# Geology and Water Resources of the Santa Fe Area, New Mexico

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*With contributions by* F. E. KOTTLOWSKI *and* E. L. BARROWS, *and a section on* Geophysics *by* H. A. WINKLER

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# PREFACE

The severe drought of 1950–51 emphasized the need for detailed information on aquifers from which additional water supplies could be developed in the vicinity of Santa Fe, N. Mex. Since 1941 the large increase in population in Santa Fe, attendant upon the growth of the Atomic Energy Commission's project at Los Alamos, and an increase in per capita use of water have greatly increased municipal water consumption. Because the severe drought of 1950–51 followed an 8-year period in which there were 6 years of subnormal precipitation, the flow of the Santa Fe River, from which the city of Santa Fe obtains its water, reached record lows in 1950 and 1951. The increased use of water and contemporaneous drought reduced storage and forced a system of water rationing from February to August 1951, in spite of the availability of water from storage facilities on the Santa Fe River. Less well known were the many cases of depletion or partial depletion of private water supplies in the Santa Fe area. For the first time, Tesuque Pueblo, 7 miles north of Santa Fe, had insufficient water for irrigation, and a large reduction in cultivated acreage was necessary in 1951.

Heavy precipitation, especially in the mountains east of the city, during August 1951 and the winter of 1951–52 again filled the reservoirs, temporarily reduced the water-use requirements, and provided an adequate supply of water. However, climatic fluctuations are such that similar droughts must be expected in the future. As surface- and ground-water supplies within the area are limited and are controlled by the geology and by the precipitation, optimum development of available supplies is dependent upon assembly and interpretation of all facts concerning the geology and the occurrence of water.

Owing to realization of the need for information on the Santa Fe area, the second most heavily populated area in New Mexico, an intensive cooperative study of the availability of water supplies in the vicinity of Santa Fe was made in 1951 and 1952 by State and Federal agencies, as part of a series of areal studies begun in 1947. At the outset of the present investigation it was apparent that the supply of surface water was not adequate for the community's long-term needs and that additional water at times must be obtained from ground-water reservoirs. These reservoirs were found to be largely restricted to the geologic units of fairly recent geologic age, but a great many features of these units could not be understood without detailed study of the geology of the entire area.

Geologic mapping of the area around Santa Fe was done by Brewster Baldwin, Frank E. Kottlowski, and Wayne M. Bundy under the direction of Eugene Callaghan, director of the New Mexico Bureau of Mines and Mineral Resources, a division of the New Mexico Institute of Mining and Technology. Particular attention was paid to the sand, gravel, and lava units in the Rio Grande trough near Santa Fe. Discussions with Callaghan in the field and in the office, and with other geologists—particularly C. S. Ross, R. L. Smith, A. E. Disbrow, and Zane Spiegel, U.S. Geological Survey, and C. E. Stearns, now of Tufts College—have served as the basis for many of the ideas and interpretations presented. M. S. Sun, New Mexico Bureau of Mines and Mineral Resources, examined many of the thin sections of the Precambrian rocks and Tertiary igneous rocks.

Subsurface distribution of the main rock units was clarified by geophysical studies made by the geophysical laboratory of the New Mexico Institute of Mining and Technology under the general supervision of E. J. Workman, president of the Institute. H. A. Winkler supervised the fieldwork and made interpretations; C. R. Holmes assisted in the fieldwork.

Hydrologic studies were made by the U.S. Geological Survey under the direction of C. S. Conover, former district engineer, at Albuquerque. Zane Spiegel collected data on wells and springs and correlated the hydrology with the geology and geophysics to evaluate the water resources of the area; E. L. Barrows assembled and analyzed data on precipitation and streamflow; T. P. Gerber and others made periodic measurements of the spring flow constituting the natural discharge of the main aquifers in the Santa Fe area.

Well drillers and well owners furnished much useful information on wells in the area, and their observations permitted some comparisons with past conditions. The Public Service Co. of New Mexico made available its records of surface-water storage, groundwater pumpage, water levels in wells, and logs of wells.

The combined attack on geology and hydrology revealed the areas in which both large and small additional water supplies are obtainable within the Santa Fe area, made possible preliminary estimates of the natural water yield of the area, and pointed to the best methods of conserving and utilizing the total water supply. At the same time a need was demonstrated for certain continuing records of surface flow, ground-water levels, ground-water pumpage, and precipitation. This additional information would be a most important guide to future development and use of the somewhat limited water resources available to the city, and to more accurate determinations of the water-supply potential in the Santa Fe area.

This report, based on results from the several lines of investigation noted above, was organized by Spiegel and Baldwin. For purposes of discussion, the Santa Fe area is subdivided into four main areal units that are valid from geologic, physiographic, and hydrologic standpoints. The organization within certain sections of the report follows this geographic treatment. A summary of the parts of the report is given here to indicate specific authorship and general organization:

"Part 1, Geography," by Spiegel and Baldwin, presents background material pertinent to the remaining parts.

"Part 2, Geology," by Baldwin, presents the stratigraphic, structural, and economic geology and summarizes the geologic history. The section on Precambrian rocks and part of the section on structure were written by Kottlowski. Certain detailed descriptions are deferred to Part 5. Incorporated in pertinent sections are interpretations of subsurface conditions, based on geophysical, geologic, hydrologic, and topographic data. These interpretations were agreed upon in conferences between Winkler, Baldwin, and Spiegel.

"Part 3, Water resources," by Spiegel, includes interpretations of data on precipitation and surface water compiled and analyzed by Barrows. The early history of water use in the Santa Fe area and definitions of hydrologic terms are given in introductory sections. The hydrologic properties of each of the geologic units are described. The hydrologic cycle in the different surface- and ground-water basins is discussed and preliminary estimates of the annual water yields of each basin are made, with emphasis on the interrelations of precipitation, surface water, and ground water. The hydrologic data were found to be the best single source of geophysical information in the area.

"Part 4, Geophysics," was originally written by Winkler. Subsequent to Winkler's resignation from the Institute, Victor Vacquier and C. R. Holmes revised the section with the assistance of Baldwin. Methods and techniques of geophysical exploration other than hydrologic are summarized. The section on results includes specific application of geophysical studies in the Santa Fe area and a summary of geophysical properties of the several main types of rock in the area.

"Part 5, References and appendix," includes a list of selected references as well as supplementary reports. Among the latter is a detailed petrographic description of Precambrian and some Tertiary rocks in the area, written by Kottlowski. A detailed description of

Pennsylvanian sedimentary rocks also was written by Kottlowski. Quotations of the original description of the Santa Fe marls were taken from a report by F. V. Hayden (1869). A summary of the laboratory procedure followed by Bundy in analysis of sediments was written by Baldwin.

Tables giving records of wells and springs in the area, an index to source of streamflow data, and the computed natural flow of the Santa Fe River at McClure Dam also are included in the appendix.

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# GEOLOGY AND WATER RESOURCES OF THE SANTA FE AREA, NEW MEXICO

By Zane Spiegel and Brewster Baldwin

## ABSTRACT

The Santa Fe area, a 15-minute quadrangle of 243 square miles in north-central Santa Fe County, N. Mex., was investigated to determine the general geologic and hydrologic conditions. Santa Fe, capital and second largest city in New Mexico, is at the west base of the Sangre de Cristo Mountains, in the northeastern part of the area. The population of the area is about 30,000. The principal natural resources of the region are rangelands, timber, water, base metals, turquoise, and construction materials. Intangible resources include the varied scenery, the salubrious climate, and the numerous points of archeological and historical interest.

The map area is divided into four principal subareas: (a) the timbered foothills in the eastern part, at altitudes of 7,000 to 9,000 feet, underlain principally by Precambrian rocks that extend upward to nearby alpine peaks more than 12,500 feet high; (b) an extensive semiarid grassland piedmont slope at altitudes of 6,000 to 7,000 feet, developed on downfaulted blocks of sediments of the Santa Fe group, of late Cenozoic age; (c) the Cerrillos, a faulted igneous complex intruded into Mesozoic—early Tertiary sediments and middle Tertiary volcanos, forming low hills in the southwest corner; and (d) a lava mesa on the west side, underlain by Quaternary(?) basalt flows, in part uplifted by normal faults.

The Precambrian rocks consist of a sequence of schist and gneiss intruded successively by gray granite, amphibolite, and red granite. Pre-Carboniferous brecciated zones are abundant. Limestone, shale, and sandstone, mostly of Pennsylvanian age (Magdalena group) crop out in small areas in the foothills near Santa Fe. Sedimentary rocks of Cretaceous age are the oldest rocks exposed in the southwestern corner, where they represent the upper part of a sequence of upper Paleozoic to middle Tertiary rocks more than 2 miles thick. The overlying rocks are the Galisteo formation, a conglomeratic to silty sandstone of Eocene and Oligocene(?) age, about 1,300 feet thick in the map area, and flows and intrusive centers of intermediate composition and of Oligocene and Miocene(?) age. A few scattered exposures of the igneous rocks occur along the mountain front south of Santa Fe.

The Santa Fe group consists of alluvial fans, river channel deposits, and interbedded volcanic rocks of middle(?) Miocene to Pleistocene(?) age, preserved in a complex of depressed fault blocks within the Rio Grande depression. The group contains the Tesuque formation (newly named), which is equivalent to the Santa Fe Formation of some reports; the Ancha formation (newly named), which includes several remnant graded surfaces locally buried by gravel deposits, hitherto designated as "the Ortiz surface," and basalt flows.

The Tesuque formation, best exposed north of the Santa Fe River, consists principally of several thousand feet of stream-deposited pinkish-tan soft arkosic sandstone and minor siltstone and conglomerate. It is correlative with sediments to the north that bear the classic Santa Fe fauna of late Miocene and early Pliocene age. Interbedded near the base of the Tesuque formation are the Bishops Lodge member (newly named), consisting of 50–530 feet of locally tuffaceous volcanic-derived sediments, and thin flows of olivine basalt. The Bishops Lodge member was formed largely of debris from the Oligocene and Miocene(?) volcanic rocks but in part from the products of contemporaneous volcanism; it is tentatively correlated northward with the Abiquiu tuff of Smith. The arkosic sediments of the Tesuque formation were derived from the Precambrian rocks to the east. Faulting and westward tilting of the Tesuque formation accompanied the last stage of uplift. Subsequent erosion removed the Tesuque formation from the southern part of the area.

