near the center of sec. 4, T. 25 N., R. 1 E. the shale of the medial unit is cut out by an unconformity at the base of the Ojo Alamo, and in the $NE\frac{1}{4}$ sec. 4 the Ojo Alamo Sandstone rests unconformably on the massive sandstone of the Fruitland and Kirtland. These combined sandstones cap the high hogback or cuesta above the steep slopes of Lewis Shale in T. 27 N., R. 1 E. Thin remnants of the shale of the medial unit of the Fruitland and Kirtland are present at places along the sandstone cliffs on the east face of the cuesta, and ~~it is possible to differentiate~~ the sandstone of the Fruitland and Kirtland can be differentiated from the overlying Ojo Alamo Sandstone at these places. Elsewhere along the cliffs, the contact was mapped arbitrarily at a notch 50-60 feet above the base of the lowest thick sandstone bed. The combined sandstones of the Ojo Alamo and the undivided Fruitland and Kirtland in T. 26 N., R. 1 E. are those mapped and described by Dane (1946 and 1948) as the basal sandstone of Animas Formation at this place.

In the southeastern and southern parts of the area the upper part of the undivided Fruitland Formation and Kirtland Shale consists of several beds of fine-to coarse-grained sandstone and interbedded olive and gray shale. Some of the sandstone beds in this upper unit are lithologically similar to the overlying Ojo Alamo Sandstone, but they are more evenly bedded and slightly finer grained. Locally, sandstone beds of the upper unit of the Fruitland and Kirtland Formations rest on a channeled surface. In the NE$\frac{1}{4}$ sec. 26, T. 20 N., R. 2 W. the sandstone beds in the upper unit of the Fruitland and Kirtland Formations hold up two prominent topographic benches separated by a slope which is underlain by shale. The upper unit ~~of sandstone and interbedded shale~~ is about 90 feet thick, but ~~on the~~ south ~~side~~ of the erosional reentrant south of the benches most of the unit is cut out by an erosion surface at the base of the Ojo Alamo Sandstone which caps Mesa Portal. Farther south the sandstones of the upper unit are present beneath the Ojo Alamo, but they wedge out into shale of the Fruitland and Kirtland near the southeastern edge of Mesa Portal. Ledge-forming sandstones present locally in the upper part of the Fruitland and Kirtland Formations in the southwestern part of the area probably are equivalent to the upper unit at the east side of Mesa Portal.

To the north and northeast on both sides of the Rio Puerco sandstones of the upper ~~part~~ unit of the Fruitland and Kirtland ~~Formations~~ hold up small topographic benches below the Ojo Alamo, but these sandstones seem to have been truncated by the Ojo Alamo in the eastern part of sec. 8, T. 20 N., R. 1 W., where the total thickness of the undivided Fruitland Formation and Kirtland Shale is about 126 feet, in contrast to a thickness of 246 feet west of the Rio Puerco.

The units of the undivided Fruitland Formation and Kirtland Shale are recognizable to some degree in the subsurface. In the southwestern part of the area the lowest beds consist of carbonaceous to coaly shale with a few beds of persistent carbonaceous siltstone and fine-grained sandstone, all about 30-40 feet thick. Shale beds above the basal unit contain a few thin beds of siltstone which thicken to the north and northeast and grade laterally into shaly sandstone which is apparently equivalent to the coarse-grained *Halymenites*-bearing sandstone that crops out in the Northern Hogback Belt. The *Halymenites*-bearing sandstone may be equivalent to the Pictured Cliffs Sandstone of the northern part of the San Juan Basin (the "northeast lobe of the Pictured Cliffs" of Silver, 1950, p. 111-112), but this has not been established with certainty.

Sandstone beds of the medial unit thin westward and become shaly but some of the sandstone beds are locally as much as 70 feet thick at wells drilled for oil and gas east of the Continental Divide near the San Pedro Foothills and Northern Hogback Belt. Beds of sandstone that are equivalent to those in the upper unit of the Fruitland and Kirtland ~~Formations~~ in the southeastern and southern parts of the area become thinner and finer grained in the subsurface northward and westward from the outcrops.

Contacts.--The basal unit of the undivided Fruitland Formation and Kirtland Shale rests conformably on the Pictured Cliffs Sandstone in most of the area. At places in the San Pedro Foothills the basal unit is absent, and stratigraphically higher coarse-grained sandstone of the medial unit rests on fine-to medium-grained sandstone of the Pictured Cliffs. Where these relations were observed the contact is irregular and scoured. The local thickening and thinning and the erosional relations of units within the Fruitland and Kirtland ~~Formations~~ indicate that slight folding of the rocks occurred in the vicinity of the east side of the area of investigation during deposition of the Fruitland and Kirtland.

The contact of the Fruitland and Kirtland ~~Formations~~ with the overlying Ojo Alamo Sandstone is unconformable. At all localities where the contact was observed the Ojo Alamo rests on an irregular erosional surface cut on beds of the Fruitland and Kirtland. The variation in thickness of the Fruitland and Kirtland in the eastern part of the area indicates slight local folding, tilting and erosion prior to deposition of the Ojo Alamo.

Water-bearing properties.-- Only one well (20.3W.35.244; see fig. 10) is known to have obtained potable water from the undivided Fruitland Formation and Kirtland Shale in the area. This well which is no longer in use, yielded only small amounts of water. Elsewhere in the southern part of the area sandstone beds in the Fruitland and Kirtland ~~Formations~~ probably would yield small quantities of water to wells where these rocks are below the water table.

In the southeastern part of the area, east of the Rio Puerco, the Fruitland and Kirtland Formations contain only a few beds of sandstone. These beds are clayey, and they probably have low porosity and permeability. These sandstones would yield only very small quantities of water, if any, and the water probably would be very saline. Similar conditions are to be expected in the San Pedro Foothills and the southern part of the Northern Hogback Belt. The basal sandstone of the medial unit might yield small amounts of water where it is thick in the Northern Hogback Belt.

Deep wells drilled for oil and gas have yielded highly saline water and natural gas from the Fruitland and Kirtland ~~Formations~~. Rocks of the lower part of the Fruitland and Kirtland and the underlying Pictured Cliffs Sandstone are reservoirs for some of the extensive natural gas fields of the eastern part of the San Juan Basin.

Ojo Alamo Sandstone

Extent and thickness.--The Ojo Alamo Sandstone of Late Cretaceous age crops out in an irregular band above the undivided Fruitland Formation and Kirtland Shale almost continuously across T. 20 N., Rs. 1 to 5 W. (fig. 5) where it caps northward-sloping cuestas and 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 fig. 5 of this report). In a composite section measured in the NW¼NE¼ sec. 26 and the NE¼NE¼ sec. 23, T. 20 N., R. 2 W., the Ojo Alamo is 70 to 80 feet thick (excluding ~~upper~~ sandstones of the upper unit of the Fruitland and Kirtland ~~Formations~~ that were mapped with the Ojo Alamo at this place by Dane, 1936). East of the Rio Puerco the Ojo Alamo forms northwestward-sloping cuestas. In the SE¼NE¼ ~~of~~ sec. 8, T. 20 N., R. 1 W. the Ojo Alamo is a little more than 60 feet thick, and in the S½NE¼ sec. 22, T. 21 N., R. 1 W. it is 91 feet thick.

In the San Pedro Foothills the Ojo Alamo Sandstone dips steeply west, and at places it is vertical or slightly overturned. The Ojo Alamo forms low, rounded ridges exposed in the walls of the canyons which drain San Pedro Mountain in this sector. 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 north of San Jose Creek in the SW¼NE¼ sec. 34, T. 23 N., R. 1 W., where it is about 90 feet thick.

The Ojo Alamo Sandstone is poorly exposed or covered at many places in the Northern Hogback Belt, but the outcrops are adequate to establish its identity and persistence in this region. In secs. 10 and 15, T. 23 N., R. 1 W. the pebble-bearing Ojo Alamo is poorly exposed on the slopes west of a high rib formed by sandstone of the Fruitland and Kirtland. ~~formations.~~ The Ojo Alamo forms low, westward-dipping ridges of conglomeratic sandstone in the northeastern part of T. 23 N., R. 1 W. and near the southeast corner of T. 24 N., R. 1 W. In the NE$\frac{1}{4}$ sec. 2, T. 23 N., R. 1 W. the Ojo Alamo is about 110 feet thick. The Ojo Alamo forms a poorly exposed low ridge of pebble-bearing sandstone just east of the Northcutt ranch house in sec. 30, T. 24 N., R. 1 E. ~~In the SE$\frac{1}{4}$ sec. 20, T. 24 N., R. 1 E.~~ In the SE$\frac{1}{4}$ sec. 20, T. 24 N., R. 1 E. the Ojo Alamo is tentatively identified as a poorly exposed yellowish sandstone lying just west of a ranch road. A light gray sandstone containing silicified wood on the ridge just east of the road is included with the Fruitland and Kirtland formations. In sec. 17, T. 24 N., R. 1 E. the poorly exposed Ojo Alamo forms a low ridge and rests on dark-gray and black shale of the Fruitland and Kirtland. The Ojo Alamo is covered by alluvium at most places in the northern part of T. 24 N., R. 1 E. and the southern part of T. 25 N., R. 1 E. but at places it holds up low hills masked largely by sandy soil. Along the Forest Service road in the SE$\frac{1}{4}$ 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 Fruitland and Kirtland formations. Northward from sec. 8, T. 25 N., R. 1 E., the Ojo Alamo is more resistant to erosion, and it forms westward-sloping ledges. It caps a high cuesta in T. 26 N., R. 1 E., where it rests on sandstone of the Fruitland and Kirtland. In the SW$\frac{1}{4}$SE$\frac{1}{4}$ sec. 33, T. 26 N., R. 1 E. the Ojo Alamo is almost 200 feet thick, and it rests unconformably on sandstone, about 50 feet thick, of the medial unit of the Fruitland and Kirtland. These combined sandstones were described as the basal sandstone of the Animas Formation by Dane (1946 and 1948). The Ojo Alamo caps the high cuestas from sec. 33, T. 26 N., R. 1 E. to the northern boundary of the area, and it rests on sandstone of the Fruitland and Kirtland formations from which it can be differentiated with certainty at only a few places.

The Ojo Alamo Sandstone is distributed continuously throughout the area in the subsurface. In the southern part of the area the Ojo Alamo ranges in thickness from 80 to 100 feet, and it thickens to the north and northeast as it does at the surface. Thin tongues of sandstone in the lower part of the Nacimiento Formation of Tertiary age ~~also~~ thicken northward and merge with the underlying Ojo Alamo Sandstone (figs. 6 and 7). In the northern part of the area the Ojo Alamo ranges in thickness from about 180 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 containing thin lenses of olive to gray shale. The sand is mostly angular to subangular quartz. Other common constituents are coarse grains and granules of pink feldspar and red, gray, and green chert. ~~and pink feldspar.~~ Pebbles ranging from half an inch to several inches in diameter are scattered through the sandstones 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, and pebbles of sandstone and shale also are present. In sec. 36, T. 24 N., R. 1 W., the Ojo Alamo contains numerous 2 to 3-inch pebbles of volcanic rock including a distinctive pink rhyolite porphyry. Logs replaced by silica or limonite are common in the Ojo Alamo at many localities. These fossils are similar to those found in sandstone of the Fruitland and Kirtland. ~~formations.~~

At outcrops the Ojo Alamo Sandstone is moderately indurated by silica, clay, and ferruginous compounds that cement the sand grains. Some hard, thin beds are highly ferruginous and rusty-weathering. Tangential cross-bedding characterizes the formation, but the several beds of sandstone tend to weather as massive units. In the southern part of the area the lower half, approximately, of the Ojo Alamo forms a massive cliff. The upper half, which is more highly cross-bedded and less resistant, forms rounded slopes and ledges set back from the cliffs of the lower half.

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 channeling at the base of the Ojo Alamo may be observed at many places. Reeside (1924, p. 26) discussed the contact of the Ojo Alamo with underlying beds in the western part of the Central Basin. He said that the evidence of an erosional and slightly angular unconformity is clear in that region. However, Dane (1936, p. 118-121) reasoned that the erosion surface at the base of the Ojo Alamo is no more than the result of scouring and channeling by streams competent enough to transport and deposit coarse sediment. He believed that there was no hiatus between the Ojo Alamo and underlying rocks.

The evidence of erosional unconformity at the base of the Ojo Alamo is clear in the area of this investigation and the erosional unconformity is displayed well along the east side of Mesa Portal. The variation in thickness of the Fruitland and Kirtland Formations in the eastern part of the area seems to indicate that slight folding and erosion occurred there before deposition of the Ojo Alamo Sandstone.

The undivided Fruitland Formation and Kirtland Shale are as much as 450 feet thick in the subsurface of the western part of the area, but in the eastern part of the area these rocks are less than half as thick. Individual beds in 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 as postulated by Dane (1936, p. 120-121); in fact, some sandstone beds thicken and coarsen eastward (figs. 7 and 8). It appears that, from west to east, successively lower beds of the Fruitland and Kirtland are truncated by the Ojo Alamo Sandstone 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 basin were tilted gently to the west and part of the Kirtland was eroded from the eastern part of the basin. This interpretation is essentially the same as the conclusion of Silver (1950, p. 112).

Brown (1910), Sinclair and Granger (1914, p. 304, and pl. 22), and Bauer (1916, p. 276) described an erosional unconformity at the top of the Ojo Alamo Sandstone in the vicinity of its type locality. However, the Ojo Alamo Sandstone seems to be conformable with the overlying Nacimiento Formation in the area of this investigation. No evidence of unconformity was observed in outcrops, and subsurface data seem to indicate that the Ojo Alamo in this area is conformable with the Nacimiento and intertongues with it.

Water-bearing properties.--The coarse-grained conglomeratic sandstones of the Ojo Alamo ~~are~~ is porous and permeable and ~~have~~ has the physical characteristics of a good aquifer. The sandstone is only moderately well cemented at outcrops. In the Northern Hogback Belt the Ojo Alamo is friable, and at many places it forms low rounded hills covered by sandy soil. Where the Ojo Alamo forms broad slopes, as in T. 26 N., R. 1 E. and across the southern part of the area in T. 20 N., Rs. 1-5 W., the upper part of the Ojo Alamo is only moderately cemented, and in places it weathers to soft sandy soil and dune sand. This characteristic of the Ojo Alamo probably facilitates infiltration of water from precipitation and from streams flowing across the outcrops in the southern and eastern parts of the area. Water-well drillers ~~have~~ reported that the Ojo Alamo beneath the surface is soft at places, and that it behaves like "quicksand" during drilling. This indicates that the Ojo Alamo at places in the subsurface is highly porous and permeable because the spaces between sand grains are only partly filled with cementing material. The yields of wells that tap the Ojo Alamo Sandstone are given in table 3.

The Ojo Alamo Sandstone is underlain at most places by clay shale or silty, sandy shale of the Fruitland and Kirtland ~~formations~~ and it is overlain by clay shale and silty sandy shale of the Nacimiento Formation. In the subsurface the underlying and overlying shale beds tend to confine the water in the Ojo Alamo giving rise to artesian pressures.

Most of the water from the Ojo Alamo Sandstone is potable (table 9) but its chemical quality varies. In the Penistaja Cuestas west of the Rio Puerco the water from springs and wells is soft and of good chemical quality. Water from the Ojo Alamo near Cuba is hard, and it contains much dissolved iron.

The Ojo Alamo Sandstone probably is saturated with water in the subsurface of the area. Electric logs of wells drilled for oil and gas indicate that the water is not highly saline. However, data on the yield and quality of water are not available except in or near the outcrop area.

Rocks of Tertiary age

Nacimiento Formation

Rocks of earl~~iest~~y Tertiary (paleocene) age in the area of this investigation were first mapped by Gardner (1909, 1910) as parts of the Puerco and Torrejon Formations of the Nacimiento Group. 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 Nacimiento Group of Gardner (1910, p. 713).

Dane (1936) mapped a restricted unit as the undivided Puerco(?) and Torrejon Formations. The lower part of Gardner's (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 that Gardner (1909, 1910) and Renick (1931) had included in the Torrejon Formation were mapped by Dane as part of the Wasatch Formation (now classified as the San Jose Formation#). In a later work Dane (1946) used the term 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. (Also see Simpson, 1959.)

Dane (1946) traced the Nacimiento Formation from the vicinity of Cuba northward along the east side of the San Juan Basin and found that it is equivalent generally to rocks mapped as the Animas Formation of Cretaceous and ~~Tertiary~~ Paleocene age by investigaters in Colorado. For this reason Dane (1946) ~~arbitrarily~~ restricted the use of the ~~the~~ term Nacimiento Formation to the area south of Canoncito de las Yeguas in T. 25 N., R. 1 E. and applied the term Animas Formation to approximately the same rocks north Canoncito de las Yeguas.

The Nacimiento Formation of the present report is approximately the same as the unit mapped as the undivided Puerco(?) and Torrejon Formations by Dane (1936) and Wood and Northrop (1946) in the southern and southeastern parts of the area. 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 with the undivided Fruitland and Kirtland ~~Shale~~ and the Ojo Alamo Sandstone. Beds above the Ojo Alamo in the northern part of the area that were designated as the Animas Formation by Dane (1946, 1948) are designated the Nacimiento Formation, and the name Animas Formation is not used in this report.

Extent and thickness.--The Nacimiento Formation of early Tertiary (Paleocene) age 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 (fig. 5). In the southeastern part of the area at the Shell Oil Co. No. 1 Pool Four well (21.5W.22.44 center) the Nacimiento is about 850 feet thick. The composite stratigraphic section measured in the SE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 14 and at the south end of Mesa de Cuba in sec. 11, T. 20 N., R. 2 W. (localities 1c and 1d, fig. 5; also see fig. 8) indicates that the Nacimiento Formation is about 800 feet thick west of the Rio Puerco.

In the San Pedro Foothills the Nacimiento Formation is exposed discontinuously in the walls of canyons and sides of valleys where its beds of somber clay and thin sandstone are vertical to slightly overturned, or dip steeply to the west. Near the center of sec. 11, T. 21 N., R. 1 W. the Nacimiento is 537 feet thick. Farther north in T. 22 N., R. 1 W. the Nacimiento is thinner, but the formation is estimated to be about 1,000 feet thick in sec. 34, T. 23 N., R. 1 W. north of San Jose Creek.

The Nacimiento Formation is poorly exposed in discontinuous low ridges separated by alluvial valleys in the southern part of the Northern Hogback Belt. In sec. 20, T. 24 N., R. 1 E. the Nacimiento is about 600 feet thick, or possibly slightly more because the base of the formation was not determined with certainty owing to poor exposures. In the west half of sec. 8, T. 24 N., R. 1 E. the base was not determined with certainty but the Nacimiento is at least 1,250 feet thick. North of Canoncito de las Yeguas, near the center lines of secs. 17 and 18, T. 25 N., R. 1 E., the Nacimiento is about 1,400 feet thick, and the base is not exposed at the point of measurement.

The Nacimiento Formation thickens generally northward, although the thickness is varied in the outcrops along the east side of the area. In the subsurface a similar but more regular northward thickening of the Nacimiento takes place (figs. 6, 7, and 8). 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 northern boundary of the area. Well data indicate also that the Nacimiento thins irregularly eastward in the subsurface near the eastern side of the Central basin.

Lithology.--The Nacimiento Formation consists of shale and interbedded soft to resistant sandstone. These rocks are of two ~~distinctly~~ different lithologic facies in the southern and northern parts of the area; however, the lateral change in facies takes place so gradually and exposures are so discontinuous on the eastern side of the area, that it was impossible to map any logical lithologic boundary between facies. The Nacimiento Formation of the southern part of the area consists mainly of clay shale with some interbedded 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 northern boundary of the area more than half of the formation consists of sandstone.

In the vicinity of the southern part of Mesa de Cuba the Nacimiento Formation consists mostly of soft gray and olive-gray, silty, sandy clay shale. Soft, gray and tan, fine to coarse-grained, argillaceous sandstone beds occur at several stratigraphic positions in the formation, and several thin, dark-brown to black lignite beds occur also. Several lenticular beds of resistant sandstone interbedded in gray and olive-gray shale are present in the upper half of the formation. Farther west, in the Penistaja Cuestas, several of these sandstone beds are fairly persistent, and they form small cuestas.

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. At places the lower part of the formation contains thick, fine- to coarse-grained sandstone and interbedded olive-gray and gray carbonaceous shale. The middle of the formation is poorly exposed but where observed it seems to consist mainly of gray to olive-gray shale with 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-gray shale and shaly sandstone. In the San Pedro Foothills between the north fork of the Rio Puerco and the upper part of Arroyo Naranjo these upper conglomeratic arkosic sandstones of the Nacimiento are cut out by an unconformity at the base of the San Jose Formation which overlies the Nacimiento. The upper sandstones are present locally in sec. 16 and part of sec. 20, T. 21 N., R. 1 W., but seem to be cut out by the unconformity farther south.

The above described general lithologic character of the Nacimiento Formation seems to persist in the Northern Hogback Belt as far as the northern boundary of the area. However, where the lower part of the Nacimiento was observed it seems to have a smaller proportion of sandstone north of the central part of T. 24 N., R. 1 E. than it does to the south. 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 sec. 20, T. 24 N., R. 1 E. the upper conglomeratic, arkosic sandstones of the Nacimiento are persistent and are overlain by dark-gray and olive-gray 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 lithologic character of the Nacimiento Formation is similar to that of the surface exposures. 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 at the surface 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. Near the outcrops of the Nacimiento Formation in the southern part of the area the upper part of the Nacimiento is not present because of the erosional and slightly angular unconformity at the base of the overlying San Jose Formation (figs. 6, 7, and 8).

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 Sandstone.

The contact of the Nacimiento Formation and the overlying San Jose Formation is an angular and erosional unconformity throughout most of the area. The erosional nature of the contact is apparent at most exposures. In a branch canyon of one of the tributaries of the upper Rio Puerco in the $SW\frac{1}{4}NE\frac{1}{4}SW\frac{1}{4}$ sec. 11, T. 21 N., R. 1 W., the angular nature of the contact between the San Jose and Nacimiento Formations is apparent. Here the Nacimiento beds of the are only 537 feet thick. They are overturned and dip about 85° ~~to the~~ east. The basal sandstone of the San Jose dips about 69° west at the contact. On the north wall of the deep canyon just north of these exposures the basal sandstone of the San Jose Formation cuts out almost 200 feet of Nacimiento beds of the between the bottom of the canyon and the top of the north wall of the canyon.

Faulted, fossil-bearing, variegated shale and sandstone of the San Jose Formation overlap the Nacimiento Formation and rest unconformably on rocks as old as the Lewis Shale in the $SE\frac{1}{4}SW\frac{1}{4}$ sec. 23, T. 22 N., R. 1 W. These outcrops were observed and their significance 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 Formation at places in the San Pedro Foothills and Northern Hogback 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 No. 1 Duff well (24.1W.24.424), 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 Formation 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 southward thinning of the Nacimiento Formation in the subsurface is due partly to intraformational thinning of certain beds. However, correlation of lithologic units penetrated in deep wells show that the basal sandstone of the San Jose Formation bevels successively younger rocks of the Nacimiento from north to south (figs. 6 and 8), and the contact is thus one of erosion and slight angular unconformity.

