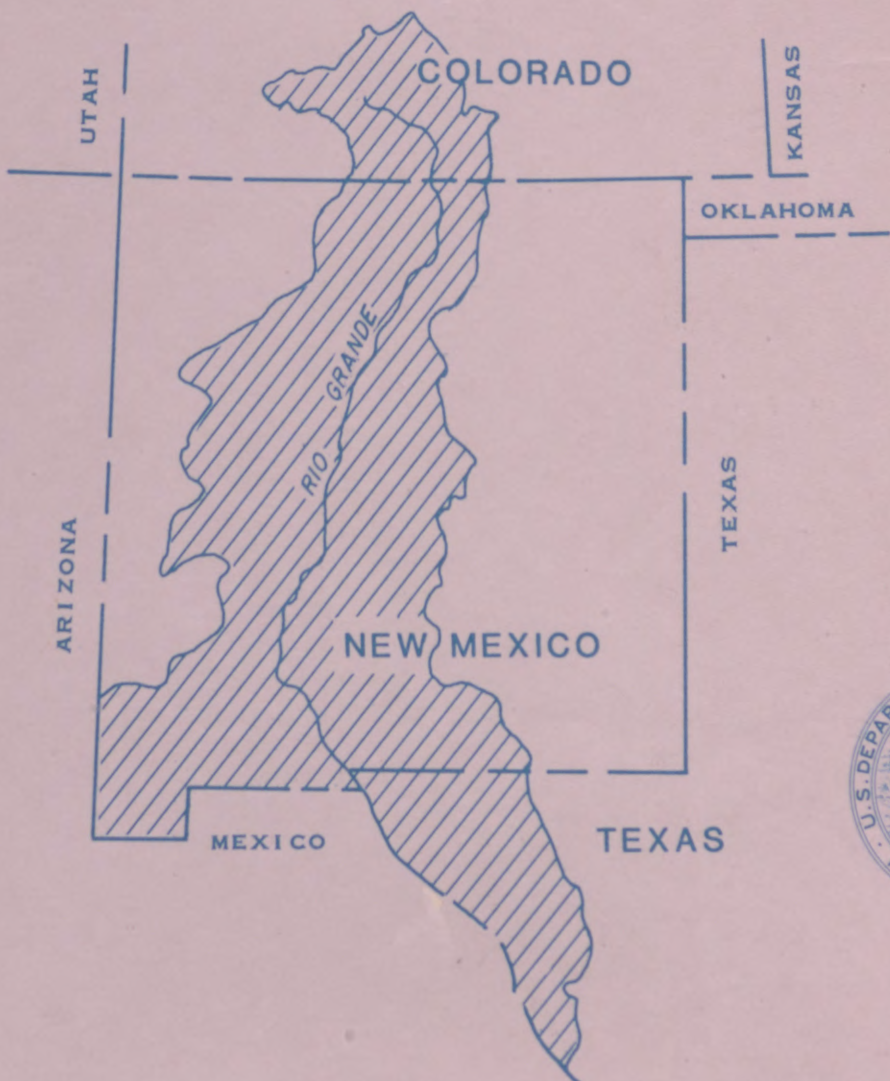
GEOHYDROLOGY OF THE SOUTHWEST ALLUVIAL BASINS REGIONAL AQUIFER-SYSTEMS ANALYSIS, PARTS OF COLORADO, NEW MEXICO, AND TEXAS

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 84-4224



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By D.W. WILKINS

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DONALD PAUL HODEL, Secretary

GEOLOGICAL SURVEY

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CONVERSION FACTORS

Figures for measurements in this report are given in inch-pound units only. The following table contains factors for converting to metric units.

Multiply inch-pound units	By	To obtain metric units
acre	0.4047	hectare (ha)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per mile ($ft^3/s/mi$)		cubic meter per second per kilometer ($m^3/s/km$)
foot (ft)	0.3048	meter (m)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
gallon per minute (gal/min)	0.06308	cubic meter per second (m^3/s)
gallon per minute per foot (gal/min/ft)	0.2070	cubic meter per second per meter ($m^3/s/m$)
inch (in.)	25.40	millimeter (mm)
mile (mi)	1.609	kilometer (km)
square miles (mi^2)	2.59	square kilometers (km^2)

GEOHYDROLOGY OF THE SOUTHWEST ALLUVIAL BASINS

REGIONAL AQUIFER-SYSTEMS ANALYSIS,

PARTS OF COLORADO, NEW MEXICO, AND TEXAS

By D.W. Wilkins

ABSTRACT

The Southwest Alluvial Basins study is part of the National Regional Aquifer-Systems Analysis program. Twenty-two structural basins extend from the San Luis Basin in southern Colorado to the Presidio Basin in western Texas. Closed surface-water basins west of the Guadalupe Mountains and east of the Peloncillo Mountains are included in the study.

The study area is bounded on the east by predominately Precambrian and Paleozoic rocks. Tertiary and Quaternary volcanics also are present. Tertiary and Quaternary volcanic rocks, and also Mesozoic rocks west of the Española and Albuquerque-Belen Basins, form the west boundary. The east and west boundary units converge at the north end of the study area to form the north boundary. The study area extends south to the international border between the United States and Mexico.

The Santa Fe Group sediments of late Oligocene to middle Pleistocene age comprise the main aquifer in the area. Estimated maximum depths of sediments in the rift basins range from 8,000 feet in the Tularosa-Hueco Basin to 30,000 feet in the San Luis Basin. The average thickness of sediments in closed basins is about 4,000 feet. Santa Fe deposits are composed of layers of gravel, sand, silt, and clay interbedded with local volcanic flows or tuffs. Lacustrine deposits are more prevalent in the closed basins. Wells produce as much as 2,000 gallons of water per minute.

Potentiometric-surface altitudes for 1971-82 indicate that water recharges in the highland areas around the basins and discharges in the center of valleys. Water generally flows from the east and west southward along the axis of the valleys.

Ground-water quality for the region has been zoned into calcium sulfate, calcium chloride, magnesium sulfate, magnesium chloride; sodium sulfate, sodium chloride; sodium bicarbonate; and calcium bicarbonate, magnesium bicarbonate types.

INTRODUCTION

The U.S. Geological Survey initiated a program in 1978 to systematically study aquifer systems at a regional scale. The Southwest Alluvial Basins study is part of this program. The objectives of Regional Aquifer-Systems Analysis (RASA) are: (1) to describe the water-resource system, (2) to analyze changes in the system, (3) to develop a data base from existing information, and (4) to simulate the hydrologic system using mathematical models.

Hydrologic data, geologic descriptions of basin boundaries, and aquifer properties presented in this report were compiled from the many previous studies completed in the regional study area. Regional interpretations resulting from analysis of existing data are also presented in this report.

The study area encompasses parts of Colorado, New Mexico, and Texas (pl. 1) and is structurally and hydrologically divided into 22 surface-water open and closed basins (pl. 1). The Rio Grande is the primary hydrologic connection through the open basins of southern Colorado, New Mexico, and western Texas. Closed basins in southwestern New Mexico and western Texas make up the rest of the area. The study area includes approximately 70,000 square miles (mi^2): about 7,700 mi^2 in Colorado, 52,500 mi^2 in New Mexico, and 9,800 mi^2 in Texas.

The study area is located within or adjacent to four separate physiographic provinces (pl. 1). In the northern part of the study area, the boundaries of the Southern Rocky Mountains Province are formed by the Sangre de Cristo, San Juan, and Jemez Mountains. For the purpose of this study, the Basin and Range Province includes the Rio Grande Rift northward to the southern end of the Española Basin. The Colorado Plateau Province is northeast of the Basin and Range Province and west of the Southern Rocky Mountains Province. The Great Plains Province is adjacent to the east boundary of the study area (pl. 1).

GEOLOGY

The Rio Grande Rift is the dominant geologic feature of the area. The rift affected the configuration of the bounding uplands, which in turn affect precipitation, ground-water recharge, source material of the aquifer, aquifer characteristics, and water quality. The regional geologic framework includes Cenozoic and younger units. Detailed descriptions of bordering rocks and geologic features may be found in Chapin (1971), Hawley (1978), and Riecher (1979). Many other geology-related publications are listed in bibliographies by Stone and Mizell (1979), and Wright (1978, 1979a, 1979b). Most of the following discussion of the regional geology is taken from Wilkins, Scott, and Kaehler (1980).

Cenozoic Sediments

The Santa Fe Group, a rock-stratigraphic unit, is classified mainly on the basis of lithology and depositional environment rather than fossils or time boundaries. The Santa Fe Group is composed of unconsolidated to moderately consolidated sedimentary deposits and some volcanic rocks. Bryan (1938, p. 205) applied the name "Santa Fe Formation" to the basin deposits of presumably Pliocene age along the Rio Grande. Bryan used four criteria in defining his Santa Fe Formation:

> (1) All the beds are slightly cemented, and the fine-grained members have concretions of calcium carbonate; (2) all the deposits are deformed, mostly by normal faults, although in the centers of the basins the deformation is so slight as to pass unnoticed except under intensive search; (3) the beds within any one basin are of diverse lithologic types, ranging from coarse fanglomerate to fine silt and clay, and abrupt changes in the kind and sizes of the contained pebbles are characteristic; and (4) these markedly different materials attributed to one formation conform in their arrangement to a geographic pattern consistent with the laws of deposition in basins.

The Santa Fe Formation has been renamed the Santa Fe Group (Spiegel and Baldwin, 1963). Its subunits have been redefined and given various names. The term "Santa Fe" has been applied by some workers to sediments in intermontane valleys that are adjacent to the Rio Grande depression in the southern half of New Mexico. A correlation chart (fig. 1) illustrates the many formations and subdivisions in the Santa Fe Group and age variation of these units.

The base of the Santa Fe Group generally is placed above the middle Tertiary (Oligocene) volcanic and associated sedimentary rocks. In southern New Mexico, the upper limit generally is at the surface of the youngest basin-fill deposits that predate initial entrenchment of the present Rio Grande valley in middle Pleistocene time (Weir, 1965; King and others, 1971). Most workers in the northern half of the study area (Bryan and McCann, 1937; Smith, 1938; Stearns, 1953; Galusha, 1966; Kelley, 1977, fig. 2) have excluded early Pleistocene gravels from the Santa Fe Group.

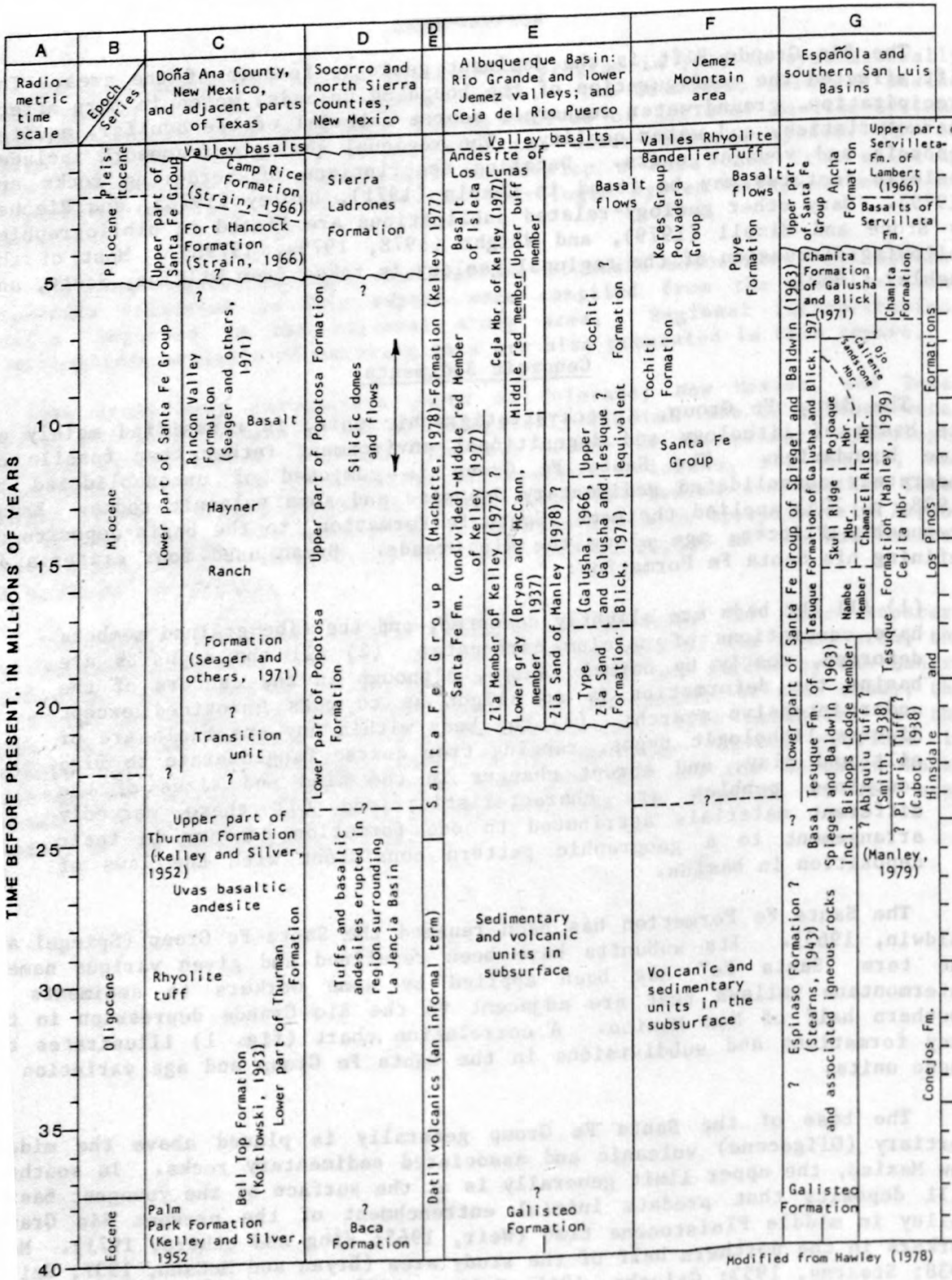

Figure 1.--Santa Fe Group and equivalent units in selected areas of the Rio Grande Rift.

References for figure 1

Modified from J.W. Hawley (1978, p. 239)

Column B: Berggren and Van Couvering (1974), Galusha (1974), Izett (1977)

Column C: Strain (1966), Chapin and Seager (1975), Clemons (1976), Hawley (1975), Kelley and Silver (1952), Kottlowski (1953), Seager (1973, 1975), Seager and others (1971)

Column D: Bachman and Mehnert (1978), Chapin and Seager (1975), Chapin and others (1978), Machette (1978)

Column E: Bachman and Mehnert (1978), Bryan and McCann (1937), Galusha (1966), Galusha and Blick (1971), Kelley (1977), Kudo and others (1977), Lambert (1968), Manley (1978a)

Column F: Bailey and others (1969), Doell and others (1968), Smith and others (1970)

Column G: Bachman and Mehnert (1978), Cabot (1938), Galusha (1974), Galusha and Blick (1971), Lambert (1966), Lipman and Mehnert (1975), Lipman and others (1978), Manley (1978b), Manley and Naesser (1977), Ozima and others (1967), Smith (1938), Spiegel and Baldwin (1963), Stearns (1943), Manley (1979)

Basins are characterized by a variety of alluvial-fan, coalescent-fan, and pediment-cover deposits around the basin margins. These deposits generally grade into, or intertongue with, fine-grained lacustrine or alluvial basin-floor deposits (King and others, 1971). In open basins, medium to coarse fluvial facies, with relatively small amounts of fine-grained sediment, were deposited in the central parts of the basins by axial streams. Volcanism continued during deposition of the Santa Fe Group, but to a lesser extent than during the early Tertiary. Interbedded volcanic rocks, mainly basalts and occasionally andesites, rhyolites, and tuffs, are present in the Santa Fe Group. The interbedded volcanic rocks, which generally range from 50 to 200 feet (ft) thick, are more prevalent north of Socorro (Bryan, 1938, p. 207).

The Santa Fe Group is estimated to have a maximum thickness ranging from 1,200 to 3,000 ft in most basins (Weir, 1965, p. 24; King and others, 1971, p. 17-22; Trauger, 1972, pl. 27; Baltz, 1978, p. 215-19; Lovejoy and Hawley, 1978, p. 59). Gaca and Karig (1966, p. 1) estimated there may be as much as 30,000 ft of sediments similar to those of the Santa Fe Group in the San Luis Basin. Mattick (1967) estimated a thickness of about 9,000 ft in the Tularosa-Hueco Basin near the New Mexico-Texas State line. Budding (1978, p. 197) reported a thickness of 6,900 ft in the western part of the Española Basin; Kelley (1977, p. 45) estimated more than 9,000 ft of Santa Fe Group in the Albuquerque-Belen Basin.

The equivalent of the Santa Fe Group in the Mimbres Basin and westward into Arizona is the Gila Conglomerate (or Formation). The boundary between the two has been arbitrarily placed along the eastern drainage divide of the Mimbres Basin (Hawley and others, 1969, p. 55; King and others, 1971, p. 16). The general depositional setting (early basin filling with sediment followed at some locations by cyclic partial dissection of the older basin sediment due to the development of through-flowing drainage) is similar to that of the Santa Fe Group (Trauger, 1972, p. 27). In Grant County, New Mexico, the lower part of the Gila Conglomerate, which may be more than 2,000 ft thick, generally is composed of consolidated and deformed fanglomerate, conglomerate, sandstone, silt, and occasional thick deposits of clay. The lower part of the Gila Conglomerate is intertongued and interbedded locally with Tertiary volcanics. The upper part of the Gila Conglomerate, generally less than 1,000 ft thick, contains interbedded basaltic andesite flows and is only slightly deformed (Hawley, 1969, p. 140; Trauger, 1972, p. 27).

Quaternary deposits primarily consist of alluvial fans, colluvium, pediment gravels and sands (including dunes), playa muds and sands, river terraces, and inner river-valley flood-plain and channel deposits. A correlation chart of the major Quaternary stratigraphic and geomorphic units is shown in figure 2.

After deposition of the Santa Fe Group, during middle Pleistocene time prior to incision of the present Rio Grande valley, widespread geomorphic surfaces were formed in the Rio Grande depression by repeated episodes of erosion and deposition over large areas of piedmont slopes. The deposits, which are composed of alluvial gravel, silt, and sand, range from 0 to more than 500 ft thick (Weir, 1965, p. 25). Deposition has continued along mountain fronts in bolsons that are not yet integrated with the Rio Grande drainage system.

Incision of the Rio Grande valley was cyclic in nature; there were at least three periods of stabilization, backfilling, and erosion. This process led to the formation of gravel, sand, and silt terraces 30 to 175 ft above the present flood plains. Maximum entrenchment of the Rio Grande during late Quaternary was between 60 and 130 ft below the present flood plain (Hawley, 1969, p. 140; King and others, 1971, p. 23; Kelley, 1977, p. 33). Volcanism took place in the Quaternary both contemporaneously with and after formation of the highest basin surface (Bryan, 1938; Dane and Bachman, 1965; Kelley and Kudo, 1978).

Geologic History and Structure

During the Paleozoic Era, the region primarily was low lying and partly covered by sea, except for the southern Colorado area, which was uplifted. Low plains were present during the Triassic and Jurassic Periods, and continental sediments, mainly red beds, were deposited. Triassic and Jurassic rocks were either not deposited in the southern part of the area or were eroded prior to deposition of the Cretaceous rocks. During the Cretaceous and early Tertiary Periods, seas and low-lying plains were the sites of deposition of large thicknesses of limestone and clastic sediments. The original thicknesses of Paleozoic and Mesozoic rocks varied according to the topography. Slight uplift and erosion occurred between depositional periods. Strong, broad uplift and compressional deformation took place during Late Cretaceous through Eocene (Laramide) time. During this time, the Nacimiento Peak area, the Sierra Lucero front, and the Franklin Mountains were at least partly formed and numerous faults were active (Bryan, 1938; Kelley, 1977; Lovejoy and Hawley, 1978). The Laramide activity aided erosion of some of the older deposits, resulting in unconformable deposition of early basin deposits on rocks as old as Precambrian. Volcanic and intrusive activity also took place locally during this time and continued through the Oligocene.