The Ancha formation, consisting of silt, sand, and gravel, forms a blanket 100–300 feet thick over two-thirds of the area. The Ancha formation is inferred to be of late Pliocene or early Pleistocene age. It rests on a westward-sloping erosion surface that bevels beds of the Tesuque formation. A second westward-sloping graded surface was buried by a layer of basalt lapilli tuff which blankets the Ancha-Tesuque contact in the northwestern part of the area. The tuff is overlain by Quaternary(?) flows of basalt, which intertongue with gravel of the Ancha formation. The ancestral Santa Fe River was diverted southward by the basalt flows to Cienega at the junction of basalt flows from the northwest and south. During the existence of a local base level on the basalt, the Santa Fe River cut and partly refilled a wide valley in the piedmont slope. Lenses of pumice, which correlate with the pumice of the early stages of volcanism in the Valles Mountains 35 miles to the west, are interbedded in the upper 50 feet of the Ancha formation in the central and eastern parts of the Santa Fe area.

Downfaulting during the Pleistocene epoch southwest of the area permitted active erosion and eventual lowering of the local base level at Cienega, whereupon the present erosion of the Santa Fe area began. The channel of the Santa Fe River, flanked by terraces, now is north of and 60 feet below its former gravel-filled course.

A structural basin in the basement (Precambrian(?)) rocks is from 7,000 to 14,000 feet deep and trends north-northwest, according to geophysical studies. The basin and the rocks preserved in it are divided into two east-west structural blocks by the Santa Fe river fault, which trends west-southwest through Santa Fe. South of the Santa Fe River, subparallel faults bounding the east side of the basin trend north-northwest and have vertical displacement totaling 3,000–6,000 feet along a zone 1½ miles wide. North of the Santa Fe River, the faults east of the basin trend north. The west side of the basin is formed by faults trending north-northwest. Pre-Santa Fe rocks are exposed west of the fault zone in the southwest part of the area. The wedge of Tesuque formation preserved in the basin thickens northward. The faulting was post-Tesuque in part, but it may have occurred during the deposition of the Tesuque formation. The Ancha formation has apparently not been faulted significantly in the map area, although elsewhere equivalent beds were faulted appreciably.

Indian pueblos were located at springs and marshy places before the Spanish colonization in 1598. By the mid-1700's the main springs and perennial streams were used for irrigation by Spanish settlers. Wells were used for

domestic and stock supplies after 1716. The Santa Fe River drains most of the map area and the mountains to the east. Water from the upper canyon of the main river is stored for municipal use by Santa Fe. Increased use of water and concurrent droughts after World War II necessitated development of ground water to supplement surface supplies. At the same time, ground water for irrigation was developed in the area of the city well field, and water levels declined locally as a result of heavy pumping during the 1950–51 drought.

A linear relation was formed in graphing the logarithm of the precipitation against altitudes ranging from 5,000 to 10,600 feet in north-central New Mexico. The average annual total water yield of the Santa Fe area ranges from about 0.5 inch (4 percent of the precipitation) on the piedmont slope to 6.9 inches (27 percent of the precipitation) in the upper canyon of the Santa Fe River. The annual water yield averages about 10,000 acre-feet in the piedmont area and about 12,000 acre-feet in the mountains.

Water yield from the mountain area consists of snowmelt, storm runoff, and ground water from glacial sediments, alluvium, and fractured Precambrian rocks. Streamflow and precipitation recharge the aquifers of the Santa Fe group. Water in these extensive aquifers moves generally westward and is discharged naturally in tributaries of Galisteo Creek, tributaries of the Santa Fe River in the vicinity of Cienega, the Rio Tesuque, and the Rio Grande.

The pre-Santa Fe rocks may be considered the "bedrock floor" of the water-bearing formations in the area. Small supplies of ground water are obtained from the Precambrian rocks in the larger valleys and at depths of less than 100 feet. However, dry holes or wells affording insufficient yields for domestic supply are common even in these areas. Discontinuous limestone beds of the Magdalena group in the larger areas of outcrop locally yield small water supplies. Cretaceous rocks in the vicinity of the Cerrillos are generally fine grained, have low permeability, and generally contain water high in sulfate. The Galisteo formation also has a low permeability but may yield small supplies in the southern part of the area. Extrusive and intrusive Tertiary rocks generally yield very small supplies.

The Tesuque formation is generally favorable as a source of domestic or larger supplies of water, except locally near the base of the formation and near the mountains. Moderate to large yields are obtained from the Tesuque formation within the corporate limits of Santa Fe, and similar yields are probably available southwest, west, and northwest of Santa Fe, and locally in Tesuque.

In the southern part of the area the Ancha formation is generally underlain by pre-Santa Fe rocks at depths of about 200 feet; in the remainder of its extent the Ancha formation overlies the Tesuque formation. Except in a few places the Ancha is not saturated.

Terrace sediments along the Santa Fe River received recharge by irrigation until the water from the river was diverted for public use. Alluvium, which is underlain by nearly impermeable rocks in mountain valleys and near Cienega, yields small quantities of ground water of good quality. West of the mountains, alluvium in the arroyos absorbs runoff readily and transmits the water downward to underlying aquifers. Slope wash and eolian sediments probably are not saturated anywhere in the area, but they aid recharge by absorbing precipitation readily and transmitting it downward.

Ground water south of the Santa Fe River and north of the drainage of Gallina Arroyo discharges in the Cienega area and is represented by the

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base flow of the Santa Fe River below Cienega. The annual natural discharge of the Cienega area is about 4,700 acre-feet, 2,500 of which is now used consumptively above the temporary gaging point. The average unit water yield for the 131 square miles tributary to the Cienega discharge area is about 0.7 inch. Of this, a mountain drainage area of 23.8 square miles contributes about 1,600 acre-feet. The piedmont slope contributes the remaining 3,100 acre-feet, mostly as ground water, corresponding to an average annual ground-water discharge of 0.5 inch.

The median discharge of the Santa Fe River near Santa Fe for the 39-year period of record through 1951 is about 5,800 acre-feet. The average annual supply capturable by storage and use from above Santa Fe, under 1951 conditions, is about 4,800 acre-feet. As the runoff in some wet years is more than the sum of current use and existing surface storage, there should be occasional periods of spill. The water supply from the Santa Fe river must be supplemented by ground water in many dry years, and if the demand increases as much as 15 percent, supplemental supplies of ground water will be required in most years. Water-level and pumpage data for the city well field suggest interference among wells, amplified by boundaries. Excessive declines of water level in the easternmost wells are due to boundary effects and to overpumping of individual wells. Therefore, the surplus surface flow in wet years might advantageously be used to replenish the ground-water supplies withdrawn in dry years. The capacity of existing wells in and near Santa Fe already exceeds the annual average recharge and ground-water inflow, but the actual average withdrawal may be less than the average annual inflow and recharge for many years to come.

The water in all aquifers in the Santa Fe area is of good to fair chemical quality for most uses. The hardness generally ranges from 80 to 220 ppm (parts per million); the hardness of the ground water used for auxiliary municipal supply at Santa Fe averages 150 ppm. The hardness of surface water in the Sangre de Cristo Mountains varies with the discharge but is generally less than 30 ppm.

Gravimetric, magnetic, electrical-resistivity, and refraction seismic methods were used to confirm subsurface features inferred from the geologic and hydrologic data. Although the hydrologic study was found to furnish the best data, several features were delineated more precisely by applying one or more of the standard geophysical methods. The Precambrian rocks have an average bulk density of 2.7 grams per cubic centimeter, resistivity of about 1,000 ohm-feet, and seismic velocities between 13,700 and 16,000 feet per second. The rocks of Mesozoic age have an average bulk density of 2.55 grams per cubic centimeter and resistivities of 50 to 1,000 ohm-feet. The lower and middle Tertiary rocks have bulk densities ranging from 2.18 to 3.08 (average 2.54), resistivities ranging from 400 to 1,000 ohm-feet, and seismic velocities of 8,900–12,000 feet per second. The Tesuque formation has an estimated average bulk density of 2.1 grams per cubic centimeter, resistivities of 30–600 ohm-feet dry and 10–500 ohm-feet wet, and seismic velocities of 7,000–8,500 feet per second. The Ancha formation and alluvium have averaged bulk densities of 1.7 grams per cubic centimeter, resistivities of 100–2,000 ohm-feet dry and 30–500 ohm-feet wet, and seismic velocities of 600–3,600 feet per second dry and about 6,000 feet per second wet. Volume susceptibilities and magnetization are essentially zero for alluvium, the Ancha and Tesuque formations, and the rocks of Mesozoic age, but they vary considerably for the Tertiary volcanic and intrusive rocks.

# PART 1—GEOGRAPHY

By Zane Spiegel and Brewster Baldwin

## LOCATION AND ACCESS

The Santa Fe area of this report is a 15-minute quadrangle of 243 square miles in the north-central part of Santa Fe County, in the upper Rio Grande drainage area of north-central New Mexico (figs. 1, 2). The county has a land area of 1,928 square miles.