Water-bearing properties.--The water-bearing properties of the Nacimiento Formation vary from south to north because of the lithologic change from a predominantly shale facies at the south to a facies of thick sandstones with interbedded shales at the north.

Surface exposures and logs of wells show that most of the Nacimiento Formation is clay shale and clayey siltstone in the southern part of the area. These rocks have low permeability and porosity and are not good aquifers. The shale contains interbedded soft lenticular sandstone, but these sandstones are clayey and probably are poor aquifers although they might yield small quantities of water to wells. Several beds of lenticular coarse-grained sandstone in the middle and upper parts of the Nacimiento Formation in the southern part of the area may contain some ground water.

The proportion of sandstone in the Nacimiento Formation increases markedly northeastward from a line extending diagonally across the area from about Otero Ranch (sec. 32, T. 24 N., R. 5 W.) to upper La Jara Creek (sec. 29, T. 22 N., R. 1 W.). The northeastward increase in the proportion of sandstone takes place in the lower half approximately, of the formation, and as much as 30-40 percent of the lower half is sandstone. Five to seven miles north of the diagonal line the proportion of sandstone in the upper part of the Nacimiento Formation increases abruptly and in the northwestern and north-central parts of the area as much as 40-50 percent of the Nacimiento is sandstone. Most of the sandstone beds range in thickness from less than 50 feet to about 100 feet, but some beds in the upper part of the formation are as much as 200 feet thick.

Where the sandstone beds of the Nacimiento Formation crop out in the northern part of the San Pedro Foothills and Northern Hogback Belt they are coarse-grained and conglomeratic, and they appear to be fairly porous and permeable; thus, they should be good aquifers. The sandstones in the upper half of the formation are especially coarse-grained, conglomeratic, and friable, indicating that they are not tightly cemented, and that they are porous and permeable. The only well (24.5W.18.421) known to obtain water from the upper part of the Nacimiento reportedly yields 42 gpm. The water is used for domestic and industrial purposes. The yields of other wells that tap the Nacimiento Formation are given in table 4. Electric logs of wells indicate that sandstone beds lower in the Nacimiento in much of the area probably are saturated with water. Data on the quality of water in the deeper beds are not available.

The sandstone beds of the Nacimiento Formation are interbedded with relatively impermeable shale, and the water in the sandstones is under artesian pressure. Because of the shaly nature of the Nacimiento Formation in outcrops along the southern margin of the Central basin, it is doubtful that much recharge of the formation occurs there. Most of the recharge probably occurs in the Northern Hogback Belt, where the sandstone facies crops out at higher altitudes than the altitude of the Nacimiento in the basin. The main areas of discharge of water from the Nacimiento Formation are probably in the deep canyons west and northwest of the area of investigation.

San Jose Formation

Rocks of early Tertiary age in the present area were described first by Cope (1875) who found vertebrate fossils of Eocene age in badland areas south of Canoncito de las Yeguas. Cope applied the name "Wasatch" to the sequence of sandstone and variegated shale which form the youngest sedimentary rocks of the Central basin.

The term Wasatch Formation was used for these rocks by later workers although different investigators included different rocks in the lower part of the formation. Gardner (1909, pl. 2) and Renick (1931, pl. 1) mapped the thick variegated shales and interbedded sandstones lying north of Mesa de Cuba as the Wasatch Formation. Dane (1936, p. 125 and pl. 39) mapped the Wasatch to include not only the Wasatch of Gardner and Renick, but to include also the underlying thick sandstones which cap Mesa de Cuba and other mesas and cuestas to the west. These sandstones had been included in the Torrejon Formation by Gardner and by Renick. Dane (1946, 1948) and Wood and Northrop (1946) placed the lower contact of the Wasatch Formation 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) pointed out that the rocks called Wasatch in the San Juan Basin were deposited in an entirely different sedimentary basin from that of the ~~type~~ Wasatch in Wyoming and Utah, and that the age spans of the two formations, although overlapping, were not the same. For these reasons, Simpson proposed that the name San Jose Formation be applied to the rocks which had been called Wasatch in the San Juan Basin. The type locality of the San Jose Formation was designated by Simpson (1948, p. 281) as the badlands area in the upper drainage of San Jose Creek along and near the Continental Divide about 1 mile northwest of Regina, New Mexico. In the present area the San Jose Formation is of early Eocene age. The San Jose Formation of the present report is equivalent to the San Jose as defined by Simpson (1948, p. 281, p. 367), and is essentially the same unit as the Wasatch mapped by Dane (1936, 1946, 1948), and by Wood and Northrop (1946).

The San Jose Formation consists of several major intergrading lithologic facies. This fact was recognized by Dane (1946) and by Simpson (1948, p. 367-374) who both briefly described the stratigraphic relations but did not map the facies of the formation. During the present investigation four complexly related lithologic units in the San Jose were distinguished and mapped as members of the formation. A widespread basal sandstone is defined as the Cuba Mesa Member of the San Jose Formation. In the southern part of the area the Cuba Mesa Member is overlain by variegated shale and interbedded sandstone which are defined as the Regina Member of the San Jose Formation. In the northern part of the area the Cuba Mesa Member is overlain by sandstone which is defined as the Llaves 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 westward and southward into red shale and interbedded sandstone which are defined as 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 in the northern part of the Tapicitos Plateau. The stratigraphy of the members is discussed more completely in following pages.

Extent and thickness.--The San Jose Formation is the surface formation in most of the area of this investigation. The San Jose has been eroded deeply and the differential resistance to erosion of its units of sandstone and shale has produced a varied and, in places, rugged physiography. Because of this varied physiography the thickness of the San Jose varies considerably.

In the Penistaja Cuestas sector 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. 21 N., R. 4 W., near the Skelley Oil Co. No. 1 White well (21.4W.8.14 center). North of Mesa de Cuba the composite thickness of the San Jose is about 1,435 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 SW$\frac{1}{4}$ sec. 2 and SE$\frac{1}{4}$ 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 composite thickness of the San Jose is about 1,650 feet.

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. The base of the San Jose rises structurally to the south and its upper beds have been eroded from the southern part of the Tapicitos Plateau. The thickness of the San Jose in the southern part of T. 24 N., R. 2 W is 1,300 feet and less.

(followed by page 89a)

In the Largo Plains more than half of the San Jose Formation has been removed by erosion. The formation is thinnest along Canon Largo and the western parts of its tributaries. 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
the plains the San Jose is 800-900 feet thick in the northern part of
is 200-400 feet thick. In the eastern part of T. 22 N., R. 3 W.

Cuba Mesa Member.--Throughout the area of this investigation, and elsewhere in the San Juan Basin, the lower part of the San Jose Formation consists of pebble-bearing, conglomeratic, arkosic sandstone containing a few lenticular beds of 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. ~~A~~ The type stratigraphic section of the member was measured along State Highway 44 northwest of Cuba from the NE$\frac{1}{4}$NW$\frac{1}{4}$ sec. 20, T. 21 N., R. 1 W. to the SW$\frac{1}{4}$ sec. 2, T. 21 N., R. 2 W. The locality of measurement (no. 2) is shown on the geologic map (fig. 5) and a detailed description is given at the end of this report. The Cuba Mesa Member rests on the Nacimiento Formation and is overlain by the Regina Member of the San Jose Formation.

At the type locality the Cuba Mesa Member is 782 feet thick, and it consists mainly of buff and yellow, rusty-weathering, tangentially cross-bedded, arkosic, coarse-grained, conglomeratic sandstone. The lower part contains several thin beds of gray and purplish-gray sandy shale. The upper part of the member is split by two tongues of the Regina Member consisting of soft gray and pale-red shale containing thin beds of soft sandstone. These tongues of the Regina Member wedge out into the Cuba Mesa Member south of State Highway 44. The main part of the Regina Member rests on the upper part of the Cuba Mesa Member and 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 intertongues with the Regina Member at many places in the area. Where sandstone tongues of the Cuba Mesa Member are present, the persistent lower sandstone is designated on the map (fig. 5) as unit 1, and the tongues are designated, in ascending order, as units 2, 3, and 4.

The Cuba Mesa Member is much thicker at the north end of Mesa de Cuba and in the subsurface northwest of the mesa (fig. 8) than it is elsewhere in the area. In the vicinity of Arroyo Chiuilla the upper part of the member is split into two tongues, which wedge out westward into the Regina Member near the southwestern corner of T. 21 N., R. 2 W. The lower part of the Cuba Mesa Member persists to the west and is estimated to be about 230 feet thick in sec. 33, T. 21 N., R. 2 W. From sec. 33, T. 21 N., R. 2 W. westward to sec. 25, T. 21 N., R. 5 W. the Cuba Mesa Member is split into two persistent units of sandstone separated by a thick unit of variegated shale which was mapped as a tongue of the Regina Member. The lower sandstone unit of the Cuba Mesa Member is about 50 feet thick, and it forms a low ledge above the Nacimiento Formation. The upper unit, which is locally more than 60 feet thick, forms a higher prominent escarpment of sandstone above the tongue of the Regina Member. An upper tongue of sandstone of the Cuba Mesa Member occurs in parts of T. 21 N., Rs. 3 and 4 W. In T. 21 N., R. 5 W. and farther northwest, the Cuba Mesa Member is essentially one massive unit of cliff-forming, thick-bedded sandstone, about 220 feet thick, that contains very little shale. Lenticular sandstones similar to those of the Cuba Mesa Member occur in the lower part of the overlying Regina Member, but they are separated from the Cuba Mesa Member by gray and variegated shale of the Regina Member.

Northeastward from the type section at the north end of Mesa de Cuba, the two sandstone tongues of the upper part 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 by a northeastward-thickening tongue of variegated shale of the Regina Member. ~~The two~~ Both units of sandstone persist as far north as the SW$\frac{1}{4}$ sec. 2, T. 21 N., R. 1 W., where the lower sandstone, containing several beds of shale, ~~and~~ is 152 feet thick; the tongue of the Regina Member is about 200 feet thick; and the overlying sandstone tongue of the Cuba Mesa Member is only 37 feet thick. The upper ~~sandstone tongue~~ unit of the Cuba Mesa Member either tongues ~~wedges~~ out northward or is represented by thin, soft, lenticular sandstone included with the Regina Member to the north. The lower sandstone unit of the Cuba Mesa Member 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 locality, is folded sharply in the San Pedro Foothills, and it dips steeply west or is vertical. The dip of the Cuba Mesa Member becomes less steep northward from sec. 20, T. 24 N., R. 1 W.

Along the east side of the area the thickness of the Cuba Mesa Member varies because of the erosional and angular unconformity at its base. It is probably not more than 150 feet thick in much of the San Pedro Foothills and the southern part of the Northern Hogback Belt, and at most places 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. 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 SW$\frac{1}{4}$NE$\frac{1}{4}$ 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 Member is 51 feet thick; the medial sandstone unit of the Cuba Mesa Member is 61 feet thick; the upper shale tongue of the Regina Member is 144 feet thick; and the upper sandstone unit of the Cuba Mesa Member, 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 merge into a thick unit which is mainly sandstone. At the surface in sec. 30, T. 25 N., R. 1 E. the shale tongues of the Regina Member are thin, and they wedge out as the three sandstone units of the Cuba Mesa Member merge northward and form a unit that is mostly sandstone and is 335 feet thick in the SW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 18, T. 25 N., R. 1 E.

At the east side of the Yeguas Mesas 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 it 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 estimated to be about 200 feet, on the basis of 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 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. Several beds of ledge-forming sandstone of varied thickness in the lower part of the Regina Member are similar to the sandstone of the Cuba Mesa Member. These rocks of the Regina Member hold up low mesas in the topographically lower parts of the Largo Plains. To the north the lowest shale beds of the Regina are replaced laterally ~~to the north~~ 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 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 (fig. 8). In the subsurface of the northern part of the area the Cuba Mesa Member ~~is thicker~~ thickens northward as the result of merging with northward-thickening tongues of sandstone in the lower part of the Regina Member (fig. 6) 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 (fig. 6) are arbitrarily separated from the overlying Llaves Member on the basis of thickness (about 375 feet) which is similar to the thickness of the Cuba Mesa Member (335 feet) at the surface north of Canoncito de las Yeguas.

Regina Member.--In most of the area the Cuba Mesa Member is overlain by a thick sequence of clay shale, siltstone, soft sandstone, and some ledge-forming, hard sandstone. These rocks are here named the Regina Member of the San Jose Formation for exposures near the town of Regina. The upper part of the Regina Member consists of the rocks described in Simpson's (1948, p. 371-374) stratigraphic sections 2 and 3, which are parts of his composite typical section of the San Jose Formation. Simpson's stratigraphic sections 2 and 3 do not include the lower part of the San Jose, and he estimated (1948, p. 374) that the base of the formation is 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 stratigraphically lowest section may be 700-800 feet above the base of the San Jose. For this reason the type locality of the Regina Member is here specified to be in the badlands and steep slopes to the west in the SW$\frac{1}{4}$ sec. 31, T. 25 N., R. 1 E. and the SE$\frac{1}{4}$ sec. 36, T. 25 N., R. 1 W. The locality of measurement (3b) is shown on the geologic map (fig. 5), and a detailed description of the stratigraphic section at the type locality is given at the end of this report. At the type locality the main part of the Regina Member is 574 feet thick, and it rests conformably on pebble- and cobble-bearing, coarse-grained, arkosic sandstone of the upper tongue 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 (SW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 31, T. 25 N., R. 1 E.), is about 900 feet in the vicinity of the type locality.

The Regina Member throughout the area consists mainly of soft beds of clay shale, siltstone, mudstone, shaly sandstone and sandy shale, but it 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 one-quarter of the member throughout the region. 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, p. 371) to be the lower part of the "Largo facies." No persistent, mappable lithologic boundary was found to separate the of the Almagre facies beds from the ~~lower part of the~~ of the Largo facies beds.

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 beds thicken northward as the intervening shale units of the Regina thin or grade laterally into shaly sandstone. North of sec. 19, T. 25 N., R. 1 E. the rocks laterally equivalent to the Regina Member are mostly sandstone and shaly sandstone which are assigned to the Llaves Member. 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 (fig. 6).

At the type locality the Regina Member is overlain by a ledge-forming conglomeratic sandstone bed of the Llaves Member. This sandstone and several stratigraphically higher sandstone beds of the Llaves Member wedge out to the south between southward-thickening tongues of the Regina Member (fig. 5). Because of this relationship, the upper contact of the Regina Member is stratigraphically higher to the south than at the type locality, and the Regina is thicker to the south. The highest thick beds of sandstone of the Llaves Member on the ridge above the type locality of the Regina are believed to be at about the same stratigraphic position as a persistent medial sandstone unit of the Llaves Member that 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 in the upper part 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 ~~Canon Large~~. The sandstone beds in the upper part of the Regina south of Canada Larga are difficult to differentiate from the persistent medial sandstone of the Llaves Member except by continuous tracing of beds. Thick lenticular sandstone beds are present in the upper part of the member also in the western part of the Tapicitos Plateau in the northwestern part of the area. Relatively persistent, resistant sandstones interbedded in thick shale are fairly common 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.

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 is varied greatly. In the subsurface of the northern part of the Tapicitos Plateau the Regina Member is about 1,040 feet thick at the Humble Oil and Refining Co. No. 1 Jicarilla M well (25.4W.23.441). Most of the Regina Member is replaced to the northeast by thick sandstone of the Llaves Member.

The Regina Member has been eroded deeply in the southern part of the Northern Hogback Belt and in the San Pedro Foothills. The thickness of the member ranges from 400-500 feet at the east to about 800 feet near the Continental Divide. Most of the Regina Member is preserved in the high hills west of the Continental Divide west of the head of Arroyo Blanco, and ~~At~~ at the Abraham No. 1 Abraham well (24.1W.17.414) the Regina Member is about 1,640 feet thick. This is almost twice ~~three times~~ the total thickness of the member at the type locality. The southward thickening is partly the result of the southward rise of the upper contact of the Regina Member because of the intertonguing relationship with the overlying Llaves Member. However, the thickening is probably due mainly to southward thickening of rocks within the Regina Member, and the member appears to be thickest near the axis of the San Juan Basin.

The part of the Regina Member that is preserved along the Continental Divide in the northern ~~southern~~ part of the Penistaja Cuestas ~~area~~ is no more than 500-600 feet thick. In the western part of the Largo Plains the preserved part of the Regina 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, Refining, and Mining Co. No. 2-2 Jicarilla 137 well (23.4W.2.441).

Llaves Member.--The San Jose Formation in the Yeguas Mesas is composed mainly of resistant, arkosic, pebble- and cobble-bearing conglomeratic sandstone which forms massive ledges. The sandstone 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 $1\frac{1}{4}$ miles northwest of the Llaves Post Office. A stratigraphic section of the lower part of the Llaves Member was measured up the eastward-projecting spur of the mesa in the $N\frac{1}{2}$ sec. 18, T. 25 N., R. 1 E. (locality 4, fig. 5). The lower part of the Llaves Member at that locality is almost 700 feet thick, and it rests on sandstone of the Cuba Mesa Member which is about 335 feet thick.

Because the of the Llaves beds dip west, stratigraphically higher beds are preserved farther west. The highest beds measured on the mesa near the mouth of Canoncito de las Yeguas are believed to correlate approximately with a thick sandstone exposed at the base of the north wall of Canoncito de las Yeguas in the $SW\frac{1}{4}$ sec. 4, T. 25 N., R. 1 W. Between the bottom of Canoncito de las Yeguas ~~the canyon~~ and the top of the ridge in sec. 33, T. 26 N., R. 1 W. (locality 5, fig. 5), approximately 450 feet of upper beds of the Llaves Member are present. These rocks consist of yellow and buff arkosic, conglomeratic sandstone and interbedded red sandstone and some red and gray shale. Similar beds, estimated to be about 150 feet thick, are present farther west near the Continental Divide; thus the Llaves Member is about 1,300 feet thick in the Yeguas Mesas type area. The localities of measurements (4 and 5) are shown on the geologic map (fig. 5), and a description of the stratigraphic sections is given at the end of this report.

Most of the Llaves Member is very coarse grained, arkosic, conglomeratic sandstone. However, the Llaves Member contains numerous thin beds of clay shale and mudstone, which are predominantly maroon but also green and gray. Thin beds of red sandstone, sandy shale, and shaly sandstone are common also and, at places, especially in the upper 500 feet of the member, rocks of this type form units as much as 50-60 feet thick. Red sandstone with red shaly partings forms the basal unit, 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. However, the lower part of the Llaves persists northwestward in the subsurface (fig. 6) where it is 300-700 feet thick. A persistent unit of sandstone, containing a few beds of shale at places and ranging in thickness from 50-100 feet or more, 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. The stratigraphic position of this persistent unit of sandstone is near the middle of the Llaves Member. Remnants of sandstone believed to be 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, occurs only in the Yeguas Mesas. The beds of the upper part of the Llaves thin to the south and west, and they 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 (fig. 5) have been generalized slightly. The units mapped as tongues of the Llaves Member are sandstone beds which are persistent and which can be traced into the massive sequence of sandstones of the Llaves. The units mapped as ~~parts~~ 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. Isolated 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 connect now with the Llaves, so they were mapped with the Tapicitos Member. A similar philosophy of mapping was applied in delineating the Llaves and Tapicitos Members at the west side of the Yeguas Mesas.

Tapicitos Member.--On the northern part of the Tapicitos Plateau, a sequence of maroon and variegated shale and interbedded thin to thick lenticular sandstone lies on the persistent medial sandstone of the Llaves Member. This shaly 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 member is well exposed also in the upper drainage of Gavilan Creek above Gavilan and 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 Gavilan Creek in secs. 1, 2, and 11, T. 25 N., R. 2 W. may be considered as typical of the Tapicitos Member, although a detailed stratigraphic section was not measured. At this locality/ the Tapicitos Member, which is estimated to be about 450 feet thick, rests on the persistent medial sandstone of the Llaves Member. The lower part of the Tapicitos Member is about 300 feet thick, and it consists mostly of slope-forming pale-red to maroon clay shale, siltstone, and mudstone and some variegated white, gray, and purple beds. The shale contains lenticular, soft, white and yellow sandstone and some beds of hard gray sandstone. These beds are overlain by a tongue of the Llaves Member, consisting of several beds of hard coarse-grained sandstone of varied thickness. This sandstone tongue, 20 to 30 feet thick, holds up 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, all 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 describing the "Largo facies" was measured by Simpson (1948, p. 370-371) near the head of the north branch of Oso Arroyo (locality 6, fig. 5), and a modified description of this section is included at the end of this report. The exact locality of measurement was not specified by Simpson, but it appears to be in sec. 30, T. 25 N., R. 1 W. 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 probably are 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 red to maroon shale, but at all places 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, cross-bedded, coarse-grained, and locally conglomeratic. They are similar to sandstone of the Llaves Member. The thickness of the Tapicitos Member varies considerably because its upper surface has eroded deeply. The maximum thickness is about 500 feet, and at most places the preserved part of the member is no more than 200-300 feet thick. In the western and southern parts of the Yeguas Mesas the Tapicitos Member grades laterally into sandstone of the upper part of the Llaves Member. The lower part of the Tapicitos Member locally interfingers with the upper part of the persistent medial sandstone unit of the Llaves Member.

Contacts.--The San Jose Formation rests on the Nacimiento Formation with erosional and angular unconformity. The Cuba Mesa Member in the subsurface truncates successively lower beds of the Nacimiento Formation from south to north (figs. 6 and 8). In most of the area the angularity between the Cuba Mesa and Nacimiento is less than 1° regionally, inasmuch as only about 600 feet of rocks of the Nacimiento are truncated in more than 30 miles.

The thickness of the Nacimiento Formation on the eastern side of the Central basin varies considerably in short distances, and the angular unconformity at the base of the San Jose Formation in the eastern part of the area 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 ~~this~~ the same vicinity thin remnants of rocks tentatively assigned to the Regina Member occur at the tops of narrow divides between the deep canyons. These rocks dip about 10° west, at ~~about 10°~~ and they are overlain with erosional unconformity by high-level terrace deposits of pinkish-orange boulder gravel of probable late Tertiary or Quaternary age. The rocks tentatively assigned to the Regina Member consist of white to gray conglomeratic sandstone; coaly shale; gray, olive-green, and maroon shale; and red sandstone containing pebbles of chert and limestone. The best exposed and thickest remnant of these rocks is in a cliff above a steep slope in the south-central part of sec. 2, T. 21 N., R. 1 W., where they are about 130 feet thick and rest with marked angular unconformity on overturned beds of the Nacimiento Formation, Ojo Alamo Sandstone, Fruitland Formation and Kirtland Shale, ~~Formations,~~ and the Lewis Shale. Remnants of red shale and sandstone assigned to the Regina Member rest on the Lewis Shale to the east, and are preserved at the tops of narrow ridges in sec. 11, T. 21 N., R. 1 W.