Rifting began at least 18 million years ago, during middle Miocene time (Chapin, 1971). Structure models and the observed fault patterns indicate that regional extension caused by differential drift within the continental plate (Chapin, 1971; Kelley, 1977) or broad regional uplift (Baltz, 1978) resulted in down-dropped basins (grabens) and tilted fault blocks that formed the Rio Grande depression. The San Agustin Basin, Tularosa Basin, and the Arkansas graben in central Colorado also were formed by this rifting (Burroughs, 1971). The southern limit of the rift is open to debate; Woodward and others (1975, p. 239) placed the rift's southern limit at Socorro, New Mexico, while others extend the rift "all the way to the Sierra Nevada and Big Bend country, essentially becoming inseparable from the Basin and Range Province." Seager and Morgan (1979, p. 101) extended the rift into western Texas and northern Chihuahua, Mexico, based on shallow manifestations of the deep structure, such as "active faults and volcanoes, high heat flow and exceptionally deep basins." A tectonic map by Woodward and others (1975) shows "generally thick synorogenic sedimentary deposits in Rio Grande rift; Miocene to Holocene" as far south as Presidio, Texas. Sediments mapped as QTs (Quaternary and Tertiary sediments) or Qa (Quaternary alluvium) on plate 2 are assumed to be contemporaneous with Santa Fe Group and Quaternary sediments, respectively.

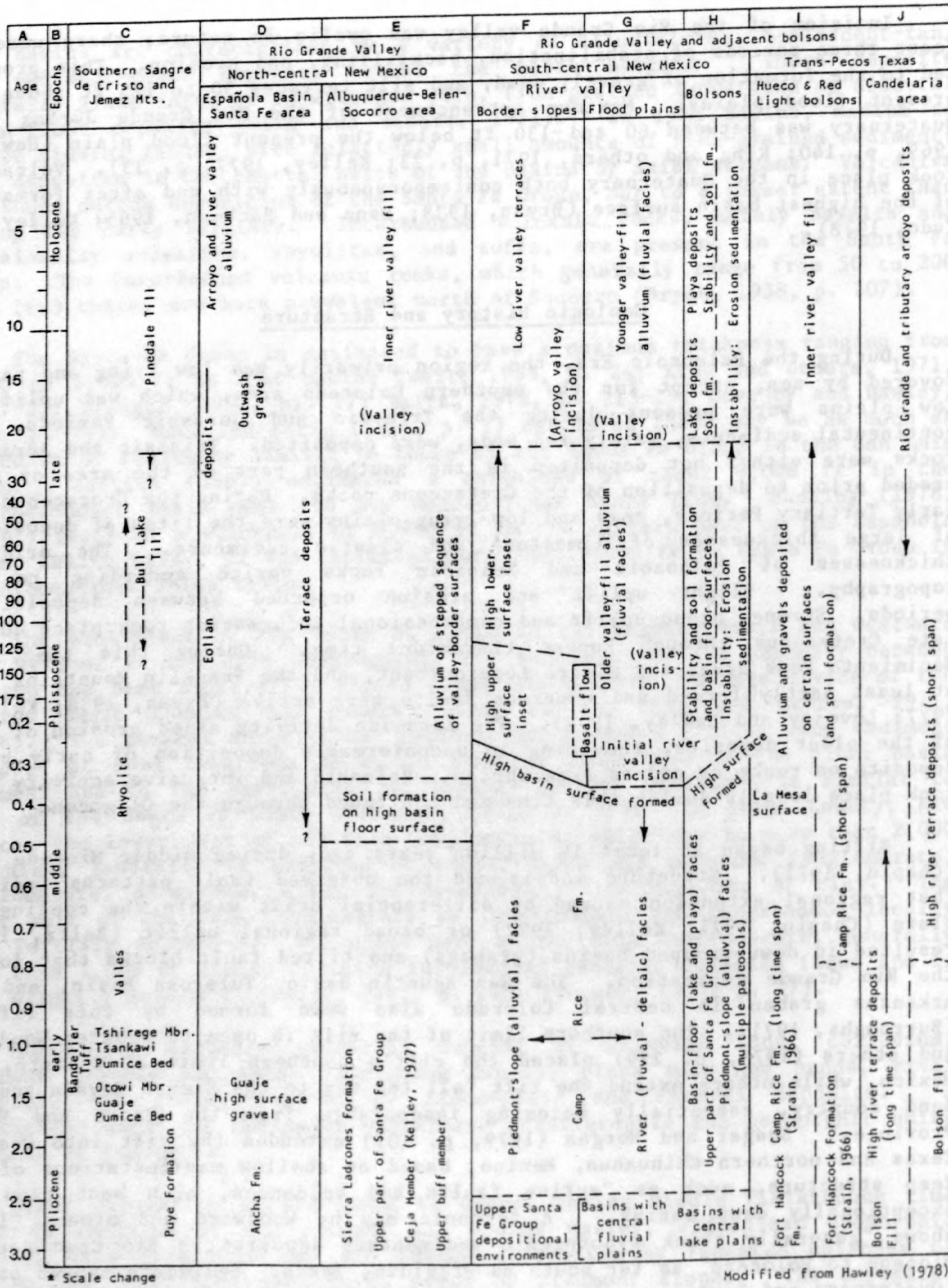

Figure 2.--Major Quaternary stratigraphic and geomorphic units in the Rio Grande Rift.

References for figure 2

Modified from J.W. Hawley (1978, p. 238)

Column C: Bailey and others (1969), Clark and Read (1972), Doell and others (1968), Richmond (1963), Smith and others (1970)

Column D: Manley (1976), Manley and Naesser (1977)

Column E: Bachman and Mehnert (1978), Kelley (1977), Kudo and others (1977), Lambert (1968)

Column F: Hawley (1975), Hawley and others (1976)

Column G: Hawley (1975), Hawley and others (1976)

Column H: Hawley (1975), Hawley and others (1976)

Column I: Albritton and Smith (1965), Hawley (1975), Kottlowski (1958), Strain (1966)

Column J: Groat (1972), Hawley (1975)

Rifting took place along a general north-south structural grain. The structural grain was established during the Laramide orogeny (Kelley, 1977) and possibly earlier tectonic activity (Miller and others, 1963; Kelley and Northrop, 1975; Baltz, 1978; Cordell, 1978). The basins and bounding uplifts generally are arranged with each basin or uplift offset slightly to the east of the one to its south. This pattern plus gravity anomaly lineaments indicate that the crust broke along north-northeast and north-northwest trends oblique to the main north-south structural grain (Ramberg and others, 1978). Kelley (1977) postulated that strike-slip faulting took place during formation of the rift. During this period of rifting, regional extension also began to cause formation of graben-type basins in the remainder of the Basin and Range Province. The Santa Fe Group and its equivalents were deposited in the subsiding basins from late Oligocene through middle Pleistocene time.

The graben structures are complex; many have subsidiary horsts (uplifted blocks) and grabens within the main graben. The basins are often asymmetrical due to a greater total magnitude of fault movement on one side compared to the other. For the rift in general, structural relief is greater on the east side than on the west (Chapin, 1971).

Late Tertiary uplift of the bordering highlands caused erosion of large thicknesses of Oligocene volcanics associated with the rift (Chapin, 1971). Faulting, warping, and tilting deformed the Santa Fe beds, especially at their margins, prior to deposition of the upper Quaternary sediments. A period of relative tectonic quiescence with possible minor warping, local faulting, and slow uplift of borders (Kelley, 1977, p. 53) took place after deposition of the Santa Fe Group (middle to late Pleistocene). The ancestral Rio Grande became a through-flowing river in the basins beginning in Pliocene time (2 to 5 million years ago) (Bachman and Mehnert, 1978). The ancestral river formed a base level to which the high basin surfaces were graded.

Following development of these high basin surfaces, tectonism and localized volcanism occurred. Warping and faulting have caused erosion of large areas of these surfaces (Kelley, 1977; Bachman and Mehnert, 1978). Incision of the Rio Grande probably was affected by integration of the upper Rio Grande system with the lower Rio Grande system and the Gulf of Mexico in the late Pleistocene. Basins outside the rift area also display internal, cyclic, partial dissection of the older basin fill as local drainage developed within the basin.

The present position of the Rio Grande valley was affected by Pliocene and Pleistocene tectonic events (Hawley, 1969; Baltz, 1978), but the morphology, including the formation of the inset terraces, may have been controlled by climatic fluctuation (King and others, 1971). Maximum entrenchment of the river occurred between 11,000 and 22,000 years ago (King and others, 1971, p. 11).

GEOHYDROLOGY OF GROUND-WATER BASINS

Bryan (1938) applied the term "Rio Grande depression" to the series of structural basins separated by canyons or restriction through which the Rio Grande flows. Basin floors consist of broad plains between mountains; they range from 1 to 35 mi wide and from 30 to 135 mi long. More than 50 percent of the study area is within the Rio Grande drainage basin. The part of the study area not within the Rio Grande drainage consists of closed basins, which have no external surface-water drainage.

Highland areas adjacent to the basins are a variety of rock types from Precambrian through early Cenozoic age. As previously discussed, the basin fill is mainly Cenozoic sediments and interbedded igneous rocks. The areal distribution of the various geologic units is shown on plate 2.

Fault scarps and minor displacement in alluvial fans, inner-valley fill, and younger (Pleistocene) basin fill indicate tectonic activity has continued during the Holocene (Hawley, 1969; Chapin, 1971). Sediment deposition continues to take place along mountain fronts and in closed basins.

The occurrence of ground water in basins is controlled primarily by geologic structure and secondarily by the stratigraphy and lithology of rock units. West and Broadhurst (1975, p. 11-13) divided rocks into four basic types: (1) Basin fill--unconsolidated to poorly consolidated sand and gravel interbedded or intermixed with clay and silt; (2) volcanic rocks--primarily basalt, including other volcanic flow rocks, tuff, and small intrusive bodies; (3) consolidated sedimentary rocks--primarily shale and sandstone, including limestone, gypsum, and salt; and (4) crystalline rocks--intrusive igneous rocks and metamorphic rocks.

Thick basin-fill deposits form the principal ground-water reservoir, including recent fan deposits, the inner-valley alluvium, and the Santa Fe Group. These deposits are hydraulically connected and collectively comprise an aquifer system that is anisotropic and heterogeneous. Ground water is generally unconfined, but locally, confined conditions may exist.

Coalescing fan deposits overlie the Santa Fe Group adjacent to mountains. Fan deposits, which may be as much as 200 ft thick near the mountains, contain poorly sorted mudflow materials and well-sorted stream gravels. Along mountain fronts, the deposits may be saturated and yield a few tens of gallons per minute of water to wells, but the deposits generally are above the water table.

Rio Grande flood-plain alluvium is similar in appearance and composition to the underlying Santa Fe Group from which the alluvium is largely derived. The contact of flood-plain alluvium with the Santa Fe Group, generally between 100 and 200 ft below land surface, is probably characterized by a change in lithology and consolidation. Because of the flood-plain deposits' excellent capacity for recharge, transmission, and storage of water, they are capable of supplying as much as 3,000 gallons per minute (gal/min) to wells. Most irrigation and domestic wells along the Rio Grande are completed in the flood-plain alluvium.

The Santa Fe Group is the most important and extensive basin-fill deposit in the Rio Grande depression. It underlies the surficial-fan and flood-plain deposits, but locally is exposed east and west of the river. The Santa Fe consists of beds of unconsolidated to loosely consolidated sediments and interbedded volcanic rocks. Permeability generally is relatively high except in localized areas of fine-grained sediments or along fault zones where cementation has occurred. Wells completed in the Santa Fe Group can yield from several hundred to several thousand gallons of water per minute. The Santa Fe Group is the principal source of water for public and industrial use.

Several individual flow systems occur in the basin. The Rio Grande and associated flood-plain alluvial sediments form one flow system (fig. 3). Tributaries to the Rio Grande and their flood-plain sediments are another (fig. 4). Santa Fe sediments, or basin aquifers, and flood-plain sediments of the Rio Grande and its tributaries form the third system (fig. 5). Interaction of these flow systems is not always the same in all basins.

In basins in which the Rio Grande is present, there is flow of water between the river and alluvial sediments within the flood plain of the river (fig. 3). During years of low river flow, ground-water withdrawal from flood-plain sediments increases, lowering the water table in the flood plain. In periods of high flows, water will be lost from the river and stored in the flood-plain sediments. In basins where ground-water withdrawal from flood-plain sediments is small, water levels in the flood-plain aquifer are, on the average, constant because of good hydraulic connection between the stream, the aquifer, and drains. Evapotranspiration by native vegetation in the flood plain is a significant withdrawal that can cause flow of water from the stream to the flood-plain sediments. Ground-water withdrawal from the flood plain will eventually capture water from surface flow or intercept recharge to the flood-plain sediments or both.

Irrigation water is a recharge source. Surface water is diverted and distributed to fields as canals convey water through a basin. Ground water for irrigation is withdrawn from flood-plain sediments or the basin aquifer. Regardless of the source of irrigation water, when it is applied to fields it is used by crops, recharged to the flood-plain sediments, extracted by drains, if they are present, or recharged to the basin-aquifer system.

The Rio Grande flood-plain system is hydraulically connected to the surrounding basin-aquifer system; the following discussion also applies to tributary stream-aquifer systems (fig. 4). If recharge from a stream is perched above the basin aquifer, the recharge does not immediately affect the basin-aquifer system. There is, however, leakage through unsaturated flood-plain sediments downward to the basin aquifer, as long as there is flow in the river. Recharge to the basin aquifer is constant and controlled by characteristics of unsaturated sediments between the flood plain and the basin aquifer. In the case of saturation between flood plain and Santa Fe sediments, flow between these two systems is controlled by permeability of the sediments and the ground-water gradient between the flood plain and the basin-aquifer water surfaces. If the gradient is such that direction of flow is toward the flood plain, the basin aquifer is a source of recharge and the

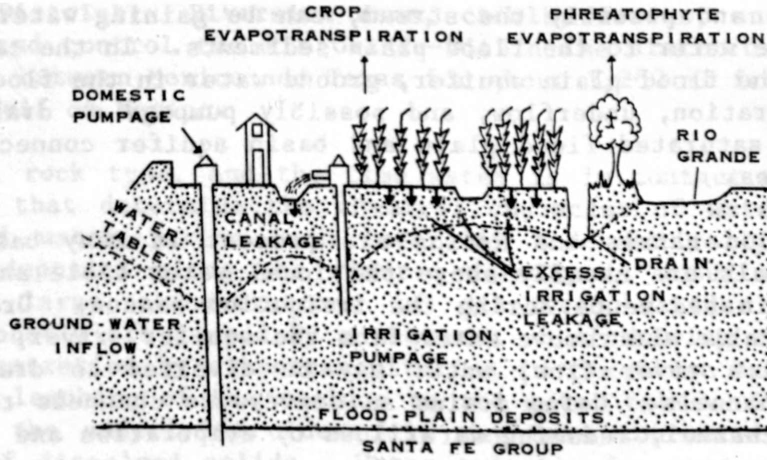

Figure 3.--Generalized Rio Grande flood-plain flow system.

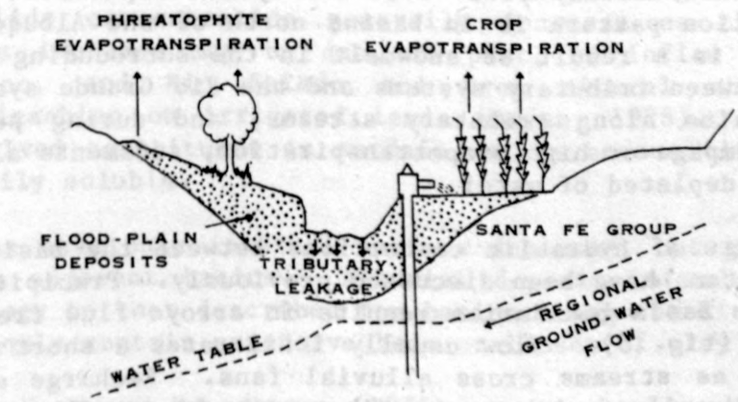

Figure 4.--Generalized tributary flood-plain flow system.

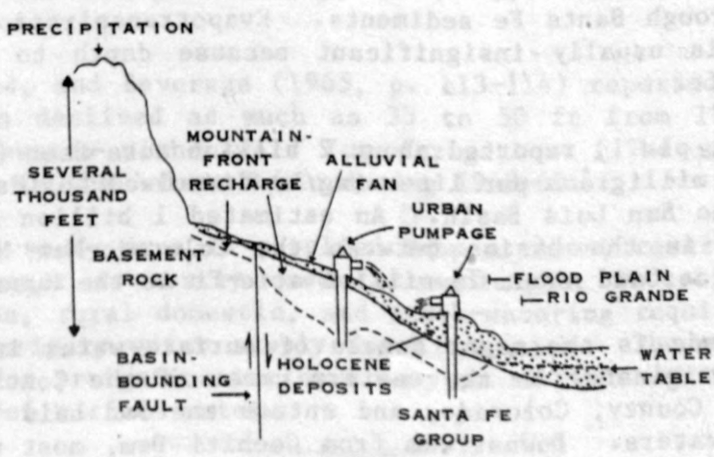

Figure 5.--Generalized basin-aquifer and flood-plain flow system.

flood plain, and possibly the stream, can be gaining water. The stream may, however, lose water to the flood-plain sediments. In the case of both sources recharging the flood-plain aquifer, ground water in the flood plain is lost by evapotranspiration, underflow, and possibly pumpage or drain flow. Both the perched and saturated flood plain and basin aquifer connections are found in the study area.

Irrigation canals and drains are present in many basins along the Rio Grande. Canals are usually above the local water table and contribute water to flood-plain sediments during the irrigation season. Drains are below the local water table and remove water from the aquifer, river, and canals. During periods of low river flow, water may be diverted to drains, which become conveyance channels. Using drains as conveyance channels reduces the surface area of the channel, reducing water loss by evaporation and leakage.

The flow system of Rio Grande tributaries and associated flood-plain sediments (fig. 4) is very similar to the river flood-plain system. Surface-water recharge to a tributary flood plain is erratic and results from summer thunderstorms that usually occur between May and September. The exception to this precipitation pattern is in basins north of the Albuquerque-Belen Basin where recharge is a result of snowmelt in the surrounding mountains. Other differences between tributary systems and the Rio Grande system are there are usually no drains along tributary streams, and during periods of maximum ground-water pumpage or high evapotranspiration, sediments along the tributary streams may be depleted of water.

Some aspects of hydraulic connections between the basin aquifer and the flood-plain systems have been discussed previously. Precipitation on highland areas that form basin boundaries results in arroyo flow from the surrounding uplifted areas (fig. 5). Flow usually infiltrates a short distance from the mountain front as streams cross alluvial fans. Recharge at the margins of basins results in a ground-water gradient that forces flow toward the axis of the basin, generally also the location of the Rio Grande. As water reaches the vicinity of the central stream, the flow lines swing more or less parallel to the stream channel and may become part of the stream flood-plain flow system. In some basins, there may be significant ground-water flow in and out of the basin through Santa Fe sediments. Evapotranspiration from the basin-aquifer system is usually insignificant because depth to water is usually greater than 20 ft.

Kelly (1974, pl. 1) reported about 2 billion acre-feet (acre-ft) of fresh (less than 1,000 milligrams per liter (mg/L) dissolved solids) ground water is in storage in the San Luis Basin. An estimated 1 billion acre-ft of ground water is stored in the basins between the Colorado-New Mexico border and Socorro, New Mexico, and about 7½ million acre-ft in the Hueco Basin area.

The Rio Grande is the major source of surface water in the study area. The Rio Grande originates on the eastern crest of the Continental Divide in eastern San Juan County, Colorado, and enters the San Luis Valley some 65 mi east of its headwaters. Downstream from Cochiti Dam, most water is diverted into canals of the Middle Rio Grande Conservancy District and the Elephant

Butte Irrigation District. Diversion dams, canals, drains, and levees are used to regulate and control the Rio Grande within the districts. The river forms the boundary between Mexico and Texas for about 1,250 mi from El Paso to its mouth at the Gulf of Mexico.

Stratigraphy, rock type, and the time water is in contact with rock are principal factors that determine the chemical character of water. Chemical quality of ground water varies both laterally and vertically. Water in shallow alluvial deposits along the river generally is unsuitable for many uses because of large concentrations of dissolved solids. The large concentrations probably are caused by a sequence of dissolving soil salts and fertilizers, concentration by evapotranspiration in the first few feet of the soil profile, and leaching of the residue to the water table. Water at a few thousand feet in the underlying older fill may have concentrations greater than 3,000 mg/L of dissolved solids. Water suitable for most uses generally occurs at intermediate depths in the Santa Fe Group.

Rio Grande water generally is clear with dissolved-solids concentrations less than 500 mg/L in the San Luis Valley. In New Mexico, the sediment load and dissolved-solids concentration generally increase as the river flows downstream. This increase may be due, in part, to inflow from the Jemez River, Rio Puerco, and Rio Salado and from mineral concentration by evaporation and leaching on irrigated lands (Bryan, 1938). Sulfate is the predominant dissolved constituent in surface waters because it is present in rocks and is readily soluble.