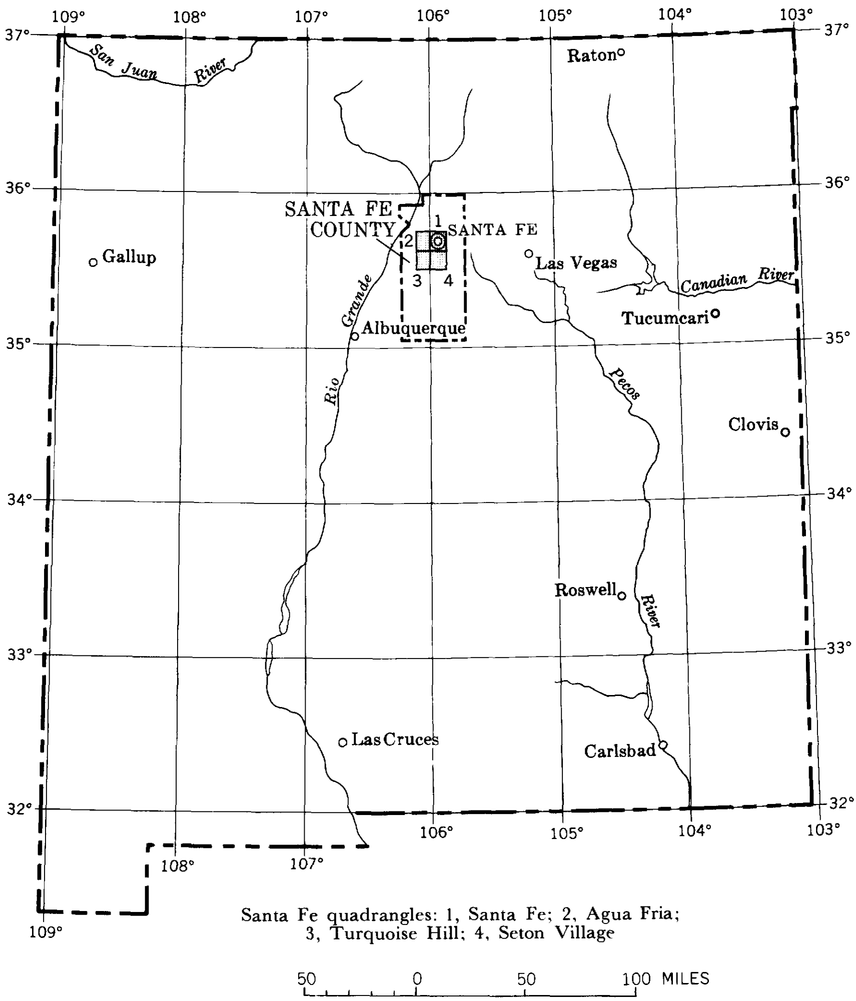



**Figure 1.—Index map of New Mexico, showing location of the Santa Fe area.**

About 80 percent of the 38,153 inhabitants of the county (1950 census) live within the area investigated. Most of these live in the city of Santa Fe, the capital of New Mexico, in the northeastern part of the area. The city is on the Santa Fe River at the foot of the Sangre de Cristo Mountains, at an altitude of about 7,000 feet. This setting, important to the early development of the city and its historic tradition, is climatically and scenically suitable for a State capital.

The Santa Fe area as used in this report extends about 14 miles from east to west and 17 miles from north to south, and lies within the limits of four 7½-minute topographic quadrangles of the United States Geological Survey as shown in figure 1. The area thus forms a 15-minute rectangle that straddles the 106th meridian and is bounded on the north by parallel 35°45′ N.

Access to the area is principally by highway or airline. Surfaced highways connect Santa Fe with Los Alamos, Taos, and the San Luis Valley of Colorado to the north; Las Vegas and Raton to the northeast (skirting the southern tip of the Sangre de Cristo Mountains); Cerrillos and Madrid to the south; and Albuquerque 62 miles to the southwest. Daily flights scheduled by airlines also give access to and from Santa Fe. A rail spur for freight connects Santa Fe with the main line of the Atchison, Topeka, and Santa Fe Railway at Lamy, 20 miles southeast of Santa Fe, but passenger service between Santa Fe and Lamy is provided by bus. Main highways and improved roads within the area are shown in plates 1–4 and figure 4.

## PHYSIOGRAPHY

### REGIONAL SETTING

The Santa Fe area is on the east side of the Rio Grande trough, a roughly linear compound structural depression which extends from southern Colorado to southern New Mexico (Kelley and Silver, 1952, fig. 20). The valley of the Rio Grande drains southward within the trough, and all streams draining the Santa Fe area discharge to it. The borders of the Rio Grande trough are irregular; the width ranges from 20 to 40 miles. The exact lateral limits cannot be marked everywhere, but the approximate boundary is taken as the inner base of the mountain ranges that parallel the trough.

The Rio Grande structural trough in the latitude of Santa Fe (fig. 2) is about 40 miles wide, bordered by the Sangre de Critso Mountains on the east and by the south end of the Sierra Nacimiento on the west. These two ranges are the eastern and western prongs of the southern Rocky Mountains, and the trough itself can be considered a modified part of the Basin and Range province.

Northeast of Santa Fe, peaks of the Sangre de Cristo Mountains rise to altitudes of more than 13,000 feet, though they are lower in the southern part of the range. These mountains have also been referred to as the Truchas Range and as the Santa Fe Mountains. The lower parts of the mountains are rugged, whereas the higher parts have a rounded and subdued appearance (Cabot, 1938, p. 103–104). Lake Peak (alt. 12,409 ft) and Santa Fe Baldy, 3 miles to the north, are two prominent peaks near Santa Fe. Westward from the foot of the mountains, an alluvial plain or piedmont slope is inclined toward the Rio Grande and forms most of the Santa Fe area. From the west edge of the area to the Rio Grande, the plain is buried under extensive lava flows which form a mesa. Figure 3 is a general view of the Santa Fe area from near the area's southwest corner. The regional relations are shown in figure 2.

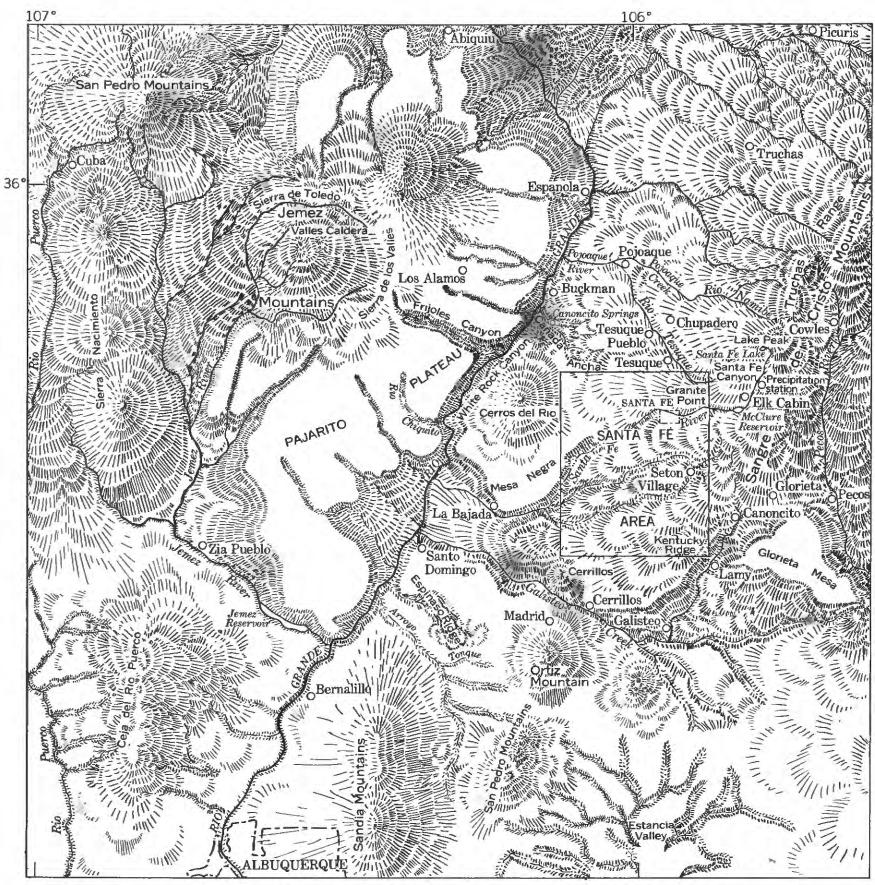



**Figure 2.**—Regional setting of the Santa Fe area in north-central New Mexico.

FIGURE 3.—View northeast toward the Sangre de Cristo Mountains from cinder cone on south end of Mesa Negra de la Bajada (sec. 14, T. 15 N., R. 7 E.). Cienega area in middleground; Santa Fe at base of mountains beyond Cienega Creek.

The lava mesa extends 24 miles from north to south and 12 miles from east to west. Its west border is White Rock Canyon of the Rio Grande. The mesa has two general levels. The lower level is about 6,200–6,600 feet in altitude and is marked by centers of fairly recent volcanic activity. The southern part of this irregular lower surface is called the Mesa Negra de la Bajada, and the northern part is sometimes called Pankeys Mesa. The entire area is referred to in this report as the lava mesa. Above the main level is the second level formed by the Cerros del Rio—broad, high dissected mesas that reach altitudes of about 7,300 feet.

White Rock Canyon, which is 1,000 feet deep, separates the lava mesa on the east from the east-sloping Pajarito Plateau on the west. The plateau is capped by tan welded tuff and is cut into long, narrow mesas by deep canyons of streams tributary to the Rio Grande. Rito de los Frijoles, in Frijoles Canyon, is one of these streams. The plateau rises westward toward the Valles Mountains, which are remnants of a prehistoric volcano. To the west of the Valles Mountains the Sierra Nacimiento forms the west border of the Rio Grande structural depression in the latitude of Santa Fe. The Valles and Nacimiento masses together are popularly called the Jemez Mountains.

The piedmont slope, an alluvial plain that forms much of the Santa Fe area, is bounded in part by drainage courses on the north and south. The plain abuts against the Cerrillos ("little hills") to the southwest. Both the plain and the Cerrillos end in a digitate escarpment that descends southward to Galisteo Creek. South of Galisteo Creek are the Ortiz Mountains and the northward-facing escarpment forming the north boundary of the Estancia Valley. The plain in the northern part of the Estancia Valley may be a continuation of the piedmont slope south of Santa Fe. The valley of Galisteo Creek separates these two plains.

To the north, the rolling piedmont slope gives way to a higher, more dissected area which forms the divide between the Santa Fe River drainage of the plains and the northerly drainage of Pojoaque and Tesuque Creeks. The northerly drainage has caused intricate dissection and moderately strong local relief, including some badlands. This rough area is sometimes known as the Santa Fe Hills. It descends northward into the Espanola Valley of the Rio Grande.