The remnants are similar to rocks assigned to the Regina Member in the valley of La Jara Creek to the north. The faulted variegated shale and conglomeratic sandstone that rest unconformably on the Lewis Shale in the SW$\frac{1}{4}$ sec. 23, T. 22 N., R. 1 W. are assigned to the Regina Member and contain teeth of Hyracotherium ("Eohippus") (G. G. Simpson, oral communication, 1959), thus they are definitely of Eocene age. The Regina Member overlaps the steeply tilted Cuba Mesa Member in the NW$\frac{1}{4}$ sec. 23, T. 22 N., R. 1 W., and rests on steeply dipping beds of the Nacimiento Formation. Th~~is~~e angular relationship between the Regina and the older indicates that there was deformation in this area during the deposition of the San Jose Formation. A later episode of deformation is indicated by the fact that the overlapping beds of the Regina Member also are tilted ~~folded~~ and are broken by faults.

The San Jose Formation is overlain unconformably by high-level terrace gravel of Quaternary or Tertiary age and by lower-level gravel of Quaternary age in the San Pedro Foothills. Valley-filling deposits of Quaternary alluvium rest on the San Jose at many places in the area.

Water-bearing properties.-- Sandstone beds of the San Jose Formation yield water to wells in many parts of the area. The yields of wells that tap the San Jose are given in table 5. Most of the water is potable, although owners of some wells report that the taste of the water is objectionable. Analyses indicate that the sodium, bicarbonate, and sulfate content of water from the San Jose is generally high (table 9).

The thick, coarse-grained sandstone beds of the Cuba Mesa Member yield water to wells in the southern and western parts of the area (fig 10), and they are potential sources of water throughout most of the area. Rocks of the Cuba Mesa Member have not been analyzed for porosity, but their general appearance indicates that they are at least as porous as sandstones of the Mesaverde Group, which Renick (1931, p. 49) reported to have porosities ranging from 13.71 to 28.32 percent. The Cuba Mesa Member in most of the area averages slightly more than 200 feet thick, and it is about 782 feet thick in the subsurface northwest of Cuba, where it may contain relatively large quantities of water. ¶ The Cuba Mesa Member crops out in extensive areas across the southern and eastern parts of the area, where it can receive the recharge from precipitation, and from water moving through thin overlying alluvium the Member in sandy washes. ~~on the outcrops.~~ Part of the water is discharged at seeps on the outcrops, but part of it moves downdip through the sandstone and away from the outcrops.

Thus, the general movement of water in the Cuba Mesa Member is toward the deeper part of the basin.

No. ¶ All of these outcrops are near the margins of the Central basin, and the rocks dip from the outcrops toward the deeper part of the basin. In the subsurface of most of the area the Cuba Mesa Member is a confined aquifer underlain by shale of the Nacimiento Formation and overlain by shale of the Regina Member of the San Jose Formation. However, the Cuba Mesa Member is exposed along Canon Largo, and the lower parts of its tributaries in the western part of the area, and water discharges at seeps and springs on these outcrops, notably at Otero Ranch in sec. 32, T. 24 N., R. 5 W.

The water-bearing properties of the Regina Member vary because of variations in its lithologic character. In the Penistaja Cuestas and in the Largo Plains the lower part of the Regina Member contains several beds of fairly persistent coarse-grained sandstone interbedded in thick shale. These sandstones yield small amounts of water to domestic and stock wells.

The upper part of the Regina Member in the southern part of the Tapicitos Plateau contains numerous lenticular to relatively persistent, thick, coarse-grained sandstones interbedded in shale. These sandstones yield small amounts of water to domestic and stock wells. East of the Continental Divide in parts of Tps. 23 and 24 N., R. 1 W., the Regina Member is mostly shale with interbedded clayey sandstones. The lower and upper parts of the member contain thick discontinuous sandstones which yield small amounts of water, but wells drilled in the thick medial shale did not obtain water, or they obtained only very small amounts of water. Most of the wells drilled in the shale are shallow, but several were drilled to depths ranging from 345 to 734 feet. The thick shale persists westward in the subsurface beneath the Tapicitos Plateau, but in the vicinity of Lindrith thick tongues of the Llaves Member occur in the Regina Member in the subsurface (fig. 6), and these sandstones yield water to wells.

The lithologic character of the Llaves Member is generally similar to that of the Cuba Mesa Member, and the rocks consist largely of coarse-grained to gravelly sandstone and some thin interbedded shale and sandy shale. The sandstones appear to be porous and they yield water to wells and springs. The water is potable and generally is reported to be of fair to good quality. Precipitation on the outcrop areas in the Yeguas Mesas is the source of recharge of much of the Llaves Member. Part of the water is discharged at numerous seeps and springs, which feed water into the alluvium at the bottom of Canoncito de las Yeguas and its deeply incised tributary canyons. The rocks of the Llaves Member dip west toward the deep, axial portion of the San Juan Basin, and part of the water moves toward the deep part of the basin.

The upper part of the Llaves Member tongues out westward into the Tapicitos Member near the Continental Divide, but the persistent medial sandstone is distributed across the Tapicitos Plateau nearly to the northwest corner of the area, and it yields water to wells in this region. The lower part of the Llaves Member persists to the northwest beneath the Tapicitos Plateau, where it is as much as 700 feet thick and consists mostly of thick beds of sandstone. Most of these sandstones wedge out to the south into the Regina Member before reaching outcrop areas on the margins of the Tapicitos Plateau. Several wells in the vicinity of Lindrith obtain water from thick tongues of the lower part of the Llaves Member which are confined within the shale of the Regina Member at depths of 400 to 500 feet or more. Reconnaissance examination outside of the area of this investigation indicates that most of the beds of the lower part of the Llaves Member tongue out northward also into shaly rocks. Thus, most of the sandstone beds of the lower part of the Llaves Member are probably confined aquifers in the area and the available data indicate that these rocks may contain large quantities of water in the subsurface of the north-central part of the Tapicitos Plateau. Rocks probably equivalent to the lower part of the Llaves Member are exposed in deep canyons northwest of the area. Water moving through these rocks from recharge areas in the Yeguas Mesas is probably discharged into the canyons northwest of the area investigated.

Sandstone beds in the Tapicitos Member yield small amounts of water to domestic and stock wells where these rocks are preserved on the northern part of the Tapicitos Plateau. The sandstones are coarse-grained and similar to those of the Llaves Member, but they are lenticular and interbedded in thick units of red shale which form 50 to 75 percent of the member at most places. The water from the Tapicitos Member is generally potable, but it is reported to be unpotable at places. Deposits of white salts are common at seeps and around wells producing water from the Tapicitos Member. The Tapicitos Member contains a sufficient amount of water for stock and domestic supplies at many places on the Tapicitos Plateau. However, it is doubtful that it contains large bodies of ground water, particularly in the western part of the plateau, because the lenticular sandstones are of limited extent and because the plateau is deeply dissected allowing the water that infiltrates the sandstones to discharge at the extensive areas of outcrop along the canyons and mesas. Sandstones in the lower part of the member in the subsurface of the eastern part of the plateau probably contain confined water under artesian pressure.

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 it trends about N. 8° E. Another dike to the north in sec. 24 is about three-quarters of a mile long and trends N. 27° E. A third dike, which is north and east of the short dike begins in the southern part of sec. 18, T. 26 N., R. 2 W., and extends northward past the northern boundary of the area. This dike trends N. 8° E., and it 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 in 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~~, partly digested~~ material, most of which is recognizable as altered wall rock of the San Jose Formation. The wall rock has been baked for several feet on either side of the dikes. The dikes at places have vertical and horizontal joints.

The dikes ~~described above~~ are similar in lithologic character, structure, and alignment to those of a broad, dike swarm a few miles to the north. The north-northeast-trending lamprophyre dikes of the swarm were mapped by Dane (1948) who described their relations to the rocks of the northeastern part of the San Juan Basin. He concluded that they are probably of Miocene age. By analogy, the dikes in the present area are classified also as Miocene(?).

The dikes yield no water to wells, but they may have some affects on the hydrology of the northern part of the Tapicitos Plateau. Although the dikes probably do not form impermeable barriers to ground water, they may locally impede the westward movement of water in the San Jose Formation and older rocks.

Gravel of Tertiary or Quaternary age

Gravel of late Tertiary or Quaternary age caps westward-sloping high-level terraces at the western foot of San Pedro Mountain. The pebbles, cobbles, and boulders which compose the gravel are mostly pink to brown, coarse-grained, dense, hard granite. This granite is identical in appearance to ~~with~~ the of Precambrian age granite of the core of ~~the~~ San Pedro Mountain from which the gravel ~~they~~ must have been derived. The high-level gravel deposits consists of local remnants, 50 to 100 feet thick, that are preserved at altitudes ranging from 8,000 to 8,400 feet. The gravel was deposited on a westward-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 are preserved beneath the gravel deposits.

Remnants of gravel deposits consisting mainly of fragments of sedimentary rocks are present also in the higher part of the foothills just north of San Pedro Mountain (east of the mapped area). These gravel deposits lie at altitudes similar to those of the high-level gravel deposits west of San Pedro Mountain, and probably are equivalent to them.

The remnants of the erosional surface on which the gravel deposits rest north of San Pedro Mountain was correlated by Bryan and McCann (1936) with the Ortiz surface which they considered to be of Pliocene or Pleistocene age. A study of topographic maps of the northern part of the San Juan Basin indicates that the remnants of the erosional surface on which the high-level gravels were deposited at the west and northern sides of San Pedro Mountain may have been part of a formerly widespread erosional surface. This surface may be equivalent to the erosional surface on which the Bridgetimber Gravel was deposited south of Durango, Colorado. Atwood and Mather (1932, p. 89 and pl. 2) considered the erosional surface beneath the Bridgetimber Gravel to be part of the late Pliocene San Juan Peneplane, and considered the Bridgetimber Gravel to be of Pliocene or Pleistocene age. For these reasons the high-level gravel deposits at the west side of San Pedro Mountain are assigned a Pliocene or Pleistocene age. They probably were deposited as parts of alluvial fans on a westward-sloping pediment cut at the base of San Pedro Mountain.

~~Wells that tap the Pliocene or Pleistocene gravel deposits were not found.~~ Some of the high-level gravel contains small amounts of water which infiltrates from precipitation on the deposits and from intermittent streamflow at the mouths of small canyons on the side of the San Pedro Mountain. Small seeps of water were observed near the west side of the gravels in sec. 11, T. 21 N., R. 1 W. None of the remnants of high-level gravel are believed to contain much ground water, and they have not been tapped by wells.

Sediments of Quaternary age

Terrace gravel, colluvium, and stream channel gravel

Gravel of Pleistocene and Recent age caps terraces at several topographic levels and occurs in stream channels in the upper parts of valleys in the San Pedro Foothills. The gravel consists mainly of pebbles, cobbles, and boulders of derived from rocks of Precambrian age ~~granite~~, but some of the fragments are limestone and sandstone derived from the Paleozoic and Mesozoic rocks exposed along the west side of San Pedro Mountain. The gravel also contains sand, silt, and clay. At most places these deposits are less than 100 feet thick. Slope wash on the sides of valleys and walls of canyons consists of colluvium weathered from the underlying bedrock and gravel slumped from the terraces.

According to Bryan and McCann (1936, p. 160-164) these deposits and the high-level gravel deposits of Tertiary or Quaternary age were laid down mainly on the westward-sloping "La Jara pediment." However, during the present investigation it was found that Bryan and McCann's concept of a single, westward-sloping pediment is not correct. Although the high-level gravels of Tertiary or Quaternary age may have been deposited on a pediment, the lower-level gravels were deposited in the valleys of westward-flowing streams which debouched from deep canyons cut in Precambrian rocks on the west side of San Pedro Mountain. Gravel-capped terraces at several topographic levels indicate a complex history of erosion and deposition during the Quaternary period. 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 are not distinguished on the geologic map (fig. 5), but they are combined as Quaternary colluvium and gravel.

Small patches of colluvium, colluvial boulders, and pebble and cobble gravel occur on remnants of a steep, eastward sloping erosional surface cut mainly on the Lewis Shale, but also on younger rocks, in Tps. 25 and 26 N., R. 1 E. This erosion surface seems to have been the west side of a broad valley which sloped generally southward. New valley surfaces have been cut recently 100 to 200 feet below the remnants of the older valley.

The deposits of Quaternary age gravel are of limited extent in the San Pedro Foothills, but some of them are aquifers in that area. Water of good chemical quality issues from springs in the gravel deposits of the upper valleys of La Jara Creek and Rito de Los Pinos and it is used for domestic and stock supply. Water for the public supply of the town of Cuba is collected from springs and seeps issuing from gravel along the south side of the gravel-capped mesa in the southern half of sec. 14, T. 21 N., R. 1 E. Rain and snow on the gravel deposits ~~probably~~ infiltrate, and the upper parts of perennial streams such as San Jose Creek, La Jara Creek, Rito de los pinos, and the Rio Puerco, lose part of their surface flow because of infiltration into the gravels. The gravels feed water into alluvium at lower levels by underflow and by seeps and springs that discharge from the gravels in the lower parts of the main stream valleys. At most places the water in the gravel is perched on relatively impermeable shale underlying the gravel.

Alluvium

Alluvium, consisting of sand, silt, clay, and some gravel occurs in the valleys of all of the major perennial and intermittent 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. The alluvium, as shown on the geologic map (fig. ~~5~~ 4), includes only the thicker alluvial deposits of the major valleys that may be water bearing. Sparse data indicate that the alluvium generally less than 100 feet thick.

Ground water occurs in alluvium in the valleys of all of the major streams of the area. The yields of wells that tap the alluvium are given in table 6. The alluvium is recharged by precipitation, by infiltration of surface water, and by seepage from bedrock aquifers. The alluvium in Cañon Largo, Canada Larga, Canon Ojitos, and Tapicitos Creek in the western and northwestern parts of the area contains water that probably is received mainly by underflow from the sandstone aquifers of the San Jose Formation. Thin deposits of alluvium near the heads of most of the small valleys of the area contain very little ground water. Water infiltrates into the underlying bedrock from the alluvium at places, depending on local conditions.

The quality of water in the alluvium is somewhat varied, but at most places the water is potable. Water in the alluvium of the Rio Puerco Valley near Cuba is not considered to be potable by many of the residents, because of its high content of dissolved mineral matter. Also, in this populated area the risk of pollution by untreated sewage is great.

Geologic structure

Structure contour map

The general structure of most of the area is portrayed on figure 9 by structure contour lines which connect points on the base

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Figure 9.--Structure contour map of the southern part of the Jicarilla Apache Indian Reservation and adjacent region to the south and east, N. Mex.

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of the Ojo Alamo Sandstone that are of equal altitude above sea level. The interval between contours is 100 feet, except near the eastern margin of the map where the interval is 500 feet. The structure contours are solid lines where subsurface data were considered to be adequate to determine their positions, and where the altitude of the base of the Ojo Alamo at outcrops could be determined from topographic maps. The structure contours are shown as dashed lines where their position was determined by interpolating, by constructing cross sections based on the dip and thickness of overlying rocks, or by projecting downward from marker beds whose altitude was determined from topographic maps and whose stratigraphic position above the Ojo Alamo is known from measured stratigraphic sections.

The base of the Ojo Alamo Sandstone was chosen as the contour datum because it is easily determined and correlated by means of electric logs of most wells drilled for oil and gas in the region. The position of the base of the Ojo Alamo ~~at~~ on the logs of a few wells was uncertain, but ~~in almost all of these cases~~ the stratigraphic interval in question is less than 50 feet ~~thick~~, which is less than half of the contour interval. The contours do not depict the exact structure of rocks older than the Ojo Alamo because of the unconformity at the base of the Ojo Alamo; however, the structure of the older rocks is not greatly different from that of the Ojo Alamo except near the eastern edge of the area. Also, the structure of rocks of the San Jose Formation is not exactly the same as that of the Ojo Alamo because of the unconformity at the base of the San Jose.

The base of the Ojo Alamo was chosen as the contour datum also because this formation is the deepest aquifer from which it seems practical to obtain water in most of the area. The depth to the base of the Ojo Alamo can be determined, approximately, by subtracting the altitude of the base at any point from the altitude of the ground surface at that point.

~~Description~~

Most of the area investigated lies within the Central basin of the San Juan Basin (fig. ~~4~~ 3), and its geologic structure is simple. The structural axis of the eastern part of the basin trends southeast ~~northwestward~~ and extends diagonally across the northeastern part of the area from the northwest corner of 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 along the east side of the basin (fig. ~~5~~ 4). Most of the area is southwest of the axis of the basin, and the rocks in this part of the area dip gently northeast. At most places on this structural slope the dip is 1° or less.

In the southeastern part of the area the structure contours bend northeastward through a series of north-northwest-plunging anticlines and anticlinal bends, and the regional dip is northwest. The regional dip is locally more than 10° in this part of the area, but it is progressively less to the northwest toward the interior of the basin.

In the western part of the San Pedro Foothills the rocks dip 2°-20° west and the contours trend north regionally. However, the contours are deflected locally through several north-northwest-plunging subsurface anticlinal noses. The positions of the contours on the nose in T. 22 N., R. 1 W. are based mainly on surface stratigraphic data which indicate thickening and thinning of the Nacimiento Formation in the San Pedro Foothills. The depicted positions of contours on the northwest-trending noses farther north are partly controlled by both surface and subsurface data. The north-northwest-plunging noses which lie north of the Rito Leche anticlinal nose are reflected only slightly in the San Jose Formation. The noses Probably were ~~appear to have been~~ formed mainly in late Paleocene time before the deposition of the San Jose Formation, with only slight additional folding occurring after the deposition of the San Jose.

In the eastern part of the San Pedro Foothills rocks have been folded abruptly along a major north-trending synclinal bend. The surface trace of the eastward-dipping axial plane of the synclinal bend is shown on figure 5. At most places in the San Pedro Foothills the rocks just west of the trace of the axial plane dip 10°-30° west; whereas just east of the trace, the dip of the beds ranges from about 60° west 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. The synclinal bend is younger than the north-northwest-trending folds as is shown partly by the fact that it cuts across them. Also, the north-northwest-trending folds are mainly older than the San Jose Formation which is folded sharply along the synclinal bend. The angular unconformity between the Regina Member and the 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 in early Eocene time. However, the tilting and faulting of the overlapping beds of the Regina indicate that there was also post-San Jose deformation along the eastern side of the area.

Renick (1931, p. 71-74) and Wood and Northrop (1946) found that the steeply folded and overturned rocks along the synclinal bend are west of a fault along which the rocks of the Nacimiento uplift were elevated relative to the San Juan Basin. This north-trending fault (fig. 4), which was called the "Sierra Nacimiento overthrust zone" by Renick and the Nacimiento fault by Wood and Northrop, is east of the outcrop belt of the Mesaverde Group and was not mapped during the present investigation. West of San Pedro Mountain the vertical component of displacement on the Nacimiento fault is as much as 6,000 feet, but the amount of displacement on the fault is less farther north. North of San Pedro Mountain the Nacimiento fault passes into a north-northeast-trending normal fault in the French Mesa-Gallina uplift. The orientation of the staggered system of north-northwest-plunging folds in the eastern part of the basin suggests that, during the late Paleocene stage of deformation, the folds were formed because of right shift along the Nacimiento fault; that is, the rocks of the San Juan Basin may have been shifted north relative to the Nacimiento uplift. Probably the synclinal bend was formed as part of a monocline which was ruptured later because of vertical movements on the Nacimiento fault.

In the northern Hogback Belt the rocks dip 10°-65° west on a sinuous, west-facing monoclinal flexure which is at the west side of the French Mesa-Gallina uplift. ~~Archuleta anticlinorium.~~ The synclinal bend extends northward from the San Pedro Foothills and marks the foot of the monocline in the Northern Hogback Belt (fig. 5). The beds are not vertical or overturned as they are in the San Pedro Foothills, and the dips of the rocks on the monocline decrease generally to the north. In the southeastern part of T. 24 N., R. 1 W. and the 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, steeply dipping segment of the monocline. Beds of the Regina Member of the San Jose Formation are the folded rocks at the surface. The interpretation of the subsurface structure of the Ojo Alamo Sandstone (fig. 9) is based on construction of cross sections using the dips of rocks of the San Jose Formation at the surface. However, it is possible that the Schmitz anticline is mainly a shallow-seated structure in the San Jose Formation, and was caused by crowding and crumpling of the San Jose rocks near the southeastward-dipping axial plane of the synclinal bend at the foot of the monocline. If this is so, the anticline may die out with depth.

In T. 26 N., R. 1 E., the north-trending contours on the monocline are deflected west along the west limb of the north-west-plunging Puerto Chiquito anticlinal nose. On the basis of the outcrop pattern of the Mesaverde Group the surface trace of the axial plane of the Puerto Chiquito anticlinal nose probably trends diagonally through secs. 2 and 3, T. 26 N., R. 1 E.

The rocks are broken by faults at places in the area. In secs. 24 and 25, T. 20 N., R. 3 W., the Ojo Alamo Sandstone near the crest of the Johnson anticline is offset along a north-northeast-trending normal fault downthrown to the west. The stratigraphic displacement on this fault is probably 50 feet or less, and the fault seems to die out to the north. Small northwest-trending normal faults, downthrown to the west, displace the Mesaverde Group on the San Pablo anticline near the southeastern corner of the area. Several northwesterly trending normal faults, downthrown to the east, occur in the San Jose Formation and older rocks in sec. 20, T. 22 N., R. 1 W. The stratigraphic displacement of overlapping beds of the San Jose Formation is probably less than 200 feet on each of these faults.

In the NE$\frac{1}{4}$SW$\frac{1}{4}$ 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 about 50 feet along an east-dipping low-angle fault 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. This may be a high-angle reverse fault. A similar fault throws the Lewis Shale against the Nacimiento Formation in the NW$\frac{1}{4}$ sec. 23, T. 22 N., R. 1 W.

Rocks in the Northern Hogback Belt are displaced at several places along normal faults that are nearly transverse to the strike of the beds. Steeply dipping rocks of the 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 along the sharp bend in the monocline in secs. 21, 29, and 32, T. 24 N., R. 1 E. All of these faults have the common characteristic of having the block south of the fault offset to the east relative to the block north of the fault.

Ground water

Ground water is a renewable resource within the upper layer of the earth. In contrast to most other mineral resources much of the ground water is in constant motion. The movement of water underground is one phase of the hydrologic cycle, which includes evaporation from bodies of surface water and leaves of plants; transportation in the atmosphere; precipitation, as rain or snow; and infiltration into the ground or accumulation on the land surface.

Part of the water that infiltrates into the ground replenishes the soil moisture. After the soil moisture has been restored to capacity, the excess water percolates downward to the zone of ground-water saturation. The soil moisture is evaporated directly, or it is absorbed and transpired by plants. The water that reaches the zone of saturation may return to the atmosphere by evapotranspiration (evaporation and transpiration) where the top of the zone of saturation is only a few feet below the surface, or it may move underground to places where it discharges at springs and seeps. If the volume of discharge is large, perennial streams are sustained.