Closed basins have only internal surface drainage, but ground water may move to and from adjacent basins. Alluvial deposits of closed basins are similar in lithology to that described for basins along the Rio Grande, except the deposits commonly contain extensive beds or lenses of clay and silt.

According to West and Broadhurst (1975), water supplies in closed basins are derived almost entirely from ground water. Chemical quality of ground water near the central parts of closed basins is such that water may be unusable for many purposes. Dissolved solids are increased by evaporation of ponded water and leaching of minerals in the upper soil profile to the water table.

Hale, Reiland, and Beverage (1965, p. 113-114) reported water levels in the Mimbres Basin declined as much as 35 to 50 ft from 1940 to 1960 as a result of ground-water withdrawals for irrigation. The same magnitude of decline was noted in the Animas Basin during 1948-60.

Water in the study area is supplied from streams, reservoirs, and ground water. Ground water is mostly used for municipal, industrial, commercial, mineral-production, rural domestic, and stock-watering requirements. Surface sources are the primary water supply for irrigation. The quantity of ground water withdrawn for irrigation varies from year to year and depends in part on the availability of surface water.

San Luis Basin

The San Luis Basin is the northernmost basin and extends from Poncha Pass in the northeast corner of Saguache County, Colorado, to the valley constriction near Embudo, New Mexico (pl. 1). Alamosa, Colorado, and Taos, New Mexico, are in this basin. The basin is about 135 mi long and as much as 40 mi wide. The northern part of the basin is closed and has only interior surface drainage. The southern part is drained by the Rio Grande and includes the area south of the San Luis Hills and the Sunshine Valley in New Mexico. The topographic divide that marks the southern extent of the closed basin is roughly parallel to and just north of Colorado State Highway 149 and U.S. Highway 160. Total annual precipitation ranges from about 7 in. at Alamosa, Colorado, to about 68 in. at Wolf Creek Pass. Precipitation in the Sunshine Valley is about 12 in. per year.

The following discussion applies only to that part of the San Luis Basin in Colorado, locally called the San Luis Valley. The San Luis Valley is bounded on the west by the San Juan Mountains, which are mainly volcanic flows, tuffs, and breccias (pl. 2). The Sangre de Cristo Mountains form the eastern boundary and are igneous, metamorphic, and sedimentary rocks (Larsen and Cross, 1956, p. 62). Gaca and Karig (1966, p. 1) reported as much as 30,000 ft of alluvium, volcanic debris, and interbedded volcanic flows and tuffs in the basin. Many lava flows and tuffs in the San Juan Mountains dip eastward under the valley. In the southwestern part of the valley, these dipping beds restrict the vertical movement of ground water. A clay series, 10 to 80 ft thick in much of the central and northern part of the valley at depths from 50 to 130 ft below land surface, also restricts vertical ground-water flow (Emery and others, 1971). The clay series and volcanic flows and tuffs are discontinuous confining beds creating a confined (artesian) system north of the Rio Grande. Sections through the San Luis Valley are shown in figures 6-9. The sections run north to south through the valley (A-A'), along the Rio Grande (B-B'), and along the Conejos River (C-C'). These sections show the clay and volcanic rocks that act as confining beds. The blue clay with layers of sand and gravel shown on the three sections probably corresponds to part of the confined aquifer described above. The detail on the three sections is not sufficient to show the discontinuous character of the clay and volcanic confining beds. The sections do, however, in general correspond to zones of transmissivity values reported by Emery, Patten, and Moore (1975, pl. 2).

Emery, Patten, and Moore (1975, p. 8) estimated transmissivity of the unconfined aquifer to be from 1,300 to 26,800 feet squared per day (ft^2/d). Transmissivity is the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient (Lohman and others, 1972, p. 13). Transmissivity in the confined aquifer was estimated to be between 3,400 ft^2/d and 201,000 ft^2/d for the interval from 120 to 1,620 ft below land surface. For the interval from 1,620 to 3,120 ft below land surface, transmissivity was estimated at 40,000 ft^2/d.

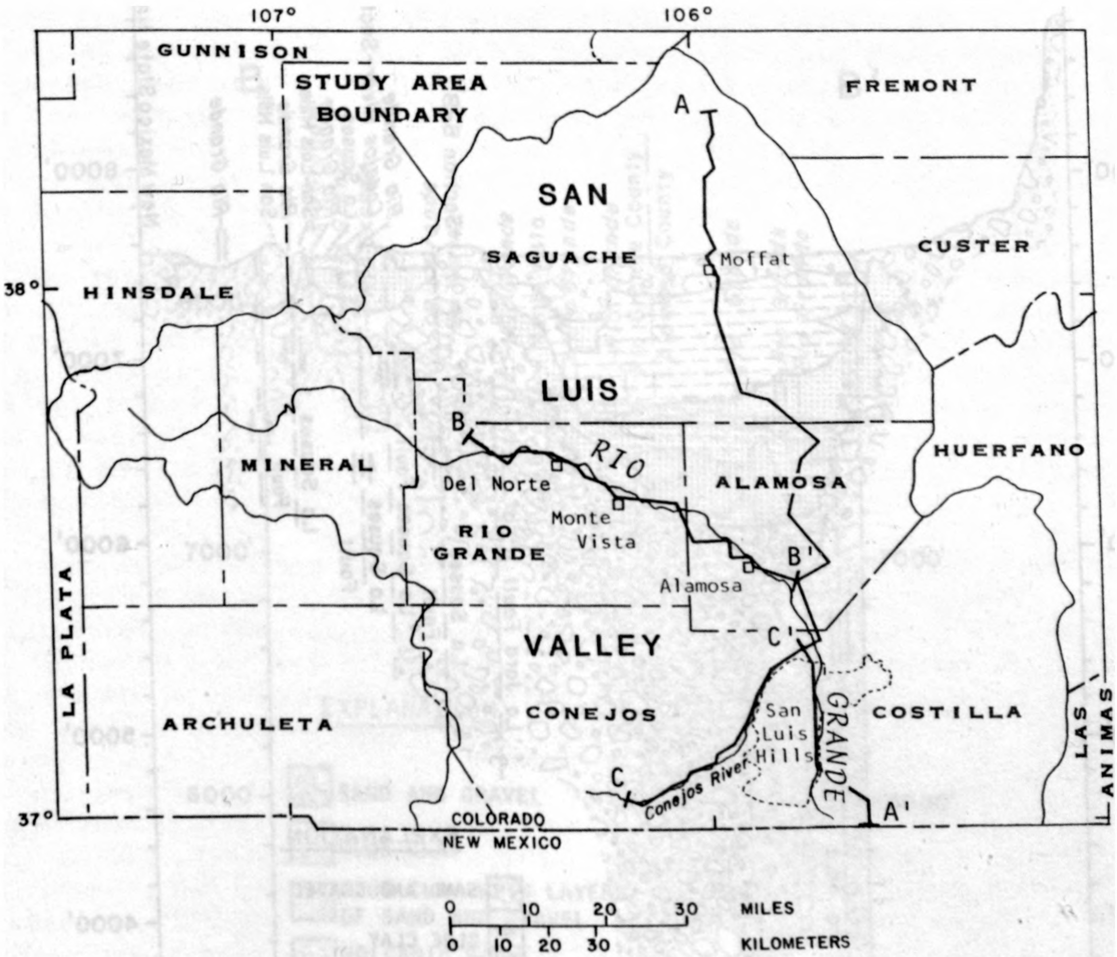

Figure 6--Approximate location of generalized structure sections A-A', B-B', and C-C' in the San Luis Valley, Colorado.

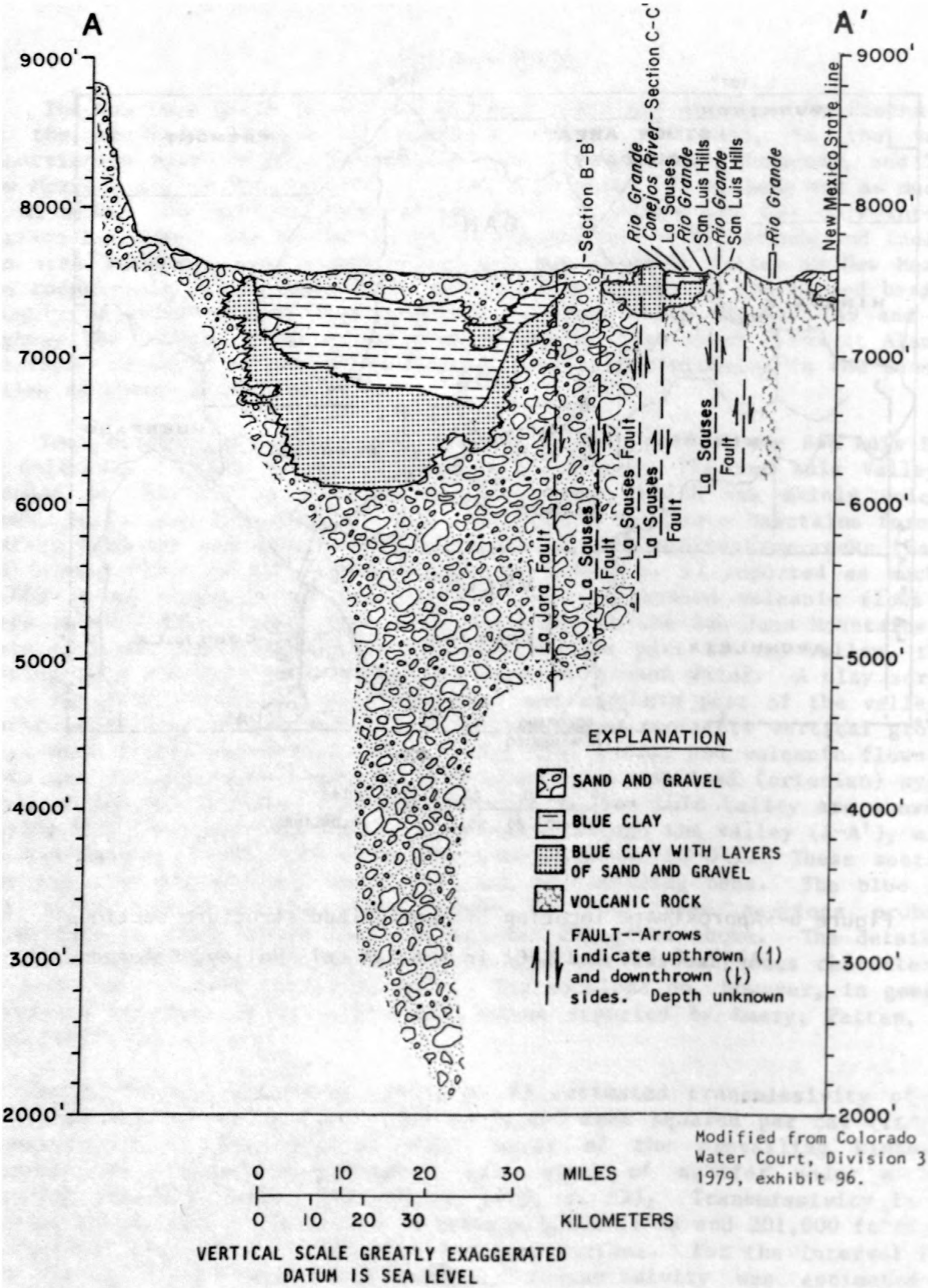

Figure 7.--Generalized structure section A-A', north to south, in the San Luis Valley, Colorado.

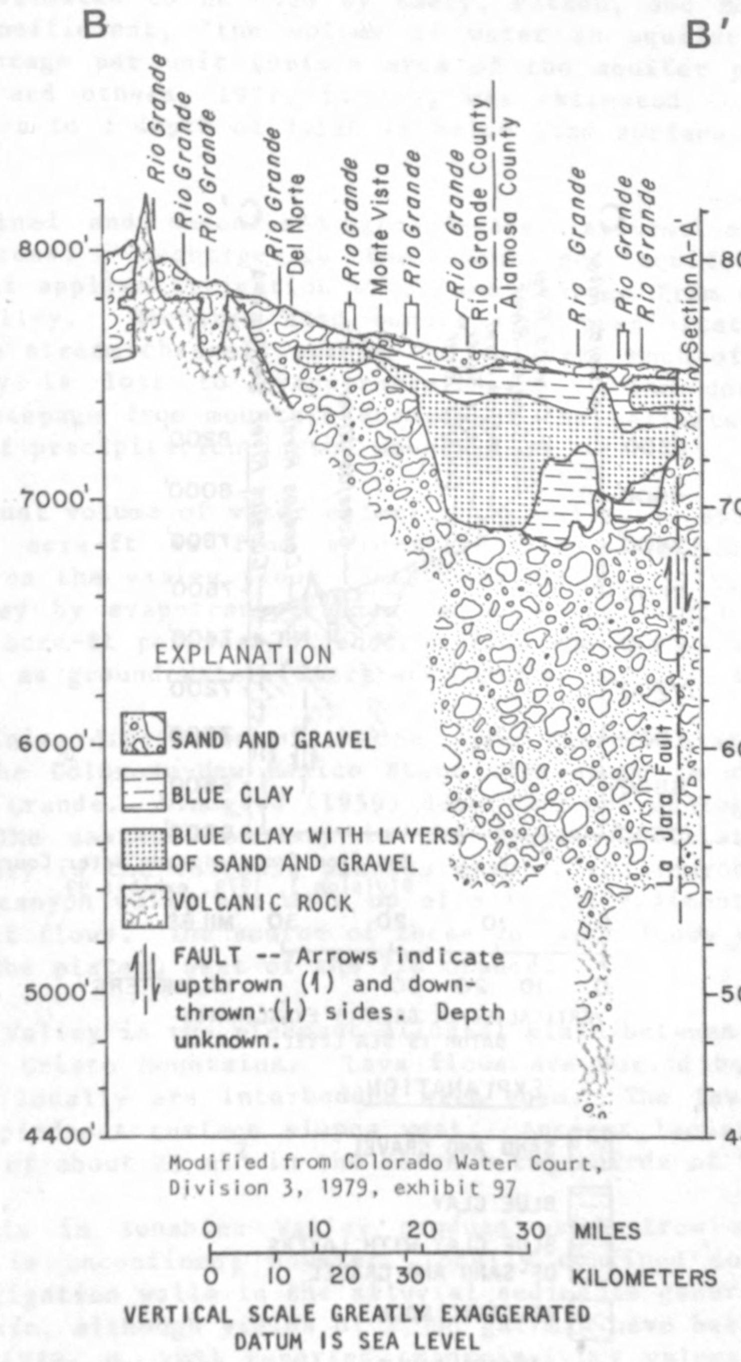

Figure 8.--Generalized structure section B-B' along the Rio Grande, San Luis Valley, Colorado.

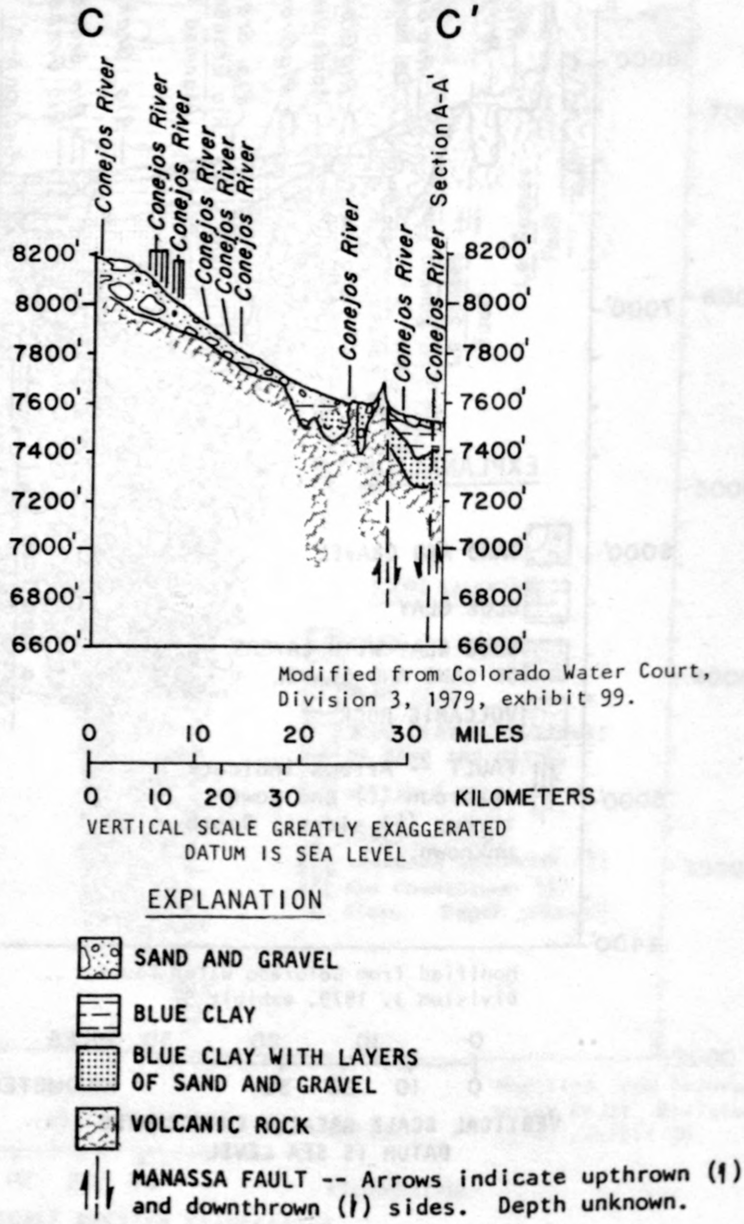

Figure 9.--Generalized structure section C-C' along the Conejos River, San Luis Valley, Colorado.

Specific yield, the ratio of the volume of water that saturated rock will yield by gravity drainage to the volume of the rock (Lohman and others, 1972, p. 12), was estimated to be 0.20 by Emery, Patten, and Moore (1975, p. 8). The storage coefficient, "the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head" (Lohman and others, 1972, p. 13), was estimated to be 0.008 for the confined aquifer to a depth of 3,120 ft below land surface (Emery and others, 1975, p. 8).

The confined and unconfined ground-water systems are recharged from different sources. Recharge to the unconfined aquifer is mainly from infiltration of applied irrigation water and leakage from ditches and canals within the valley. Recharge also occurs from precipitation on the valley floor and from stream channels within the valley. Much of the precipitation in the valley is lost to evapotranspiration. The confined aquifer is recharged by seepage from mountain streams at the perimeter of the basin and infiltration of precipitation in the mountains.

Total annual volume of water entering the valley is about 2,800,000 acre-ft; 1,580,000 acre-ft is from streamflow and 1,220,000 acre-ft is from precipitation on the valley floor (Emery and others, 1975, p. 3). Discharge from the valley by evapotranspiration is about 2,400,000 acre-ft per year. About 330,000 acre-ft per year discharges from the valley as surface flow and 50,000 acre-ft as ground water (Emery and others, 1975, p. 4).

The remaining discussion of the San Luis Basin pertains to the Sunshine Valley from the Colorado-New Mexico State line south to where the Red River joins the Rio Grande. Winograd (1959) described the geology and hydrology of this area. The eastern boundary is the Sangre de Cristo Mountains. The western boundary is the volcanic plateau west of the canyon formed by the Rio Grande. The canyon walls are made up of alluvial sediments interbedded with andesite-basalt flows. The source of these volcanic flows was the now-extinct volcanoes on the plateau west of the Rio Grande.

Sunshine Valley is the piedmont alluvial plain between the Rio Grande and the Sangre de Cristo Mountains. Lava flows are buried beneath the alluvial sediments and locally are interbedded with them. The lava flows dip to the east and the piedmont surface slopes west. Ancient lacustrine clay deposits cover an area of about 20 mi^2 in the eastern two-thirds of T. 30 N., R. 12 E.

Most wells in Sunshine Valley produce water from alluvial sediments. Ground water is unconfined; however, locally confined conditions have been reported. Irrigation wells in the alluvial sediments generally yield from 600 to 1,200 gal/min, although yields of 3,000 gal/min have been reported. Wilson and Jenkins (1979, p. 298) reported transmissivity values from 900 to 7,000 ft^2/d in the Toso-Valdez area for the Santa Fe sediments, and well yields from 15 to 30 gal/min.

Recharge in Sunshine Valley is primarily from losses in perennial streams and related irrigation ditches and from precipitation. At least 20,000 acre-ft per year recharges the valley: in excess of 10,000 acre-ft from surface water and at least 10,000 additional acre-ft from precipitation. Most of the recharge is to the alluvial sediments. A small amount is thought to occur directly to the lava from precipitation on Ute and Guadalupe Mountains; however, most recharge to the lava probably is leakage from the alluvium.