## PHYSIOGRAPHIC UNITS

Four physiographic units make up the Santa Fe area (figs. 4 and 5). Highlands, in which Precambrian and Pennsylvanian rocks crop out form the east border of the area; the Cerrillos and outlying knobs of rocks of middle Tertiary(?) age appear in the southwest corner; basalt flows of the lava mesa form the northern and central western portions; and a westward-sloping, broad, dissected piedmont slope forms the main part of the area. The Santa Fe River, the principal stream of the area, crosses the piedmont slope from northeast to southwest in a broad, terraced valley, toward which nearly all the drainage lines west of the mountains converge.

The highlands unit of Precambrian and Pennsylvanian rocks forms the foothills of the Sangre de Cristo Mountains, which rise to altitudes of more than 10,100 feet immediately east of the area. Within the area proper the highlands generally range in altitude from 7,000 to 9,000 feet. The foothills are youthfully dissected and rugged in appearance, in contrast to the mature higher mountains. Rocks of the western limit of the highlands are exposed below late Tertiary and Quaternary sediments at approximate altitudes of 7,400 feet in the northeastern part of the area, 7,200 feet near Santa Fe, and 7,000 feet southeast of Santa Fe. In the southern part of the highlands, peaks of the bordering range are much lower than those farther north, and the valleys in the foothills are broader and more mature. One prominent valley, followed by the Santa Fe–Las Vegas highway (U.S. 85) is about 1 mile wide and trends N. 30° W.; its western limit is a line of low hills that trend N. 25° W.

The Cerrillos are a group of small hills that lie just south of the southwest corner of the area and just north of Galisteo Creek. Their

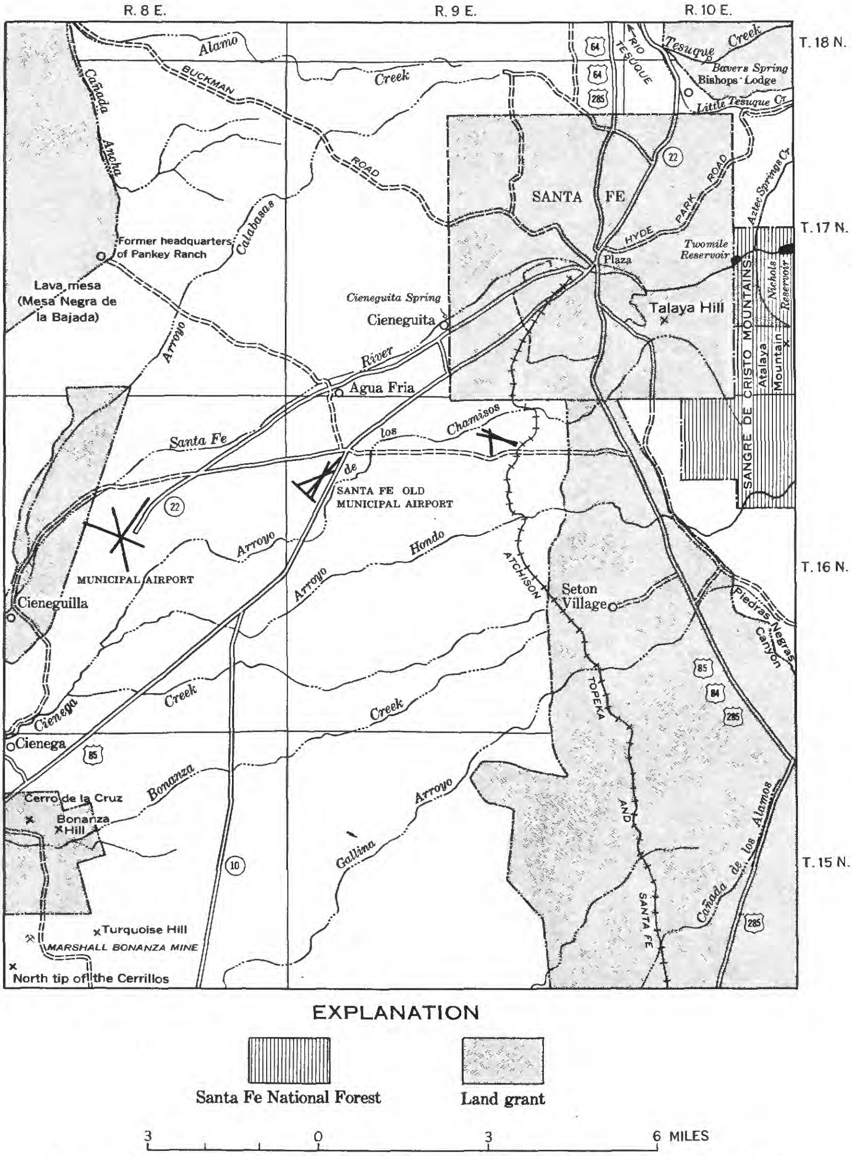
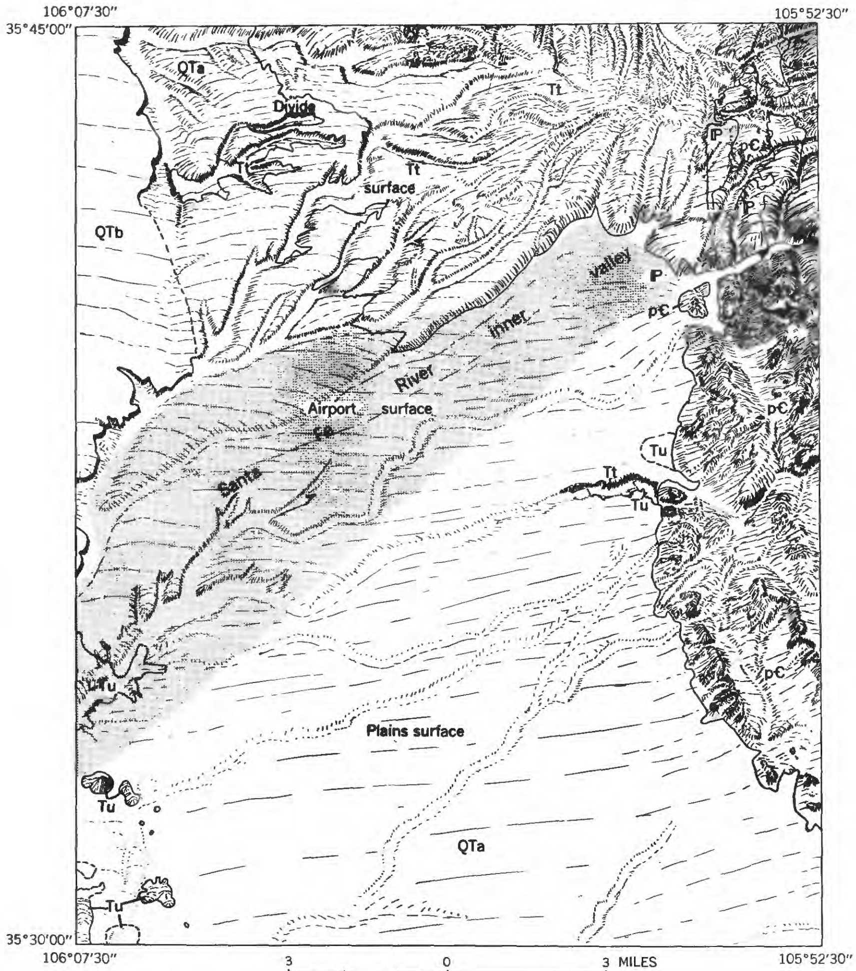



**FIGURE 4.—Cultural and drainage features of the Santa Fe area, New Mexico.**

area is roughly 20 square miles, and altitudes of the higher hills range from 6,500 to 7,000 feet. The northern tip of the Cerrillos projects into the very southwestern corner of the Santa Fe area, where there is a hill having an altitude of 6,616 feet. Farther north and east a number of knolls, knobs, and small hills attain altitudes as high as 6,500 feet. One of these is Cerro de la Cruz (Calvary

Butte), a black conical butte that forms a landmark. Its summit lies at about 6,460 feet. A dissected erosion-surface remnant in the southwest corner of the area slopes northward from the Cerrillos toward Alamo Creek, and the isolated knobs and hills stand above this surface.

The west border of the area is marked by the eastern part of the lava mesa (Mesa Negra de la Bajada to the south; Pankeys Mesa to the north). The mesa projects a few miles into the Agua Fria quadrangle, but to the south the edge of the mesa is just west of the




EXPLANATION

Ancha formation, QTa; basalt flows, QTb; Tesuque formation, Tt; pre-Santa Fe Tertiary rocks, Tu; Pennsylvanian rocks, P; Precambrian rocks, p€

FIGURE 5.—Geologic and topographic sketch map of the Santa Fe area, New Mexico.

Turquoise Hill quadrangle. The high, dissected mesas of the Cerros del Rio lie west of the area, except for an eastern tip on the border of the Agua Fria quadrangle. Much of the eastern edge of the lava mesa is a basalt-capped cliff, which is 300 feet high in places. This cliff diminishes in height near the divide between southward and northward drainage in the Agua Fria quadrangle; at the divide, within 1 mile of the former Pankey ranch headquarters, the eastward-sloping mesa merges with the westward-sloping alluvial plain.

The largest part of the Santa Fe area is the somewhat dissected piedmont slope that laps against the mountains to the east and against the Cerrillos to the southwest, and is buried under the lava flows of the mesa to the west. The piedmont slope can be divided into three units which can be seen from the upland north of Arroyo Hondo (see fig. 4) in the southwestern part of the Santa Fe quadrangle. From this point south the slope is here called the Plains surface. It is a smooth, rolling plain that slopes southwestward and is dissected by widely spaced, broad valleys that drain to the Santa Fe River or Galisteo Creek. North of Arroyo Hondo is a partly dissected, shallow valley about 3 miles wide. Remnants of the valley floor form the Airport surface (fig. 5), and the Santa Fe River and its terraces form an inner valley on the north side. Beyond the Santa Fe River rises the broad Divide area, which occupies the northern third of the area. The Divide surface is a dissected upland whose remnants form a surface that is convex westward. Drainage is fine textured, and the resulting badland topography forms a marked contrast with the relatively smooth plain to the south.