The capacity of rocks to store and transmit water depends on the size, shape, and arrangement of openings in the rocks. The volume of accessible openings affects the storage capacity of the rocks. The size, shape, and degree of interconnection of the openings determines the permeability, that is, the capacity of the rock to transmit water.

The primary openings in sandstone and alluvial aquifers are the interstices between sedimentary particles. The size of the interstices varies with the size and sorting of the particles. Therefore, fine-grained materials, such as clay and silt ~~shale~~, transmit little water in comparision to sandstone and coarse alluvium. Well-sorted coarse sand and gravel are the best aquifers. Cementation and compaction of sedimentary particles reduce the original size of interstices.

~~S~~econdary openings in sandstone aquifers ~~are~~ fractures are. These openings vary in size, spacing, and interconnection. Vertical fractures generally transmit water more readily than do horizontal fractures because the horizontal fractures tend to be closed by the weight of the overlying rock~~s~~. Ground water moves more readily parallel to the bedding planes than it does across the bedding planes, especially where the sediments consist of alternating beds of fine and coarse material.

The zone of rocks that is saturated with water is termed simply the zone of saturation. Generally, the depth to the top of the zone of saturation is least in the valleys and greatest on the ridges. However, a perched zone of saturation above the main zone of saturation may exist beneath the surface of some ridges, where water-bearing sandstone overlies nearby impermeable shale.

Water that infiltrates into ~~outcrops of~~ alluvium ~~and~~ or into outcrops of sandstone in the area moves down the valleys, or, commonly, down the dip of the beds, particularly in the vicinity of recharge areas. If the water in an aquifer has a free upper surface, the aquifer is said to be unconfined, and the level at which water would stand in a well is approximately the same as that of the top of the zone of saturation. If the water moves down the dip of the aquifer beneath a bed of less permeable material, the water becomes confined in the aquifer. The water level in a well that taps a confined aquifer would be higher than the top of the aquifer, and the aquifer is said to be artesian. Nearly all the beds of sandstone in the area are artesian aquifers downdip from their outcrops.

The accessibility of ground water depends largely on the topographic situation and the structural attitude of beds. The depth to an aquifer is greater beneath the ridges and mesas than beneath the intervening valleys and plains. The depth to an aquifer increases downdip, and the dips of beds in the area range from 1° to about 90°. The dip at most places ranges from 1° to 5°, or 92 to 462 feet per mile.

Most of the water wells in the area were drilled with percussion (cable-tool) or hydraulic rotary drills, although shallow hand-dug wells are common in the alluvium of some valleys. The wells generally are cased to their total depths, and the casings are perforated through the water-bearing zones. Data on all the wells and springs that were inventoried are given in tables 7 and 8, and the locations of most of the water wells in the area, the depths to water in them, and the principal aquifers are shown on figure ~~10~~ 8.

Figure ~~10~~ 8 stat.--Map showing locations of water wells and springs in the southern part of the Jicarilla Apache Indian Reservation and adjacent region to the south and east, New Mexico

Recharge, movement, and discharge

The principal sources of ground-water recharge are precipitation and streamflow on outcrops of the aquifers. Vertical leakage of water from one aquifer to another also is a form of recharge. Any place that an aquifer crops out is a potential area of recharge, although water is rejected at some outcrops because the aquifer at those places is filled and possibly is discharging water. In general, aquifers are recharged where their outcrops are highest, and they discharge water where their outcrops are lowest.

Most of the recharge in the area occurs in the eastern and southern parts, at altitudes of 7,000-8,000 feet. The ground water moves through the rocks away from the areas of recharge towards outcrops at lower altitudes generally to the north and northwest, where it discharges as springs and seeps in stream valleys or migrates into other stratigraphic units by vertical or lateral leakage. Much of the recharge water moves directly from recharge areas on plains, mesas, and ridges to discharge points in adjacent escarpments and canyons. A few small perennial streams are fed by ground-water discharge in the eastern part of the area. Most of the beds of sandstone probably are saturated with ground water in the subsurface of the interior of the Central basin, which includes most of the project area. The relationship of the topography and the geologic structure of the region suggests that the regional movement of deep ground water is northwestward and westward from the recharge areas through part of the Central basin to discharge points along Canon Largo and its tributaries and the San Juan River.

Withdrawal of large amounts of ground water from wells on the Jicarilla Reservation might eventually affect the discharge of ground water to the San Juan River. The water of the San Juan River has already been allocated according to local water rights and interstate compacts, and depletion of the streamflow by ground-water withdrawal would affect the apportionment that has been made. Two seepage investigations of the San Juan River were made in December 1958 and September 1959, during periods of low flow, in an attempt to learn the magnitude of ground-water discharge to the San Juan River down the piezometric gradient from the project area. The results of the seepage investigations are summarized in tables 9

The seepage investigations consisted of measuring the flow of the San Juan River at selected localities and measuring all tributary inflow to determine, if possible, the amount of ground-water discharge to the river in each reach. A sample of water was collected from each measuring point and was analyzed chemically, to determine whether ground-water discharge to the river could be detected by changes in the chemical quality of water in the river. Only the concentration of sulfate, the hardness, and the specific conductance of the water are listed in tables 9 and 10, because these chemical and physical properties probably would be most diagnostic of ground water intermixing with the surface water.

western part of the central basin STeT

Neither the discharge measurements nor the chemical analyses provided conclusive evidence of ground-water discharge into the river. Some ground water probably is discharged from the Ojo Alamo Sandstone and younger formations to the San Juan River, but the amount in any particular reach of the river is so small that it is within the percentage of error in gaging large flows in natural channels and within the range of fluctuations in streamflow. For example, the river appeared to lose 9 cfs (cubic feet per second) of flow (the arithmetic sum of the gains and losses) between Rosa, N. Mex. and Bloomfield, N. Mex. when the seepage investigation was made December 2-3, 1958. The river appeared to lose 11 cfs of flow between the same two stations when the seepage investigation was made September 14-16, 1959. The flow past the regular gaging station at Rosa decreased from 110 cfs on December 2, 1958 to 90 cfs on December 3, 1958, and decreased from 98 cfs on September 14, 1959 to 85 cfs on September 16, 1959 (U.S. Geological Survey, 1959). The decreases in flow past Rosa during the seepage investigations could more than account for the apparent loss in flow between Rosa and Bloomfield.

The concentration of sulfate in the river water increased from 124 ppm at Blanco to 167 ppm at Bloomfield, a reach of the river where there was no surface inflow, during the seepage investigation of December 2-3, 1958 and increased from 131 to 201 ppm in the same reach during the investigation of September 14-16, 1959. The hardness and specific conductance of the water increased similarly. The seepage investigations were made in 2 or 3 days each time and during the low evaporation season, so that the concentration of dissolved solids by evaporation would have been negligible. The chemical data probably indicate that ground water, which is typically high in sulfate in the region, was discharging into the river at the time of the investigations. However, part of the increase in concentration of chemical constituents may have been caused by return flow of irrigation water.

The seepage investigations do not show conclusively whether or not ground water discharges to the San Juan River down the structural slope from the project area. The small change in streamflow between Rosa and Bloomfield does indicate that only relatively small amounts of ground water could be entering the river in that reach so that withdrawal of ground water in the Jicarilla Reservation will not measurably affect the flow of the San Juan River.

Much of the ground water that moves through the Nacimiento and San Jose Formations in the Central basin is ~~must be~~ discharged from small springs and seeps along Canon Largo and its tributaries within and west of the area of investigation~~s~~. George C. Taylor (written communication) estimated that in a half mile reach of Canon Largo near Otero Ranch, 450 gpm of water was discharging from springs and seeps in 19~~5~~39. Part of the water probably migrates from the sandstone aquifers into the valley alluvium and the soil from which most of the water is dissipated by evapotranspiration before reaching the San Juan River. Some of the areas of evapotranspiration are indicated by accumulations of salts on the valley floors in the western part of the Jicarilla Reservation.

Chemical quality of water

Water in the formations of Cretaceous and Tertiary age varies widely in chemical quality. Not only does the chemical quality of the water differ from one stratigraphic unit to another, it also differs within the same unit (table 11). The difference in the chemical quality of the ground water is influenced by the quality of the recharge water, the relative abundance and types of minerals with which the water comes in contact, and the amount of ground-water circulation through the rocks. The quality of water in any stratigraphic unit may be affected also by leakage from one unit to another.

Part of the recharge is from direct infiltration of rain and snowmelt on the outcrops, and part is from infiltration of water from intermittent and perennial streams which cross the outcrops. The recharge water derived from direct infiltration of rain and snow is of low salinity when it begins its underground journey in the host rock; but the salinity increases progressively with movement through the rock. The recharge water which infiltrates from streams may have high salinity when it begins its underground journey, because the water contains dissolved matter derived from materials over which the streams flow or because the streams may be fed by springs discharging saline ground water. For example, a sample of water collected July 23, 1957 from the Rio Puerco, where it is crossed by State Highway 44 in Cuba, contained 587 ppm of dissolved solids. The discharge of the stream was 0.5 cfs, after a peak flood flow of 25 cfs. Another sample of water collected October 13, 1959 at the same place contained 1,220 ppm of dissolved solids. The second sample was collected from the small amount of base flow (the flow from ground-water discharge to the stream). A sample of water collected July 23, 1957 from an unnamed tributary of the Rio Puerco 4.2 miles south of Cuba, where the stream is crossed by State Highway 44 in sec. 16, T. 20 N., R. 1 W., contained 4,840 ppm of dissolved solids. The flow of the stream was very small, and the water was derived from springs or seeps.

The large variations in the quality of water in the Rio Puerco and its tributaries must affect significantly the quality of ground water in the aquifers that are recharged by infiltration of surface water in the valley of the Rio Puerco. The wide range in quality of water in the Ojo Alamo Sandstone in the vicinity of Cuba (table 11) reflects the variations in quality of the recharge water.

As saline recharge water moves underground, the concentration of dissolved minerals may increase, ions in the water may be exchanged for ions in the rocks, or, rarely, the water may remain unchanged. Water that moves from one stratigraphic unit to another improves or degrades the quality of water in the new host rock, depending partly on the relative quality of water in each unit.

The dissolved solids in ground water are commonly concentrated by evaporation from capillary openings and by transpiration of plants where the top of the zone of saturation is within a few feet of the land surface. Evapotranspiration probably has concentrated the dissolved solids in the shallow ground water at places in the valleys of all the major streams of the area.

Most of the samples of water collected in and near the southern part of the Jicarilla Reservation for chemical analysis were from the Ojo Alamo Sandstone and the San Jose Formation. One sample was from the Nacimiento Formation and several from of Quaternary age alluvium and gravel. The chemical character of most of the ground water is similar. The water is typically high in sodium relative to calcium and magnesium and generally high in bicarbonate and sulfate. (See table 11.) All of the samples of water from the Ojo Alamo Sandstone and the Nacimiento Formation and most of the samples from the San Jose Formation were collected from shallow wells (or springs) at places which are within a few miles of probable recharge areas. It is not known whether the quality of the water in these rocks is similar where the rocks are deeply buried in the interior of the central basin.

The quality, or the suitability, of water can be evaluated only on the basis of its intended use. The general suitability of ground water in the southern part of the Jicarilla Reservation for domestic, irrigation, and general industrial uses is summarized in the following paragraphs. This evaluation is based on 66 analyses of water from wells and springs that are listed in table 11. For more detailed descriptions of sources of soluble materials in natural water and water-quality criteria, the reader is referred to U.S.Geological Survey Water-Supply Paper 1473 (Hem, 1959), California State Water Pollution Control Board (1952) publication 3, and U.S. Public Health Service (1946) Drinking Water Standards.

Silica has little affect on the suitability of water for irrigation but silica in boiler water tends to form a hard scale. Concentrations of silica (7.6 to 39 ppm) in the 39 samples of ground water that were analyzed for silica are not high enough to warrant further discussion.

Iron in relatively low concentrations may impart an undesirable color and taste to water and will stain plumbing fixtures. The recommended upper limit of iron plus manganese in drinking water is 0.3 ppm (U.S. Public Health Service, 1946). The Geological Survey generally does not analyze water for manganese. The sampling and handling of water for accurate iron determinations requires special precautions, which commonly are not exercised in routine sampling. Iron, in a solid form, or steel may be incorporated in the water sample as pieces of scale from the pump and pipes or as iron minerals in fine particles of sediments. If, in making a determination of total iron in the sample, the iron introduced in the solid state is included, the value reported is not a true value of the iron content of the water. Upon exposure to the air some dissolved iron in a sample of ground water may be oxidized and precipitated. Precipitation of the iron can be avoided by acidifying the sample of water at the time it is collected. However, acidification may dissolve some of the iron from steel flakes or iron minerals that were collected with the sample. For these reasons, the laboratory determination of iron content in water is generally slightly inaccurate. The concentration of soluble iron in 20 samples analyzed ranged from 0.00 to 5.2 ppm. The total iron content was as high as 21 ppm (table 11). Eleven of the samples contained more than 0.3 ppm of iron.

Calcium and magnesium, which are similar elements, cause hardness in water and influence the suitability of water for household and some industrial uses because they contribute to the formation of boiler scale and deposits in water heaters. The recommended upper limit of magnesium in drinking water is 125 ppm (U.S. Public Health Service, 1946). Only one analysis shows concentrations of magnesium higher than this limit (well 21.1W.28.211, table 11). Drinking water which has high concentrations of magnesium along with sulfate is a mild to severe cathartic. Relatively high concentrations of calcium and magnesium can be beneficial in irrigation water, especially if the water is used on alkali soils. The concentrations of calcium and magnesium in the samples that were analyzed ranged from 1.6 to 548 ppm and 0.0 to 126 ppm, respectively (table 11). Most of the samples contained less than 100 ppm of calcium and less than 50 ppm of magnesium.

Sodium and potassium are similar elements, and commonly they are not separated in ordinary chemical analyses. Generally, the amount of potassium relative to sodium is negligible. Potassium is essential for vigorous growth of most plants, but excessive amounts of sodium cause alkali soils. A high ratio of sodium to calcium and magnesium in water makes it poor for irrigation use, because the sodium tends to form alkali soil, especially if the soil is poorly drained. A high concentration of sodium along with sulfate in drinking water is likely to have a laxative effect on persons unaccustomed to drinking the water. Concentrations of sodium and potassium generally found in natural waters have little effect on its industrial use. The concentration of these elements, reported as sodium in the samples of water that were analyzed, ranged from 3.0 to 7$\overset{4}{\cancel{5}}$5 ppm (table 11).

The concentration of bicarbonate in the waters that were sampled ranged from 29 to 888 ppm, but most samples contain 200 to 400 ppm. The carbonate concentrations as analyzed ranged from 0 to 53 ppm (table 11). Hardness due to calcium and magnesium equivalent to the bicarbonate and carbonate generally is referred to as carbonate or "temporary hardness." The temporary hardness can be removed by boiling the water or by adding lime. Excessive concentration of bicarbonate and sodium in irrigation water causes the accumulation of sodium carbonate (commonly termed "black alkali") in soils, especially if they are poorly drained.

The recommended limit of sulfate in drinking water is 250 ppm (U.S. Public Health Service, 1946). Only 16 of 46 samples that were analyzed contained less than 250 ppm of sulfate, and the range was from 6.2 to 2,440 ppm (table 11). Sulfate in conjunction with calcium and magnesium contributes to the formation of hard scale in steam boilers and increases the cost of softening the water. Because of the high concentrations of sulfate, much of the water in and near the southern part of the Jicarilla Reservation is to some degree undesirable for domestic and some industrial uses. Sulfate in the quantities found does not affect adversely the suitability of the water for irrigation.

The recommended limit for chloride in drinking water is 250 ppm (U.S. Public Health Service, 1946). The samples that were analyzed contained 1.0 to 486 ppm, but only one contained more than 250 ppm and only four contained more than 50 ppm. These concentrations are low enough that the water is acceptable for ordinary uses.

The desirable range for fluoride in drinking water is 0.5 to 1.5 ppm (U.S. Public Health Service, 1946; Dean, 1936). Concentrations of fluoride in the samples that were analyzed ranged from 0.1 to 4.0 ppm (table 11). The concentration was within the recommended limits for fluoride in 26 of the 44 samples that were analyzed and was above the recommended limit in only ~~6~~ six samples. Fluoride has little effect on the industrial or agricultural utility of water.

The suggested upper limit of nitrate in water that is used for infant feeding is 44 ppm (Hem, 1959, p. 239). The concentration of nitrate in the samples that were analyzed ranged from 0.0 to 70 ppm (table 11). However, the nitrate exceeded 44 ppm in only one sample (well 20.1W.6.432, table 11). Nitrate commonly is associated with bacterial contamination of water, so that a high concentration of nitrate in ground water indicates that a bacterial analysis of the water should be made.

Boron is essential to normal plant growth, but the quantities required are very small. The boron concentrations in the ~~7~~ seven samples that were analyzed (table 11) are below the maximum limit for even the most boron-sensitive crops (U.S. Salinity Laboratory Staff, 1954), and range from 0.04 to 0.07 ppm.

The recommended upper limit of dissolved solids in drinking water is 500 ppm, but when water of this quality is not available, water containing 1,000 ppm of solids is considered acceptable (U.S. Public Health Service, 1946). Many municipal and domestic water supplies in New Mexico contain more than 1,000 ppm of dissolved solids and apparently the water has no deleterious effects on the people who drink it. All but 4 of the 42 samples that were analyzed contained more than 500 ppm of dissolved solids and 19 of the samples contained more than 1,000 ppm (table 11). The concentration of dissolved solids ranged from 56 to 4,010 ppm. Waters containing dissolved solids in this range generally can be used for irrigation if the individual constituents and other factors affecting irrigation are favorable. In general industries which require large quantities of water need water having less than 1,000 ppm of dissolved solids.

Water having more than 250 ppm of hardness is unsatisfactory for many industrial uses, and it requires large amounts of soap in normal household use of the water. Hardness in domestic, municipal, and industrial supplies preferably should be less than 100 ppm. Suggested limits of boiler water range from 2 to 80 ppm, depending on the pressure (California State Water Pollution Control Board, 1952, p. 129). Hardness has little affect on the usability of water for irrigation. The hardness of waters that were sampled ranged from 4 to 1,860 ppm in 64 samples (table 11); the hardness of 24 samples exceeded 250 ppm. Hardness can be removed by cation-exchange softeners for small supplies and by lime and soda-ash treatment for large supplies.

The U.S. Department of Agriculture formerly classified water with respect to its usability for irrigation on the basis of the percent sodium and the total concentration as electrical conductivity (specific conductance) of the water. Percent sodium is the percentage ratio of the concentration of Na^+ to the sum of Ca^{++}, Mg^{++}, Na^+, and K^+, all expressed in milliequivalents per liter. The specific conductance of a water, which is a measure of its capacity to conduct an electric current, varies with the composition and salinity of a solution. Either a high percent sodium or high specific conductance may indicate a water of poor quality for irrigation. The percent sodium in the waters that were analyzed ranged from 7 to 99 and the specific conductance ranged from 287 to 4,490 micromhos.

The classificiation according to percent sodium is not wholly satisfactory because it does not directly measure the potentiality of sodium adsorption by the soil, sothe U.S. Department of Agriculture (U.S. Salinity Laboratory Staff, 1954, p. 79-81) introduced a system of classification based on the sodium-adsorption-ratio (SAR) and the conductivity (specific conductance).

The SAR is defined by the equation

$$SAR = Na^{+}/\sqrt{(Ca^{++} + Mg^{++})/2}$$

in which, Na^{+}, Ca^{++}, and Mg^{++} represent respective sodium, calcium, and magnesium concentrations in milliequivalents per liter. Because sodium and potassium commonly are reported together in Geological Survey analyses, the combined concentration of sodium and potassium is treated as sodium in calculating the SAR. The SAR may be plotted against conductivity on a standard diagram from which the sodium (alkali) and salinity hazard of the water is classified (U.S. Salinity Laboratory Staff, 1954, p. 79-81). The SAR classification of 37 samples is shown in figure ~~11~~ 9, and the analyses are summarized in table 12. The

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Figure ~~11~~ 9.--Classification of ground water in and near the southern part of the Jicarilla Apache Indian Reservation, N. Mex., for irrigation use.

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classificiation chart was designed for a maximum SAR of 32, and 8 of the samples had SAR of more than 32.

Much of the water in and near the southern part of the Jicarilla Reservation is undesirable for domestic use because of high concentrations of dissolved solids, commonly including high concentrations of sulfate. However, the concentration of sulfate and other dissolved solids is not so high as to classify it as impotable. Water containing more than 250 ppm of sulfate is likely to have a laxative effect for a short time on new users (California Water Pollution Control Board, 1952, p. 377-378). Nearly all the water is acceptable for livestock supply.

Table 12.--Summary of suitability of ground water in and near the southern part of Jicarilla Apache Indian Reservation, N. Mex., for irrigation.

Number of samples	Salinity class 1/	Sodium class 2/
4	C2	S1
11	C3	S1
5	C3	S2
2	C3	S3
15	C3	S4
3	C4	S2
3	C4	S4

1/ C2. Medium-salinity water, can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most cases without special practices for salinity control.

C3. High-salinity water, cannot be used on soils with restricted drainage. Special management for salinity control may be necessary. Plants with good salt tolerance should be selected.

C4. Very high-salinity water, not suitable for irrigation under ordinary conditions, but may be used occasionally under very special circumstances.

Table 12.--Summary of suitability of ground water -- Continued

2/ S1. Low-sodium water, can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium.

S2. Medium-sodium water, will present an appreciable sodium hazard in fine-textured soils having high cation-exchange capacity, especially under low leaching conditions, unless gypsum is present in the soil.

S3. High-sodium water, may produce harmful levels of exchangeable sodium in most soils and will require special soil management--good drainage, high leaching, and organic matter additions. Gypsiferous soils may not develop harmful levels of exchangeable sodium from such waters.

S4. Very high-sodium water, generally unsatisfactory for irrigation purposes except at low and perhaps medium salinity, where the solution of calcium from the soil or use of gypsum or other amendments may make the use of these waters feasible.

The excess of sodium relative to calcium and magnesium ~~of~~ in some of the shallow ground water in and near the southern part of the Jicarilla Reservation makes it ~~an~~ unsuitable ~~source of water~~ for irrigation, and special soil management probably would be necessary for successful production of irrigated crops with much of the water. All the variations in concentrations and kinds of dissolved constituents in water from different water-bearing beds at all places cannot be delineated from the data now available; however, some inferences can be made.

The quality of water in the deeply buried beds of sandstone, especially the thick beds in the San Jose and Nacimiento Formations and the Ojo Alamo Sandstone, probably does not differ greatly from that represented by the analyses in table 11 because the analyzed samples were collected from many different beds of sandstone in the San Jose Formation and from the Ojo Alamo Sandstone at widely separated places and from the various depths. The specific conductance of only 8 of 51 samples from the sandstone was more than 2,250 micromhos, the division between waters of "high salinity hazard" and "very high salinity hazard" (fig. ~~11~~ 9). Three of the 8 samples whose conductance exceeded 2,250 micromhos were from the Ojo Alamo Sandstone in the Rio Puerco Valley, where the recharge water is likely to be high in dissolved solids; 4 samples were from the Regina Member of the San Jose Formation, which consists predominantly of shale; and 1 sample was from the Tapicitos Member of the San Jose Formation, which also is predominantly shale. The concordance of the general upper limit of specific conductance of the 66 samples (table 11) from so many source beds suggests that the same range of conductance could be expected throughout the area, even where the beds are deeply buried.