Ground-water flow is from east to west. Ground water discharges through evapotranspiration in the south-central part of Sunshine Valley where depth to water is shallow. Water in the lava discharges to the Rio Grande. Total discharge to the Rio Grande and Red River between the Lobatos gage on the Rio Grande in Colorado and the confluence of the Red River is about 80,000 acre-ft per year. Ground water discharges to the Rio Grande from Sunshine Valley east of the Rio Grande and from the plateau west of the river, but a lack of data precluded separate estimates of discharge from the east and west sides of the river. Winograd (1959, p. 40) estimated 12,000 acre-ft per year accretion to Red River is from Sunshine Valley. Irrigated acreage in San Luis and Sunshine Valleys was estimated at 796,500 acres (Sorensen, 1977; U.S. Department of Agriculture Soil Conservation Service and Colorado State University Experiment Station, 1979a, b, and c and 1980a and b).

Española Basin

The Española Basin, south of the San Luis Basin (pl. 1), is 40 to 50 mi long and 18 to 40 mi wide. Within the Española Basin are the cities of Santa Fe and Española, New Mexico. The Rio Grande is the major stream; the Rio Chama enters the Rio Grande about 8 mi north of Española. Annual precipitation ranges from about 10 in. at Alcalde to about 16 in. at Santa Fe.

The northern boundary is the Embudo constriction where Precambrian rocks crop out through Tertiary sediments (pl. 2). The Sangre de Cristo Range is the eastern boundary, which is the longest and largest mountain range in New Mexico (Kelley, 1956, p. 111). The southern boundary is a volcanic highland through which White Rock Canyon is cut. The western boundary (Kelley, 1956, p. 111) is the Jemez Uplift. Faults along the uplifted western boundary are covered by Bandelier Tuff and Valles Rhyolite and have brought lower and middle Tertiary rocks of the Jemez Uplift adjacent to upper Tertiary Santa Fe rocks.

Rocks of the Santa Fe Group are pinkish or light tan (Kelley, 1956, p. 113) and are typically nonvolcanic. On the west side of the basin, coarse fragments are almost exclusively volcanic, representing the pyroclastic breccia and tuff around the Jemez Uplift. In the eastern half of the basin, the Santa Fe Group is tilted westward 5 to 10 degrees at the fault scarp along the west front of the Sangre de Cristo Range. The axis of the basin is along the Rio Grande; here the beds are nearly horizontal. The exposed Santa Fe beds along the west display a low easterly dip (Kelley, 1956, p. 111). High pediment gravels are principally post-Santa Fe deposits described as the Ancha Formation (Kelley, 1978). The Ancha is angular to subangular gravel ranging in size from pebbles to large boulders. Titus (1961, p. 188) differentiated Santa Fe sediments from recent alluvium on the basis that recent sediments contain larger amounts of gravel, clay, and organic matter.

Sediments of the Santa Fe Group and Quaternary alluvium are the important aquifers in the Española Basin. Borton (1974, p. 353) reported a maximum Santa Fe sediment thickness of about 12,000 ft near Española from preliminary gravity studies. Cordell (1979, p. 61) indicated low-density rocks, which he considered primarily Santa Fe Group (including volcanics), may be as thick as 8,200 to 16,400 ft in a graben just south of Española (Manley, 1979, p. 79). In a graben south and east of Los Alamos the low-density rocks might be between 7,900 and 19,000 ft thick (Cordell, 1979, p. 62). South of Santa Fe, out of the flood plain of the Rio Grande, Cordell (1979, p. 63) showed low-density rock thickness from 4,300 to 6,900 ft. Cordell (1970, p. 158) reported intradepression basins south of Abiquiu and a northwest-trending, transverse, structural high in the El Rito-Embudo area.

Titus (1961, p. 186) reported well yields west of Santa Fe to be 500 to 700 gal/min. He (Titus, 1961, p. 188) reported artesian conditions, from 1 to 4 mi west of the Rio Grande, with pumping rates ranging from 250 to 650 gal/min. Borton (1974, p. 353) reported artesian conditions northwest and southwest of Chimayo; one well reportedly flowed at 200 gal/min. Large-diameter, gravel-packed wells at Española will produce as much as 250 gal/min (Borton, 1974, p. 354). Wilson and Jenkins (1979, p. 295) reported transmissivity values from 100 to 5,000 ft^2/d near Santa Fe and about 800 ft^2/d for the Buckman well field 15 mi northwest of Santa Fe. Hearne (1981, p. 13-14) estimated transmissivity values of 1,200 to 2,100 ft^2/d for the upper 2,000 ft of the Tesuque Formation of the Santa Fe Group in canyons east of Los Alamos near the flood plain of the Rio Grande. Hearne (1981, p. 19) estimated a range of hydraulic conductivity from 0.5 to 1.0 foot per day (ft/d) for the Pojoaque River basin. Hydraulic conductivity is the volume of water that will flow through a unit area under a unit hydraulic gradient; hydraulic conductivity multiplied by the thickness of the aquifer equals transmissivity.

Most recharge to the Santa Fe Group is derived from precipitation on the mountains east and west of the valley floor. The aquifers are recharged from percolation at the margins of the aquifers and leakage from surface streams. Spiegel and Baldwin (1963, p. 173) estimated leakage from the Santa Fe River to be 1 cubic foot per second per mile (ft^3/sec/mi). This estimate was based on the loss of flow between two gages on the Rio Tesuque. Hearne (1981, p. 34) estimated recharge to the Tesuque aquifer to be about 24 cubic feet per second (ft^3/sec).

Discharge from the Española Basin aquifer system is from pumpage, evaporation, transpiration from crops and native vegetation, and discharge to streams. Spiegel and Baldwin (1963, p. 16) reported average potential evaporation at Santa Fe of about 65 in. per year. Hearne (1981, p. 53) showed that pumpage from the Los Alamos Canyon, Guaje Canyon, Pajarito Mesa, and Buckman well fields was about 7,470 acre-ft in 1977. Hearne (1981, p. 44) estimated ground-water inflow to the Rio Grande throughout the Española Basin to be about 0.5 ft^3/sec/mi or less and no greater than 1 ft^3/sec/mi. In 1978, irrigated acreage in the Española Basin included 22,600 acres using surface water, 420 acres using ground water, and 730 acres using surface and ground water combined. Ground-water withdrawals in the basin for irrigation are probably insignificant.

Santo Domingo Basin

The Santo Domingo Basin begins at the mouth of White Rock Canyon and extends for about 20 mi southward along the Rio Grande to the Jemez River (pl. 1). The basin is about 20 mi wide. Kelley (1952, p. 95) indicated that there is a structural basin divide between the Albuquerque-Belen and the Santo Domingo Basins. A small prong of Mesozoic rocks crops out east of the Rio Grande. West of the Rio Grande volcanic rocks are broken by a system of small parallel faults that extend to the Jemez Mountains. There are no large population centers. About 5,500 acres are irrigated with surface water and 130 acres with both surface and ground water.

Albuquerque-Belen Basin

Within the Albuquerque-Belen Basin are Bernalillo, Albuquerque, Los Lunas, and Belen (pl. 1). The northern boundary is the valley constriction created by mesas near San Felipe Pueblo. The Sandia, Manzano, and Los Pinos Mountains are the eastern boundary; the constriction at San Acacia is the southern boundary. The western boundary is formed by Ladron Peak and adjacent mountains in the southwest and the Sierra Lucero and Jemez Mountains in the north. The basin is about 80 mi long and 25 to 35 mi wide. Precipitation ranges from 11 in. at Bernalillo to 8 in. at Los Lunas. Precipitation on the crest of the Sandia Mountains is about 16 in. per year.

The following discussion of basin boundaries and aquifer characteristics is taken from Bjorklund and Maxwell (1961). The upfaulted blocks of the eastern boundary are of Precambrian, Paleozoic, and Mesozoic age and form the Sandia and Manzano Mountains (pl. 2). The western boundary is highlands of Mesozoic-age rocks west of the Rio Puerco and Permian and Pennsylvanian rocks around Ladron Peak.

Upper Tertiary and Quaternary rocks crop out over most of the area and are the aquifers in this basin. Beds of the Santa Fe Group dip slightly from the east and west basin margins toward the axis of the graben where they are nearly horizontal. The aquifer associated with the Santa Fe is unconsolidated to loosely consolidated sediments and interbedded volcanic rocks. The Santa Fe Group in the Albuquerque-Belen Basin is equivalent to the Ancha Formation and upper part of the Tesuque Formation in the Española Basin. The Sandia and Manzano Mountains contribute fragments of mainly feldspar and quartz to the basin sediments east of the river. The material is coarse and unsorted near the mountains and becomes finer grained and better sorted toward the center of the basin. Sediments west of the river are fine-grained sand, silt, and clay debris from rocks of Mesozoic and Paleozoic age. In the center of the basin the material is a mixture of sediments from all source areas.

Bjorklund and Maxwell (1961, p. 21) reported maximum thickness of Santa Fe sediments greater than 9,000 ft. Birch (1980a) used existing gravity data to define a layer with a density of 2.20 grams per cubic centimeter that he called the Neogene; he includes the Santa Fe and Quaternary deposits in the Neogene (Birch, 1980a, p. 3). Birch (1980a, p. 19) described a Neogene thickness of 6,500 to 8,200 ft in a north-south belt along the east side of the basin (pl. 3).

Average permeability of the Santa Fe sediments generally is high except in the Rio Puerco valley and in the lower part of the aquifer along the Sandia and Manzano Mountains (Bjorklund and Maxwell, 1961, p. 21). These authors (1961, p. 71-86) reported a range in transmissivity from 6,700 to 80,000 ft^2/d. Estimates of transmissivity from specific capacity data range from 290 to 40,000 ft^2/d (U.S. Army Corps of Engineers, 1979, p. 3-22 - 3-24).

Recharge to the ground-water system in the Albuquerque Greater Urban Area (AGUA) (U.S. Army Corps of Engineers, 1979, p. 2-19, 2-56) ranges from 231,000 acre-ft in 1971 to 316,000 acre-ft in 1976 for 1967-77. Bjorklund and Maxwell (1961, p. 52) estimated 30,000 acre-ft of Rio Grande underflow moves into the Albuquerque-Belen Basin.

Discharge from the basin is through evapotranspiration, ground-water pumpage, and outflow. The U.S. Army Corps of Engineers (1979) reported that discharge from the ground-water system ranged from 258,000 acre-ft in 1968 to 352,000 acre-ft in 1976. The Corps (1979) estimated the change in storage during 1967-77 to be in excess of 300,000 acre-ft. Discharge from the basin as underflow is unknown. In 1978, about 60,000 acres were irrigated in the basin, of which about 34,100 acres were irrigated with surface water, 1,200 acres with ground water, and 24,600 acres with both surface and ground water.

Socorro Basin

The Socorro Basin is south of the Albuquerque-Belen Basin. The northern boundary is at the constriction near San Acacia (pl. 1). The town of Socorro is the major population center. The basin is about 35 mi long, the southern boundary being at San Marcial. The Socorro Basin is 8 to 12 mi wide and the flood plain is 1 to 3 mi wide. The western boundary is formed by the Lemitar Mountains, Socorro Peak, and the Chupadera Mountains. The eastern boundary includes the Joyita Hills and the Loma de las Canas Uplift. The basin is adjacent to the La Jencia on the west and the Jornada del Muerto on the east.

The area has not undergone intensive development that would require extensive use of ground or surface waters. Water use in the basin is for agriculture; crops are grown on the flood plain, and in the surrounding areas, there is ranching.

Socorro Peak and the Lemitar Mountains (pl. 2) are Precambrian, Paleozoic, and Tertiary volcanic rocks (Waldron, 1956, p. 51-56). The Chupadera Mountains are Tertiary volcanics and Tertiary Popotosa Formation (Chamberlin and Osburn, 1976-77, map 1). Dane and Bachman (1965) showed the Socorro Basin as being bounded on the east by Permian and Pennsylvanian rocks from the Joyita Hills to just north of the Cerro Colorado.

Bushman (1963, p. 155) defined two aquifer systems: the Quaternary alluvium and the Quaternary-Tertiary aquifer of the Santa Fe Group. Waldron (1956, p. 80) described the Quaternary-Tertiary aquifer in the Socorro area as cropping out in the mountains to the west and dipping eastward to the Rio

Grande valley and also westward to Snake Ranch Flats. The Quaternary alluvial aquifer is flood-plain material of unconsolidated gravel, sands, and clays. Birch (1980b) showed maximum thickness of the Neogene, south of Socorro, to be about 3,300 ft (pl. 3), aligning with the axis of the basin.

Waldron (1956, p. 150-163) reported transmissivities for an aquifer test in sediments of the mountain slopes west of the river to be about 4,100 ft^2/d and for a test in flood-plain sediments to be about 6,700 ft^2/d. Bushman (1963, p. 157), reporting on work by Hantush, reported an average transmissivity of about 44,100 ft^2/d in the Socorro and Lemitar areas.

Bushman (1963, p. 156) showed ground-water flow in the flood plain from north to south with little noticeable inflow from the surrounding area. He noted there is probably recharge from the mountains, but it does not influence the general slope of the water table. Precipitation at Socorro and Bosque del Apache averages about 8 in. per year. Potential evaporation at Elephant Butte Dam is about 105 in. per year. Waldron (1956, p. 110) reported the Lemitar Mountains restrict eastward flow from La Jencia Basin, but some ground water may flow through the Socorro Mountains. He based this conclusion on the existence of Socorro Spring on the east side of the Socorro Mountains.

The city of Socorro uses about 670 acre-ft per year (New Mexico Interstate Stream Commission and New Mexico State Engineer Office, 1974b, p. 18). Approximately 2,300 acres are irrigated with surface water and 12,000 acres with surface and ground water combined.

San Marcial Basin

The constriction near San Marcial divides the Socorro Basin from the San Marcial Basin (pl. 1). The San Marcial Basin is about 15 mi long, 10 to 20 mi wide, and includes the upper end of Elephant Butte Reservoir. The basin is bounded on the east by Black Mesa (pl. 2). The Magdalena and San Mateo Mountains form the western boundary; both mountain ranges are composed of the Tertiary Datil Formation (Dane and Bachman, 1965). The southern boundary is the constriction formed by the northern end of the Fra Cristobal Range on the east and the southern end of the San Mateo Mountains to the west. There is virtually no development in the basin and therefore little geohydrologic data.

Engle Basin

The Engle Basin is the next downstream basin (pl. 1); it is about 15 mi long and 20 mi wide and contains most of Elephant Butte Reservoir. The southern boundary is a narrow constriction between the north end of the Caballo Mountains, east of the river, and the Mud Spring Mountains, west of the Rio Grande. The basin is bounded by the Fra Cristobal Range to the east and the Cuchillo Mountains to the west. The area is arid with about 8 in. of annual precipitation at Truth or Consequences and about 11 in. at Winston in the Black Range west of the basin.

The Fra Cristobal Range separates the Engle Basin from the Jornada del Muerto Basin to the east and probably acts as an impermeable hydrologic boundary. The Fra Cristobal Range is composed mainly of Precambrian and Paleozoic rocks (pl. 2) (Harley, 1934, p. 195). The Cuchillo Mountains are an impermeable hydrologic boundary, principally of Paleozoic rocks but with some Tertiary intrusive rocks. Tertiary extrusive rocks form the east side of the mountains; these same extrusive rocks are in the San Mateo Mountains (Harley, 1934, p. 113). The Mud Springs and San Mateo Mountains are the southern boundary. The Mud Springs Mountains are composed of Paleozoic rocks with a basement of Precambrian rocks (Harley, 1934, p. 193). The Caballo Mountains, which form the southeast boundary, will be discussed later.

The main aquifer is composed of the Santa Fe Group. Borton (1961, p. 6-9) described the sediments west of Interstate 25 as a varying thickness of silt, sand, and gravel derived from volcanic rocks of preexisting highlands to the north and west. He reported that the beds generally dip northeastward at 5 degrees or less and the aquifer thickens eastward.

Two wells in the flood plain of the Cuchillo Negro Creek were drilled into bedrock at about 225 to 386 ft (Borton, 1961, p. 8). Birch (1980b) showed a Neogene thickness of more than 6,500 ft immediately west of the south end of the Fra Cristobal Range (pl. 3). Birch also showed a small area almost directly north of the Mud Springs Mountains with a depth greater than 6,500 ft corresponding to the axis of the basin.

Borton (1961, p. 14) reported yields for irrigation wells of 500 gal/min. Artesian conditions were reported to exist south and east of the Cuchillo Negro area. Recharge is from surrounding mountains at the bedrock-alluvial interface and through channels of streams flowing across alluvial material.

Irrigation is along tributaries to the Rio Grande. Total acreage using surface water is 590 acres, ground water 320 acres, and combined ground and surface water 330 acres. A total of about 1,240 acres is irrigated in the basin.

Palomas Basin

The Palomas Basin is south of the Engle Basin; it is 30 to 35 mi long and about 12 mi wide. Hatch is the population center. The basin narrows considerably and changes from a southerly to a southeasterly orientation near Hatch. Hawley and Seager (1978, p. 72) showed the Palomas as a major Rio Grande Rift basin as far south as the Robledo Mountains where the basin is truncated by Quaternary faulting. The basin is connected to the Engle Basin by the Rio Grande and a structural trough west of the Mud Spring Mountains (pl. 1) (Kelley, 1952, p. 99). The Precambrian, Paleozoic, and Pennsylvanian Caballo Mountains form the eastern boundary (pl. 2). The mountains are a fault-block feature gently tilted to the east with Santa Fe Group and pediment gravels downfaulted against Precambrian on the west side. The Animas Mountains, composed of Tertiary volcanic and Paleozoic rocks, form the western boundary. The southern boundary is the constriction near Leasburg. Also included in the area is Uvas Valley, which is bounded by the Sierra de las Uvas on the east and the Goodsight Mountains on the west. These mountain areas are described by King and others (1971, p. 15) as volcanic rocks and associated sedimentary rocks of middle Tertiary age.

Murray (1959, p. 7-11) described the valley fill from Truth or Consequences to Caballo Dam as unconsolidated or partly consolidated sand, gravel, and clay. Near the mountains, clay and fine sand disappear and the sediments are poorly sorted conglomerate with volcanic pebbles. The strata generally dip eastward; near Mud Springs Draw, the beds are nearly horizontal. Tertiary igneous rocks probably underlie the area. Birch (1980b) reported a maximum thickness of Neogene sediments of 4,900 ft near Caballo Reservoir and westward (pl. 3).

South of Caballo Dam to near San Diego Mountain is the Rincon Valley of the Palomas Basin (Wilson and others, 1981, p. 6). King and others (1971, p. 58) reported a depth of the late Quaternary aquifer in the Rincon Valley of about 80 ft. Below this aquifer, King and others (1971, p. 17) described a nonproductive clay facies greater than 2,000 ft thick.

The Uvas Valley's main aquifer is Quaternary gravel and sand deposits. An upper sedimentary member of the Tertiary Bell Top Formation (Kottlowski, 1953) and a scoriaceous zone of the Tertiary Uvas basaltic andesite also are aquifers, transporting water from outcrops in the Sierra de las Uvas westward under the Uvas Valley (Clemons, 1979, p. 21).

In parts of the northern Palomas Basin, ground water occurs under confined conditions. Along Mud Springs Draw, Animas Creek, and Percha Creek, artesian wells are reported. Along the Rio Grande from near Truth or Consequences to Arrey, 18 miles to the south, wells produce from a confined aquifer. The confined conditions are associated with clays in the center of the basin that act as confining layers (Murray, 1959, p. 11). Flow from artesian wells is reported to range from a few gallons per minute to almost 300 gal/min (Murray, 1959, p. 11-12).

Murray (1959, p. 26) reported a maximum transmissivity for the confined aquifer in the Mud Springs Draw area of about 1,500 ft^2/d. Wilson and others (1981, p. 40-41) reported specific capacities for the unconfined system in the Rincon Valley from 17 to 79 gallons per minute per foot (gal/min/ft) and averaged 50 gal/min/ft. They estimated the hydraulic conductivity at about 170 ft/d from earlier work done by Conover (1954).

Recharge to both the confined and unconfined aquifer north of Caballo Dam is mostly from the west (Murray, 1959, p. 19). Murray (1959, p. 19-20) indicated the most important sources of recharge are perennial streams that head west of the Hillsboro-Cuchillo Mountains and flow eastward. All flow is usually infiltrated after entering the northern Palomas Basin. Flash flooding in ephemeral streams also contributes recharge to the unconfined aquifer. Murray (1959, p. 20) believed that Caballo Reservoir does not recharge the confined aquifer system because of the relatively low altitude of the reservoir.