## DRAINAGE

The Santa Fe River is the principal drainage feature in the area. It heads high in the south end of the Sangre de Cristo Mountains, in a large composite cirque dominated by lofty Lake Peak about 15 miles northeast of Santa Fe. For 10 miles the river trends southwest from the crest of the mountains, draining many of the highest mountain slopes in the vicinity of Santa Fe. The river then trends westward for 7 miles and emerges from the mountains at Santa Fe. Three main surface reservoirs in this stretch of the river store runoff for municipal use; otherwise the river would have a perennial flow through Santa Fe. The channel through the city is usually dry, except for local storm and snowmelt runoff and the discharge from a few small springs.

Beyond the mountains, the river's channel and valley widen to form an arroyo trending west-southwestward to the west edge of the area. There the river valley drains southward, parallel to the foot of the basalt-capped cliff, until it reaches Cieneguilla. Surface flow in the Santa Fe River west of the mountains is ephemeral, although there are springs at Cieneguita (fig. 4) and Cieneguilla. Drainage from a large part of the lava mesa west of the area is to the Santa Fe River near Cieneguilla.

Just west of the area, in the deep canyon downstream from Cieneguilla, the Santa Fe River flows perennially. It emerges from the canyon at La Bajada, and surface flow again ceases because of infiltration into gravel there.

Most of the mountain slopes and plains south of Santa Fe are drained by Arroyo de los Chamisos, Arroyo Hondo, and other arroyos that join Cienega Creek, which in turn enters the Santa Fe River in its canyon 3 miles below Cieneguilla. Arroyo Hondo has a small perennial flow in the mountains, and the other tributaries have scattered small springs and seeps. All these streams are ephemeral west of the mountain front, except in their lowermost reaches near their junction with the Santa Fe River in the Cienega area where springs emerge.

The southernmost tip of the Sangre de Cristo Mountains and the south margin of the plains are drained by tributaries of Galisteo Creek. Of these, Canada de los Alamos has a small perennial flow in the mountains outside the area and Arroyos San Marcos and Coyote have a small perennial flow near the crossings of State Highway 10, just south of the area. Galisteo Creek heads between the south end of the Sangre de Cristo Mountains and the north end of Glorieta Mesa. Its course is southwest to Galisteo and then northwest to its confluence with the Rio Grande at Santo Domingo.

The northeastern part of the Santa Fe area is drained by Tesuque and Little Tesuque Creeks, which head in canyons on the west slope of the Sangre de Cristo Mountains. Little Tesuque Creek has a small perennial flow above Bishops Lodge, and Tesuque Creek has an appreciably larger flow which is derived principally from the uppermost portion of its basin, above 10,000 feet. Tesuque and Little Tesuque Creeks merge at the north margin of the Santa Fe quadrangle to form Rio Tesuque. About 15 miles north of the Santa Fe area, Rio Tesuque joins the Pojoaque River, which in turn joins the Rio Grande above White Rock Canyon.

Canada Ancha drains a small area in the northwestern part of the Agua Fria quadrangle north of the Santa Fe River, including part of the lava mesa. It trends northwest at the foot of the basalt cliffs and joins the Rio Grande at Buckman, an abandoned community 7 miles northwest of the Santa Fe area. No springs or perennial flow exist in the area, but a small spring exists a few miles north, in a narrow canyon.

In summary, perennial flow occurs only in the mountain drainage basins of the Rio Tesuque and the Santa Fe River, and in the lower canyon of the Santa Fe River and other streams of the Cienega area. Perennial springs are found in the mountains, in the Cienega area, and at Cieneguita (at the west city limits of Santa Fe). The rest of the area is traversed by arroyos, in which surface flow occurs only during storms and is quickly absorbed by the arroyo fill, whence it either is evaporated or transpired or seeps downward to the ground-water bodies. Only rarely is there direct surface flow from the Santa Fe area to the Rio Grande or Galisteo Creek.

## CLIMATE

Climate is a function of many variables, chief of which are the latitude, altitude of the land surface, and source and general movement of air masses (see Dorroh, 1946). Air movements are influenced considerably by topography, especially by large mountainous areas. Altitudes in the area investigated range from about 6,000 feet in the southwestern part, along the Santa Fe River, to 7,500 feet or more on the plains and badlands in the east and north, and to as much as 9,000 feet in the foothills within the Santa Fe and Seton Village quadrangles. Peaks of the Sangre de Cristo Mountains to the east rise to 12,000 feet, constituting an important topographic barrier to movements of air masses. Temperature and precipitation differ markedly with topographic location and altitude. However, if any one aspect of climate in the Southwest is typical, it is the extreme variability with time and location as well as with altitude.

Climatological data over long periods are available only for Santa Fe, where a weather station has been maintained nearly continuously from 1853 to the present. Although the station has been at various locations in the city, its altitude is about 7,000 feet, and data from this station (table 1) thus probably reflect the general conditions over most of the area investigated.

The climate in this area, as in most of New Mexico, is semiarid. Summer days are generally warm to cool according to altitude, and even at the lower altitudes nights are generally cool owing to rapid radiation of heat through the relatively thin and dry atmosphere. Temperatures as high as the upper nineties are rare, and night-temperature minima average 24° F. below daytime maxima in the summer. Beginning in September, temperatures decline gradually but high diurnal differences continue. The diurnal temperature range in winter averages about 21° in Santa Fe. The severest weather in the Santa Fe area is in December through February, but snow may fall at higher altitudes as early as September and as late as June. Both the total precipitation and the proportion occurring as snow increase with altitude, whereas the evaporation rate decreases. The higher parts of the mountains retain snow cover through the entire winter until April or later. Below about 8,000 feet, the snow may stay only a few days before melting or evaporating, except in sheltered places. On the lower plains, snow cover seldom lasts long after the storm that produced it leaves the area.

These climatic factors are important to the agricultural economy, because water stored as snowpack in the high mountains is usually released at about the time it is needed for irrigation, to start crops at lower altitudes in the otherwise dry spring months. Spring in New Mexico is especially critical for agriculture, not only because of low precipitation at the lower altitudes but also because strong, warm, and extremely dry southwest winds are common in March, April, and May. These dry southwest winds represent the movement of hot, dry, tropical continental air masses that originate in Mexico and the extreme southwestern part of the United States. In some years these dry winds evaporate a considerable part of the snowpack in the mountains. The evaporation rate is an important factor to consider with respect to water use by plants and to the available water supply. Evaporation rates in turn are influenced greatly by temperature, wind velocity, and relative humidity.

Below altitudes of 7,500 feet, about one-half the annual precipitation occurs from June to September, when there is an increase of moist air masses from the Gulf of Mexico. Most of this summer precipitation occurs in July and August because of the increase in convection due to intense solar radiation. Precipitation in these months generally occurs as sudden, heavy showers, runoff from which is generally large and rapid. These showers are generally spotty in distribution and any one shower may wet only a small area. Thus precipitation records of plains stations, even at similar altitudes, may be representative of large areas only if they cover a period of considerable length. Records of stations at different altitudes are discussed on pages 146–150. Precipitation at higher altitudes is generally more frequent and greater, but less intense, than on the piedmont slope.

A tabular summary of the climatological data from the Santa Fe city station, which is presented in table 1, was compiled by E. L. Barrows from climatological summaries by the U.S. Weather Bureau.

Unfortunately, the average figures given in the accompanying table do not show the wide deviations from the average monthly and annual rates of precipitation and evaporation that are characteristic of the semiarid Southwest, nor do they show the intensity

TABLE 1.—*Summary of climatological data, Santa Fe, N. Mex.*

[Data from U.S. Weather Bureau records]

| | Temperature (° F) | | | | | Precipitation (inches) | | Mean relative humidity (percent) | | | | Sky condition (average number of days) | | | Sunshine (average percent of possible time) | Wind (average miles per hour) | Mean evaporation from class A pan (inches) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Average maximum | Average minimum | Highest recorded | Lowest recorded | Mean | Greatest in 24 hours | 5:30 a.m. | 11:30 a.m. | 5:30 p.m. | 11:30 p.m. | Clear | Partly cloudy | Cloudy | | | |
| Years of record | 72 | 72 | 72 | 72 | 72 | | 67 | 68 | 23 | 68 | 5 | 68 | 68 | 68 | 50 | 58 | 10 |
| January | 28.8 | 39.6 | 18.9 | 76 | −13 | 0.67 | 1.22 | 66 | 50 | 55 | 68 | 17 | 9 | 5 | 72 | 6.9 | 1.53 |
| February | 33.1 | 43.7 | 22.8 | 75 | −15 | .75 | 1.82 | 66 | 49 | 41 | 61 | 13 | 9 | 6 | 69 | 7.2 | 2.13 |
| March | 39.7 | 51.2 | 28.1 | 82 | −2 | .80 | 1.07 | 60 | 41 | 39 | 58 | 14 | 11 | 6 | 71 | 8.0 | 3.96 |
| April | 46.7 | 59.5 | 35.0 | 84 | 11 | 1.00 | 1.36 | 54 | 33 | 32 | 55 | 13 | 12 | 5 | 73 | 8.2 | 6.15 |
| May | 55.7 | 68.5 | 43.3 | 86 | 20 | 1.26 | 2.12 | 51 | 32 | 29 | 47 | 14 | 13 | 4 | 74 | 8.0 | 8.51 |
| June | 64.8 | 78.6 | 52.3 | 94 | 33 | 1.08 | 2.15 | 47 | 28 | 27 | 43 | 16 | 12 | 2 | 80 | 7.3 | 10.14 |
| July | 69.0 | 81.2 | 57.1 | 96 | 43 | 2.38 | 2.12 | 60 | 36 | 41 | 57 | 9 | 18 | 4 | 69 | 6.3 | 8.93 |
| August | 67.4 | 79.6 | 56.1 | 97 | 40 | 2.28 | 1.67 | 65 | 38 | 43 | 68 | 10 | 17 | 4 | 71 | 5.9 | 8.06 |
| September | 60.9 | 73.4 | 49.3 | 91 | 21 | 1.45 | 2.83 | 63 | 39 | 40 | 58 | 16 | 10 | 4 | 76 | 6.1 | 6.55 |
| October | 50.4 | 62.5 | 38.7 | 85 | 13 | 1.18 | 1.83 | 60 | 39 | 42 | 65 | 19 | 8 | 4 | 80 | 6.5 | 4.81 |
| November | 38.9 | 50.3 | 28.0 | 77 | −11 | .68 | 1.29 | 60 | 42 | 48 | 61 | 18 | 8 | 4 | 76 | 6.7 | 2.55 |
| December | 30.7 | 41.0 | 20.5 | 65 | −13 | .74 | .87 | 66 | 51 | 56 | 70 | 17 | 9 | 5 | 73 | 6.8 | 1.39 |
| Year | 48.8 | 60.8 | 37.5 | 97 | −15 | 14.27 | 2.83 | 59 | 40 | 41 | 59 | 176 | 136 | 53 | 74 | 7.0 | 64.71 |

of the rainfall, which is important for estimating surface runoff, ground-water recharge, and soil-moisture retention. The annual precipitation may be as much as 100 percent more or 50 percent less than the average annual amount, and the monthly precipitation may deviate as much as several hundred percent from the average.