Electric logs of wells in the interior of the basin show that the resistivity (conductivity is the reciprocal of resistivity) of the beds of sandstone and their contained water commonly is no higher at depths as great as 3,500 feet than at depths of less than 500 feet which is the zone generally penetrated by water wells. The spontaneous potential curves on the electric logs show that most of the beds of sandstone are porous, so that the resistivity probably is high because the water in the sandstone contains relatively low concentrations of dissolved solids. However, the quantity and kinds of dissolved solids cannot be determined from the electric logs.

Berry (1957, p. 8) reported that a sample of water obtained from the Ojo Alamo Sandstone at a depth of 2,249 to 2,300 feet by a drill stem test in the Humble Oil and Refining Co. No. J-5 Jicarilla well (25.5W.7.114) had a resistivity of 695 ohm-cm (equal to a specific conductance of 1,440 micromhos), and it contained 1,057 ppm (calculated) of dissolved solids. This analysis is within the range of those in table 11.

The mixture of water that would be obtained from a well that taps a large number of water-bearing beds might be suitable for agricultural use, even though the water from some beds is unsuitable (fig. 9 ~~11~~). Improvement could result from dilution of the unsuitable water with water of good quality. Improvement could result also from the combination of water having a high SAR value with water having a low SAR value if the salinities of both are satisfactorily low and approximately equivalent.

The requirements of water for industry are too diverse for simple appraisal. The ground water in and near the southern part of the Jicarilla Reservation is suitable for many types of industrial use, such as cooling water and oil-field flood water, but the water could be unsuitable or would require treatment for some industrial uses.

General availability of ground water

Almost all the Upper Cretaceous and Tertiary formations with which this report is concerned are clastic rocks. The rocks are layered in vertically alternating stratigraphic units of shale and sandstone; only the sandstone units are aquifers. The availability of ground water in the entire area cannot be described in general terms because of the variety of stratigraphic, structural, and physiographic features, all of which affect the occurrence of ground water. For this reason, the availability is discussed for each of the physiographic sectors.

The locations of most of the wells and springs inventoried are shown on figure ~~10~~ 9, and the physiographic sectors are delineated. Areas of outcrops of the geologic formations mentioned in the following discussion are shown on figure ~~5~~ 4. The subsurface distribution of rocks in parts of the area is shown on the correlation diagrams (figs. 5, 6, and 7 ~~6, 7, and 8~~).

Penistaja Cuestas

The Mesaverde Group, the Lewis Shale, the Pictured Cliffs S ndstone, the undivided Fruitland Formation and Kirtland Shale, the Ojo Alamo Sandstone, and the Nacimiento and San Jose Formations crop out in broad, arcuate, westward-trending bands in the Penistaja Cuestas sector (figs. ~~5~~ 4 and ~~10~~ 9). The rocks dip northeast, north, and northwest in the western, central, and eastern parts, respectively, of the sector, so that the depth to a formation increases generally to the north. The land surface rises irregularly, but generally to the north. Only the Mesaverde Group, the Ojo Alamo Sandstone, the San Jose Formation and the alluvium in valleys are considered to be potential sources of potable water in this sector.

Ground water probably could be obtained from sandstone in the upper and lower parts of the Meseverde Group which is 500-600 feet thick in the southeastern part of the area. The Mesaverde Group is at the surface in the southern and eastern parts of T. 20 N., R. 1W. However, it dips north and west, and the depth to the top of the Mesaverde is 1,000 feet or more in the valley of Senorito Creek and the Rio Puerco in T. 20 N., R. 1 W.

In the eastern parts of Tps. 20-21 N., R. 1 W. potable water probably could be obtained at a depth of 200 feet and less by drilling into the steeply dipping rocks of the Mesaverde Group at places where the major valleys cross its narrow outcrop belt. The Mesaverde dips steeply under the Lewis Shale and the depth to the top of the group is probably 800-1,000 feet just a few hundred feet west of the outcrop belt on Rito Leche and Nacimiento Creek, and 1,800-2,000 feet near Cuba.

The depth to the top of the Mesaverde Group is about 1,500 feet in T. 20 N., R. 5 W. The Mesaverde Group in that part of the area is about 1,700 feet thick, and nearly half of the interval consists of sandstone beds, some of which are almost 200 feet thick. The sandstones of the Mesaverde in this part of the area probably would yield large amounts of water to deep wells, but the quality of the water is not known. Where the Mesaverde is deeply buried it is likely to contain very saline water.

The Ojo Alamo Sandstone yields potable water to numerous wells and several springs (fig. ~~10~~ 4 and tables 7 and 8) on and near the outcrops of the formation in the Penistaja Cuestas. Analyses of water from well 20.2W.3.200 and from Ojo Encino (S20.5W.23.334) show that the water is potable and soft (table 11) in the southern parts of T. 20 N., Rs. 2-5 W., where the Ojo Alamo Sandstone ranges in thickness from 80-170 feet. Cottonwood trees growing where Penistaja Arroyo, Arroyo San Ysidro, and Arroyo Chiuilla cross the outcrop belt of the Ojo Alamo indicate shallow ground water in the sandy alluvium of the washes. This shallow water probably is discharged from the Ojo Alamo into the alluvium at the topographically lowest parts of the outcrop belt. It is doubtful that wells drilled into the Ojo Alamo on the higher parts of the cuestas in the southern part of T. 20 N., Rs. 2-5 W. would obtain more than small amounts of water because the discharge of water from the sandstone into the nearby washes tends to keep the sandstone mostly drained.

Domestic and stock wells near the northern margin of the outcrop belt of the Ojo Alamo Sandstone and in the outcrop belt of the Nacimiento Formation in T. 20 N., Rs. 2-4 W. obtain 2-20 gpm of water from the Ojo Alamo Sandstone (table 3). Additional supplies of potable water could be developed by drilling into the Ojo Alamo in the outcrop belt of the Nacimiento Formation. The Ojo Alamo dips to the north and northeast and the depth to the top of the sandstone increases from a few feet in the southern parts of T. 20 N., Rs. 2-5 W. to more than 1,000 feet in the southern parts of T. 21 N., Rs. 2-5 W. The Ojo Alamo is confined in the subsurface between relatively impermeable shales so that the water is under artesian pressure. Greater yields of water might be developed from the Ojo Alamo where it is at greater depth than where it is at or near the surface because the deep wells would permit large drawdown.

In the Penistaja Cuestas east of the Rio Puerco the Ojo Alamo Sandstone is 60-90 feet thick and it dips to the west and northwest and forms cuestas that slope toward the Rio Puerco. It is doubtful that the sandstone on the cuestas contains much ground water in Tps. 20 and 21 N. R. 1 W., except near the valley of the Rio Puerco. Wells that obtain water from the Ojo Alamo Sandstone near Cuba yield 14-30 gpm (table 3). These wells are mostly in the valley of the Rio Puerco, where the top of the Ojo Alamo lies at depths ranging from a few feet at the east side of the valley to 100-200 feet near the Rio Puerco. The depth to the top of the Ojo Alamo near the west side of the valley west of Cuba is probably 300-500 feet but farther south the depth is less, and the Ojo Alamo is at the surface in the channel of the Rio Puerco in sec. 7, T. 20 N., R. 1 W.

Additional supplies of potable water can be obtained from the Ojo Alamo Sandstone in the valley of the Rio Puerco west of its outcrops. However, the shallow ground water in the overlying alluvium may be organically contaminated, and some of this water may filter into the Ojo Alamo on the east side of the valley where the alluvium lies on the sandstone. The danger of obtaining possibly contaminated water from wells in this part of the area would be lessened by casing out the water in the alluvium. Most of the water obtained from the Ojo Alamo Sandstone near Cuba is potable, but it has an unpleasant taste, it is hard, and contains enough dissolved iron to damage plumbing fixtures (table 11).

The sandstones of the Cuba Mesa Member of the San Jose Formation yield amounts of water adequate for domestic and stock supplies from shallow depths in T. 21 N., Rs. 2-5 W. (table 5). The Cuba Mesa Member will yield less water to wells on the cuestas near the southern margin of the outcrop belt than to wells near the northern margin of the outcrop belt, or to wells in the outcrop area of the Regina Member (fig. ~~5~~ 4). Wells that penetrate all the sandstone will yield more water than wells that penetrate only the upper part. The Cuba Mesa Member is 200-220 feet thick west of T. 21 N., R. 2 W., and it is about 750 feet thick northwest of Mesa de Cuba.

~~The depth to~~ The top of the Cuba Mesa Member at places along the drainage divide at the northern boundary of the Penistaja Cuestas sector, is as much as 400 feet below the land surface, but at most places it is shallower. The lower part of the Regina Member contains several beds of coarse-grained sandstone which also will yield small amounts of water to wells at shallower depth than the Cuba Mesa Member in the northern and central parts of T. 21 N., Rs. 1-5 W.

The top of the Cuba Mesa Member in the valley of San Jose Creek west of La Jara is about 150-200 feet beneath the surface and the member is about 500 feet thick, including several thick tongues of shale of the Regina Member. Water wells have not been drilled through the Regina Member into the Cuba Mesa Member in the valley of San Jose Creek, except in and near its outcrop (fig. ~~5~~ 4). Shallow domestic and stock wells that obtain water from the Cuba Mesa Member northwest of Cuba yield 3-5 gpm. The water is potable, but it contains much dissolved iron.

Wells drilled as deep as 500 feet into the Regina Member near Regina did not obtain water. The Regina Member east of the Continental Divide is composed mainly of shale and contains very few beds of sandstone that might be aquifers. ## Near Regina, the Cuba Mesa Member is the largest potential source of water and is about 1,200 feet below the surface. Larger yields could be obtained from wells that penetrate all the beds of sandstone in the San Jose and Nacimiento Formations and the Ojo Alamo Sandstone near Regina. However, in most of the Penistaja Cuestas the Nacimiento Formation does not contain enough sandstone to be considered as a source of ground water.

Small supplies of water can be obtained from alluvium at depths of less than 100 feet in the valleys of all the major intermittent and perennial streams of the Penistaja Cuestas. The thickness of the alluvium at most places probably is less than 100 feet, but its thickness is difficult to estimate at any particular place because of the irregular topographic surface on which the alluvium was deposited. Wells are more likely to be successful near the present arroyos or stream channels. Most of the water from the alluvium is potable. However, many of the residents of Cuba report that the water in the alluvium in the Rio Puerco valley is not suitable for domestic use. The shallow ground water in the vicinity of Cuba may be polluted by organic matter.

Largo Plains

The San Jose Formation crops out in the Largo Plains and the Nacimiento Formation and the Ojo Alamo Sandstone are present in the subsurface. The rocks dip gently ~~[to the]~~ northeast, but the dip is so gentle as to be nearly imperceptible north of Canon Largo. All these formations are potential aquifers in parts of the Largo Plains, but at most places the Nacimiento Formation and the Ojo Alamo Sandstone are buried too deeply to be practical sources of small ground-water supplies. However, they would contribute significantly to the yield of deep wells which penetrate all the beds of sandstone to the base of the Ojo Alamo. The Ojo Alamo Sandstone is 80-160 feet thick, and is present in the subsurface of the Largo Plains at depths ranging from 1,400-1,500 feet at the south to about 2,400-2,600 feet at the northeast. No wells are known to obtain water from the Ojo Alamo in the Largo Plains.

The Nacimiento Formation is about 1,100 feet thick at the south, and almost 1,800 feet thick in the northern part of the Largo Plains. Near Otero Ranch the top of the Nacimiento Formation is 200 feet and less below the surface, but in the northern and eastern parts of the plains the top of the Nacimiento is 600-1,000 feet below the surface, depending on local topography. Most of the Nacimiento Formation consists of shale south of the latitude of Otero Ranch. However, farther north the Nacimiento contains thick beds of sandstone which are aquifers. Two wells of the El Paso Natural Gas Company obtain water from sandstone near the middle of the Nacimiento Formation in the SE$\frac{1}{4}$ sec. 18, T. 24 N., R. 5 W. The chemical quality of the water is acceptable for domestic use. One of the wells is 796 feet deep, and it yielded 42 gpm with a drawdown of 562 feet after 12 hours of pumping. The water is obtained from a sandstone between the depths of 765 and 785 feet.

Stock wells in the Largo Plains obtain water from thin sandstones interbedded in shale of the lower part of the Regina Member of the San Jose Formation and from sandstone of the underlying Cuba Mesa Member. These wells yield 2-10 gpm from depths of less than 300 feet. Small supplies of water could be developed almost anywhere in the Largo Plains from sandstones of the San Jose Formation at depths of 300 feet or less. The water is potable, although some of it has a slightly unpleasant taste. Deposits of white salts around wells and tanks are common.

The Cuba Mesa Member of the San Jose Formation is 200 feet or more thick and is the shallowest aquifer in which fairly large amounts of ground water are to be expected. The Cuba Mesa Member is at the surface in the western part of the Largo Plains, but the depth to the member increases toward the east and south. The top of the Cuba Mesa Member may be 300-400 feet below the surface at some of the mesas south of Canon Largo in T. 22 N., Rs. 4 and 5 W., but in the deeper washes and valleys it is 250 feet or less below the surface. Some of the sandstones of the lower part of the Regina Member, that are exposed on the low mesas south of Canon Largo, may contain small quantities of ground water at depths of 200 feet or less.

In the southeastern part of the Largo Plains the depth to the main part of the Cuba Mesa Member may be as much as 700 feet in part of T. 23 N., R. 3 W. However, in part of this township thick upper sandstone tongues of the Cuba Mesa Member are present in the Regina Member, and these sandstones would yield water to wells. The top of the upper tongue of the Cuba Mesa Member is about 300 feet below the valley of Canon Largo in sec. 10, T. 23 N., R. 3 W. The upper tongues of the Cuba Mesa Member are not present in the southwestern part of the township, but lenticular sandstones in the Regina Member probably contain water at depths of 200-300 feet. The top of the main part of the Cuba Mesa Member in the southwestern part of T. 23 N., R. 3 W. is about 590-700 feet below the surface. Wells that tap the Cuba Mesa Member in the southern and southeastern parts of the Largo Plains would yield 8-10 gpm and probably more.

Along the east side of the Largo Plains, the top of the Cuba Mesa Member is 400-600 feet below the surface at most places. Some of the wells obtaining water from the upper part of the Cuba Mesa Member east of Canon Largo yield 2-7 gpm. Deeper wells at these places would penetrate a thicker section of sandstone and would have greater yields. Water can be obtained at depths of 100-400 feet from beds of sandstone in the Regina Member in the eastern and northern parts of the plains, especially in T. 26 N., R. 5 W. and the northern part of T. 25 N., R. 5 W. where the lower part of the Regina Member contains several thick beds of sandstone interbedded in shale.

Water occurs at shallow depth in the alluvium of all ~~of~~ the major canyons. Part of the water probably filters into the alluvium from precipitation and from surface runoff. However, much of the water is discharged from sandstone beds of the San Jose Formation into the alluvium where the sandstones crop out in the valleys and canyons. At some of these places the water is close enough to the surface to be obtained in shallow bulldozed pits. The water in the alluvium probably is similar in chemical quality to the water in the San Jose Formation, but the shallow water in the alluvium may be more mineralized because of salts concentrated by evapotranspiration.

Tapicitos Plateau and Yeguas Mesas

The Tapicitos Plateau and Yeguas Mesas are formed of rocks of the San Jose Formation, which is the principal aquifer in these sectors. The rocks are nearly horizontal in much of the Tapicitos plateau, but they dip gently north in the southern part, and they dip gently west in the eastern part of the plateau and in the Yeguas Mesas. The Ojo Alamo Sandstone and the Nacimiento Formation extend throughout the sectors in the subsurface, but they are too deep to be considered as practical sources of small supplies of ground water. At most places they would contribute to the yield of deep wells. The Ojo Alamo Sandstone ranges in thickness from 150 feet to a little more than 200 feet, and the depth to the top of the sandstone ranges from about 2,450 feet in the northwestern part of T. 22 N., R. 2 W., to about 3,450 feet in the east-central part of T. 26 N., R. 3 W. The Nacimiento Formation ranges in thickness from about 1,000 feet in the southern part of the Tapicitos Plateau to 1,700-1,800 feet thick in the northern part of the plateau. The depth to the top of the Nacimiento Formation is 1,300-1,400 feet in the southern part of the plateau and 1,500-1,700 feet in the northern part. The Nacimiento Formation consists mainly of shale in the southern part of the plateau, but north of the central parts of T. 23 N., Rs. 1-3 W. this formation contains thick sandstone beds which would yield water to deep wells.

Wells obtain water from sandstones of the Llaves, Regina, and Tapicitos Members of the San Jose Formation in the Tapicitos Plateau and the Yeguas Mesas. The Cuba Mesa Member is present at the base of the formation but it has not been tapped by water wells in this part of the area. The yields of the wells in the San Jose Formation in the Tapicitos Plateau and Yeguas Mesas range from less than 1 to 45 gpm, and the water is obtained from depths of 111 to 753 feet. Most of the water is potable, but it contains relatively large amounts of sodium and sulfate (table 11). Small supplies of water probably could be obtained from beds of sandstone in the San Jose Formation at depths of less than 400 feet in most of the Tapicitos Plateau-Yeguas Mesas region.

South of the latitude of Lindrith the high mesas of the Tapicitos Plateau are capped by thick lenticular beds of sandstone with interbedded shale in the upper part of the Regina Member. Only two wells are known to obtain water from these sandstones. Well 23.3W.11.333 is 153 feet deep, and it yields 7 gpm. The zone of thick sandstones persists ~~to~~ ~~the~~ eastward as far as the Continental Divide. Additional small supplies could be obtained at depths of 250 feet or less from these sandstones.

Thick lenticular sandstones in the upper part of the Regina Member yield small supplies of potable water to domestic and stock wells from depths of 100 to 275 feet in the upper valley of Canada Larga south of Lindrith and in the hills east and southeast of Lindrith. Yields range from less than 1 gpm to 8 gpm. Additional water for stock and domestic supplies could be obtained in most of this area, probably at depths of 300 feet or less. Larger supplies could be obtained from deep wells, particularly those which would tap sandstone beds in the lower part of the Regina Member and the Cuba Mesa Member. The top of the lower zone of sandstone in the Regina Member is about 500 feet below the surface in Canada Larga near Lindrith, and is 200-300 feet deeper in areas to the east and southeast. The Cuba Mesa Member is about 200 feet thick, and is about 1,100 feet below the surface in Canada Larga south of Lindrith.

The municipal supply well of the Lindrith Mutual Water Users Association (24.2W.15.244) is about 753 feet deep, and it obtains water from a sandstone tongue of the Llaves Member enclosed in the Regina Member. North and northeast of Lindrith the upper part of the Regina Member consists mainly of shale, and at most places between Oso Canyon and Canada Jaques the depth to water is 300-500 feet. Thick beds of sandstone are present in the lower part of the Regina Member at depths of 800-1,000 feet in this part of the plateau.

In the northern part of the Tapicitos Plateau, north of Oso Canyon, wells obtain water for domestic and stock supplies from the San Jose Formation at depths of 50-510 feet. Additional supplies can be obtained at most places at depths of 300 feet or less. The reported yields of wells range from less than 1 gpm to about 45 gpm. The yield of most wells in this part of the plateau is probably about 2-5 gpm.

The Cuba Mesa Member of the San Jose Formation has not been tapped by water wells in the northern part of the Tapicitos Plateau. The member is 250-350 feet thick and consists mainly of sandstones which probably are good aquifers. The depth to the top of the Cuba Mesa Member ranges from 600-800 feet in the canyons of the northwestern part of the plateau to 1,000-1,500 feet in the north-central and northeastern parts.

The upper part of the Regina Member contains a few beds of sandstone which yield small amounts of water to wells in the northern part of the plateau. The lower part of the Regina Member contains thick sandstone tongues of the lower part of the Llaves Member which would yield larger amounts of water to wells 700-1,000 feet deep.

The persistent medial sandstone of the Llaves Member is present in the subsurface throughout the northern part of the plateau. The sandstone is as much as 100 feet thick at places and it yields relatively large amounts of water compared to other sandstone beds tapped by wells in this part of the area. A well at Ojitos (25.3W.1.240a) yields 25-30 gpm from the medial sandstone at a depth of 302 feet. Another well in the upper part of Canon Ojitos (26.2W.34.421) yeilds 45 gpm from the medial sandstone at a depth of about 400 feet. Other wells that obtain water from the medial sandstone yield 1-10 gpm. The water from the medial sandstone unit of the Llaves Member is reported to be more suitable for domestic use than water from the overlying Tapicitos Member. The depth to the medial sandstone of the Llaves Member ranges from less than 100 feet in the deeper valleys of the northwestern part of the plateau to 400-500 feet on the mesas in the northeastern part of the plateau. In most of Tps. 25 and 26 N., Rs. 1-3 N., the lower part of the Llaves Member and the underlying Cuba Mesa Member consist mainly of sandstone that would yield large amounts of water to wells 1,000-1,800 feet deep.

The lenticular sandstone beds of the Tapicitos Member yield water at depths ranging from 50-260 feet. The water contains much sodium and sulfate and the owners of some wells do not consider the water to be suitable for domestic use. In the northeastern part of the plateau the Tapicitos Member contains thick sandstone tongues of the Llaves Member and water can be obtained from these sandstones at depths of 300 feet or less. Wells are reported to yield 2-10 gpm from the sandstone tongues.

In the Yeguas Mesas sufficient amounts of water for domestic and stock supplies can be obtained at depths of 250 feet or less at most places. It is likely that the sandstones of the Llaves and Cuba Mesa Members would yield relatively large amounts of water to wells drilled to depths of several hundred feet in the deeper canyons. The water is soft and potable. Relatively large supplies of water could be obtained from deep wells that penetrate all the beds of sandstone to the base of the Ojo Alamo Sandstone throughout the sector.

Water occurs in sandy alluvium in all the major valleys at depths of 50 feet or less at most places in the Tapicitos Plateau and Yeguas Mesas. However, the alluvium may be too thin or too deeply entrenched by arroyos to contain water in the upper parts of some of the canyons. At these places water probably can be obtained by drilling into the underlying bedrock, and at most places the depth to water is 250 feet or less.

San Pedro Foothills

Rocks of the Mesaverde Group, the Lewis Shale, the undivided Fruitland Formation and Kirtland Shale, the Ojo Alamo Sandstone, the Nacimiento Formation and the lower part of the San Jose Formation are tilted steeply and crop out discontinuously at the foot of ~~the~~ San Pedro Mountain in the eastern part of the sector. The upper part of the San Jose dips gently west and crops out in most of the western two-thirds of the sector. Gravel of Tertiary~~(?)~~ and Quaternary Age caps high terraces and occurs in the upper valleys of some streams and alluvium occurs in the valleys of all major streams. The Mesaverde Group, the Ojo Alamo Sandstone, parts of the Nacimiento and San Jose Formations, and terrace gravels and valley alluvium are potential aquifers in the sector.