Recharge to the aquifer system south of Caballo Dam is from the east and from irrigation systems. The Jornada del Muerto and the Palomas Basin in T. 19 S., R. 2 W. are hydraulically connected (King and others, 1971, p. 58). Wilson and others (1981, p. 43) reported that long-term recharge in the flood plain is about equal to the discharge.

Murray (1959, p. 20) reported the discharge area north of Caballo Dam is the Rio Grande. The confined aquifers probably leak water upward to the unconfined system, which discharges to the river. From seepage runs, Wilson and others (1981, p. 66) determined the Rio Grande gains water from about Caballo Dam to near Hatch. From north of Hatch to the south end of the Rincon Valley, it could not be determined if the Rio Grande was gaining or losing. Irrigated acreage in the basin includes about 70 acres by surface water only, 14,200 acres by ground water only, and 22,700 acres by both surface and ground water. The total acreage under irrigation was about 37,000 acres in 1979.

Mesilla Basin

The Mesilla Basin is south of the Palomas Basin; they are separated by narrows at Leasburg (pl. 1). The basin is about 50 mi long and 7 to 15 mi wide and includes Las Cruces, New Mexico, and Anthony, Texas. The flood plain of the Rio Grande is used extensively for agriculture. The area is arid with an average annual rainfall at Las Cruces of about 8 in.

Boundaries on the east are the Doña Ana, Organ, and Franklin Mountains. The Doña Ana Mountains are a domal uplift of Tertiary igneous rocks, with monzonite intrusive rocks in higher peaks (pl. 2) (King and others, 1971, p. 9). The northern Organ Mountains are a mass of Tertiary intrusive rocks. The southern Organs are Paleozoic, Cretaceous, and lower Tertiary sedimentary rocks (King and others, 1971, p. 15). The Franklin Mountains are sedimentary rocks and Precambrian and Tertiary intrusive rocks similar to those described for the Organ Mountains. The southern Organs and Franklins are tilted fault blocks hinged on the east.

Western basin boundaries are the East and West Potrillo Mountains on the south and the Aden, Sleeping Lady, and Rough and Ready Hills to the north. The East Potrillo Mountains are Paleozoic, Cretaceous, and lower Tertiary sedimentary rocks (King and others, 1971, p. 15). King and others (1971, p. 9) described the West Potrillo Mountains as the only mountains in southwestern Doña Ana County that reflect "the primary form of the basaltic volcanic cones and flows that underlie that particular upland area" of Quaternary age. The Aden, Sleeping Lady, and Rough and Ready Hills comprise a belt of small peaks, ridges, buttes, and elongated mesas that appear to be remnants of a former cover of andesites, basalts, rhyolites, tuffs, and associated sedimentary rocks of middle Tertiary age (King and others, 1971, p. 9, 15). West of the Rio Grande, the Mesilla Basin extends southward into Mexico.

The Mesilla Basin contains flood-plain alluvium along the Rio Grande and predominantly fluvial deposits of the Santa Fe Group outside and beneath the flood plain (Wilson and others, 1981). The flood-plain alluvium is 60 to 80 ft thick with a 30- to 40-ft basal layer of gravel overlain with sand, gravel, and clay.

The fluvial facies of the Santa Fe Group represent through-flowing Rio Grande deposition. The deposits are predominantly sand with layers of gravel, silt, clay, and sandy clay. A thick sequence of clay and sandy clay is reported on the east side of the valley from about T. 25 S., R. 3 E. to south of Anthony, Texas (Wilson and others, 1981, p. 39). A zone indicative of an eolian depositional environment is found in the well field a few miles north of Canutillo, Texas. These deposits are uniform fine-grained brown sand with practically no clay for the interval from 600 to 1,100 ft below land surface. Water is under confined conditions in this area.

In a test hole near Hill, New Mexico, close to the Robledo Mountains, sediments are about 390 ft thick. South of Goat Mountain, near an igneous bedrock high, which partially restricts ground-water flow from the Organ Mountains and the southern part of the Jornada del Muerto Basin into the Mesilla Valley, 500 ft of sediments are present. Test hole 24S.1E.8.123, on the West Mesa, penetrated 2,700 ft of Santa Fe sediments. Birch (1980b), using his definition of Neogene, showed the maximum thickness of Neogene sediments at about 9,800 ft southwest of Las Cruces and about 1,600 ft west of El Paso, Texas (pl. 3). The axis of the basin is in a northwest-southeast direction located a few miles west of the river (Birch, 1980b).

Wilson and others (1981, p. 60, 82) estimated the transmissivity to be about 10,000 ft^2/d on the mesa west of the flood plain. The transmissivity increases to a maximum of about 40,000 ft^2/d in the river valley.

Recharge at the basin margins is mainly from the eastern mountains. Wilson and others (1981, p. 66) reported the Rio Grande is a gaining stream from about Radium Springs to a bridge about 6 mi north of Las Cruces. From the bridge to "the narrows" near El Paso, Texas, the river loses an average of 2.5 $ft^3/sec/mi$.

No long-term decline in ground-water levels or significant change in storage has taken place in the flood plain within the Mesilla Valley. The water table is lowered during years of low surface-water flow, but the aquifer is recharged during those years of full surface-water allotments (3 acre-ft per acre) (Wilson and others, 1981, p. 67). Declines of about 60 ft are present for the city of Las Cruces well field just east of the city (Wilson and others, 1981, pl. 9).

Irrigated acreage in the basin, using both surface and ground water, is about 69,300 acres. Ground water is used to irrigate another 5,700 acres for total irrigated acreage of about 75,000 acres in 1979. Wilson and others (1981, p. 125) reported that urban water use in 1978 for Doña Ana County was 9,705 acre-ft.

Tularosa-Hueco Basin

Immediately downstream of "the narrows" the Rio Grande flows into the Hueco Basin. North of the New Mexico-Texas border the basin is usually called the Tularosa Basin (pl. 1). Because there is no known structural or ground-water divide near the New Mexico-Texas boundary, the Tularosa and Hueco areas are considered as one basin in this study. The Tularosa part is a closed surface-water basin about 115 mi long and 35 mi wide. White Sands Missile Range, Holloman Air Force Base, Alamogordo, and Tularosa, New Mexico, are in the basin. The Hueco part of the basin is about 100 mi long, ending at Fort Quitman, Texas, and is 20 to 25 mi wide. El Paso, Texas, and Ciudad Juarez, Mexico, are population centers in the Hueco part of the area.

The Tularosa-Hueco Basin is bounded on the north by a broad, high, topographic divide. The eastern and western boundaries are mountain masses resulting from normal faults that have dropped the basin relative to the mountains. Sierra Blanca, the Sacramento and Hueco Mountains, Diablo Plateau, and the Finlay, Malone, and Quitman Mountains bound the area to the east. Sierra Blanca is mainly batholithic rocks flanked by Tertiary volcanics (pl. 2) (Herrick and Davis, 1965). Mesozoic rocks crop out near Sierra Blanca (Sandeen, 1954, p. 81). The Sacramento Mountains are a thick sequence of Paleozoic rocks (Sandeen, 1954). The Hueco Mountains and Diablo Plateau are primarily carbonate and clastic rocks of Paleozoic and Cretaceous age. The Finley and Malone Mountains are mostly Paleozoic, Jurassic, and Cretaceous carbonate and clastic rocks. The Quitman Mountains are carbonate rocks of Cretaceous age and volcanic rocks of Tertiary age (Gates and Stanley, 1976, p. 6). The western boundary is formed by Chupadera Mesa, Sierra Oscura, and the San Andres, Organ, and Franklin Mountains. Chupadera Mesa, at the northwestern edge of the basin, is composed of Permian rocks. In the Sierra Oscura, Precambrian and Paleozoic rocks are found. The San Andres Mountains have extensive exposures of Precambrian granitic and metamorphic rocks as well as Paleozoic rocks (McLean, 1970, p. 13). The Organ and Franklin Mountains are described in the Mesilla Basin section. The basin continues into Mexico and is bounded on the west by Sierra de Juarez, Sierra de Guadalupe, Sierra de los Frailes, and Sierra de las Vacas (DeFord, 1969, p. 62; McLean, 1970, p. 6). The mountains in Mexico are mostly limestone, sandstone, and siltstone of Cretaceous age (Gates and others, 1978, p. 93).

Sandeen (1954, p. 86) described the Cenozoic basin-fill deposits as heterogeneous, poorly consolidated sediments that cover underlying Mesozoic and Paleozoic sedimentary rocks. The deposits in the Tularosa area are generally fanglomerates, conglomerates, soft sandstones, caliche, shale, and gypsum. Streams flowing into the basin deposit coarse material near the mountain front and fine-grained material toward the center. Lacustrine deposits are dominant in the center of the basin and may correlate with the Pliocene Fort Hancock Formation of Strain (1966) in the Mesilla and Hueco Basins. Strain (1969) described the Fort Hancock Formation of the Mesilla and Hueco Basins as a lacustrine deposit of horizontal bentonitic claystone, siltstone, and silt from ancient Lake Cabeza de Vaca.

Overlying this deposit in the Hueco Basin is the Pleistocene fluvial Camp Rice Formation of Strain (1966). This formation is characterized by horizontal strata, mainly stream-channel and flood-plain deposits, interfingering with fanglomerate around the margin of the basin. The Camp Rice Formation is composed of gravel, sand, silt, volcanic ash, and caliche. Strain (1969) concluded that Fort Hancock and Camp Rice Formations should be included in the Santa Fe Group because of similarities in source areas with Santa Fe sediments to the north.

Thickness of Cenozoic deposits in the Tularosa Basin was estimated by McLean (1970, p. 17) to be 8,000 ft at the southern end and 5,000 ft southeast of Rhodes Canyon. Seismic and gravity data indicate a thickness of 3,000 ft south of Alamogordo. Birch (1980b) estimated about 13,000 ft of Neogene deposits, just east of Sulfur Canyon in the San Andres Mountains (pl. 3). East of this thick section is a zone of sediments about 6,600 ft thick. Neogene deposits about 9,800 ft thick are located east of the southern end of the Organ Mountains and west of the basin axis. Adjacent to the Sacramento Mountains, in the vicinity of Grapevine Canyon, is a thickness of about 6,600 ft.

Cenozoic deposits in the Hueco Basin are reported to be about 9,000 ft thick in a trough parallel to the Franklin Mountains (Gates and others, 1978, p. 93). Between El Paso and Esperanza, sediments are less than 1,000 to about 5,000 ft thick. Deposits of the ancient Rio Grande from 300 to 700 ft thick are found along the eastern front of the Franklin Mountains. Airborne-electromagnetic and resistivity data indicate that these deposits continue along the edge of the mesa, parallel to the Rio Grande, to the southern end of the Hueco Basin. Recent Rio Grande alluvium has an estimated thickness of about 200 ft (Gates and others, 1978, p. 96).

Well production is variable, with maximum yields in the Tularosa Basin from coarse sediments high on the alluvial fans. McLean (1970, p. 17) reported yields of 1,400 gal/min and transmissivities of 47,000 ft^2/d. Lower on the alluvial fan, yields of 300 to 700 gal/min and transmissivities of 1,000 to 2,000 ft^2/d were reported. Toward the center of the basin, reported yields dropped as low as 15 gal/min. A well drilled about 8 mi east of White Sands Missile Range Headquarters produced 740 gal/min; the transmissivity was 2,640 ft^2/d. Transmissivities of deposits east of the Franklin Mountains range from 6,700 to 33,400 ft^2/d with wells producing as much as 1,800 gal/min. Irrigation wells in the El Paso Valley yield 2,000 gal/min (Gates and others, 1978, p. 96). Meyers (1976, p. 15) reported transmissivities from 1,300 to 37,500 ft^2/d and an average of 4,000 ft^2/d for alluvium in the Rio Grande valley. Meyers (1976, p. 6) reported confined conditions in the valley from the northern flood-plain escarpment near El Paso to the south, including most of the El Paso Valley and Ciudad Juarez.

Recharge to the Tularosa-Hueco Basin is along mountain fronts where intermittent streamflow infiltrates into the alluvial-fan material. McLean (1970, p. 6) reported most recharge occurs in the winter months. High-intensity summer thunderstorms produce short duration flows, affording little opportunity for recharge. Meinzer and Hare (1915, p. 101) estimated recharge to the Tularosa Basin to be greater than 100,000 acre-ft per year. Most recharge comes from the Sacramento Mountains, Sierra Blanca, and the younger lava flows in the northern part of the basin. Gates and others (1978, p. 96) estimated recharge to the United States part of the Hueco Basin to be about 14,000 acre-ft per year from the mountains bordering the area. Ground-water pumpage in the bolson sediments has resulted in the Rio Grande recharging the flood-plain sediments from 10,000 to 20,000 acre-ft per year during 1953-73 (Gates and others, 1978, p. 97).

Aquifer discharge is through evaporation on the playâs, ground-water pumpage, and consumptive use by crops and phreatophytes. Pumpage centers in the Tularosa part of the area are White Sands Missile Range, Holloman Air Force Base, and the cities of Alamogordo and Tularosa. McLean (1970, p. 7) reported that for 1962-66 Alamogordo extracted 580 acre-ft of water from the nearby alluvial-fan deposits and 1,900 acre-ft from springs in La Luz and Alamo Canyons. During 1968 Holloman pumped 3,000 acre-ft of water south of Alamogordo. White Sands Missile Range used about 2,800 acre-ft in 1967 from alluvial deposits in the reentrant between the Organ and San Andres Mountains. Irrigated acreage in the Tularosa Basin included about 650 acres that used surface water, 6,400 acres that used ground water, and 2,000 acres that used both surface and ground water, for a total of about 9,050 acres in 1979. Gates and others (1978, p. 100) reported that "In 1975, 72,000 acre-ft was pumped from the Texas part of the northern bolson and about 40,000 acre-ft was pumped from the Ciudad Juarez area, for a total of 112,000 acre-ft." The same authors reported that there are no long-term trends of dewatering in the Rio Grande alluvium in the Hueco Basin. Pumpage from this aquifer has ranged from 150,000 acre-ft to less than 10,000 acre-ft per year, depending on the available surface water for irrigation.

San Agustin Basin

The San Agustin Basin in Catron and Socorro Counties, New Mexico, is a northeast-trending basin about 50 mi long and 10 to 15 mi wide (pl. 1). Fitzsimmons (1959, p. 113) summarized the possible basin types the San Agustin could be, as: a Basin and Range graben, more or less an accident resulting from piling up volcanic material in a ringing barrier, or perhaps a great caldera. Chapin (1971, p. 199) called the basin a graben resulting from a series of en echelon northeast-trending faults called the San Agustin lineament.

The basin is filled with alluvial material and is surrounded by hills and mountains of mostly volcanic material (pl. 2). Thickness of lacustrine sediments near the southwestern end of the basin is at least 2,000 ft in a well drilled by Oberlin College (Foreman and others, 1959, p. 112). Chapin (1971, p. 199) reported the Sun No. 1 San Agustin oil test well, T. 3 S., R. 9 W., penetrated only 230 ft of alluvial material. This well was drilled on a structural saddle separating the basin into southwest and northeast segments. Birch (1980b) showed Neogene sediments in the basin are about 3,300 ft thick in a trough roughly parallel to the axis of the basin (pl. 3). A Pleistocene lake as large as 34 mi long, 11 mi wide, and about 165 ft deep was once present (Chapin, 1971, p. 199).

Recharge is from precipitation (14 in. annual average) (Blodgett and Titus, 1973, p. 17) on the surrounding highlands and the basin floor. Blodgett and Titus (1973, p. 1) reported no permanent streams or surface-water bodies in the basin; flow in the arroyos usually infiltrates into the alluvial fans at the base of the mountains. Discharge is from evapotranspiration and outflow of ground water. Blodgett and Titus (1973, p. 21) estimated recharge and discharge for the basin to be about 105,000 acre-ft per year. There are about 600 acres of land irrigated with ground water in the San Agustin Basin.

La Jencia Basin

The following description of the La Jencia Basin is taken from Waldron (1956). The basin is between the Magdalena Mountains on the west and the Lemitar Mountains and Socorro Peak on the east (pl. 1). The basin floor is about 6,000 ft above sea level with the Quaternary and Tertiary sediments and Quaternary basalts tilted toward the west at 10 to 30 degrees. The deepest part of the basin is probably next to the Magdalena Mountains, where the Quaternary alluvial sediments are about 400 ft thick. No aquifer tests have been conducted.

Recharge is principally from underflow in Water Canyon in the Magdalena Mountains. The Rio Salado to the north and Socorro Canyon to the south are the discharge areas for the basin. Ground water is used for stock watering. There has been virtually no change in storage in the basin.

Jornada del Muerto Basin

East of Socorro Basin is the northern end of the Jornada del Muerto Basin (pl. 1). The Jornada del Muerto is 12 to 30 mi wide and about 120 mi long. The eastern boundary is formed by the Sierra Oscura and the San Andres Mountains; the western boundary is formed by the Fra Cristobal Range and Caballo Mountains. The southern end of the Los Pinos Mountains is at the northwestern extent of the basin and the Doña Ana Mountains near the southwestern end. Rocks in all the bordering highlands are predominantly Pennsylvanian and Permian (pl. 2).

The Jornada del Muerto is different from other rift basins; it is a broad syncline formed by eastward-dipping Paleozoic and Mesozoic rocks along the Caballo Mountains and Fra Cristobal Range and westward-dipping Paleozoic rocks in the San Andres Mountains. This structure is inherited from two Laramide uplifts and is not part of Tertiary structure.

A northern depression in the basin contains about 3,000 ft of alluvial fill and is apparently bounded on the west by a steep fault. The central part of the basin is probably the most shallow (Chapin, 1971, p. 198). Hawley and others (1969, p. 62) described the Santa Fe deposits north of Point of Rocks as being thin on the west side of the basin. Their conclusions were based on pre-Santa Fe volcanic and sedimentary rocks cropping out in the area. They suggested that in the eastern half there may be relatively thick deposits of the Santa Fe Group. South of Point of Rocks, Hawley and others (1969, p. 62) explained that the basin floor is a constructional plain underlain by gypsiferous lake (?) beds and by fluvial deposits of an ancestral Rio Grande. It is thought the river entered the Jornada del Muerto from the west. Thickness of Santa Fe sediments south of Point of Rocks is estimated to be more than 1,000 ft. Birch (1980b) showed a maximum thickness of Neogene sediments of 6,600 ft east of the Doña Ana Mountains about in the center of the basin (pl. 3).

There is very little agricultural or industrial development in the basin. Water is used mainly for stock purposes. In 1978 there were 440 acres irrigated with ground water.

Mimbres Basin

The Mimbres Basin in southwestern New Mexico is about 55 mi long and 55 mi wide (pl. 1). The basin is bounded on the east by the West Potrillo and Goodsight Mountains and on the north by the southern end of the Black Range and the Cobre Mountains. To the west the boundary is along the Burro Mountains, the Continental Divide, then south to the Cedar Range and the Carrizalillo Hills. The basin extends south into Mexico as the Los Muertos Basin. The area is arid with an average annual rainfall of about 10 in. around Deming and Columbus and about 12 in. at Faywood in the northern part of the basin.

The rock descriptions for the West Potrillo and Goodsight Mountains are in the Mesilla and Palomas Basin discussions. The Black Range and Cobre Mountains are primarily Tertiary volcanics and rocks of Pennsylvanian, Mississippian, and Devonian age (Dane and Bachman, 1965) (pl. 2). Gillerman (1970, p. 115) described the Big Burro Mountains as mostly granite, quartz diorite, and associated rocks of Precambrian age with some Tertiary volcanics. Darton (1916, p. 94) described the Carrizalillo Hills as a detached southern continuation of the Cedar Range with the hills having an eastward dip.

Darton (1916, p. 5) called the water-bearing sediments bolson deposits of Quaternary age. These deposits are sand, gravel, and clay. He (Darton, 1916, p. 51) reported wells near Columbus penetrated thin sheets of basalt layered between sands and clays of bolson deposits.

Thickness of the bolson deposits has not been defined in great detail. Trauger and Doty (1965, p. 221) reported an oil test well, 18 mi southeast of Deming, bottomed in bolson deposits at 4,011 ft. The thickness of Neogene sediments for part of the Mimbres Basin (Birch, 1980b) is shown on plate 3.

Commercial seismic-refraction data interpreted by the U.S. Geological Survey (Hans Ackermann, written commun., 1980) provided some estimates of thickness of porous alluvial sediments. The approximate thickness of alluvial material interpreted from the seismic-refraction data and the location of the shot lines is shown on plate 4. Velocity measurements less than 11,500 ft are considered alluvial-aquifer material. The sections on plate 4 show relative thickness of sediments and are not intended to be used to infer faulting or other geologic structural features.