Appreciable local fluctuations of temperature, not indicated in the data presented, are caused by differences in radiation, sun exposure, cold-air drainage at night, and local surface wind currents. For example, radiation and cold-air drainage at night cause temperature inversions in the valley bottoms, where frost may form on many nights even when temperatures on the higher slopes are well above freezing.

No continuous, long-term climatological records are available for the adjacent mountain areas, but some short records have been obtained. These are discussed in the section on the "Hydrologic cycle." In summary, it should be emphasized that climatic records are incomplete and had been kept for a maximum of only 72 years at the time of this report (1955). No definite evidence of a long-term trend in climate is apparent from these records, and the future climate cannot be predicted with certainty. However, it is probable that the future range of climate will be much as has been recorded in the past few decades. More important to a consideration of water resources in the Santa Fe area are the marked fluctuations that occur seasonally, yearly, and over periods of a few years.

## VEGETATION

Vegetation zones are largely controlled by changes in climate with altitude. The zones overlap and grade upward as functions of the increase of precipitation and the decrease in temperature with altitude. Lower evaporation rates are indirect effects of the decrease in temperature with altitude but are probably nearly as important as the precipitation itself in the control of vegetative zones. The limits of each zone vary according to local climate, exposure, and soil moisture but are in general as follows:

| *Altitude (feet)* | *Vegetation* |
|---|---|
| 12,000+ | Alpine grass |
| 9,000–12,000 | Spruce and fir |
| 7,500–9,000 | Ponderosa pine |
| 7,000–8,000 | Pinyon pine |
| 6,500–7,500 | Juniper |
| 6,000–7,500 | Grassland, predominantly grama grass |

Cottonwoods and willows are native to stream valleys below about 7,500 feet, and chamise (Spanish "chamiso," locally known as "chamisa") is common on drier valley slopes at that altitude or lower. Aspen is dominant on the valley floors of the canyons in the Sangre de Cristo Mountains, as well as on slopes having perennially high soil moisture, or where it has become established after destruction of the shading, slow-growing conifers by forest fires.

## POPULATION

The population of Santa Fe County, according to the census taken in April 1950 (U.S. Bureau of the Census, 1951), increased from 30,826 in 1940 to 38,153 in 1950, a gain of 7,327 or 23.8 percent. The land area of Santa Fe County in 1950 was 1,928 square miles, giving an average population density of 19.8 persons per square mile, compared to the state average of 5.6 persons per square mile. The population of the city of Santa Fe in April 1950 was 27,998, an increase of 7,673 or 37.8 percent over the 1940 population of 20,325. As the gain of the city is more than the gain of the county, the rural areas have lost some population (owing in part to transfer of the northwestern part of the county to Los Alamos County, which was created in 1949). The recent increase in the population of Santa Fe is attributed largely to the influence of nearby Los Alamos, the expanded hand-crafts industry, and increased tourist trade. Retired persons and healthseekers also have helped to swell the population.

The population of the area outside the Santa Fe city limits but within the area investigated is estimated to be about 2,500 and is concentrated chiefly in Agua Fria (954), Tesuque (732), and Cienega (146), and in the foothills along the Las Vegas highway. The population of the entire area investigated is thus about 30,500, averaging 75 to the square mile. It is difficult to evaluate the transient tourist population, but it is obvious that the true average population of Santa Fe is much greater than is indicated by the census figures. The average tourist population is estimated to be about 2,000 to 3,000. An important consideration affecting water supply is that 50 percent of the tourist increment is concentrated in June to August, 20 percent in August alone. June to August are also the months in which lawn irrigation is at its peak for the year, especially if the usually heavy July and August rains are below normal.

## ECONOMY

The present population of the city of Santa Fe is largely employed in Government establishments or in serving the large tourist trade. Light industry, mostly the manufacture of products destined for the tourist market, provides some employment. A considerable proportion of the labor force is employed in construction accompanying the recent rapid growth of the city. Much of the governmental employment is in connection with the nearby atomic-energy project at Los Alamos. Offices of the State government—which require many employees—county and city governments, and several Federal agencies account for the remainder employed in governmental positions.

Except for the desirable climate, scenery, and outdoor recreation potential which attract tourists, water is probably the principal natural resource of the Santa Fe area. At present the very small amount of the surface flow of the Santa Fe River not used for city supply is utilized in small-scale irrigation along the Santa Fe River in the eastern part of town. Water discharged from the city's modern sewage plant is used to irrigate feed crops southwest of the city and to irrigate the municipal golf course. In the Cienega area extensive springs and seeps are utilized in the irrigation of various crops. The surface flow of the Rio Tesuque is utilized in orchard and crop irrigation all along the Tesuque valley. Wells supply ground water for stock use, enabling the extensive mesa areas to support many cattle. In addition, irrigation with ground water has been developed to a small extent by a relatively few operators along the Santa Fe River and the Rio Tesuque.

Most of the rural population not employed in Santa Fe or Los Alamos is engaged in agriculture. Irrigating is done chiefly in the Cienega and Tesuque areas by diversion of spring flow. Beans, corn, alfalfa, and tree fruits are the principal crops. Although only a very small proportion of the population is engaged in cattle raising, most of the area investigated is utilized for this purpose. The national-forest areas at the east margins of the Santa Fe and Seton Village quadrangles are a reserve of timber. Small mines in the Cerrillos have yielded turquoise, lead, and zinc. Sand and gravel for roads and construction are obtained from several gravel pits near Santa Fe.

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# PART 2—GEOLOGY

By Brewster Baldwin

## INTRODUCTION

### PREVIOUS WORK

Previous geologic work in north-central New Mexico has been of considerable aid in understanding the geology of the Santa Fe area itself, but detailed geologic mapping has been limited to a few areas. Stevenson (1881, p. 28–38) summarized the notes made by others in some of the early explorations. Hayden (1869) named the Santa Fe marls and the Galisteo sand group; several pertinent parts of his report are reprinted in the appendix. Interest in the abundant fauna in Hayden's Santa Fe marls in the Espanola Valley, north of the present area, began with Cope (1874, 1884) and is continuing with Frick's extensive and intensive studies of the several groups of mammals, some of which have been published (Frick, 1930a, 1933, 1937).

The Cenozoic geology of the Rio Grande trough long interested the late Kirk Bryan, and since 1936 this interest has resulted in many reports concerned with the problem, prepared by Bryan and his students. Most of the reports are taken from dissertations and are largely discussions accompanied by maps on a scale of about 6 miles to the inch. The most comprehensive single regional study is Bryan's report (1938) on the geology and ground-water conditions of the Rio Grande depression. Cabot (1938) presented conclusions on the fault border of the Sangre de Cristo Mountains. Denny (1940a) described the lithology of the Santa Fe formation in the Espanola Valley, where most of the fossil collections have been made, although he was not able to make a columnar section of the formation. The past studies most pertinent to the present report are those by Stearns (1943, 1953a,b) on the Galisteo-Tonque area, which lies just south of and includes part of the Santa Fe area. The area described in the several reports of Bryan and his associates are indicated by Stearns (1953a, fig. 6). Kelley (1952) summarized the tectonic features of the Rio Grande depression and later (1954) prepared a detailed tectonic map.

Areas east and west of the present area have not been mapped in detail. Early reports on the Sangre de Cristo Mountains, which form the eastern border, are limited to general comments by Stevenson (1881) and Darton (1928a,b), and a note by Lindgren and others (1910, p. 28). The lava mesa and White Rock Canyon west of the area have not been mapped in detail, although current work by several parties of the U.S. Geological Survey is being done in this area and farther west in the Valles Mountains. Published material is limited essentially to Bryan's comments (1938). Reports that deal with parts of the present area are of more specific concern. Johnson's dissertation on the Cerrillos (1903) includes some information on the southwestern part of the present area. A preliminary map by Read and others (1944) of the U.S. Geological Survey includes much of the Santa Fe area, but the scale is 3 miles to the inch and the Precambrian and Cenozoic rocks are generalized.

The many references to reports by Stearns (1943, 1953a,b) indicate the value of his study of the Galisteo-Tonque area. The first report (1943) described the Galisteo formation. One report (1953b) is concerned with volcanism during the early Tertiary; it describes the Espinaso volcanics, the Cerrillos complex of intrusive and extrusive rocks, and the Cienega area, and in it the Cieneguilla limburgite is named. Another (1953a) deals with regional aspects of Tertiary geology, including basins of deposition of the Santa Fe formation (as Stearns used the name) and associated formations; it is accompanied by a geologic map on a scale of 2 miles to the inch.

In 1944 and 1945, W. C. Stoll mapped most of the Cerrillos complex as part of a strategic minerals investigation for the U.S. Geological Survey. In 1950 and 1951, A. E. Disbrow mapped the Mesozoic and Cenozoic formations around the Cerrillos, and the report was submitted as a thesis at the University of New Mexico. In 1951 a cooperative arrangement was made by the New Mexico Bureau of Mines and the U.S. Geological Survey, on the basis of which Disbrow completed the mapping of the Cerrillos area with some modification of Stoll's work (Disbrow and Stoll, 1957). The map of the Cerrillos includes the southwestern part of the Santa Fe area.

A detailed report on the Tertiary igneous complex of the Cienega area has been made by Sun and Baldwin (1958).