Potable water probably could be obtained at shallow depths from steeply tilted sandstone beds of the Mesaverde Group, Ojo Alamo Sandstone, and Cuba Mesa Member of the San Jose Formation by drilling where the deep canyons cross the outcrop belts of these formations in the eastern part of the sector (figs. 5 and 10). North of La Jara Creek the Nacimiento Formation also contains several thick beds of sandstone which may be aquifers. Because these rock dip steeply they are buried deeply just a short distance west of their outcrop belts. In the western part of the sector the top of the Mesaverde Group is 3,700-4,000 feet below the surface; the top of the Ojo Alamo is 1,500-2,000 feet; and the top of the Nacimiento Formation is 700-1,000 feet below the surface. The Mesaverde Group, Ojo Alamo Sandstone, and Nacimiento Formation have not been ~~drilledd~~ utilized as sources of water in the San Pedro Foothills but they would yield relatively large amounts of water to deep wells drilled west of their outcrop belts. The water in the Mesaverde Group may be highly mineralized where it is deeply buried west of its outcrop belt, and the Ojo Alamo Sandstone is the deepest aquifer which is likely to contain potable water in the subsurface of the central and western parts of the foothills sector.

The San Jose Formation yields potable water to a few domestic and stock wells in the San Pedro Foothills. These wells obtain water at depths ranging from 40-300 feet from coarse-grained sandstone beds in the Regina Member near La Jara (table 7). Additional small supplies of water could be obtained from these lenticular sandstone beds at depths of 200-300 feet, or a little less, in most of the southern part of the San Pedro Foothills. However, in the northern part of the San Pedro Foothills near Regina no permeable sandstones were found in dry holes (23.1W.33.112) that were drilled as deep as 345 feet in the Regina Member. Electric logs of wells west of Regina indicate that only a few thin beds of permeable sandstone occur in the Regina Member, which is more than 1,200 feet thick in this part of the area.

The Cuba Mesa Member is the shallowest bedrock aquifer from which fairly large amounts of water could be obtained in most of the San Pedro Foothills. The Cuba Mesa Member consists mainly of sandstone and is 150-200 feet thick at outcrops in the eastern part of the sector and 400-500 feet thick in the subsurface of the western part of the sector. The top of the Cuba Mesa Member just west of its outcrop belt is 500-700 feet below the surface, and at the western margin of the San Pedro Foothills sector near Regina the top of the member is about 1,100 feet below the surface. Farther south it is shallower. In the San Pedro Foothills the Cuba Mesa Member has been utilized as a source of water only near its outcrops on Rito de los Pinos.

The high-level deposit of terrace gravel~~s~~ at the foot of San Pedro Mountain in secs. 2 and 11, T. 21 N., R. 1 W. may contain a small quantity of ground water as indicated by seeps at its western margin, but the other high-level deposits probably do not.

The lower deposits of terrace gravel and gravelly alluvium in stream channels in the eastern part of the sector (figs. 5 and 10) yield water to wells and springs at places in the San Pedro Foothills. Additional supplies could be obtained at depths of 50 feet or less by wells drilled into the gravel~~s~~ in the topographically lower parts of the upper valleys of Rito de los Pinos, La Jara Creek, and San Jose Creek.

The water supply for the town of Cuba is collected from springs and seeps which issue from a large erosional remnant of stream-channel gravel that caps the mesa called Vallecito del Rio Puerco in the southern half of sec. 14, T. 21 N., R. 1 W. These springs are on the south side of the mesa. Other springs and seeps occur on the mesa, and at the west and north sides of the mesa. Most of the springs and seeps are not being utilized, or are only partly utilized. Additional small supplies could be developed at depths of less than 50 feet by drilling into the gravel on the mesa. The water body in the gravel is perched on shale beds and receives recharge from precipitation and from infiltration of some of the surface flow of the upper part of the Rio Puerco just east of the mapped area.

Several domestic and stock wells obtain water from alluvium in the valleys in the San Pedro Foothills. Most of the wells are less than 50 feet deep. Water is most likely to occur where the alluvium is thickest and where it is not deeply trenched by arroyos. In general, wells drilled near the present streams and arroyos are most likely to obtain water from the alluvium.

Northern Hogback Belt

The Mesaverde Group, the Lewis Shale, the undivided Fruitland Formation and Kirtland Shale, the Ojo Alamo Sandstone, the Nacimiento Formation, and the lower part of the San Jose Formation crop out in a belt of westward-dipping rocks in the Northern Hogback Belt (figs. ~~8~~ 4 and ~~10~~ 9). The upper part of the San Jose Formation dips gently west~~ward~~. Outcrops of these rocks are separated by the broad alluviated valleys of intermittent streams draining eastward. The Mesaverde Group, the Ojo Alamo Sandstone, parts of the Fruitland Formation and Kirtland ~~Formations~~ Shale, parts of the Nacimiento and San Jose Formations, and valley alluvium are potential aquifers in the sector.

Wells could obtain supplies of potable water for domestic and stock use at depths of 200 feet or less from the Mesaverde Group and the Ojo Alamo Sandstone in the eastern part of the sector, where their outcrop belts are crossed by streams (figs. ~~8~~ 4 and ~~10~~ 9). Water probably could be obtained from these rocks in the interstream areas, also, but the wells would have to be drilled a short distance west of the outcrops in order to intercept the westward-dipping rocks where they are below the water table. Wells drilled for oil and gas in the Northern Hogback Belt tapped highly saline water at shallow depth in the Mesaverde Group a short distance west of its outcrop belt, indicating that the Mesaverde may not have been flushed to a very great depth by infiltrating meteoric water. Data are not adequate to predict the depth to which the saline water may have been flushed. In the western part of the Northern Hogback Belt the Mesaverde Group is buried deeply and is not a source of potable ground water.

North of sec. 20, T. 24 N., R.1 E., the undivided Fruitland Formation and Kirtland Shale dip steeply west and contain a unit of fine- to coarse-grained sandstone as much as 70 feet thick at places. Wells drilled west of the outcrop belt of the Fruitland and Kirtland probably would intercept the sandstone below the water table and it might yield sufficient amounts of water for domestic and livestock use. No wells are known to have obtained potable water from this sandstone. In the western part of the Northern Hogback Belt the undivided Fruitland Formation and Kirtland Shale are more than 2,500 feet below the surface and at places contain mineralized water and natural gas. The Ojo Alamo Sandstone is 100-200 feet thick and probably contains large amounts of water under artesian pressure in the subsurface of the western part of the Northern Hogback Belt south of T. 25 N., but the top of the sandstone is 2,200-3,000 feet below the surface, depending on local topography. North of Canoncito de las Yeguas well 25.1E.17.234 (table 7) yields 5-6 gpm of water from coarse sand and gravel between 85 and 100 feet below the surface. This sand and gravel is probably the Ojo Alamo Sandstone which is covered by alluvium in a small valley. Additional supplies probably could be obtained north of Canoncito de las Yeguas by wells drilled one-quarter of a mile or less west of the outcrop of the Ojo Alamo Sandstone. These wells would intercept the sandstone at depths ranging from a few feet near the outcrop to depths of 200-500 feet a little farther west. The thick unit of sandstone probably would yield moderate amounts of water under artesian pressure.

No ¶ Water moves from the Ojo Alamo Sandstone into overlying alluvium north of Canoncito de las Yeguas in T. 25 N., R. 1 E. and feeds Mud Spring (S26.1E.17.333, table 8) and other seeps. Chupadera Spring (S26.1E.33.314) discharges water directly from the Ojo Alamo. The water from the springs and well 25.1E.17.234 is potable and only moderately hard.

The Nacimiento Formation has not been utilized as a source of water south of Canoncito de las Yeguas. Wells 23.1W.22.222 and 23.1W.22.411 (table 7) in the southern part of the sector were drilled to depths of 328 and 330 feet respectively, and were bottomed in hard sandstone of the lower part of the Nacimiento Formation without obtaining water. The sandstones are fine- to medium-grained, and they appear to be tightly cemented. Farther north, several dry holes, ranging in depth from 40 to 241 feet, were drilled in coarse-grained sandstones in the upper part of the Nacimiento. However, these holes were on well-drained hills where the possibility of local recharge is small, and the wells apparently did not reach the water table.

The only well known to obtain water from the Nacimiento Formation in the Northern Hogback Belt is in the valley north of the mouth of Canoncito de las Yeguas. This well (25.1E.17.314, table 7) is 117 feet deep and bottomed in sandstone. The well yields less than $\frac{1}{2}$ gpm of potable water. Water probably could be obtained at depths of 200 feet or less from sandstone beds of the Nacimiento Formation in the topographically lower parts of the broad valleys crossing its outcrop in the Northern Hogback Belt (figs. ~~8~~ 4 and ~~10~~ 9).

The San Jose Formation crops out in the western part of the Northern Hogback Belt from Canoncito de las Yeguas south. Rocks of the San Jose Formation dip steeply west~~ward~~ in the eastern part of their outcrop belt, but the San Jose dips gently west~~ward~~ in most of the sector.

Well 24.1E. 6.344 (table 7) is 98 feet deep, and it yields 12 gpm of potable water from the basal sandstone of the Cuba Mesa Member. Additional supplies could be obtained from the Cuba Mesa Member from depths of 100-500 feet a short distance, west of its outcrops at most places in the Northern Hogback Belt. Wells drilled into the Cuba Mesa Member where it is overlain by alluvium in the major valleys would also yield adequate supplies of water for domestic and stock use. The depth to the Cuba Mesa Member becomes greater to the west, and in the upper drainages of Arroyo Blanco and Almagre Arroyo the top of the member is 800 to 1,200 feet below the surface.

Lenticular sandstone in the lower part of the Regina Member yields water to three wells in the sector. Well 24.1E.18.333 (table 7)* yielded only a small amount of water from a depth of 80 feet. The water was reported to be too saline for domestic or livestock use, and the well was abandoned. Well 24.1E.19.111 yields water suitable for domestic use from a depth of 95 feet. Well 24.1W.1.433 (table 7) yields 1 gpm from a depth of 140 feet. Well 23.1W.3.414 (table 7) which was drilled to a depth of 734 feet in the Regina Member, yielded less than $\frac{1}{4}$ gpm from a sandstone between the depths of 520 and 524 feet. A few other wells that were drilled in the Regina Member were dry.

Alluvium in the major valleys and in some of the smaller valleys yields potable water to several wells at depths of 4 to 50 feet (tables 6 and 7). Additional supplies adequate for domestic and stock use can be obtained from the alluvium at many places. Water is most likely to be obtained where the alluvium is thickest near the present stream channels in the topographically low parts of the valleys.

In most of the western part of the Northern Hogback Belt, if water is not obtained in alluvium in the valleys, the only reliable source of water to be expected is in the Cuba Mesa Member at depths ranging from a few feet at the eastern margin of the outcrop belt of the Regina Member to 1,100-1,200 feet in the western part of the sector. Relatively large supplies of water could be obtained from deep wells that penetrate all the beds of sandstone to the base of the Ojo Alamo Sandstone in the western part of the sector.

Potential yield of deep wells

The potential yield of deep wells in the southern part of the Jicarilla Reservation would depend largely on the cumulative thickness of beds of water-bearing sandstone that would be penetrated, because the specific capacity (yield in gallons per minute per foot of drawdown) of a well is largely a function of the permeability and the thickness of water-bearing material that the well penetrates. All the water wells in the region are shallow and none tap all the beds of sandstone to the base of the Ojo Alamo Sandstone, except where the Ojo Alamo is shallow. Accordingly, the potential yield of deep wells can only be estimated. For comparison, data are presented on the yields of similar sandstone aquifers in another part of the San Juan Basin.

Deep wells at Gallup, N. Mex., tap beds of sandstone which are somewhat similar to those in the Jicarilla Reservation. The cumulative thickness of the sandstone beds at Gallup is 500 feet. The wells yield an average of about 250 gpm with a drawdown of 500 feet, and have a specific capacity of about 0.5 gpm per foot of drawdown. In terms of unit measure, the average specific capacity is 0.001 gpm per foot of sandstone (West, 1961, p. 9). Data on 49 other wells which obtain water from similar beds of sandstone in the San Juan Basin, indicate that the average specific capacity per foot of sandstone may be in the same order of magnitude. The apparent range is 0.0002 to 0.009.

The Ojo Alamo Sandstone and many beds of sandstone in the Nacimiento and San Jose Formations are coarser textured, and less cemented than many of the older sandstone units in the San Juan Basin, so that the Ojo Alamo and younger formations should be better aquifers than many of the older formations. The specific capacity per foot of sandstone penetrated was determined for 8 wells that tap the Ojo Alamo and younger formations in or near the Jicarilla Reservation. The specific capacity ~~yields~~ of these wells ranged from 0.002 (well 24.5W.18.421a) to 0.015 (well 26.7W.15.412) gpm per foot of water-bearing sandstone penetrated; the average was 0.008.

The range of 0.0002 to 0.015 gpm per foot of drawdown per foot of sandstone penetrated is used in the following hypothetical example to illustrate a method of estimating the probable range in yields from a unit of ~~stratigraphic section containing beds of~~ sandstone, if the specific capacity per foot of sandstone penetrated and the cumulative thickness of sandstone are known. Assuming that the total thickness of the beds of sandstone is 500 feet and assuming that a drawdown of 300 feet could be tolerated, the yield of a well tapping all the sandstone beds could range from 30 to 2,250 gpm (.0002 X 500 X 300 and .015 X 500 X 300). The average value of 0.008 gpm per foot of drawdown per foot of sandstone penetrated would indicate a possible average yield of 1,200 gpm (.008 X 500 X 300) under the conditions specified above. The average yield of 0.008 gpm per foot of drawdown per foot of sandstone penetrated probably is a little more than could be sustained during long periods of pumping because the specific capacity of wells generally is determined from short periods of pumping, which may sample the aquifer only in a relatively short distance from the well.

Many of the beds of sandstone in the Nacimiento and San Jose Formations are discontinuous, or they vary markedly in thickness. Some of the beds of sandstone are certain to thin and wedge out in some direction from any well (figs. 5, 6, and 7 ~~6, 7, 8~~), causing a decrease in transmissibility away from the well. This condition~~s~~ would cause an eventual increase in drawdown in a pumped well. However, this effect probably would be offset in part by the greater thickness~~,~~ and the higher transmissibility of the beds of sandstone in the directions opposite to those of thinning. The lenses of sandstone that are enclosed completely in shale would be dewatered eventually, except that slow vertical leakage from the enclosing shale would continue to supply a little water. A drawdown of 300 feet at most places would gradually dewater the beds of sandstone in the interval of drawdown, and the cessation of contribution from these beds would cause the yield to decrease or cause the drawdown to increase. The extent to which the yield would decrease would depend largely on the thickness of dewatered sandstone.

The above-described method of estimating the potential yield of deep wells in the southern part of the Jicarilla Reservation ~~could~~ might give results that are considerably in error. Certainly, the ratio of specific capacity to thickness of water-bearing sandstone penetrated would vary greatly from one unit to another. The largest departure from the average specific capacity per foot of sandstone penetrated would be expected of wells that penetrate only a few beds of sandstone, because the method of estimation is based on the average of the specific capacities of many beds. Despite the limited data, the method of relating average specific capacity to the total thickness of sandstone penetrated seems to be the best means of estimating the potential yield of untested formations in the Jicarilla Reservation.

The Bureau of Indian Affairs suggested four tracts of land in the southern part of the reservation as being suitable for irrigation, and the Jicarilla Tribe requested an evaluation to determine the tract which seems to have the greatest potential for ground-water production. The general locations of these tracts are: (1) the northwestern part of T. 22 N., R. 3 W.; (2) the vicinity of the northwest corner of T. 23 N., R. 4 W.; (3) adjacent to Lapis Canyon in T. 25 N., R. 5 W.; and (4) in the northern part of T. 22 N., R. 5 W.

The three diagrams showing the correlations of rock units (figs. 5, 6, and 7 ~~6, 7, and 8~~) were drawn along lines through or near each of the tracts in directions that best portray the changes in rock facies. The cumulative thickness of the sandstone units was computed from the control points (wells) of the diagrams and can be interpolated to some extent between the control points. A depth of 200 feet (the assumed average depth to the top of the zone of ground-water saturation) below the land surface was chosen arbitrarily as the upper cutoff point for computing the thickness of saturated sandstone at all places. If the well was not logged to within 200 feet of the surface, the probable thicknesses of the upper beds of sandstone were estimated from logs of adjacent wells. The well nearest each of the tracts was selected as a key well to show the thickness of sandstone in each; the thickness of sandstone at other places along the lines can be compared easily with that at the key wells (figs. 5, 6, and 7 ~~6, 7, 8~~).

The stratigraphic units that were penetrated by the Reynolds Mining Co. No. 1 Jicarilla D well (23.3W.33.114) (fig. ~~8~~ 7) should be representative of those in and adjoining the northwestern part of T. 22 N., R. 3 W. This well penetrated 940 feet of sandstone above the base of the Ojo Alamo Sandstone at a depth of 2,670 feet, including 300 feet of sandstone above the base of the San Jose Formation at a depth of 1,260 feet.

The stratigraphic units that were penetrated by the Skelly Oil Co. No. 1 Jicarilla D well (23.4W.6.332) (fig. ~~6~~ 5) should be representative of those in the vicinity of the northwest corner of T. 23 N., R. 4 W. This well penetrated 660 feet of sandstone above the base of the Ojo Alamo Sandstone at a depth of 2,330 feet, including 140 feet of sandstone above the base of the San Jose Formation at a depth of 500 feet.

The stratigraphic units that were penetrated by the Amerada Petroleum Corp. No. 5 Jicarilla A well (25.5W.25.441) (fig. ~~8~~ 7) are approximately representative of those along Lapis Canyon in T. 25 N., R. 5 W., except that this well was drilled on higher ground than that in Lapis Canyon. This well penetrated 1,470 feet of sandstone above the base of the Ojo Alamo Sandstone at a depth of 2,740 feet, including 600 feet of sandstone above the base of the San Jose Formation at a depth of 1,110 feet.

The stratigraphic units that were penetrated by the Humble Oil and Refining Co. No. 1 Jicarilla B well (22.5W.1.223) (fig. ~~6~~ 5) are approximately the same units that would be penetrated by a well in the northern part of T. 22 N., R. 5 W. However, the units would be reached at progressively shallower depths southwestward from well 22.5W.1.223. Some of the shallower beds of sandstone that were penetrated by well 22.5W.1.223 crop out a few miles to the southwest. This well penetrated 430 feet of sandstone above the base of the Ojo Alamo Sandstone at a depth of 1,590 feet. The well penetrated 40 feet of sandstone between the arbitrarily assumed depth (200 feet) to the top of the zone of saturation and the base of the San Jose Formation at a depth of 240 feet. Several of the beds of sandstone of the Nacimiento Formation that were penetrated by well 22.5W.1.223 are thin, and they may have low permeabilities owing to high silt and clay content. Furthermore, the San Jose Formation is thin in T. 22 N., R. 5 W., and most of the sandstone beds of the San Jose are above the zone of saturation.

The largest yield and the highest specific capacity of a deep well would be expected at places where the greatest thickness of water-bearing sandstone could be tapped. However, the ratio of the thickness of sandstone to the depth of penetration should be considered also, because the depth of drilling that would be required to penetrate a certain thickness of sandstone varies widely. The most favorable places for obtaining the largest yields with the least amount of drilling are those where the thickness of sandstone is great and the ratio of the thickness of sandstone to the depth to a certain horizon is high. All the ratios that are used in this report are based on the thickness of sandstone below a depth of 200 feet (the assumed average depth to the top of the zone of ground-water saturation) and the depth of the bases of the Ojo Alamo Sandstone and the San Jose Formation below the land surface. These ratios are shown in figures ~~6~~ 5, ~~7~~ 6, and ~~8~~ 7.

The ratio of the thickness of sandstone penetrated to the depth to stratigraphic horizons indicated is derived below for a representative well in each tract which was suggested as suitable for irrigation by the Bureau of Indian Affairs.

Tract 1.--Northwestern part of T. 22 N., R. 3 W.
(Well Reynolds 1 Jicarilla D)

$$\frac{\text{Thickness of sandstone (feet)}}{\text{Depth to base of Ojo Alamo Sandstone (feet)}} = \frac{940}{2{,}670} = 0.35$$

$$\frac{\text{Thickness of sandstone (feet)}}{\text{Depth to base of San Jose Formation (feet)}} = \frac{360}{1{,}260} = 0.29$$

Tract 2.--In the vicinity of the northwest corner of T. 23 N., R. 4 W.
(Well Skelly Oil Co. No. 1 Jicarilla D)

$$\frac{\text{Thickness of sandstone (feet)}}{\text{Depth to base of Ojo Alamo Sandstone (feet)}} = \frac{660}{2{,}130} = 0.31$$

$$\frac{\text{Thickness of sandstone (feet)}}{\text{Depth to base of San Jose Formation (feet)}} = \frac{140}{500} = 0.28$$

Tract 3.--Adjacent to Lapis Canyon in T. 25 N., R. 5 W.
(Well Amerada Petroleum Corp. No. 5 Jicarilla A)

$$\frac{\text{Thickness of sandstone (feet)}}{\text{Depth to base of Ojo Alamo Sandstone (feet)}} = \frac{1{,}470}{2{,}740} = 0.54$$

$$\frac{\text{Thickness of sandstone (feet)}}{\text{Depth to base of San Jose Formation (feet)}} = \frac{600}{1{,}110} = 0.54$$

Tract 4.--The northern part of T. 22 N., R. 5 W.
(Well Humble Oil and Refining Co. No. 1 Jicarilla B)

$$\frac{\text{Thickness of sandstone (feet)}}{\text{Depth to base of Ojo Alamo Sandstone (feet)}} = \frac{430}{1{,}590} = 0.27$$

Most of the San Jose Formation has been removed from tract 4 by erosion or it is above the zone of saturation.

The thickness of sandstone penetrated and the ratio of the thickness of sandstone to the depth to the base of the Ojo Alamo Sandstone and the San Jose Formation [~~and thus the potential yield of water~~] are highest in area 3 adjacent to Lapis Canyon in T. 25 N., R. 5 W. From the above data, the potential ground-water supply seems better along Lapis Canyon in T. 25 N., R. 5 W. than in any of the other tracts, or even in any other part of the southern half of the reservation. The ratio of thickness of sandstone to the depth to the base of the San Jose is the same as the ratio of thickness of sandstone to the depth to the base of the Ojo Alamo. A shallow well, however, would not draw on the reservoir that is represented by the 870 feet of sandstone between the base of the San Jose Formation and the base of the Ojo Alamo Sandstone. For this reason, a test well drilled to the base of the Ojo Alamo Sandstone would be more desirable than one that stops at the base of the San Jose Formation. The deep well would furnish the best data for planning additional wells and would indicate whether shallow or deep wells would be more practicable. The specific capacity of any well probably could be improved by hydraulic fracturing of the aquifers.