Line 5 on plate 4 crosses the Mimbres Basin from near Wilna east to just south of the southernmost extent of the Goodsight Mountains. Line 4 runs east to west from Hermanas to the Cedar Range through Arena, following an old railroad bed. Line 7 runs north from Columbus, turns west north of the Tres Hermanas Mountains, then continues north passing about 4 mi west of Deming and ends south of Cooke Range.

Transmissivity of the aquifer from recovery tests ranges from about 1,900 to 9,000 ft^2/d for wells of various saturated intervals (Conover and Akin, 1942, p. 257). McLean (1977) reported specific capacities for 38 wells. The average is 12.4 gal/min/ft with a range from 0.6 to 50 gal/min/ft.

Recharge to the basin is confined primarily to the channels of the Mimbres River and San Vicente Arroyo along the west side of the basin (Darton, 1916, p. 116). Discharge from the basin is by evapotranspiration and underflow. The total irrigated acreage in the basin was about 63,000 acres in 1978. About 51,000 acres used ground water as a source: 11,000 used surface water, and 1,000 used both.

Lordsburg Basin

The Lordsburg Basin, west of the Mimbres Basin (pl. 1), has only interior surface drainage. It is bounded on the east by the Burro Mountains, on the south by the Cedar Range and Little Hatchet Mountains, and on the west by the Coyote Hills, the Pyramid Mountains, and a small outcrop of Precambrian rock northwest of Lordsburg. The boundary extends northward to the Gila River drainage divide near Summit, New Mexico. The basin is about 55 mi long and 20 mi wide.

The Burro Mountains and Cedar Range are described in a previous section. The Coyote Hills and Pyramid Mountains are predominantly Tertiary volcanics with outcrops of Cretaceous rocks (pl. 2) (Dane and Bachman, 1965).

Younger basin sediments as described by Trauger (1972) are alluvium and bolson deposits of Quaternary age. The alluvium is in flood plains and channels of rivers and creeks; it is usually thin and ranges in grain size from clay to boulders. The bolson deposits are differentiated from alluvium mainly by the thickness of sediments. Bolson deposits are a thick heterogeneous mixture of rock debris from surrounding uplands (Trauger, 1972, p. 44-46). The oldest deposits are probably contemporaneous with the younger Gila Conglomerate (pl. 2).

Dane and Bachman (1965) showed Gila Conglomerate cropping out along the northern basin boundary. Trauger (1972, p. 41-43) described the Gila Conglomerate as poorly sorted sediments ranging from unconsolidated to strongly consolidated. The formation is usually divided into an upper and lower part. The lower part is mostly fragments of light-colored volcanic rocks derived from weathering of older volcanics. The matrix is usually fine sand, silt, and tuffaceous material. The upper part of the Gila Conglomerate is usually slightly consolidated and has a varied composition. Deformation and upward faulting of older rocks cause them to become the source of material for the upper part of the Gila Conglomerate.

The saturated thickness of alluvial material varies in the basin. Morgan (1942, p. 263) reported the bedrock slopes from the Pyramid Mountains toward the valley at about 150 feet per mile (ft/mi). The water table slope is about 20 to 30 ft/mi, causing the saturated thickness to increase toward the center of the basin. Morgan (1942) showed the thickness of saturated sediments as about 150 to 200 ft near Lordsburg and 3 or 4 mi to the southeast. Line 5 (pl. 4) crosses the basin east to west from about the center of the Pyramid Mountains to south and west of Wilna. The northern part of line 1 runs from near the southern limit of the Pyramid Mountains north to the northern end of the mountains (pl. 4).

The capability of the aquifer to yield water was tested and reported by Morgan (1942, p. 266) and by Murray (1942, p. 272). Specific capacities of wells near Lordsburg range from about 7 to 13 gal/min/ft. Murray (1942, p. 278) reported a transmissivity determined from a well with 200 ft of perforated casing in T. 23 S. R. 18 W. to be about 4,800 ft^2/d.

Recharge and discharge in the Lordsburg Basin have not been studied in detail. Trauger (1972, p. 64) estimated that probably no more than 10 acre-ft of water per year per mile of arroyo channel in the Burro and South Burro Mountains was recharged to the Lordsburg Basin. Lordsburg used about 1,600 acre-ft of ground water in 1970 (New Mexico Interstate Stream Commission and New Mexico State Engineer Office, 1974a, p. 20). Ground water is used to irrigate 9,100 acres in the basin; surface water is not used for irrigation.

Hachita Basin

The Hachita Basin is south of the Lordsburg Basin and west of the Mimbres Basin (pl. 1). The basin boundary on the east and north is formed by the Cedar Range and on the west by the Little Hatchet, Big Hatchet and Alamo Hueco Mountains. The basin extends southward into Mexico. The Little Hatchet Mountains are mainly Cretaceous mudstone, shale, and limestone (pl. 2). The Big Hatchet Mountains are Permian and Pennsylvanian limestone, shale, and quartzitic sandstone. The Alamo Huecos are mainly Tertiary volcanics with some outcrops of Cretaceous rocks. The Apache Hills and Sierra Rica separate the north-south trending arm of the basin from the northeast-southwest branch.

Little information is available about hydrologic conditions in the area. Quaternary bolson deposits are the water-bearing unit (Dane and Bachman, 1965). Trauger and Herrick (1962, p. 11) described the sediments as weathered detrital material from the mountains with a caliche zone from 2 to 5 ft thick commonly just under the surface of alluvial-fan material. Some wells finished as open holes have caved in, indicating the unit may not be well indurated. Thickness of the water-bearing unit is reported by Trauger and Herrick (1962, p. 12) to be 454 ft east of the Big Hatchet Mountains near the Mexican border. They estimated the depth of water-producing sediments to be about 1,500 ft just east of the Big Hatchet Mountains in the northwest corner of T. 31 S., R. 15 W.; the deepest part of the basin was estimated to be about 3½ mi west of the axis of the north-south arm of the basin.

Two seismic lines were run in the Hachita Basin (pl. 4). Line 4 enters the basin from the west and passes between the Coyote Hills and the Little Hatchet Mountains. The line then passes through Hachita and continues eastward through the gap between the Cedar Range and the Carrizalillo Hills. Line 2 enters the basin from the west, just north of the Alamo Hueco Mountains, and continues east to the Mexican border.

Specific capacities for wells in the basin range from 0.2 gal/min/ft in a well near the Big Hatchet Mountains to 10 gal/min/ft near the Mexican border in T. 31 S. (Trauger and Herrick, 1962, p. 19-20).

Recharge to the area is small because only 4 in. of annual precipitation is available and because caliche layers restrict infiltration through the upper sediments. Most recharge occurs through stream channels that have eroded through the caliche layers (Trauger and Herrick, 1962, p. 14). Discharge is also small. In 1978 there was no irrigated land in this basin. Wells are used for domestic and stock supply.

Playas Basin

The Playas Basin is west of the Hachita Basin (pl. 1). This basin is about 50 mi long and 7 to 10 mi wide. The Coyote Hills and the Pyramid Mountains form the northern boundary. The Animas Mountains form the western boundary. The basin extends into Mexico. The Animas Mountains are primarily Tertiary volcanics, but at the northern end, Dane and Bachman (1965) showed outcrops of Cretaceous, Pennsylvanian, and Permian rocks (pl. 2).

Doty (1960, p. 10-11) described the basin as a bolson undergoing typical bolson deposition. He described the sediments along the fan slopes as a calichelike conglomerate, with clay in the playa lakes and low places, and wind-blown sand and fine particles along the playa lakeshores and on fan slopes. Doty (1960, p. 11) reported drillers' logs for wells in the valley fill showed intermixed lenses of sand, gravel, silt, and clay. Clay beds more than 60 ft thick were reported, but lack of data made it impossible to determine their areal extent.

Thicknesses of saturated sediments are estimated from parts of three seismic lines (pl. 4). Lines 2 and 4 cross the basin from east to west, and line 1 is along the axis of the basin. The aquifer's capacity to produce water is largely unknown. Doty (1960, p. 19) reported an average specific capacity of 23 gal/min/ft.

Recharge to the aquifer is small because of little precipitation and caliche layers that probably impede infiltration of water. Doty (1960, p. 15) estimated average annual recharge to be about 5,000 acre-ft per year. Discharge is by evapotranspiration and pumpage. Estimated evapotranspiration is about 70 acre-ft per year. Doty (1960, p. 15) estimated pumpage for domestic and stock use at 70 to 100 acre-ft per year. About 12,000 acres were irrigated with ground water in 1978.

Animas Basin

The westernmost basin is the Animas (pl. 1). Structurally, it is a graben (Spiegel, 1957, p. 11) about 90 mi long and 5 to 10 mi wide. The basin can be divided into the upper Animas (southern part) and the lower Animas (northern part). The Animas and Pyramid Mountains are the eastern boundary, and the Peloncillo Mountains are the western boundary. The basin extends west a few miles into Arizona where the Peloncillo Mountains cross the State line. The northern boundary is the Gila River, and the basin extends south into Mexico. The Peloncillo Mountains are almost entirely Tertiary volcanics (pl. 2). Outcrops of Permian, Pennsylvanian, and Precambrian rocks are found near the center of T. 24 S.

Schwennesen (1918, p. 76) distinguished the upper Animas from the lower because the upper valley contains a trough cut by Animas Creek. He pointed out that only the upper Animas and southern Hachita Basins in southwestern New Mexico have this erosional feature. The trough is about ½ mi wide as it emerges from the Peloncillo Mountains and widens to about 1½ mi about 4½ mi south of Animas.

Reeder (1957, p. 5) reported an older alluvium (Gila Conglomerate) in the upper Animas consisting of dense reddish clay and gravelly clay that underlies the valley floor and forms the bordering slopes of the valley. Spiegel (1957, p. 11) reported interbedded basalt flows in this older deposit. Apparently, Animas Creek cut into the older sediments, and the valley has since been filling with younger alluvium. These sediments may be as much as 40 ft thick.

The lower Animas is nearly flat and was once partially covered by a lake. Spiegel (1957, p. 11) reported sand and gravel layers alternate with clay layers in the ancient lake beds. In surrounding areas, the sand, gravel, and clay are intermixed. Shorelines of the extinct lake are visible in the lower Animas Valley.

Depths of saturated porous material that could be an aquifer are indicated by seismic data (pl. 4). Line 3 passes through the axis of the valley from the international boundary to Animas. The most northern east-west line is 5; line 4 crosses the Peloncillo Mountains and continues eastward through Animas and Playas; line 2 starts near Cloverdale and runs a little southeast to the pass between the Animas and San Luis Mountains.

Reeder (1957, p. 41) reported results of aquifer tests in the lower basin. Average transmissivity is about 8,700 ft^2/d and average specific capacity for wells tested in 1955 is about 29 gal/min/ft.

Reeder (1957, p. 24-25) suggested that recharge to the aquifer is about 2,700 acre-ft per year. This estimate is based on an assumed steady-state condition of inflow equals outflow and outflow is estimated at the northern boundary. In 1978, there were 14,000 acres of irrigated land in the basin that used ground water.

Salt Basin

The project area includes four basins in western Texas (pl. 1); the Salt Basin is the largest, about 150 mi long and 10 to 25 mi wide. The Salt Basin is a graben and is usually discussed in terms of subareas (Gates and others, 1978, p. 45). The New Mexico part is called Crow Flats; a southern extension of Crow Flats is the Salt Flats area of Gates and others (1978). South of Salt Flats are the Wildhorse, Michigan, Lobo, and Ryan Flats.

The eastern boundary of Salt Basin is formed by the Guadalupe, Brokeoff, Delaware, Apache, Wylie, Chispa, and Davis Mountains. The northern part of the western boundary is marked by the Diablo Plateau, a limestone upland. The western boundary is continued by the Sierra Diablo, the Baylor, Beach, Carrizo, Van Horn, and Sierra Vieja Mountains. The basin's southern limit is marked by the Chinati Mountains. The northern extent of the basin is formed by the convergence of the limestone upland and the Guadalupe Mountains.

The Guadalupe and Brokeoff Mountains are Permian limestone and sandstone (Dane and Bachman, 1965), as are the Delaware and Apache Mountains to the south (Gates and others, 1978, p. 45) (pl. 2). The Wylie Mountains are mainly Permian limestones and dolomite. Between the Apache and Wylie Mountains are low hills of Cretaceous limestones and sandstones (Gates and others, 1978, p. 46). The Chispa, Davis, and Cuesta del Burro Mountains are Tertiary (Gates and others, 1978, p. 64). On the west side are the Diablo Plateau and Sierra Diablo of Permian limestone. The Baylor Mountains are Permian limestone and Paleozoic dolomites. The Beach Mountains are Paleozoic dolomite and sandstones and some Permian limestones. The Carrizo Mountains are Precambrian rocks (Gates and others, 1978, p. 46). Gates and others (1978, p. 56) showed the Van Horn Mountains to be Permian limestones with Tertiary volcanics in the northern part and Cretaceous sandstone and limestone in the southern part. The Sierra Vieja Mountains are Cretaceous limestone and shale and Tertiary volcanics.

The aquifer in the Salt Basin is different from those discussed so far. In the Crow and Salt Flat subareas, the Permian limestones are hydraulically connected to the overlying alluvium. In some wells the limestones are the producing units. The alluvium in Crow Flats ranges in thickness from 25 to 300 ft and is mostly limestone fragments from adjacent highlands. In the western part of the subarea, fragments of intrusive igneous rocks are common, probably coming from the Cornudas Mountains to the west. Bjorklund (1957, p. 10) reported that the Permian limestones are probably several thousand feet thick and are the principal supply of water in Crow Flats.

Basin fill in Salt Flats consists of fine-grained, predominantly lacustrine deposits. Range in fill thickness is from 800 ft north of U.S. Highway 62-180 to about 2,000 ft between the highway and Sierra Diablo. The primary aquifer is the Permian limestone. More than 1,600 ft of limestone was reported in one well near Beacon Hill (Gates and others, 1978, p. 15, 44).

South from the north end of Sierra Diablo to just south of U.S. Interstate Highway 10 (Wildhorse and Michigan Flats), Gates and others (1978, p. 45) reported bolson-type sediments in most wells. These deposits are predominantly fine-grained lacustrine clay but contain more sand and gravel than in the Salt Flats subarea. The sediments are 1,000 to 1,200 ft thick on the west side and 400 to 500 ft thick on the east (Gates and others, 1978, p. 47). A maximum thickness of 2,400 ft is indicated from vertical-electrical-sounding data north of the Baylor Mountains (Gates and others, 1978, p. 46).

In the southern Salt Basin (Lobo and Ryan Flats) the aquifer consists of basin fill and permeable volcanic clastic rocks. Gates and others (1978, p. 57) postulated the northern extent of volcanic clastic rocks underlying the bolson deposits is near the northern end of the Van Horn Mountains. The thickness of combined bolson deposits and volcanic clastic rocks is about 1,000 ft in Lobo Flats (Gates and others, 1978, p. 57) and about 1,000 to 1,500 ft in Ryan Flats (Gates and others, 1978, p. 66). Drillers in Lobo

Flats reported what are probably volcanics interbedded with the basin fill below about 100 ft. Gates and others (1978, p. 65-66) reported that in a test hole in Ryan Flats the fill was mostly clay to 210 ft, permeable sand and gravel to 385 ft, and clay or altered ash-fall tuff to 555 ft. From 555 to about 1,250 ft, medium-grained, fairly well sorted permeable sand and some thin volcanic flows were penetrated.

Specific-capacity values in Crow Flats vary considerably, depending on the aquifer being tested. Bjorklund (1957, p. 16) reported yields of as much as 3,600 gal/min and specific capacities of about 360 gal/min/ft in the limestone aquifer. Wells withdrawing water from the alluvial aquifer might be expected to have specific capacities of about 20 gal/min/ft.

Gates and others (1978, p. 39) reported a median specific capacity of 16.5 gal/min/ft and a transmissivity value of about 5,400 ft^2/d around Beacon Hill for limestone aquifers. Aquifer tests in Wildhorse and Michigan Flats for wells finished in basin fill indicated a median specific capacity of 14 gal/min/ft and an average transmissivity of about 4,600 ft^2/d (Gates and others, 1978, p. 47). For Lobo Flats, Gates and others (1978, p. 58) reported a median specific capacity of 24 gal/min/ft with a range of 4 to 46 gal/min/ft and an average transmissivity of 7,900 ft^2/d; they noted that transmissivity was decreasing due to a falling water table.

Bjorklund (1957, p. 15) and Gates and others (1978, p. 39) made no estimate of recharge to the Salt Basin north of Bitter Well Mountain. Both studies showed that recharge to the Permian limestone aquifer results from precipitation on the Guadalupe Mountains and Patterson Hills. Recharge is thought to also occur from the Sacramento River north of Crow Flats and locally from ephemeral streams. Recharge to the Salt Basin generally takes place at the basin margins and at ephemeral streams within the basin. South of Bitter Well Mountain, Gates and others (1978, p. 48) estimated recharge of 17,000 acre-ft per year.

Discharge from the basin is from evaporation in the playa areas, subsurface outflow, and pumpage. Irrigated acreage in the Salt Basin in 1979 was about 73,000 acres (T.G. Funderburk, U.S. Department of Agriculture, written commun., 1980).

Eagle Basin

The Eagle Basin is bounded on the north by Diablo Plateau and on the east by Sierra Diablo, Carrizo Mountains, and the Van Horn Mountains (pl. 1). The west boundary is formed by the Finlay and Malone Mountains, Devil Ridge, Eagle Mountains, and the Indio Mountains. Rock types and ages on the east side have been described previously. The Finlay Mountains are Cretaceous limestone and sandstone (pl. 2). The Eagle Mountains are Tertiary intrusive igneous and rhyolitic rocks; the Indio Mountains are predominantly Cretaceous limestone and sandstones (University of Texas at Austin, 1968, 1979a).

Gates and others (1978, p. 74) reported that basin fill near Allamore and to the north is probably less than 500 ft thick and is above the water table. Near the Eagle and Van Horn Mountains, fill is probably coarse grained and may be as thick as 2,000 ft. Along the axis of the basin, the sediments contain considerable fine-grained material. A test hole in southern Eagle Flats penetrated 2,012 ft of predominantly brown clay with thin beds of sand and gravel without reaching consolidated rock. In northern Green River Valley, the maximum fill thickness is between 1,700 and 2,000 ft. The material probably contains considerable coarse-grained rock and may include volcanic clastic and volcanic rocks at depth. Basin fill may be 2,800 ft thick near the Rio Grande and is probably lacustrine clay and silt (Gates and others, 1978, p. 80).

In the northwestern part of Eagle Basin, ground water is obtained from consolidated rocks of Cretaceous age. South and northwest of Allamore, ground water comes from fractures in the underlying Precambrian rocks (Gates and others, 1978, p. 74). In southeastern Eagle Flat and Green River Valley, water is obtained from the basin fill. Specific capacities indicate transmissivity values of as much as 13,000 ft^2/d in alluvium along the Rio Grande (Gates and others, 1978, p. 81).

Gates and others (1978, p. 81) estimated 4,000 acre-ft of water may be recharged to Eagle Basin, including Green River Valley. Discharge is small; some water is thought to flow to the Salt Basin between the Carrizo and Van Horn Mountains, and some water may discharge to the Rio Grande. In the Green River Valley and Red Light Basin, adjacent to the Rio Grande, there were about 1,100 acres irrigated in 1979 using surface and ground water (T.G. Funderburk, written commun., 1980).

Red Light Basin

Red Light Basin is a small basin between the Eagle and Indio Mountains on the east and the Quitman Mountains on the west (pl. 1). The Quitman Mountains are Cretaceous limestones and sandstones (pl. 2) (University of Texas at Austin, 1968, 1979a). Gates and others (1978, p. 78) reported the basin fill and volcanic clastic rocks thicken to the south from about 500 ft to as much as 3,600 ft near the Rio Grande. A test well west of the Eagle Mountains penetrated coarse-grained alluvial-fan deposits to 1,100 ft, then probably volcanic rocks. Fill near the Rio Grande is mostly fine grained, probably lacustrine clay and silt and possibly some altered tuff at depth.

Recharge and discharge in the basin are small. Gates and others (1978, p. 81) estimated recharge at about 2,000 acre-ft per year from the basin margins and ephemeral streams.