## PRESENT WORK

The geology of the Santa Fe area was mapped by personnel of the New Mexico Bureau of Mines and Mineral Resources. Brewster Baldwin mapped the Agua Fria (pl. 2) and Turquoise Hill (pl. 3) quadrangles during the period July 1951–February 1952, assisted by W. M. Bundy from July to October 1951. F. E. Kottlowski, assisted by Mr. Bundy, mapped the Santa Fe (pl. 1) and Seton

Village (pl. 4) quadrangles during the period October 1951–February 1952. The mapping was recorded on aerial photographs taken in May 1951, enlarged to a scale of 1:20,000. The geology was compiled on 1:24,000 topographic sheets of these quadrangles, issued by the U.S. Geological Survey.

The Santa Fe area is on the east border of the Rio Grande trough. Most of the area consists of piedmont slopes on the west side of the Sangre de Cristo Mountains. These slopes are underlain by late Cenozoic basin-filling deposits called the Santa Fe marls by Hayden. (See p. 38). Hayden's Santa Fe marls are here designated as a group and subdivided into 2 sedimentary formations and 1 unit of lava flows. The sedimentary units are a thick, older sequence composed principally of silty sandstones (the Tesuque formation) and a younger veneer of silt, sand, and gravel (the Ancha formation) forming a blanket generally less than 300 feet thick over two-thirds of the Santa Fe area. The present surface-water supply for the city of Santa Fe must be supplemented by ground water from the Santa Fe group, and so information on the distribution and character of these basin-filling sediments is fundamental to an understanding of the ground-water conditions. Also, the occurrence and movement of water in the Santa Fe group are controlled in part by the underlying sedimentary and igneous rocks, which serve as a "bedrock floor." Some understanding of the subsurface geology has resulted from integration of geologic, hydrologic, geophysical, and topographic data, and a map has been compiled showing the inferred topography and geology beneath the blanketing layer of generally unconsolidated sediments (pl. 5).

The basin-filling sediments were derived in large part from Precambrian rocks similar to those exposed in the mountains to the east, and structures in the bedrock under the alluvial slopes are inferred to be similar to structures in the mountains. Therefore, Kottlowski studied in detail the structures and petrography of the exposed Precambrian rocks. His petrographic descriptions, given in Part 5 of this report, are important to an understanding of the basement complex of igneous and metamorphic rocks in this source area.

Mapping was extended westward beyond the Santa Fe area proper to include the entire Cienega area, half of which lies west of the Turquoise Hill quadrangle. A detailed report on the Cienega area is presented in a separate report by Sun and Baldwin (1958). Only a summary is presented here. Similarly, a study of the economic geology of the Cerrillos is incorporated in a report by Disbrow and Stoll (1957).

Disbrow, Stearns, and Baldwin have had several discussions on the geology of the area, and there has been general agreement on essential points. Baldwin and Disbrow have agreed on geologic contacts in the southwestern part of the Santa Fe area. The present report is in accord with the geologic interpretation of this local area by Disbrow and Stoll.

The late Cenozoic history of the Santa Fe area must be considered in the light of the geology of the unmapped area to the west—the lava mesa and White Rock Canyon—and some tentative comments are made in this respect, based on a week's reconnaissance by Baldwin.

## STRATIGRAPHY

The structural and stratigraphic units in the Santa Fe area coincide with the four main physiographic units (fig. 5). The mountains in the eastern part of the area are composed mostly of Precambrian rocks; the hills in the southwest are mostly Tertiary igneous rocks; the western mesa is capped by basalt flows of Quaternary(?) age; and the intervening piedmont slope is underlain by "basin-fill" sediments of the Santa Fe group, of middle(?) Miocene to Pleistocene(?) age. Sedimentary rocks of Pennsylvanian, or possibly Mississippian, through Cretaceous age have been mapped south of the Santa Fe area (fig. 8), and although most of these rocks are not exposed in the Santa Fe area they probably underlie the basin fill in at least a part of the area. The emphasis in this report is on the units of the Santa Fe group.

Inasmuch as knowledge of certain physiographic relations is fundamental to an understanding of the Quaternary sediments, graded surfaces are discussed in terms of their stratigraphic significance, drainage diversions are noted as they affect the distribution of the post-Santa Fe sediments, and the thickness and subsurface distribution of the Santa Fe group are discussed under "structure," in the light of structural and geophysical information.

### PRECAMBRIAN ROCKS

By F. E. Kottlowski

A complex of metamorphic and igneous rocks crops out in the foothills and mountains of the eastern part of the Santa Fe area. Because of the complexity in composition, structure, and interpretation, the rock descriptions are referred to the technical classification of Turner and Verhoogen (1951); to simplify the body of the report, the petrographic descriptions are given in the appendix.

Metamorphic rocks in the Sangre de Cristo Mountains as a whole, of which the rocks near Santa Fe are a part, are considered to be of Precambrian age. The sequence of rock units in several areas of Precambrian rocks near and north of Santa Fe is compared with the sequence in the eastern part of the Santa Fe area in table 2. The similarity in sequence of gross units may be more apparent than real, and the table is presented merely to draw attention to possible relationships.

Precambrian rocks that form part of the core of the south end of the Sangre de Cristo Mountains crop out in a belt as much as 4 miles wide in the eastern part of the Santa Fe area. The rocks are closely faulted and brecciated, intricate sequences of intrusions occur, and in many places the rocks are deeply weathered and covered by disintegration products.

Five rock types were mapped (table 2). The areal extent of the different petrographic units could be mapped only approximately, because of the soil and alluvial cover and because of the complex relations of the rock types. The contacts mapped delimit the areas where the different types of rocks predominate. Some of the outcrops designated as gneiss on the map include migmatites formed by the red and the gray granites. Parts of the granitic bodies are finely foliated gneisses but are labeled granite on the map because they are believed to be deformed parts of the granite.

The oldest rocks are a foliated complex of schists and gneisses that occur as isolated roof pendants, large xenoliths, and large complexly folded masses. A quartz-feldspar-biotite-magnetite schist and a gray micaceous gneiss are the predominant rock types. Gray quartzite, chlorite-muscovite schist, quartz-mica schist, quartz-hornblende schist, biotite granulite, and hornblende-andesine schist also are present. The schists and gneisses were probably interbedded basic volcanic rocks and impure sandstone, plus igneous rocks of monzonitic composition—all of which were regionally metamorphosed.

This early foliated complex was intruded by a gray orthoclase-rich granite; as a result, schists adjacent to the intrusive dikes, sills, and chonoliths were changed to contorted lit-par-lit injection gneisses (fig. 6). The gray granite and earlier rocks were in turn intruded by an equigranular hornblende-andesine amphibolite or metadiorite. The final large-scale intrusion was by a pale-reddish-brown muscovite-microcline granite, its associated dikes and sills of pegmatite, aplite, and lamprophyre, and quartz and epidote veins. Injection by the granite and its more mobile phases formed lit-par-lit gneisses, migmatites, and biotite granulite from the older rocks. Parts of the microcline granite were deformed, producing a pink gneissoid granite; this rock with all older rocks was brecciated along wide zones (fig. 7).

TABLE 2.—*Summary of Precambrian units near and north of Santa Fe, N. Mex.*

[Similarity of sequences may be fortuitous]

| Needle Mountains, Colo.[1] | Taos Range [2] | Picuris Range [3] | Pecos mine [4] | Santa Fe area [5] |
|---|---|---|---|---|
| | Diabase, gabbro | Embudo granite (red) | Granite (pink) | Granite (red) |
| Granite | Costilla granite (red) | | | |
| Quartzite and greenstone | | (Minor amphibolite, diorite, diabase) | Amphibolite or diabase | Amphibolite |
| | | | | Gray granite |
| Schist and gneiss | Cabresto quartzite, related amphibolite, gneiss, schist | Vadito formation, schist, amphibolite, quartzite conglomerate, metavolcanics | Schist and gneiss | Schist and gneiss |
| | | Ortega formation, phyllite, schist, quartzite | | |

[1] About 170 miles northwest of Santa Fe (Cross and Larsen, 1935).
[2] Northeast of Taos (McKinley, P. F., 1951, Geology of the Costilla and Latir Peak quadrangles: New Mexico Bur. Mines and Mineral Resources manuscript rept.).
[3] 40 miles north-northeast of Santa Fe and 14 miles south-southwest of Taos (Montgomery, 1953).
[4] 17 miles east-northeast of Santa Fe, at Terrero (Krieger, 1932).
[5] This report.

FIGURE 6.—Precambrian metasedimentary rocks in spillway of McClure Dam; sec. 24, T. 17 N., R. 10 E.

The red granite and the several types of gneisses form the bulk of the outcrops of the basement complex in the mapped area. South of the Santa Fe River the gneisses, generally speaking, form the ridgetops, and the red granite crops out on the lower slopes, in the foothills, and in the valleys. Large outcrops of amphibolite occur principally in the northeastern part of the map area, especially along Tesuque and Little Tesuque Creeks. Only small bodies of the gray granite crop out, as sills, dikes, and chonoliths in the east-central part of the Seton Village quadrangle. Although these bodies appear to be older than the amphibolite, it is possible that they represent merely a phase of the red granite intrusion. Small lenticular masses of the various schists are scattered throughout the area of Precambrian outcrop; the largest masses occur along the Santa Fe River northwest of Nichols reservoir, in the westernmost foothills in the Seton Village quadrangle, and on the west slopes of Atalaya Mountain.

The early foliated complex is well exposed on the west slope of the Atalaya Mountain, where 6 of its 8 rock types are closely associated; the gray quartzite and the chlorite-muscovite schist are the only types not observed at this place. An isolated roof pendant of chlorite-muscovite schist, surrounded and intruded by red granite, crops out in the SW¼NE¼ sec. 5, T. 16 N., R. 10 E. A thin bed of gray quartzite, interbedded with quartz-mica schist, crops out 700 yards S. 67° E. of Bauers Spring in the canyon of Tesuque Creek, about 200 feet west of hill 7743 (NE¼SE¼ sec. 5, T. 17 N., R. 10 E.).