If the minimum specific capacity per foot of sandstone penetrated (0.002) that was determined in the area could be applied to the Lapis Canyon tract in T. 25 N., R. 5 W., and if 300 feet of drawdown could be tolerated, the yield of a well that tapped all the beds of sandstone to the base of the San Jose Formation would be 360 gpm (0.002 x 600 x 300) and the yield of a well that tapped all the beds of sandstone to the base of the Ojo Alamo Sandstone would be 880 gpm (0.002 x 1,470 x 300). If the average specific capacity per foot of sandstone penetrated (0.008) that was determined in the area could be applied to the Lapis Canyon tract, and if 300 feet of drawdown could be tolerated, the yield of a well that tapped all the beds of sandstone to the base of the San Jose Formation would be 1,460 gpm (0.008 x 609 x 300) and the yield of a well that tapped all the beds of sandstone to the base of the Ojo Alamo Sandstone would be 3,530 gpm (0.008 x 1,470 x 300). The actual yield probably would be something between the values computed above.

Greater pumping lifts for irrigation probably could be tolerated on the Jicarilla Reservation, because natural gas for power would be available at little or no cost to the Tribe.

Summary and Conclusions

The rocks of latest Cretaceous and Tertiary age in the southern part of the Jicarilla Apache Reservation contain beds of sandstone that yield small amounts of water to wells from depths of 300 feet and less in most of the area. Thick units of sandstone are present at the surface and in the subsurface. However, many of the thick units of sandstone are not distributed uniformly, and their variations in thickness and distribution would cause differences in the yields of deep wells drilled at different places in the area. The present investigation of the surface and subsurface stratigraphy of the area provided data to determine the general distribution and thickness of each of the major units of sandstone which is an aquifer or potential aquifer.

The stratigraphically lowest potential aquifer except in a few localities, is the Ojo Alamo Sandstone, which is present throughout the area. The Ojo Alamo ranges in thickness from 70 feet in the southern part of the area to a little more than 200 feet in the northern part. The Nacimiento Formation, which rests on the Ojo Alamo, ranges in thickness from 700 feet at the south to 1,700 feet at the north. In the southern part of the area the Nacimiento consists mainly of shale; however, in the northern part of the area the Nacimiento contains thick beds of sandstone which might yield relatively large amounts of water to deep wells. The Nacimiento Formation is overlain by the San Jose Formation which consists of several units of shale and sandstone. The Cuba Mesa Member of the San Jose Formation is present throughout most of the area. It consists mainly of sandstone and it is about 200 feet thick in much of the area, as much as 782 feet thick in the southeastern part of the area, and 300-350 feet thick in the northern part. The Llaves Member of the San Jose Formation consists mostly of sandstone and ranges in thickness from 300 to 1,300 feet; however, the Llaves Member is restricted almost entirely to the northern part of the area. The Regina and Tapicitos Members of the San Jose Formation are mainly shale, but they contain thick beds of sandstone at places, and some of these sandstone beds might contribute large amounts of water to deep wells.

Gravel and alluvium of late Tertiary and Quaternary age are lc important locally as sources of water for domestic and stock supplies, but these sediments would not yield sufficient amounts of water for large-scale irrigation and industrial use.

The principal sources of ground-water recharge are precipitation and streamflow on outcrops of the aquifers; vertical leakage of water from one bed of sandstone to another also is a form of recharge to the one receiving the water. Most of the recharge in the area is in the eastern and southern parts, at altitudes of 7,000 to 8,000 feet. The ground water moves away from the areas of recharge toward outcrops at lower altitudes, where it discharges at springs and seeps or migrates into other units. Most of the beds of sandstone in the subsurface of the Central basin of the San Juan Basin are probably saturated.

Neither discharge measurements nor chemical analyses of the water in the San Juan River provided conclusive evidence that ground water is being discharged into that stream. However, the small change in streamflow between Rosa and Bloomfield, N. Mex. indicates that only a small amount of ground water could be entering the river in that reach, and it is unlikely that withdrawal of ground water from the area of investigation would affect significantly the flow of the San Juan River. Most of the ground water that is disharged in the area probably is dissipated by evaporation and transpiration in the valleys tributary to the San Juan River.

Water in the Ojo Alamo Sandstone and the San Jose Formation varies widely in chemical quality, both from one unit to another and within a single unit from one place to another. The concentrations of all the analyzed constituents of the ground water except iron, sodium, bicarbonate and sulfate, were generally low enough for most uses. The high concentration of iron in some water makes it undesirable for domestic use, because it tends to damage plumbing. The high concentration of sodium relative to that of calcium and magnesium makes some of the water undesirable for irrigation, and the high concentration of sulfate makes some of the water undesirable for drinking, because water containing a high concentration of sulfate along with sodium or magnesium has a laxative effect on many people. All of the samples of water from the Ojo Alamo Sandstone and the Nacimiento Formation and most of the samples from the San Jose Formation were collected from places which are within a few miles of probable recharge areas. The chemical composition of ground water in these rocks at greater distances from the recharge areas may vary considerably, but the data available are insufficient to describe significant variations.

The ~~potential~~ yield of deep wells will depend largely on the cumulative thickness of sandstone penetrated. Because none of the water wells in the area tap all the beds of sandstone to the base of the the Ojo Alamo Sandstone, except where it is shallow, the potential yield of a deep well can only be estimated. The specific capacit~~y~~ies of 59 wells that tap sandstone aquifers in the San Juan Basin, including 8 in the project area, ranged from 0.0002 to 0.015 gpm per foot of sandstone penetrated. The average for the 8 wells in the project area was 0.008. ~~Assuming that the beds of sandstone at some place total 500 feet in thickness and that a drawdown of 300 feet could be tolerated, the yield of a well tapping all the beds of sandstone could range from 30 to 2,250 gpm; the average yield of wells under these conditions would be 1,200 gpm. The sustained yield probably would be less than the computed average for the area, because many of the beds of sandstone are discontinuous.~~

The thickness of sandstone below 200 feet (the assumed average depth to the top of the zone of saturation) and above the base of the Ojo Alamo Sandstone ranges from 80 feet in sec. 33, T. 21 N., R. 5 W. to 1,840 feet in sec. 24, T. 26 N., R. 3 W. in the wells drilled for oil and gas that were used to construct the correlation diagrams (figs. ~~6~~ 5, ~~7~~ 6, and ~~8~~ 7). The thickness of sandstone below 200 feet and above the base of the San Jose Formation ranges from 0 in the southwestern part of the area to 840 feet in sec. 5, T. 25 N., R. 3 W. and in sec. 25, T. 24 N., R. 2 W.

The most favorable places in the southern part of the Jicarilla Apache Reservation for obtaining the largest yields with the least amount of drilling would be those where the thickness of sandstone is great and where the ratio of the thickness of sandstone to the depth to a certain horizon is high. The ratio of the total thickness of sandstone (below 200 feet) to the depth to the base of the Ojo Alamo Sandstone in wells used in the correlation diagrams ranges from 0.13 in sec. 22, T. 21 N., R. 5 W. to 0.54 in sec. 25, T. 25 N., R. 5 W. The thicknesses of sandstone at these localities are 140 and 1,470 feet, respectively. The ratio of the thickness of sandstone to the depth to the base of the San Jose Formation ranges from 0.17 in sec. 1, T. 22 N., R. 5 W. to 0.57 in sec. 10, T. 25 N., R. 5 W. The thicknesses of sandstone at these localities are 40 and 470 feet, respectively. One of the four tracts of land that was suggested as suitable for irrigation by the U.S. Bureau of Indian Affairs was adjacent to Lapis Canyon in T. 25 N., R. 5 W., and this appears to be the most favorable tract with respect to availability of water.

If the average specific capacity per foot of sandstone penetrated (0.008) could be applied to a well in sec. 25, T. 25 N., R. 5 W. in or adjacent to the Lapis Canyon tract and if 300 feet of drawdown could be tolerated, a well that tapped all the beds of sandstone to the base of the San Jose Formation would yield 1,460 gpm, and a well that tapped all the beds of sandstone to the base of the Ojo Alamo sandstone would yield 3,530 gpm. The actual yield probably would be less than the computed yield.

The data on the physical properties of the geologic formations, the chemical quality of the ground water, the yields of shallow wells, and the computed potential yields of deep wells suggest that large supplies of ground water for irrigation or industrial use could be developed at several places in and adjacent to the southern part of the Jicarilla Apache Reservation. The validity of th~~e~~is ~~above assumptions~~ conclusion can be determined only by ~~test~~ drilling and testing; the potential seems to be great enough to warrant test drilling.

The test drilling should be carefully planned and executed, in order to obtain reliable data on which future development could be based. Each thick unit of sandstone should be isolated by using a packer or by casing off all other units, and the unit should be tested for water level, yield, and quality of water. The water could be withdrawn by swabbing, bailing, or pumping, depending on the method of isolation used. A final test with all aquifers producing would be needed to fully appraise the yield. The test well should be drilled, preferably, to the base of the Ojo Alamo Sandstone in order to appraise all the potential aquifers. The well should be cased from the land surface to the bottom of the lowest productive zone, and the casing should be perforated adjacent to all the zones that would yield water of suitable chemical quality.

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Descriptions of

stratigraphic sections of

type localities

(Sections measured by E. H. Baltz and S. R. Ash)

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Localities 1a-1d, composite section, T. 20 N., R. 2 W. Units 1-13 measured at locality 1a on the south side of the small butte in the SE¼SW¼ sec. 25. Units 14-31 measured at locality 1b on the topographic spur projecting eastward from Mesa Portal in the SW¼NW¼ sec. 25 and the NE¼ sec. 26. Units 32-52 measured at locality 1c on the mesa north of Arroyo Chiuilla in the NE¼NE¼ sec. 23, and the SE¼ sec. 14. Units 53-95 measured on the SE side of a spur of Mesa de Cuba at locality 1d in the NW¼SW¼ sec. 12, and NE¼ sec. 11.

Top	Thickness (feet)
San Jose Formation (in part):	
Cuba Mesa Member (in part):	
95. Sandstone, light-tan to brown. Composed of fine-grained to very coarse grained quartz with 10 percent pink feldspar. Contains many granules and pebbles composed mainly of quartzite. Cross-bedded, beds 1-15 feet thick. Contains silicified wood. Lower two-thirds forms nearly vertical ledges; upper one-third forms rounded ledges at the top of the southern part of Mesa de Cuba ------------------------	140+
94. Sandstone, light-gray, shaly, notch-forming. Erosional contact with overlying unit --------	6

Thickness (feet)

San Jose Formation - Continued

Cuba Mesa Member (in part) - Continued

93. Sandstone, ligh-tan, fine-grained to very coarse grained. Composed of angular to subround quartz with some rock fragments and a trace of muscovite. Forms thin, notched, rounded ledges ------------- 30

Nacimiento Formation: (measured in the vicinity of the type locality of the "Puerco Formation" of Gardner, 1910, p. 713)

92. Steep slope, mostly covered by talus from above units. Gray to olive-green silty clay shale is exposed at a few places. Upper 50 feet is a boulder-strewn bench --------------------------- 100±

91. Shale, silty clay, gray and olive-green; forms a steep slope -- 16

90. Lignite, dark-gray, silty and argillaceous; forms a conspicuous band ------------------------------ 3

89. Shale, silty and sandy, light olive-green --------- 30

88. Sandstone, light-brown, medium-grained, soft, cross-bedded. This unit thicknes southwestward and forms a strong ledge ------------------------ 3

87. Shale, sandy and silty clay, light olive-gray with a few purple bands. Near the middle of the unit is a yellow sandstone lens 4 feet thick --------- 68

Localities la-ld - Continued

	Thickness (feet)
Nacimiento Formation - Continued	
86. Clay, purple, with interbedded olive-green sandy siltstone; forms a steep slope ------------	12
85. Sandstone, light-buff to light olive-green; fine- to medium-grained and argillaceous, ~~Forms~~ soft; forms a rounded slope --------------------------------	13
84. Siltstone, olive-gray and purple, and interbedded claystone. Near the middle is a lens of ferruginous sandstone, 2 feet thick. Unit forms a steep, fluted slope --------- - - - - --------------	30
83. Sandstone, light-brown, medium-grained; forms a vertical ledge --------------------------------	8
82. Sandstone, fine-grained, argillaceous, slope-forming --	8
81. Shale, silty, clay, olive-green, sandy ---------	5
80. Clay, purple, slope-forming ---------------------	4
79. Sandstone, light-buff, fine- to medium-grained, soft. Contains a gray clay lens ----------------	27
78. Shale, silty clay, olive-gray with purple bands. Contains very thin beds of soft yellow sandstone. Forms a steep, fluted, irregular slope --------	27
77. Shale, gray clay; and buff, fine- to medium-grained sandstone -------------------------------------	6

Localities 1a-1d - Continued

Nacimiento Formation - Continued

		Thickness (feet)
76.	Claystone, light-purple; interbedded soft sandstone and olive-gray siltstone. Forms a small bench ----------------------------------	13
75.	Siltstone, olive-green with purple bands. Soft white sandstone 3 feet thick occurs near the middle. Unit forms a ~~soft~~ slope -----------	14
74.	Siltstone, argillaceous, light yellowish-gray ---	4
73.	Sandstone, light-brown to tan, medium-grained; contains pink rock fragments and black grains. Sandstone is cross-bedded and contains thin stringers of gray shale. Unit is mostly soft, but some beds form small vertical ledges ----	23
72.	Shale, silty clay, light olive-green. Upper part is sandy and contains lignite shale and silicified wood. Unit forms a rounded hill --	26
71.	Lignite, black to dark-brown; forms a conspicuous band above a small bench --------------------	3
70.	Claystone, bentonitic, olive-gray~~; forms a~~ soft; forms a slope on the lower part of a bench -----------	2.5
69.	Siltstone, shaly, yellowish-gray~~; forms a~~ soft; forms a slope --	8

	Thickness (feet)
Nacimiento Formation - Continued	
68. Sandstone, buff to yellowish-brown, fine-to coarse-grained, argillaceous; ~~forms a~~ soft; forms a rounded to vertical cliff	11
67. Shale, light olive-gray; contains several beds of sandstone 2-7 feet thick and forms a ~~soft,~~ smooth slope	42
66. Sandstone, light-buff to yellowish-brown, fine- to medium-grained; forms a rounded ledge	5
65. Shale, silty, light olive-gray; contains stringers of nodular ironstone and bands of dark olive-green bentonitic clay. Unit forms a ~~soft,~~ rounded slope	18
64. Sandstone, light-gray, similar to unit 62 below. Unit is lenticular and locally merges with unit 62. This sandstone is the upper bed of a zone characterized by soft, white-weathering sandstone and interbedded gray shale	14
63. Shale, silty clay, medium- to dark-gray, lenticular	8
62. Sandstone, light-gray, stained yellow-brown, soft; composed of very fine grained to coarse-grained quartz with a few pink, yellow, and black rock fragments and feldspar grains. The unit grades laterally into shale, and forms a ~~soft,~~ rounded, fluted, steep slope	25

Localities 1a-1d - Continued

Nacimiento Formation - Continued

		Thickness (feet)
61.	Shale, light olive-gray to dark-gray; forms a small rounded bench ----------------------	5
60.	Coal and dark-gray carbonaceous shale; forms a conspicuous notch. This bed was traced northwestward from exposures near the Torreon road into the deep canyon on the south side of Mesa de Cuba where units 61-95 were measured-	0.5
59.	Siltstone, slightly sandy, dark-brown ---------	3
58.	Siltstone, shaly, light olive-gray -----------	6
57.	Claystone, slightly sandy, dark purplish-gray; forms a dark irregular band on the slope-----	5.5
56.	Siltstone, argillaceous, light-gray; contains several thin stringers of white-weathering lenticular sandstone ----------------------	20
55.	Claystone, purple ---------------------------	1
54.	Sandstone, argillaceous, gray-white; forms an irregular band on a steep slope -------------	4
53.	Siltstone, shaly, light gray; forms a steep, fluted slope north of the Torreon road east of a cattleguard ----------------------------	8

	Thickness (feet)
Nacimiento Formation - Continued	
52. Sandstone, light-brown, very argillaceous, thin-bedded, soft. The unit forms a slope near the top of a gravel-capped butte in sec. 14, T. 20 N., R. 2 W. Units 51 and 52 dip 1°-2° north and seem to be equivalent to a white sandstone below unit 53 just north of the Torreon road ------------------------------	3
51. Sandstone, very light-tan; weathers almost white. Sandstone is fine- to medium-grained, argillaceous, soft, and slope-forming ----------------------	7
50. Siltstone, shaly, argillaceous, dark-gray --------	3
49. Sandstone, silty, shaly, light-gray, very fine grained slope-forming ------------------------	11
48. Clay, silty, light-gray weathering, slop-forming --	2.5
47. Sandstone, light-gray, very fine grained, argillaceous, shaly; forms a slight, rounded ledge --	2.5
46. Clay, silty, light-gray to olive-gray with a purplish band; slightly bentonitic ------------	9
45. Sandstone, very light-olive, very fine grained, argillaceous. Sandstone weathers almost white. --	2

		Thickness (feet)
Nacimiento Formation - Continued		
44.	Siltstone, shaly, gray ----------------------	1.5
43.	Clay, dark-gray ----------------------------	1
42.	Sandstone and sandy shale, olive-drab, argillaceous. Unit weathers ~~to~~ light yellowish-brown, and forms a slope ----	4
41.	Clay, similar to unit 39 ------------------------	8.5
40.	Sandstone, gray-white, fine-grained, argillaceous, soft. --	1
39.	Clay, light olive-gray ----------------------	2.5
38.	Sandstone, gray-white, fine-grained, argillaceous, soft --	2
37.	Clay, light olive-gray ------------------------	1.5
36.	Sandstone, gray-white, fine-grained, argillaceous, soft. --	1.5
35.	Clay; mainly drab gray with some purplish and olive bands, and some siltstone stringers. The unit forms soft rounded slopes on a butte -----	38
34.	Siltstone, argillaceous, light brownish-gray; contains stringers of yellowish sandstone, and forms a slope -------------------------------	6
	Total thickness of Nacimiento Formation --------	797

Localities 1a-1d - Continued | Thickness (feet)

Ojo Alamo Sandstone:

33. Sandstone, yellowish-brown, argillaceous, fine- to medium-grained, shaly-bedded, soft; forms poorly exposed rounded slopes ------------------ 5.5

32. Sandstone, light-buff, medium- to coarse grained, concave cross-bedding. Unit forms moderately strong, smooth ledges retreating from unit 31 on the north side of Arroyo Chiuilla. Unit 31 was correlated from the south side of Arroyo Chiuilla -- 25

31. Sandstone, fine- to coarse-grained, with granules. A thin stringer of carbonaceous shale occurs near the base. The unit forms low rounded hills on the northeastern part of Mesa Portal ------- 11

30. Sandstone, yellowish-brown; coarse-grained to very coarse-grained; grains are mostly angular to subangular quartz with fragments of feldspar common. Locally at the base of this unit are lenses of channel-filling gravel composed of small pebbles of quartz, chert, clay, and feldspar. Flattened carbonized logs are present in the gravel. The unit forms a strong cliff, but thins locally south of the locality of measurement. The base of the unit is an irregular erosional surface -- 27.5

Localities 1a-1d - Continued | Thickness (feet)

Ojo Alamo Sandstone - Continued

29. Sandstone, light-brown, fine to coarse-grained; grades into underlying unit and weathers to a notch -- 2.5

28. Clay, purplish-gray; forms rounded slopes ------- 5

27. Shale, sandy and silty, olive-gray; forms rounded slopes -------------------------------- 11

26. Sandstone, very light gray to buff; weathers light orange-brown. Sandstone is composed of fine-grained to very coarse-grained, angular to subangular quartz with a minor amount of weathered feldspar and rock fragments. The sandstone is ferruginous and contains numerous casts of logs. Bedding is irregular, and an ironstone layer 1-3 feet thick occurs near the top of the unit. The unit forms a blocky, vertical cliff and thickens and thins south of the locality of measurement ------------------ 22

Total thickness of Ojo Alamo Sandstone --------- 109.5

Kirtland Shale and Fruitland Formation, undivided:

Unit C:

25. Siltstone, and interbedded very fine grained sandstone. The lower half is olive-green; the upper half is banded gray, brown, and purple. The unit forms nodular-weathering notch ------- 9

Localities 1a-1d - Continued Thickness (feet)

Kirtland Shale and Fruitland Formation, undivided - Continued

Unit C - Continued

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 to very coarse-grained quartz, a few grains of black minerals and rock fragments, and a few clay pebbles. About 20 feet above the base is a dark-brown concretionary layer. The unit is cross-bedded and forms a vertical ledge. On the south side of the spur this unit wedges out, but is present farther south on Mesa Portal. ---------------------------------- 25

Unit B

22. Sandstone, brown to white, medium-grained, argillaceous; weathers to a notch ------------- 1

21. Sandstone, olive-gray, fine- to medium-grained, slope-forming --------------------------------- 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, similar to unit 16 ----------------------- 8

17. Sandstone, very light-brown, fine-grained to very fine grained, argillaceous and micaceous; forms a rounded ledge with a gray shale stringer near the middle ------------------------------- 11

Thickness (feet)

Kirtland Shale and Fruitland Formation, undivided - Continued

Unit B - Continued

16. Clay, banded olive-green and purple, slightly bentonitic; forms smooth, rounded, fissured hills -- 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 to light-buff to white, medium- to coarse-grained, with some granules. The sandstone is 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, with some logs as large as 2 feet in diameter. The sandstone is strongly cross-bedded and forms a strong ledge capping an isolated butte --------------------- 10

Unit A:

12. Sandstone, light olive-gray to buff, fine- to medium-grained; contains argillaceous stringers and forms a slight, rounded ledge on the butte -- 19

	Thickness (feet)
Kirtland Shale and Fruitland Formation, undivided - 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. The 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 Portal ---------	9
Total thickness of Kirtland Shale and Fruitland Formation, undivided --------------------------	203
Pictured Cliffs S ndstone:	
10. Sandstone, light-gray, medium-grained; composed of angular to subangular quartz with a few pink and black grains and black mica flakes. The unit is slightly gypseous and ferruginous, and 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 the unit is clay shale in beds 2 inches-1 foot thick. The unit is poorly exposed on the slope ----------	16.5

Localities 1a-1d - Continued

Pictured Cliffs Sandstone - Continued

	Thickness (feet)
7. Covered. Probably shale	4
6. Sandstone, light olive-gray, fine-grained to very fine grained. The lower part is poorly cemented and forms a soft slope. The upper part is "papery-bedded", brown-weathering sandstone	6
5. Shale, clay, olive-green, poorly exposed	5
4. Sandstone, fine-grained, soft, similar to unit 2; poorly exposed	4
3. Sandstone, buff, medium-grained; contains black grains; cross-bedded. The weathered surface is a ferruginous brown rind one-eighth inch thick, and the beds have a slightly concretionary appearance. The sandstone contains <u>Halymenites</u> and pelecypods, and forms small ledges capping benches. Locally the unit forms slopes	3.5
2. Sandstone, light yellowish-brown, fine-grained to very fine grained, silty. Upper half contains three 6-inch stringers of gray shale. The unit forms a rounded slope	7.5
Total thickness of Pictured Cliffs Sandstone	64.5

Localities 1a-1d - Continued | Thickness (feet)

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, New Mexico. Section measured mainly on the north side of the road. The base of the section is in the NE$\frac{1}{4}$NW$\frac{1}{4}$ sec. 20, and 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. The thickness of unit 30 in secs. 28 and 33-35, T. 21 N., R. 2 W., was estimated from topographic maps.