Presidio Basin

The Presidio Basin is the southeasternmost basin in the study area (pl. 1). The eastern boundary is formed by the Chinati and Cienega Mountains. Gates and others (1978, p. 85) described the Chinati Mountains as

Tertiary intrusives and volcanic rocks underlain by Permian siltstone, limestone, shale, sandstone, and conglomerate (pl. 2). The Cienega Mountains are Tertiary intrusive conglomerates and volcanic clastic rocks underlain by Cretaceous limestone, shale, and sandstone.

Basin fill is probably lacustrine clay and silt and may contain some volcanic clastic material. Near the Chinati Mountains, fill thickness is estimated at 1,600 ft; the thickness may be as great as 5,000 ft in the basin axis. The thickness of recent alluvium in the Rio Grande flood plain is estimated to be less than 100 ft (Gates and others, 1978, p. 87). Transmissivity estimates from specific-capacity data are from 5,000 to 21,000 ft^2/d.

Recharge to the Presidio Basin and a small basin to the south is estimated to be 7,000 acre-ft per year. This value does not include recharge from the Rio Grande. In 1979, about 5,000 acres were irrigated with surface and ground water; ground water was used primarily as a supplemental supply (T.G. Funderburk, written commun., 1980).

REGIONAL POTENTIOMETRIC SURFACE

The regional potentiometric surface is shown on plate 5. A potentiometric surface, as defined by Lohman and others (1972, p. 11), is a surface that represents static hydraulic head and is defined by levels to which water will rise in tightly cased wells. The data used to construct plate 5 were obtained from the U.S. Geological Survey's Ground Water Site Inventory (GWSI) data base. The data are 1972-81 water levels measured from November through March. All wells are completed in alluvial material. In many cases, the well was located on a geologic map to determine the probable material in which the well was finished. Water levels in the selected wells represent static head at many levels in the aquifer. Sparsity of well depth and perforated-interval data makes development of contours of potentiometric surfaces at different depths impossible.

River stage for perennial streams is also shown on plate 5. The average stage for the selected gaging stations during 1972-81 was about 3 ft above the gage datum. Therefore, 3 ft was added to all datums to establish an average elevation of the water surface at a gaging station.

Potentiometric-surface contours were drawn based on the assumption that hydraulic continuity exists between basin aquifers. This assumption appears justified from the continuity of measured water-level altitudes near some basin boundaries and the continuity of alluvial sediments between basins.

While the regional aquifer can be considered unconfined, areas with confined conditions have been identified previously. Most notable of these confined areas are part of the San Luis Valley and an area around El Paso, Texas. There are also several small zones along the Rio Grande. The contours, as drawn, make no attempt to differentiate between confined and unconfined areas. Many wells are finished in both artesian and water-table zones, making the distinction impossible.

Parts of the study area containing the alluvial aquifer are not contoured. These areas lack sufficient data in the selected time period to define the potentiometric surface. The lack of data results from a combination of no recent water-level measurements and a lack of wells in which water levels can be measured.

Contours have not been extended across areas mapped as something other than alluvium. It is recognized that there are areas where Santa Fe sediments may be capped by volcanic rocks. In these places, there is probably hydraulic continuity between adjacent alluvial sediments and sediments underlying the volcanic-capped areas, but there is usually a lack of data to define the potentiometric surface. The area west of the Rio Grande between the Colorado-New Mexico State line and Embudo, New Mexico, and the mesa between Santa Fe and the Albuquerque-Belen Basin, are two such areas. Contours within basins that are adjacent to the United States-Mexico boundary have not been extended into Mexico. It is recognized that these basins do not terminate at the boundary and that hydraulic continuity exists, but lack of data makes extending contours into Mexico meaningless.

Contours of the potentiometric surface can indicate areas of ground-water recharge and discharge, direction of flow, and the gaining and losing reaches of streams. Gutentag and Weeks (1980) presented a discussion of conclusions that can be reached from the shape and location of potentiometric-surface contours. Upgradient flexures of contours near streams indicate discharge of ground water to streams. Downgradient flexures indicate recharge to the ground-water system from streams. Upgradient flexures of contours some distance from perennial streams indicate withdrawal of ground water. Downgradient flexures or increased spacing of contours are indicative of ground-water recharge from the overlying sediments or possibly a rise in the bedrock surface in that area.

Throughout much of the study area, contours indicate the Rio Grande flood plain gains water from the basin aquifer. The river probably acts as a drain. However, locally the river may supply water to the ground-water reservoir or may not be in hydraulic connection with the basin aquifer. Contours near the Santa Fe River near Santa Fe, New Mexico, flex downstream, indicating the river supplies water to the aquifer system.

The topography in the Rio Grande Rift relates to the graben structure where valleys are bounded by uplifted areas on the sides; contours show the aquifer is recharged from the highland areas where precipitation is greater. Closed surface-water basins in southwestern New Mexico display this same characteristic.

Flexures in contours distant from streams are apparent in the Mimbres Basin. The 4,000- through 4,400-ft contours indicate the effects of withdrawals of ground water in this basin. Another example of potentiometric-surface contours indicating ground-water withdrawals is the 4,000-ft contour on the east side of the river in the Mesilla Basin. The 3,600- and 3,700-ft contours in the Tularosa-Hueco Basin also show ground-water discharge.

General ground-water movement in the study area is from the west and east to the center of the valleys and then southward. However, movement in the Animas and Playas Basins in southwestern New Mexico is northward to the Gila River. Ground-water flow in the southern Salt Basin in western Texas is also northward. Contours in the southern part of Eagle Basin show a ground-water divide at about the 3,800-ft contour. North of the divide, flow is northward to the interior of the basin; south of the divide, flow is southward to the Rio Grande.

REGIONAL WATER QUALITY

Ground-water quality for the study area is illustrated by Stiff patterns on plate 6. Surface-water quality is shown on plate 7 using Stiff patterns of average concentrations.

Ground-water-quality data for the Colorado and New Mexico parts of the study area and some data for Texas are available from the WATSTORE data base of the U.S. Geological Survey. The results of water samples collected and analyzed prior to 1968 have been entered into the data base as part of this study. Samples collected during 1968 and 1969 were analyzed by various U.S. Geological Survey laboratories and the results were entered into the system at the time of analysis. Water samples collected after 1969 were analyzed at the U.S. Geological Survey's Central Laboratory in Denver, Colorado, and entry of results into the data base was done by that facility. Some analyses for the Texas part of the study area were not done by the U.S. Geological Survey and have not been entered into the WATSTORE system. This project has converted these data to the format used by WATSTORE and stored them on digital tape at the project office.

Data were selected in preparing plate 6 by first checking the cation-anion balance. An analysis was not used if the total cations, in milliequivalents, were different from the total anions by more than 5 percent. Data were not sorted for a particular period of time, specific depth interval, or geologic environment. A Piper plot was completed (Hem, 1970, p. 267-268), including all data that met the earlier described criteria. The Piper plot was used to categorize water into water-quality types. Water-quality data were then plotted on a map of the study area. Analyses that demonstrated a particular type of water for a general area were selected and Stiff patterns (Hem, 1970, p. 259) drawn for each analysis. The Stiff patterns indicate the general ground-water-quality type found in the area around the well from which the water sample was taken.

Some general observations can be made from the data presented on plate 6. Basins that have sodium as the predominant cation are located in the southern part of the study area, with one exception. The San Marcial Basin has a sodium bicarbonate-type water throughout the basin. Basins in Texas that border on the Rio Grande generally have sodium-type waters; these are the Hueco part of the Tularosa-Hueco, and the Red Light, Eagle, and Presidio Basins. The Lordsburg, Playas, and Hachita Basins in southwestern New Mexico also have sodium-type water. Sodium bicarbonate water occurs in many basins where playas are located or at the most downgradient position in a basin, such as the closed-basin area of the San Luis Valley, the southern flood-plain area of the Española Basin, and the northern end of the Animas and the Playas Basins.

The lack of calcium may indicate waters that have been in an environment where cation exchange is the predominant reaction. Freeze and Cherry (1979, p. 287) reported, "The occurrence of sodium and bicarbonate as the dominant ions can be explained by the combined effects of cation exchange and calcite or dolomite dissolution."

Freeze and Cherry (1979, p. 243) stated that "HCO_3 is almost invariably the dominant anion in recharge areas." Bicarbonate is the dominant anion in the San Luis, Española, San Marcial, La Jencia, San Agustin, Playas, and Hachita Basins (pl. 6). The anion is usually associated with a zone characterized by active ground water flushing through relatively well-leached rocks, normally the soil zone, with the dissolution of calcite and dolomite as the source of the bicarbonate (Freeze and Cherry, 1979, p. 242).

Several basins have a calcium bicarbonate-type water around the margins, or parts of the margins, adjacent to mountain-recharge areas. The San Luis and Española Basins in the northern part of the study area and the northern part of Mimbres Basin, which is south of the Black Range, are examples of these areas. This type of water is probably representative of water that has undergone calcite or dolomite dissolution but little or no ion exchange.

Water-quality data from selected surface-water stations used to draw the Stiff patterns on plate 7 are constituent averages for the entire period of record for the site. The Stiff patterns on plate 7 show that water in the Rio Grande is a calcium sulfate or calcium bicarbonate type from the headwaters to below Elephant Butte Dam. The Jemez River, in the Albuquerque-Belen Basin, is a sodium chloride water, but this water is mixed with the larger flows of the Rio Grande and does not change the character of the Rio Grande water at Albuquerque. Rio Puerco water, at the southern end of the Albuquerque-Belen Basin, is a sodium sulfate water with a relatively large dissolved-solids concentration. This water also does not change the chemical character of Rio Grande flows as shown by the Stiff pattern for water below Elephant Butte Dam. From El Paso southward, the Rio Grande has changed to a sodium sulfate-sodium chloride water and has significantly increased concentrations of dissolved solids.

SUMMARY

The Rio Grande Rift study area encompasses about 70,000 mi^2 and includes 22 basins. The northernmost basin is the San Luis in southern Colorado and northern New Mexico. The study area extends southward to the Presidio Basin in western Texas. Closed surface-water basins west of the Guadalupe Mountains and east of the Peloncillo Mountains are included in the study area.

The eastern boundary is formed by Precambrian, Paleozoic, and volcanic rocks of Tertiary or Quaternary age. The western margin is mainly Tertiary and Quaternary volcanics with some Mesozoic rocks west of the Española and Albuquerque-Belen Basins. The Precambrian and Paleozoic rocks from the east butt against the volcanics from the west to form the northern extent of the alluvial basins.

Estimated depths of sediments in the basins associated with the Rio Grande Rift range from about 8,000 ft in the Tularosa-Hueco Basin to 19,000 ft in the Española Basin. Closed-basin sediment depths range from about 2,400 ft in the Salt Basin to about 6,000 ft in the Jornada del Muerto.

Composition of the alluvial aquifer is usually described as layers of gravel, sand, silt, and clay interbedded with local volcanic flows or tuffs. Closed-basin aquifers include lacustrine fine-grained deposits and near-surface caliche beds in places.

Transmissivity values in the river-connected basins range from 100 to more than 200,000 ft^2/d. Well yields have been reported to be as much as 2,000 gal/min. For closed basins, the reported transmissivity values are as great as 21,000 ft^2/d.

Aquifers generally are unconfined in the study area. Confined conditions are found in the San Luis Basin, southern Mesilla Basin, and in the El Paso Valley and Ciudad Juarez. Locally, ground water along the Rio Grande may be under confined conditions.

Potentiometric contours based on 1971-82 data show that ground-water recharge originates on the uplifted areas that form the study area boundaries. The water enters the alluvial-aquifer system at or near the bedrock-alluvial contact and along stream channels within the basins. In general, flow is toward the Rio Grande from the east and west, then southward along the river valley.

Stiff patterns of ground-water quality visually display the predominant water types in the study area. Stiff patterns for surface-water quality show changes in surface water from a calcium bicarbonate to sodium chloride type water from the northern to the southern extent of the study area.

SELECTED REFERENCES

Albritton, C.C., Jr., and Smith, J.F., Jr., 1965, Geology of the Sierra Blanca area, Hudspeth County, Texas: U.S. Geological Survey Professional Paper 479, 131 p.

Bachman, G.O., and Mehnert, H.H., 1978, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico: Geological Society of America Bulletin, v. 89, no. 2, p. 283-292.

Bailey, R.A., Smith R.L., and Ross, C.S., 1969, Stratigraphic nomenclature of volcanic rocks in the Jemez Mountains, New Mexico: U.S. Geological Survey Bulletin 1274-P, 19 p.

Baltz, E.H., 1978, Resume of Rio Grande depression in north-central New Mexico, in Guidebook to Rio Grande Rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 210-228.

Berggren, W.A., and Van Couvering, J.A., 1974, The late Neogene, reprinted from Palaeogeography, Palaeoclimatology, Palaeoecology: Amsterdam, Elsevier Scientific Publishing Co., v. 16, no. 1/2, 228 p.

Bingler, E.C., 1968, Geology and mineral resources of Rio Arriba County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 91, 158 p.

Birch, F.S., 1980a, Geophysical evaluation of basin hydrologic characteristics in the central Rio Grande, Part I, Gravity models of the Albuquerque-Belen Basin: Unpublished report prepared for the U.S. Geological Survey by the University of New Mexico under contract no. 14-08-0001-17879, 30 p.

_____1980b, Three-dimensional gravity model of the basin hydrologic parameters in New Mexico: Unpublished report prepared for the U.S. Geological Survey by the University of New Mexico under contract no. 14-08-0001-17899, 27 p.

Bjorklund, L.J., 1957, Reconnaissance of ground-water conditions in the Crow Flats area, Otero County, New Mexico: New Mexico State Engineer Technical Report 8, 26 p.

Bjorklund, L.J., and Maxwell, B.W., 1961, Availability of ground water in the Albuquerque area, Bernalillo and Sandoval Counties, New Mexico: New Mexico State Engineer Technical Report 21, 117 p.

Blodgett, D.D., and Titus, F.B., 1973, Hydrogeology of the San Agustin Plains, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report OF-51, 54 p.

Borton, R.L., 1961, Geology and water resources of the Alamosa-Cuchillo Negro-Palomas Rivers area, Sierra and Socorro Counties, New Mexico: New Mexico State Engineer Office open-file report, 24 p.

______1974, General geology and ground water conditions in the Truchas-Española-Velarde area of Rio Arriba County, New Mexico, in Guidebook of Ghost Ranch: New Mexico Geological Society, 25th Field Conference, p. 351-354.

Bryan, Kirk, 1938, Geology and ground-water conditions of the Rio Grande depression in Colorado and New Mexico, in U.S. National Resources Committee, Regional Planning Part VI, The Rio Grande Joint Investigation in the Upper Rio Grande Basin in Colorado, New Mexico, and Texas, 1936-37: Washington, U.S. Government Printing Office, v. 1, pt. 2, p. 197-225.

Bryan, Kirk, and McCann, F.T., 1937, The Ceja del Rio Puerco: A border feature of the Basin and Range Province in New Mexico: Journal of Geology, v. 45, p. 801-828.

Budding, A.J., 1978, Subsurface geology of the Pajarito Plateau, in Guidebook to the Rio Grande Rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 186-197.

Burroughs, R.L., 1971, Geology of the San Luis Hills, south-central Colorado, in Guidebook of San Luis Basin, Colorado: New Mexico Geological Society, 22nd Field Conference, p. 277-287.

Bushman, F.X., 1963, Ground water in the Socorro Valley, in Guidebook to Socorro Region: New Mexico Geological Society, 14th Field Conference, p. 155-159.

Cabot, E.C., 1938, Fault border of the Sangre de Cristo Mountains north of Santa Fe, New Mexico: Journal of Geology, v. 46, no. 1, p. 88-105.

Chamberlin, R.M., and Osburn, G.R., 1976-77, Generalized geologic map of the Socorro geothermal area, New Mexico, in Field guide to selected cauldrons and mining districts of the Datil-Mogollon volcanic field: New Mexico Geological Society Special Publication 7, 149 p.

Chapin, C.E., 1971, The Rio Grande Rift, Part 1, modifications and additions, in Guidebook of the San Luis Basin, Colorado: New Mexico Geological Society, 22nd Field Conference, p. 191-201.

Chapin, C.E., Chamberlin, R.M., Osborn, G.R., Sanford, A.R., and White, D.W., 1978, Geological and geophysical maps of the Socorro geothermal area, in Field guide to selected cauldrons and mining districts of the Datil-Mogollon volcanic field, New Mexico: New Mexico Geological Society Special Publication 7, 149 p.

Chapin, C.E., and Seager, W.R., 1975, Evolution of the Rio Grande Rift in the Socorro and Las Cruces areas: New Mexico Geological Society Guidebook, 26th Field Conference, p. 297-321.

Chebotarev, I.I., 1955, Metamorphism of natural waters in the crust of weathering, Geochimica et Cosmochimica Acta, 8, p. 22-48, 137-170, 198-212.

Clark, K.F., and Read, C.B., 1972, Geology and ore deposits of Eagle Nest area, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 94, 152 p.

Clemons, R.E., 1976, Sierra de las Uvas ash-flow field, south-central New Mexico: New Mexico Geological Society Special Publication 6, p. 115-121.

_____1979, Geology of Goodsight Mountains and Uvas Valley, southwest New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 169, 31 p.

Colorado Water Court, Division 3, 1979, Case W3466, In the matter of: Rules and regulations governing the uses, control, and protection of water rights for both surface and underground water located in Rio Grande and Conejos River basins and their tributaries: Alamosa, Colo.

Conover, C.S., 1954, Ground-water conditions in the Rincon and Mesilla Valleys and adjacent areas in New Mexico: U.S. Geological Survey Water-Supply Paper 1230, 200 p.

Conover, C.S., and Akin, P.D., 1942, Progress report on the ground-water supply of Mimbres Valley, New Mexico: New Mexico State Engineer 14th and 15th Biennial Report, p. 237-282.

Conover, C.S., Herrick, E.H., Wood, J.W., and Weir, J.E., Jr., 1955, The occurrence of ground water in south-central New Mexico, in Guidebook of south-central New Mexico: New Mexico Geological Society, 6th Field Conference, p. 108-120.

Cordell, Lindrith, 1970, Gravity and aeromagnetic investigations of the Rio Grande depression in northern New Mexico, in Guidebook of the Tyrone-Big Hatchet Mountains-Florida Mountains Region: New Mexico Geological Society, 21st Field Conference, p. 158.

_____1978, Regional geophysical setting of the Rio Grande Rift: Geological Society of America Bulletin, v. 89, no. 7, p. 1073-1090.

_____1979, Gravimetric expression of the graben faulting in Santa Fe County and the Española Basin, New Mexico, in Guidebook of the Santa Fe Country: New Mexico Geological Society, 30th Field Conference, p. 59-64.

Dane, C.H., and Bachman, G.O., 1965, Geologic map of New Mexico: U.S. Geological Survey map, 2 sheets.

Darton, N.H., 1916, Geology and underground water of Luna County, New Mexico: U.S. Geological Survey Bulletin 618, 188 p.

DeFord, R.K., 1969, Some keys to the geology of northern Chihuahua, in Guidebook to the border region: New Mexico Geological Society, 20th Field Conference, p. 61-65.

Doell, R.R., Dalrymple, G.B., Smith, R.L., and Bailey, R.A., 1968, Paleomagnetism, potassium-argon ages, and geology of rhyolites and associated rocks of the Valles Caldera, New Mexico, in Studies in volcanology - a memoir in honor of Howell Williams: Geology Society of America, Mem. 116, p. 211-248.

Doty, G.C., 1960, Reconnaissance of ground water in Playas Valley, Hidalgo County, New Mexico: New Mexico State Engineer Technical Report 15, 40 p.

Emery, P.A., Boettcher, A.J., Snipes, R.J., and McIntyre, H.J., Jr., 1971, Hydrology of the San Luis Valley, south-central Colorado: U.S. Geological Survey Hydrologic Atlas 381, 2 sheets.

Emery, P.A., Patten, E.P., and Moore, J.E., 1975, Analog model study of the hydrology of the San Luis Valley, south-central Colorado: Colorado Water Resources Circular 29, 21 p.

Fitzsimmons, J.P., 1959, The structure and geomorphology of west-central New Mexico, a regional setting, in Guidebook to west-central New Mexico: New Mexico Geological Society, 10th Field Conference, p. 112-116.

Foreman, Fred, Clisby, K.H., and Sears, P.B., 1959, Plio-Pleistocene sediments and climates of the San Agustin Plains, New Mexico, in Guidebook to west-central New Mexico: New Mexico Geological Society, 10th Field Conference, p. 112.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N. J., Prentice-Hall, 604 p.

Gaca, J.R., and Karig, D.E., 1966, Gravity survey in the San Luis Valley area, Colorado: U.S. Geological Survey open-file report, 21 p.

Galusha, Ted, 1966, The Zia Sand Formation, new early to medial Miocene beds in New Mexico: American Museum Novitates, no. 2271, p. 1-12.

_____ 1974, Dating rocks of the Santa Fe Group, in Guidebook of Ghost Ranch: New Mexico Geological Society Guidebook, 25th Field Conference, p. 283-286.

Galusha, Ted, and Blick, J.C., 1971, Stratigraphy of the Santa Fe Group, New Mexico: American Museum of Natural History Bulletin, v. 144, article 1, 125 p.

Gates, J.S., and Stanley, W.D., 1976, Hydrologic interpretation of geophysical data from the southeastern Hueco Bolson, El Paso and Hudspeth Counties, Texas: U.S. Geological Survey Open-File Report 76-650, 37 p.

Gates, J.S., White, D.E., Stanley, W.D., and Ackermann, H.D., 1978, Availability of fresh and slightly saline ground water in the basins of westernmost Texas: U.S. Geological Survey Open-File Report 78-663, 115 p.

Gillerman, Elliot, 1970, Mineral deposits and structural pattern of the Big Burro Mountains, New Mexico, in Guidebook to Tyrone--Big Hatchet Mountains-Florida Mountains Regions: New Mexico Geological Society, 21st Field Conference, p. 115-121.

Groat, C.F., 1972, Presidio Bolson, Trans-Pecos Texas and adjacent Mexico: Geology of a desert basin aquifer system: University of Texas Bureau of Economic Geology, Report of Inventory 76, 46 p.

Gutentag, E.D., and Weeks, J.B., 1980, Water table in the High Plains aquifer in 1978 in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-642, 1 sheet.

Hale, W.E., Reiland, L.J., and Beverage, J.P., 1965, Characteristics of the water supply in New Mexico: New Mexico State Engineer Technical Report, 31 p.

Harley, G.T., 1934, The geology and ore deposits of Sierra County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 10, 220 p.

Hawley J.W., 1969, Notes on the geomorphology and late Cenozoic geology of northwestern Chihuahua, in Guidebook of the border region: New Mexico Geological Society, 20th Field Conference, p. 131-142.

____1975, Quaternary history of Doña Ana County region, south-central New Mexico, in Guidebook to Las Cruces country: New Mexico Geological Society Guidebook, 26th Field Conference, p. 139-150.

____1978, Guidebook to Rio Grande Rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, 241 p.

Hawley, J.W., Bachman, G.O., and Manley, Kim, 1976, Quaternary stratigraphy in the Basin and Range and Great Plains Provinces, New Mexico and western Texas, in Maheny, W.C., ed., Quaternary stratigraphy of North America: Stroudsburg, Penn., Dowden, Hutchinson, and Ross, Inc., p. 235-274.

Hawley, J.W., Kottlowski, F.E., Seager, W.R., King, W.F., Strain, W.S., and Lemone, D.V., 1969, The Santa Fe Group in the south-central New Mexico border region, in Border Stratigraphy Symposium: New Mexico Bureau of Mines and Mineral Resources Circular 104, p. 52-67.

Hawley, J.W., and Seager, W.R., 1978, New Mexico-Texas State line to Elephant Butte Reservoir, in Guidebook to Rio Grande Rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, 241 p.

Hearne, G.A., 1981, Mathematical model of the Tesuque aquifer system underlying Pojoaque River basin and vicinity, New Mexico: U.S. Geological Survey Open-File Report 80-1023, 181 p.

Hem, J.D., 1970, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 1473, 363 p.

Herrick, E.H., and Davis, L.V., 1965, Availability of ground water in Tularosa Basin and adjoining areas, New Mexico and Texas: U.S. Geological Survey Hydrologic Investigations Atlas 191, 5 p., 1 sheet.

Izett, G.A., 1977, Volcanic ash beds in continental deposits of the southern High Plains: Their bearing on the time of the Blancan-Irvingtonian faunal transition (abs.): Geological Society of America, Abstracts with Programs, v. 9, no. 7, p. 1034.

Johnson, R.B., 1969, Geologic map of the Trinidad Quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-558.

Kelley, V.C., 1952, Tectonics of the Rio Grande depression of central New Mexico, in Guidebook to Rio Grande country, central New Mexico: New Mexico Geological Society, 3rd Field Conference, p. 92-105.

_____1955, Regional tectonics of south-central New Mexico, in Guidebook of south-central New Mexico: New Mexico Geological Society, 6th Field Conference, p. 96-104.

_____1956, The Rio Grande depression from Taos to Santa Fe, New Mexico, in Guidebook to southwestern New Mexico II: New Mexico Geological Society, 7th Field Conference, p. 109-114.

_____1977, Geology of the Albuquerque Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 33, 60 p.

_____1978, Geology of the Española Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources Geologic Map 48.

Kelley, V.C., and Kudo, A.M., 1978, Volcanoes and related basalts of Albuquerque Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 156, 30 p.

Kelley, V.C., and Northrop, S.A., 1975, Geology of Sandia Mountains and vicinity, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 29, 136 p.

Kelley, V.C., and Silver, Caswell, 1952, Geology of the Caballo Mountains: University of New Mexico Publications in Geology 4, 286 p.

Kelly, T.E., 1974, Reconnaissance investigation of ground water in the Rio Grande drainage basin - with special emphasis on saline ground-water resources: U.S. Geological Survey Hydrologic Investigation Atlas 510, 4 sheets.

King, W.E., Hawley, J.W., Taylor, A.M., and Wilson, R.P., 1971, Geology and ground-water resources of central and western Doña Ana County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 1, 64 p.

Kottlowski, F.E., 1953, Tertiary-Quaternary sediments of the Rio Grande valley in southern New Mexico, <u>in</u> Guidebook of southwestern New Mexico: New Mexico Geological Society, 4th Field Conference, p. 144-148.

_____1958, Geologic history of the Rio Grande near El Paso, <u>in</u> Guidebook to Franklin and Hueco Mountains, Texas: West Texas Geological Society Guidebook, 1958 Field Conference, p. 46-54.

Kudo, A.M., Kelley, V.C., Damon, P.E., Shafiquallah, M., 1977, K-Ar ages of basalt flows at Canjilon Hill, Isleta volcano, and the Cat Hills volcanic field, Albuquerque-Belen Basin, central New Mexico: Isochron/West, no. 18, p. 15-16.

Lambert, P.W., 1966, Notes on the late Cenozoic geology of the Taos-Questa area, New Mexico, <u>in</u> Guidebook of Taos-Raton-Spanish Peaks Country: New Mexico Geological Society, 17th Field Conference, p. 43-50.

_____1968, Quaternary stratigraphy of the Albuquerque area, New Mexico: University of New Mexico, Albuquerque, unpublished Ph.D. dissertation, 257 p.

Larsen, E.S., Jr., and Cross, Whitman, 1956, Geology and petrology of the San Juan region, southwestern Colorado: U.S. Geological Survey Professional Paper 258, 303 p.

Lipman, P.W., Doe, B.R., Hedge, D.E., and Steven, T.A., 1978, Petrologic evolution of the San Juan volcanic field, southwestern Colorado: Pb and Sr isotope evidence: Geological Society of America Bulletin, v. 89, no. 1, p. 59-82.

Lipman, P.W., and Mehnert, H.H., 1975, Late Cenozoic basaltic volcanism and development of the Rio Grande depression in the southern Rocky Mountains: Geological Society of America Memoir 144, p. 119-154.

Lohman, S.W., and others, 1972, Definitions of selected ground-water terms -- Revisions and conceptual refinements, U.S. Geological Survey Water-Supply Paper 1988, 21 p.

Lovejoy, E.M.P., and Hawley, J.W., 1978, El Paso to New Mexico-Texas State line, in Guidebook to Rio Grande Rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 57-68.

Machette, M.N., 1978, Geologic map of the San Acacia Quadrangle, Socorro County, New Mexico: U.S. Geological Survey Geologic Quadrangle Map GQ-1415, scale 1:24,000.

Manley, Kim, 1976, The late Cenozoic history of the Española Basin, New Mexico: University of Colorado, Boulder, unpublished Ph.D. dissertation, 171 p.

_____1978a, Geologic map of Bernalillo Northwest Quadrangle, Sandoval County, New Mexico: U.S. Geological Survey Geologic Quadrangle Map GQ-1446, scale 1:24,000.

_____1978b, Structure and stratigraphy of the Española Basin, Rio Grande Rift, New Mexico: U.S. Geological Survey Open-File Report 78-667, 25 p.

_____1979, Stratigraphy and structure of the Española Basin, Rio Grande Rift, New Mexico, in Riecher, R.E., ed., Rio Grande Rift tectonics and magnetism: Washington, American Geophysical Union, p. 71-86.

Manley, Kim, and Naesser, C.W., 1977, Fission-track ages for tephra layers in upper Cenozoic rocks, Española Basin, New Mexico: Isochron/West, no. 18, p. 13-14.

Manley, Kim, Scott, G.R., and Wobus, R.A., 1978, Preliminary geologic map of the Aztec 1° x 2° Quadrangle, northwestern New Mexico and southern Colorado: U.S. Geological Survey Open-File Report 78-466.

Mattick, R.E., 1967, A seismic and gravity profile across the Hueco Bolson, Texas: U.S. Geological Survey Professional Paper 575-D, p. D85-D91.

McKinley, P.F., 1956, Geology of Costilla and Latir Peak Quadrangles, Taos County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 42, 32 p.

_____1957, Geology of Questa Quadrangle, Taos County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 53, 23 p.

McLean, J.S., 1970, Saline ground-water resources of the Tularosa Basin, New Mexico: Office of Saline Water Research and Development, Progress Report No. 561, 128 p.

_____1977, Hydrologic maps and data in the Mimbres Basin, New Mexico: U.S. Geological Survey Open-File Report 77-314, 531 p.

Meinzer, O.E., and Hare, R.F., 1915, Geology and water resources of Tularosa Basin, New Mexico: U.S. Geological Survey Water-Supply Paper 343, 317 p.

Meyers, W.R., 1976, Digital model for simulated effects of ground-water pumping in the Hueco Bolson, El Paso area, Texas, New Mexico, and Mexico: U.S. Geological Survey Water-Resources Investigations 58-75, 31 p.

Miller, J.P., Montgomery, A., and Sutherland, P.K., 1963, Geology of part of the southern Sangre de Cristo Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 11, 106 p.

Morgan, A.M., 1942, Ground-water conditions near Lordsburg, New Mexico: New Mexico State Engineer 16th and 17th Biennial Report, p. 263-270.

Murray, R.C., 1942, Report of pumping tests conducted for U.S. Corps of Engineers on Lordsburg Army Camp well no. 1 in New Mexico: New Mexico State Engineer 16th and 17th Biennial Report, p. 271-278.

_____1959, Ground-water conditions in the nonthermal artesian-water basin south of Hot Springs, Sierra County, New Mexico: New Mexico State Engineer Technical Report 10, 33 p.

New Mexico Interstate Stream Commission and the New Mexico State Engineer Office, 1974a, County profile, Hidalgo County, New Mexico: Water resources assessment for planning purposes, 30 p.

_____1974b, County Profile, Socorro County, New Mexico: Water resources assessment for planning purposes, 28 p.

New Mexico State Engineer Office, 1980, Compilation of data and maps supplied to the U.S. Geological Survey resulting from contract no. 14-08-0001-17838.

Ozima, M., Kono, M., Kaneoka, I., Kinoshita, H., Kobayashi, K., Nagata, T., Larsen, E.E., and Strangway, D.W., 1967, Paleomagnetism and potassium-argon ages of some volcanic rocks from the Rio Grande Gorge, New Mexico: Journal of Geophysical Research, v. 72, no. 10, p. 2615-2621.

Ramberg, J.B., Cook, F.A., and Smithson, S.B., 1978, Structure of the Rio Grande Rift in southern New Mexico and west Texas based on gravity interpretation: Geological Society of America Bulletin, v. 89, no. 1, p. 107.

Reeder, H.O., 1957, Ground water in Animas valley, Hidalgo County, New Mexico: New Mexico State Engineer Office Technical Report 11, 101 p.

Richmond, G.M., 1963, Correlation of some glacial deposits in New Mexico: U.S. Geological Survey Professional Paper 450-E, p. 121-125.

Riecher, R.E., ed., 1979, Rio Grande Rift: Tectonics and magmatism: Washington, American Geophysical Union, 438 p.

Sandeen, W.M., 1954, Geology of the Tularosa Basin, New Mexico, in Guidebook of southeastern New Mexico: New Mexico Geological Society, 5th Field Conference, p. 81-88.

Schwennesen, A.T., 1918, Ground water in the Animas, Playas, Hachita, and San Luis Basins, New Mexico: U.S. Geological Survey Water-Supply Paper 422, 152 p.

Scott, G.R., Taylor, R.B., Epis, R.C., and Wobus, R.A., 1978, Geologic map of the Pueblo 1° x 2° Quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-1022.

Seager, W.R., 1973, Resurgent volcano-tectonic depression of Oligocene age, south-central New Mexico: Geological Society of America Bulletin, v. 84, no. 11, p. 3,611-3,626.

_____1975, Cenozoic tectonic evolution of the Las Cruces area, New Mexico, in Guidebook of the Las Cruces Country: New Mexico Geological Society, 26th Field Conference, p. 241-250.

Seager, W.R., Hawley, J.W., and Clemons, R.E., 1971, Geology of the San Diego Mountain area, Doña Ana County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 97, 38 p.

Seager, W.R., and Morgan, Paul, 1979, Rio Grande Rift in southern New Mexico, west Texas, and northern Chihuahua, in Riecher, R.E., ed., Rio Grande Rift: Tectonics and magmatism: Washington, American Geophysical Union, p. 87-106.

Smith, H.T.V., 1938, Tertiary geology of the Abiquiu Quadrangle, New Mexico: Journal of Geology, v. 46, no. 7, p. 933-965.

Smith, R.L., Bailey, R.A., and Ross, C.S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-571, 1 sheet.

Sorensen, E.F., 1977, Water use by categories in New Mexico counties and river basins and irrigated and dry cropland acreage in 1975: New Mexico State Engineer Technical Report 41, 34 p.

Spiegel, Zane, 1957, Geology, in Ground water in Animas Valley, Hidalgo County, New Mexico: New Mexico State Engineer Technical Report 11, p. 9-12.

Spiegel, Zane, and Baldwin, Brewster, 1963, Geology and water resources of the Santa Fe area, New Mexico: U.S. Geological Survey Water-Supply Paper 1525, 258 p.

Stearns, C.E., 1943, The Galisteo Formation of north-central New Mexico: Journal of Geology, v. 51, no. 5, p. 301-319.

_____1953, Tertiary geology of the Galisteo-Tonque area, New Mexico: Geological Society of America Bulletin, v. 64, no. 4, p. 459-508.

Steven, T.A., Lipman, P.W., Hail, W.J., Jr., Barker, Fred, and Luedlse, R.G., 1974, Geologic map of the Durango Quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-764.

Stone, W.J., and Mizell, N.H., 1979, Availability of geological and geophysical data for the eastern half of the U.S. Geological Survey's Southwestern Alluvial Basins Regional Aquifer study: New Mexico Bureau of Mines and Mineral Resources Open-File Report 109, 80 p.

Strain, W.S., 1966, Blancan mammalian fauna and Pleistocene formations, Hudspeth County, Texas: University of Texas at Austin, Memorial Museum Bulletin 10, 55 p.

_____1969, Late Cenozoic strata of the El Paso area, in Border stratigraphy symposium: New Mexico Bureau of Mines and Mineral Resources Circular 104, p. 122-123.

Titus, F.B., Jr., 1961, Ground-water geology of the Rio Grande trough in north-central New Mexico, with sections on the Jemez Caldera and the Lucero Uplift, in Guidebook to Albuquerque country: New Mexico Geological Society, 12th Field Conference, p. 186-192.

Trauger, F.D., 1972, Water resources and general geology of Grant County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 2, 211 p.

Trauger, F.D., and Doty, G.C., 1965, Ground water--its occurrence and relation to the economy and geology of southwestern New Mexico, in Guidebook to southwestern New Mexico: New Mexico Geological Society, 16th Field Conference, p. 215-227.

Trauger, F.D., and Herrick, E.H., 1962, Ground water in central Hachita Valley northeast of the Big Hatchet Mountains, Hidalgo County, New Mexico: New Mexico State Engineer Technical Report 26, 21 p.

Tweto, Ogden, 1978, Tectonic map of the Rio Grande Rift system in Colorado, in Hawley, J.W., compiler, Guidebook to Rio Grande Rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163.

Tweto, Ogden, Steven, T.A., Hail, W.J., and Moench, R.H., 1976, Preliminary geologic map of the Montrose 1° x 2° Quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-761.

U.S. Army Corps of Engineers, 1979, Albuquerque greater urban area, urban studies program, Water supply appendix III: U.S. Army Corps of Engineers, Albuquerque district, Albuquerque, New Mexico.

U.S. Department of Agriculture Soil Conservation Service and Colorado State University Experiment Station, 1979a, Important farmlands of Alamosa County, Colorado: scale 1:100,000, 1 sheet.

U.S. Department of Agriculture Soil Conservation Service and Colorado State University Experiment Station, 1979b, Important farmlands of Conejos County, Colorado: scale 1:100,000, 2 sheets.

_____1979c, Important farmlands of Rio Grande County, Colorado: scale 1:100,000, 1 sheet.

_____1980a, Important farmlands of Costilla County, Colorado: scale 1:100,000, 2 sheets.

_____1980b, Important farmlands of Saguache County, Colorado: scale 1:100,000, 2 sheets.

University of Texas at Austin, Bureau of Economic Geology, 1968, Geologic Atlas of Texas, Van Horn-El Paso sheet.

_____1979a, Geologic Atlas of Texas, Marfa sheet.

_____1979b, Geologic Atlas of Texas, Emory Peak-Presidio sheet.

Waldron, J.F., 1956, Reconnaissance geology and ground-water study of a part of Socorro County, New Mexico: Stanford, Calif., School of Mineral Sciences, Stanford University, unpublished Ph.D. dissertation, 255 p.

Weir, J.E., 1965, Geology and availability of ground water in the northern part of White Sands Missile Range and vicinity, New Mexico: U.S. Geological Survey Water-Supply Paper 1801, 78 p.

West, S.W., and Broadhurst, W.L., 1975, Summary appraisals of the Nation's ground-water resources--Rio Grande region: U.S. Geological Survey Professional Paper 813-D, 39 p.

Wilkins, D.W., Scott, W.B., and Kaehler, C.A., 1980, Planning report for the Southwest Alluvial Basins (east) Regional Aquifer-Systems Analysis, parts of Colorado, New Mexico, and Texas: U.S. Geological Survey Open-File Report 80-564, 39 p.

Wilpot, R.H., and Wanek, A.A., 1951, Geology of the region from Socorro and San Antonio east to Chupadera Mesa, Socorro County, New Mexico: U.S. Geological Survey Oil and Gas Investigations Map OM121.

Wilson, C.A., White, R.R., Orr, B.R., and Roybal, G.R., 1981, Water resources of the Rincon and Mesilla Valleys and adjacent areas, New Mexico: U.S. Geological Survey Open-File Report 81-487, 305 p.

Wilson, Lee, and Jenkins, D.H., 1979, Ground-water resources of Santa Fe County, New Mexico, in Guidebook to Santa Fe country: New Mexico Geological Society, 30th Field Conference, p. 293-298.

Winograd, I.J., 1959, Ground-water conditions and geology of Sunshine Valley and western Taos County, New Mexico: New Mexico State Engineer Technical Report 12, 70 p.

Woodward, L.A., Callendar, J.F., Seager, W.R., Chapin, C.E., Gries, J.C., Shaffer, W.L., and Zilinski, R.E., 1975, Tectonic map of Rio Grande region from New Mexico-Colorado border to Presidio, Texas, in Guidebook of the Las Cruces country: New Mexico Geological Society, 26th Field Conference, p. 239.

_____1978, Tectonic map of the Rio Grande Rift region in New Mexico, Chihuahua, and Texas, in Hawley, J.W., compiler, Guidebook to Rio Grande Rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163.

Wright, A.F., 1978, Bibliography of the geology and hydrology of the Albuquerque greater urban area, Bernalillo and parts of Sandoval, Santa Fe, Socorro, Torrance, and Valencia Counties, New Mexico: U.S. Geological Survey Bulletin 1458, 31 p.

_____1979a, Bibliography of geology and hydrology, San Juan Basin, New Mexico, Colorado, Arizona, and Utah: U.S. Geological Survey Bulletin 1481, 122 p.

_____1979b, Bibliography of geology and hydrology, eastern New Mexico: U.S. Geological Survey Water-Resources Investigations 79-76, 170 p.

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