Top	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. The 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)

Locality 2 - Continued Thickness (feet)

San Jose Formation - Continued

Cuba Mesa Member (type section), upper tongue ~~(Tsc4)~~:

29. Sandstone, rusty-brown to buff-weathering; ~~The sandstone is~~ composed of coarse-grained to granule size angular to subrounded quartz, with some feldspar. The upper part ~~of sandstone~~ is a hard, rusty, ferruginous zone. The unit thins northward, but thickens southwestward and merges with unit 22 as units 23-28 wedge out -- --------------- 52

Regina Member, tongue ~~(Tsr)~~; wedges out to southwest:

28. Shale, silty clay, 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. The unit forms a slope in a road cut -------------------- - ----------- 8

24. Sandstone, buff, fine- to medium-grained; caps a small hill and forms an irregular ledge ----- 16

23. Shale, sandy and silty clay, greenish-gray to olive-green with purple-weathering bands ----- 23

Locality 2 - Continued | Thickness (feet)

San Jose Formation - Continued

Cuba Mesa Member (type section-Continued), tongue [(~~Tsc~~$_5$)]:

22. Sandstone, light yellowish-orange; composed of fine-grained to granule-size, angular to sub-round quartz with feldspar and rock fragments; ~~The unit~~ forms a strong ledge. The lower half is composed of several stream-channel sandstones with thin interbeds of gray shale. The upper half is more massive. The 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

20. Sandstone, rusty-brown, very coarse-grained; gray shale interbedded ------------------------------ -- 5

Regina Member, tongue [(~~Tsr~~)]; wedges out to south:

19. Shale, gray, soft; contains thin beds of soft sandstone. The unit forms a slope on the high hill north of State Highway 44 ---------------- 55

Cuba Mesa Member (type section-Continued), main part:

18. Sandstone, buff, stained yellowish-brown; coarse-grained, cross-bedded; Forms smooth rounded ledges north of State Highway 44 west of Rito de los Pinos. This unit is the upper part of the lower tongue [(~~Tsc~~$_2$)] of the Cuba Mesa Member north of the locality of measurement ----------------------- 47

Locality 2 - Continued | Thickness (feet)

San Jose Formation - Continued

Cuba Mesa Member (type section-continued), main part - Continued

17. Sandstone, soft and shaly; carbonaceous shale is interbedded ------------------------------ 15

16. Sandstone, yellow and buff, very coarse grained and pebbly, cross-bedded; 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. The unit contains many silicified logs, and 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. Unit has sweeping cross beds and forms irregular, rounded ledges. Large silicified logs are numerous --------------- 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- 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 further north ------------------------------ 55

Locality 2 - Continued | Thickness (feet)

San Jose Formation - Continued

Cuba Mesa Member (type section-continued), main part - Continued

10.	Sandstone, orange-brown, coarse- to very coarse grained; forms a small poorly exposed ledge--	7
9.	Sandstone, light yellowish-brown, coarse- to very coarse grained, arkosic. The unit is similar to unit 7, and forms an irregular slope capped by hard ferruginous band --------------------	36
8.	Shale, clay, olive-gray. The lower 5 feet is brown lignitic shale that weathers purplish. The unit forms a soft slope ----------------	13
7.	Sandstone, light brownish-gray; composed of very coarse grained to granule-size subangular to subround quartz and quartzite with abundant feldspar fragments and lenses of small pebbles. The cross beds are broad and sweeping. Forms an irregular, rounded, retreating ledge. The upper 1-2 feet is highly ferruginous --------	36
6.	Sandstone, buff, rusty-brown- to red - weathering; similar to unit 5. Cross-bedded, forms ledge-	27.5

Locality 2 - Continued | Thickness (feet)

San Jose Formation - Continued

Cuba Mesa Member (type section-continued), main part - continued

5. Sandstone, buff, fine- to very coarse grained; composed of angular to subrounded quartz with a trace of pink chert, feldspar, and mica. A few clay and quartzite pebbles are present in the upper half. The unit is cross-bedded, and forms a strong cliff. Some bedding planes are marked by brown carbonized leaves and other plant debris -------------------------------- 50

4. Sandstone, buff to brown, fine-grained; and interbedded gray to light olive-gray shaly siltstone. Sandstone and shale beds are 1 inch to 1 foot thick. The shale is lignitic. Unit forms a nearly-vertical slope ---------- 9

3. Sandstone, greenish-gray, light- to dark-brown-weathering. The sand is medium- to coarse-grained, angular to subround quartz with some pink and black chert fragments, feldspar, and mica. The unit contains shale pebbles near the base, and several shale lenses. Forms a strong ledge -- 17.5

Locality 2 - Continued | Thickness (feet)

San Jose Formation - Continued

Cuba Mesa Member (type section -Continued), main part - Continued

2. Sandstone, gray; and interbedded gray and brown argillaceous siltstone. The unit seems to be a channel fill. About 30 percent of the unit is sandstone in beds 1 inch to 1 foot thick. The siltstone beds contain much lignitized plant debris. Forms small, irregular ledge. Erosional contact with underlying unit -------------------- 4

Total thickness of Cuba Mesa Member (including tongues of the Regina Member) --- --------- 782

Nacimiento Formation (in part):

1. Clay ~~Shale~~, silty, shaly ~~clay~~, olive-gray. Dark-gray carbonaceous clay is about 12 feet below the top of the unit. Unit forms a soft slope. Erosional contact with unit 2 ----------------- Not measured

Locality 3. Units 1-15 measured at locality 3a on hogbacks and slopes west of State Highway 112 in the SW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 31, T. 25 N., R. 1 E. Base of section is on shale slopes north of U.S. Forest Service fence. Units 16-56 measured at locality 3b in the valleys and on the steep escarpment in the SW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 31, T. 25 N., R. 1 E.; and the N$\frac{1}{2}$SE$\frac{1}{4}$ and the SW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 36, T. 25 N., R. 1 W.

Top	Thickness (feet)
San Jose Formation	
Llaves Member:	
56. Sandstone, gray to buff, coarse-grained and conglomeratic; contains some interbedded red shale, especially in the lower half. The unit caps the highest part of the mesa. The upper beds probably are equivalent to the persistent medial sandstone of the Llaves Member. Top eroded------	160 ±
55. Sandstone, light-gray; composed of very coarse grained to granule-size quartz with some feldspar. The unit forms a rounded ledge at the top of the ridge south of a saddle ------------------------	15
54. Shale, sandy silty clay, reddish- and green-gray; slope-forming ------------------------------------	14
53. Sandstone, buff, fine- to coarse-grained; forms small ledges ------------------------------------	10
52. Shale, silty clay, reddish- and green-gray, slope-forming ------------------------------------	25

Locality 3 - Continued	Thickness (feet)
San Jose Formation - Continued	
Llaves Member - Continued	
51. Sandstone, light-tan, medium- to coarse-grained; contains granules. Shaly sandstone in the middle one-third of the unit forms a slope separating rounded, irregular ledges -------------------	35
50. Siltstone, light greenish-gray, argillaceous, slope-forming ----------------------------------	10
49. Sandstone, tan, fine- to very coarse grained; contains lenses of gray and purple quartzite pebbles. Pebbles are 3-4 inches in largest dimension. The unit forms strong multiple ledges --	26
48. Shale, greenish-gray, with a red band near the base --	22
47. Sandstone, tan, fine- to coarse-grained, arkosic; contains small quartzite pebbles and forms a ledge --	22
Regina Member (type section):	
46. Shale, silty clay, light-gray. The upper part weathers purplish and contains small limestone nodules. The unit forms a slope -------------	30
45. Shale, red; forms a poorly exposed slope -------	18
44. Sandstone, buff, fine- to coarse-grained; forms a small ledge ---------------------------------	5

Locality 3 - Continued | Thickness (feet)

San Jose Formation - Continued

Regina Member (type section) - Continued

43. Sandstone, buff, fine- to coarse-grained, arkosic, forms a vertical ledge -- ------------------ --- 20

42. Shale, silty clay, greenish-gray and maroon ----- 30

41. Shale, silty clay, greenish-gray with rusty-brown mottling; slope-forming ---------------------- 9

40. Shale, silty clay, maroon with greenish-gray streaks; slope-forming ---- ----------------- 17

Llaves Member (tongue):

39. Sandstone, light-gray to buff; locally stained red by clay washing down from above. The sandstone is fine- to very coarse grained, and contains many lenses of granules and small-pebble ~~pebbles~~ conglomerate. Pebbles and granules are mostly quartzite, but chert fragments and weathered feldspar are common. Highly irregular stream-channel cross-bedding. Unit forms a massive vertical ledge. This tongue of the Llaves Member persists to the south where it contains thin lenses of shale ------------- --- 43

Locality 3 - Continued | Thickness (feet)

San Jose Formation - Continued

Regina Member (type section) - Continued

38.	Shale, silty clay, light-gray to olive-green; locally weathers to purplish bands. Unit forms a steep slope ----------------------------	80
37.	Shale, silty clay, dull-red - ------------------	11
36.	Shale, siltstone, light-olive-gray; weathers purplish -------------------------- -----------	7
35.	Shale, clay, [~~dull~~] red-weathering ----------------	4
34.	Sandstone, buff, medium-grained -----------------	1
33.	Shale, silty clay, light-gray -------------------	5.5
32.	Shale, clay, light-purple -----------------------	2
31.	Shale, clay; weathers light-red -----------------	3
30.	Claystone, gray, mottled brown; forms a light-tan band. To the north the unit grades into a ledge-forming sandstone tongue of the Llaves Member----	13
29.	Shale, argillaceous, and silty, light-gray -------------	29
28.	Sandstone, light yellowish-gray, coarse-grained, soft; ~~forms a soft~~ weathers yellow, ~~band~~, and contains thin lenses ~~bands~~ of lignitic clay - ----------------------	7
27.	Shale, silty clay, gray -------------------------	14.5
26.	Siltstone, brick-red, forms conspicuous band ------	5
25.	Shale, silty clay, light brownish-gray with a faint purple band near the top ------------------	30

Locality 3 - Continued

Thickness (feet)

San Jose Formation - Continued

Regina Member (type section) - Continued

24. Shale, silty clay, light-gray; contains a few lenses of soft, gray, medium- to coarse-grained sandstone 2-5 feet thick - - ---- ------------ -- 71.5

23. Sandstone, buff to light yellow-gray; contains very coarse grained to granule-size quartz with feldspar fragments and a few small clay pebbles. The unit caps a point on the east end of a small ridge and ~~lenses~~ wedges out to the west into gray shale. The unit thickens northward to form a strong ledge ------------------------------- - -- 8.5

22. Shale, silty clay, pale-tan, gray, and olive-gray; contains thin bands of soft argillaceous sandstone and siltstone. Unit forms a steep slope on an eastward-projecting spur -------------------- 60

21. Sandstone, buff-white, coarse-grained; locally contains quartzite pebbles as large as 3 inches long. ~~in longest dimension.~~ The unit is a channel deposit locally 8-10 feet thick, and forms a hard ledge capping a long low cuesta ---------------- -- -- 2.5

Locality 3 - Continued | Thickness (feet)

San Jose Formation - Continued

Regina Member (type section) - Continued

20. Shale, silty clay, light-gray to light olive-gray, contains ~~has~~ two thin beds ~~bands~~ of purple and red clay, and forms a slope --------------- - -------------- 20

19. Sandstone, light-gray; composed of very coarse grained to granule-size quartzite fragments and some feldspar. The unit is a channel deposit and forms a small ledge - ----------- ------------ 5.5

18. Shale, silty clay; upper half is olive-gray; lower half is light gray. Unit forms a slope -------- 22

Total thickness of main part of Regina Member (including tongue of Llaves Member, unit 39) --- 574

Cuba Mesa Member (upper tongue, [Tse$_3$]):

17. Sandstone, light-gray, stained light-yellow; composed of very coarse grained quartz and quartzite with a trace of feldspar and mica. Sandstone contains numerous small quartzite pebbles and forms a small ledge ------------- 15

16. Shale, silty clay, light-gray with light-red and olive-colored bands; slope-forming ---------- 27.5

Locality 3 - Continued | Thickness (feet)

San Jose Formation - Continued

Cuba Mesa Member (upper tongue, [~~Tsc~~$_3$]) - Continued

15. Sandstone, buff; ~~weathers~~ light yellowish-brown, medium- to coarse-grained, arkosic. Upper part contains numerous large cobbles and pebbles of quartzite and schist. Unit forms strong multiple ledges stepped back along shale lenses included in the sandstone. This sandstone was traced southward to the locality of measurement of unit 16--------- ----------------- - ------ -- 30

Regina Member (tongue, [~~Tsr~~]):

14. Shale, light greenish-gray and gray; contains 5 or 6 lenses of soft light-gray channel sandstone. Forms a slope and becomes thinner to the north.- 119

13. Sandstone, light-gray to buff; contains interbedded shale ---------- ------------------------------ 9

12. Shale, silty clay, greenish-gray, slope-forming---- 16

Cuba Mesa Member (lower tongue, [~~Tsc~~$_2$]):

11. Sandstone, light-gray to buff; weathers yellow-brown; medium- to coarse-grained, feldspathic. Sandstone contains thin stringers of small pebbles and is irregularly bedded. Forms a ledge- 29

Locality 3 - Continued Thickness (feet)

San Jose Formation - Continued

Cuba Mesa Member (lower tongue, ~~Tsc$_2$~~) - Continued

10. Shale, silty clay, light olive-gray; contains thin sandy lenses, and weathers to a slope--- 9

9. Sandstone, light-gray, limonite-stained; medium- to coarse-grained with a few granules. Upper half is brown and contains thin clay lenses. Unit weathers to a slope -------------------- 23

Regina Member (tongue, ~~Tsr~~):

8. Shale, silty clay, greenish-gray; lower 4 feet weathers dull red. Unit forms a slope -- ------ -- 51

Cuba Mesa Member (main part, ~~Tsc$_1$~~):

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 causes brown "cannonballs" up to 2 feet in diameter. Unit forms a strong persistent ledge ---------------- ------------------ 27

Total thickness of Cuba Mesa Member (including tongues of Regina Member) 355.5

Locality 3 - Continued

Nacimiento Formation (in part):

	Thickness (feet)
6. Shale, silty sandy clay, light olive-gray; forms poorly exposed slope ----------------	16
5. Sandstone, light-tan, fine- to medium-grained, thin-bedded; forms poorly exposed slope -------------------------------------	27
4. Shale, silty clay, dark-gray; slightly bentonitic. Upper half is brown carbonaceous ~~lignitic~~ 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 N 1/2 sec. 18, T. 25 N., R. 1 E.

Top	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-grained, arkosic, quartz sand containing small cobbles of gray to purplish quartzite. Unit is ~~Channel~~ cross-bedd~~ing.~~ed and ~~H~~holds up a narrow ledge ----------	50
48. Shale, silty clay, 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. Shale, silty clay, light-gray to olive; weathers red. Unit contains interbedded thin sandstone ---------------------------	14

Locality 4 - Continued | Thickness (feet)

San Jose Formation - Continued

Llaves Member (type section of lower part) - Continued

45. Sandstone, light-brown weathering, coarse- to very coarse grained; contains numerous lenses of pebbles which are as large as 2 inches in diameter. Unit forms a strong ledge ---------------- 40

44. Shale, silty clay, red-weathering; contains thin sandstone beds ---------------------- 37

43. Sandstone, light pinkish-brown, fine- to coarse-grained; forms a ledge on a long narrow spur ---------------------------- 20

42. Shale, silty sandy clay, light-gray to light olive-gray; contains thin sandstone beds, and 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 inches thick and separated by stringers of gray shale. Entire unit weathers red and forms a retreating slope on a small bench ------------------------ 15

Thickness (feet)

San Jose Formation - Continued

Llaves Member (type section of lower part) - Continued

39.	Sandstone, light yellowish-brown; similar to unit 37. Forms a strong ledge -----------	55
38.	Shale, clay, 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 ~~gravel~~, and fossil wood impressions. Unit is cross-bedded and forms a strong cliff ---------------------------	40
36.	Sandstone, light reddish-gray to maroon, fine- to medium-grained. Sandstone beds are about 1 foot 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.	Shale, silty clay, light olive-gray; forms a slope ------------------------------------	6
34.	Sandstone, light-brown, medium- to coarse-grained; forms a small ledge -------------	9
33.	Shale, sandy and silt~~stone~~, greenish-gray, reddish-weathering -----------------------	35

Locality 4 - Continued	Thickness (feet)
San Jose Formation - Continued	
Llaves Member (type section of lower part) - Continued	
32. Sandstone, earthy, pale-maroon, fine- to medium-grained. Fifty feet to the south this unit becomes massive, yellow, coarse-grained sandstone ------------------------	6
31. Shale, clay; weathers pale maroon ----------	12
30. Sandstone, yellow, coarse-grained; contains granules of quartz and feldspar, and pebbles and cobbles of quartzite. Unit is cross-bedded and ledge-forming -----------	14
29. Shale, silty clay, light-gray to olive-gray; weathers pale maroon, and 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 cross-bedded 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 the above unit -------------------------------------	30

San Jose Formation - Continued

Llaves Member (type section of lower part) - Continued

25. Sandstone, reddish-stained, and interbedded thin reddish shale. Sandstone is fine- to medium-grained and contains a few small pebbles. Sandstone beds are 5-12 feet thick and form retreating ledges separated by notches weathered in shale. Bedding is irregular and the sandstones are ~~channel-~~ cross-bedded -- 85

Total thickness of preserved lower part of Llaves Member ------------------------------ 695.5

Cuba Mesa Member:

24. Sandstone, buff, medium- to coarse-grained, arkosic; contains lenses of pebbles and, near the top, scattered cobbles. Forms a strong cliff ------------------------------- 94

23. Shale, silt~~stone~~, ~~claystone~~ argillaceous, and very fine grained sandstone. Unit weathers reddish- and greenish-gray, and forms a slope ---------------------- 16

Locality 4 - Continued | Thickness (feet)

San Jose Formation - Continued

Cuba Mesa Member - Continued

22.	Sandstone, gray to reddish-purple, medium- to very coarse grained, arkosic; contains large pebbles and small cobbles which are mostly quartzite. Some pebbles are feldspar, and volcanic rocks. Unit is ~~Channel~~ cross-bedded, and forms a massive cliff ------------	39
21.	Covered --	10
20.	Shale, silty clay, dark-gray, slope-forming -	25
19.	Sandstone, gray to light purplish-gray, very coarse grained; contains pebbles and is cross-bedded. Forms a rounded ledge ------	40
18.	Sandstone, olive-gray, fine- to medium-grained, slope-forming --------------------	3.5
17.	Sandstone, buff, arkosic -------------------	2
16.	Shale, clay, gray --------------------------	4
15.	Sandstone, olive-green, shaly; forms poorly exposed slope ----------------------------	7
14.	Shale, clay, siltstone; and sandstone, green to pale-purplish. Forms a soft slope -----	19
13.	Sandstone, buff to greenish-gray, thin- to shaly-bedded; forms a soft slope ----------	7

Locality 4 - Continued | Thickness (feet)

San Jose Formation - Continued

Cuba Mesa Member - Continued

12. Sandstone, buff; forms soft, retreating ledges -- 8
11. Sandstone, medium-grained; forms a small ledge -- 3
10. Shale, silty, argillaceous, sandy, greenish-gray; forms a slope ----------------------- 9
9. Sandstone, yellowish-gray, fine- to very coarse grained, arkosic; contains pebbles of quartz, quartzite, feldspar, and volcanic rock. Forms a ledge ----------------------- 18
8. Sandstone, yellow-gray, fine- to very coarse grained, arkosic; contains lenses of granules and small pebbles; ~~Channel~~ cross-bedded. Forms a massive ledge ----------- 22

Total thickness of Cuba Mesa Member --------- 334.5

Nacimiento Formation (in part):

7. Sandstone, yellow to buff, fine-grained, argillaceous; forms a notch --------------- 8
6. Shale, siltstone and clay, gray, slope-forming ----------------------------------- 12

Locality 4 - Continued

Nacimiento Formation - Continued

	Thickness (feet)
5. Sandstone, olive-green, fine-grained, soft~~,~~ shaly-bedded ------------------------------	7
4. Sandstone, similar to unit 2. Base of unit is a small ledge, upper part is a soft slope --------------------------------------	15
3. Shale, sandy clay, olive-green; slope-forming ----------------------------------	18
2. Sandstone, olive-green, fine-grained; forms a small ledge and grades into overlying unit --------------------------------------	9
1. Sandstone, yellowish-gray, medium- to very coarse grained; contains lenses of pebbles, and lenses of gray clay shale. Unit is ~~Irregular~~ cross-bedd~~ing,~~ed and ~~F~~forms a ledge ------------	40

Locality 5. Section measured on a ridge on the northern side of Canyoncito de las Yeguas east of Pasture Canyon, from the $SW\frac{1}{4}$ sec. 4, T. 25 N., R. 1 W. to the center of sec. 33, T. 26 N., R. 1 W.

Top	Thickness (feet)
San Jose Formation	
Llaves Member (type section of upper part):	
Sandstone, buff, gray, brown, and red, fine- 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 about 120 feet thick. above this is red shale with thin interbeds of sandstone about 70 feet 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 locality 4. West of locality 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 feet 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 on fig. 5). 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 to be characteristic of the "Largo facies" of the San Jose Formation by Simpson.

Top	Thickness (feet)
San Jose Formation	
Tapicitos Member, lower part (typical exposures):	
13. Sandstone, buff, massive in appearance but cross-bedded, hard, bench-forming. Top eroded. On an adjacent peak about 50 feet more of similar beds are 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
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; ~~local lens~~ wedg~~ing~~es out in a few feet laterally ---------------------------	2

Locality 6 - Continued | Thickness (feet)

San Jose Formation - Continued

Tapicitos Member, lower part - Continued

8. Clay, red, massive but slightly banded ------	15
7. Sandstone, soft; wedges out laterally -------	5
6. Clay, red, banded; contains lenses of ~~with~~ buff sandstone ~~lenses~~ in the upper part -----------------	80
5. Sandstone, light-gray, hard, cross-bedded; 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, locality 150, is 13.5 feet 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 ~~preserved~~ at this locality --------------------------	251

Base of hill; lower beds covered by slopewash. Unit 1 is about 25-50 feet above the base of the Tapicitos Member and the top of the persistent medial sandstone of the Llaves Member.