Intrusive contacts between the granites and older rocks are clearly exhibited in many outcrops. At several places along the Hyde Park Road, and along U.S. Highway 85 south of Santa Fe, granite masses surrounding roof pendants of green schist form lit-par-lit gneisses and finer grained migmatites on the borders of the schist bodies. There are large areas of pink and gray microcline-mica gneisses in the northeastern part of the Seton Village quadrangle. These appear to be the result of an intimate soaking of metasedimentary schists and gneisses by an alkali- and silica-rich solution (Sederholm's ichor, or granitic juice), supposedly generated at depth by anatexis of sialic sediments or "emanating" from the intrusive granitic magma. Actual injection of magma appears to be limited to places where bodies of foliated rocks are intruded by the granites.

A well-exposed outcrop of red granite that has intimately intruded quartz-feldspar-biotite-magnetite schist, hornblende-andesine schist, and amphibolite to form migmatites lies 700 yards southwest of Rancho Elisa along the Hyde Park Road (SW¼SW¼ sec. 9, T. 17 N., R. 10 E.). Dikes and irregular-shaped bodies of gray granite crop out 3 miles southwest of Atalaya Mountain (center of W½NW¼ sec. 8, T. 16 N., R. 10 E.), where they cut gray micaceous gneiss, inject lit-par-lit a quartz-feldspar-biotite-magnetite schist, and are cut by amphibolite, reddish-brown pegmatite, and aplite dikes.

Chonoliths of orthoamphibolite crop out along the canyon of Tesuque Creek near the east border of the area, intrude the early foliated complex, and are intruded and metamorphosed by red granite. In places the amphibolite is schistose. Certain sill-like plagioclase amphibolites within the earlier schists may once have been calcareous beds but are petrographically similar to the intrusive rock.

Metamorphism of the Precambrian rocks was of three kinds: development of foliation, brecciation, and magmatic injection. Injection by the granitic magma, especially by the more mobile phases, and an intimate soaking of the older rocks by an alkali-silica solution, formed lit-par-lit gneisses and migmatites from the older schists, gneisses, and amphibolites. Descriptions of injection gneisses and of altered amphibolite are given in Part 5.

Zones of cemented breccia (pls. 1, 4; fig. 7) are widespread though generally restricted to the red granite; the foliated rocks have apparently yielded to stresses by folding rather than by brecciation. The elongate bodies of breccia in the Seton Village quadrangle are in general parallel to the present mountain front, but the breccia masses north of the Santa Fe River trend east. These breccias are evidently pre-Magdalena and probably Precambrian in age, for in one locality breccia is overlain by unbrecciated rocks of the Magdalena group. This relation can be seen where the Hyde Park Road enters the canyon of Little Tesuque Creek (SW cor. sec. 4, T. 17 N., R. 10 E.), where a palisade of breccia is visible from the road (fig. 7); on the hill to the north, the rocks of the Magdalena group, which lie above the breccia, are virtually undeformed.

## PENNSYLVANIAN ROCKS

By F. E. Kottlowski

Rocks of Pennsylvanian age are represented in the Santa Fe area by the Magdalena group; however, those in the lowest part of the group may be Mississippian in age.[1] The Magdalena group is exposed in thick sections south and east of the Santa Fe area and has been subdivided (Read and others, 1944) into four units: the

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[1] In a recent report A. K. Armstrong (1955) reclassified this lower limestone member of the Sandia formation and named it the Arroyo Penasco formation. Fossils collected are of Merameс age. Armstrong's closest measured section (1955, p. 27) is near El Macho, on the west side of the Pecos River.

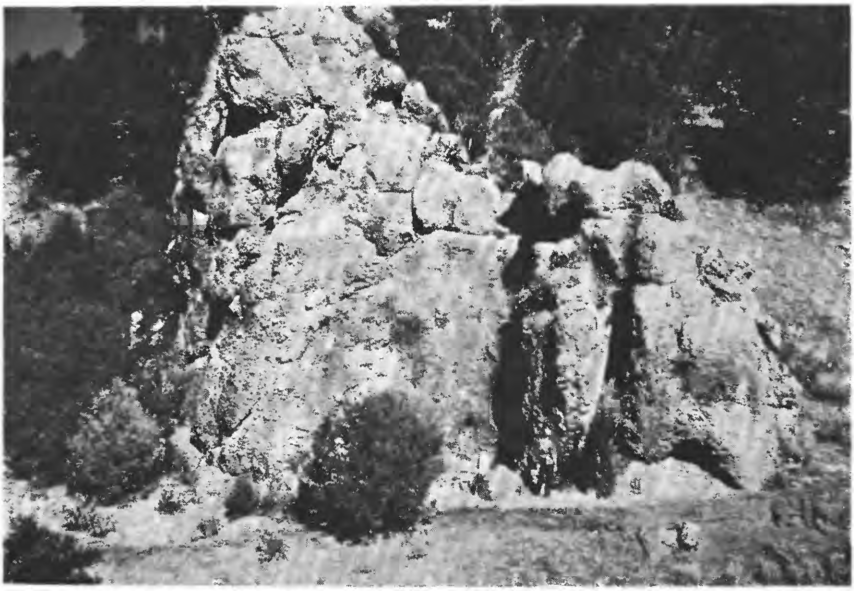


FIGURE 7.—Palisade of brecciated Precambrian granite in canyon of Little Tesuque Creek along Hyde Park Road. Man standing at base, to right of center.

lower limestone and the upper clastic members of the Sandia formation, and the lower gray limestone and the arkosic limestone members of the Madera limestone (fig. 8). This group is dominantly marine in the Santa Fe area, and fossils of Pennsylvanian age have been collected from all but the lowest member.

The group consists of limestone, shale, and sandstone, and a few coal beds. Lithologic descriptions of a measured section are given in the appendix. The sedimentary rocks crop out in two belts extending north from the Santa Fe River into the mountains and form scattered exposures near Bishops Lodge, Santa Fe, and Seton Village. In places the beds are only gently folded, but most of the outcrops exhibit closely spaced faulting and abrupt, sharp folding. The rocks rest on a surface that has as much as 150 feet of local relief, developed on deeply weathered Precambrian rocks. Along Aztec Springs Creek, depressions in this surface are filled by carbonaceous shale and shaly coal. Various thicknesses of the sedimentary rocks occur as remnants beneath the Tesuque formation, which in places rests directly on the Precambrian.

The lower limestone member of the Sandia formation is thin and discontinuous. The member is 51 feet thick along Little Tesuque Creek near Bishops Lodge, where exposures are good. Although no fossils have been found in this member in the Santa Fe area, fossils of Mississippian age have been reported from the member in

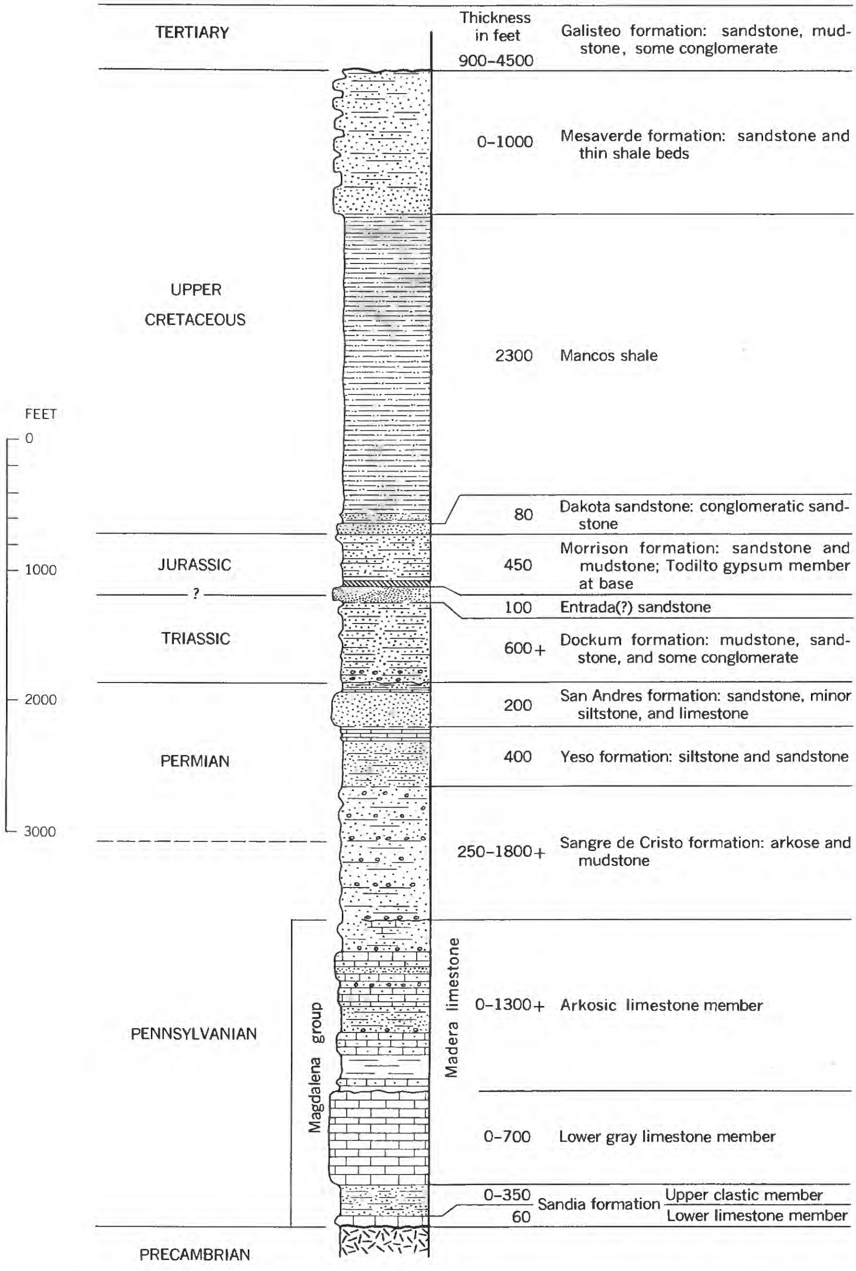



**FIGURE 8.—Pre-Tertiary formations exposed southeast of the Santa Fe area, New Mexico (modified from Read and Andrews, 1944).**

nearby areas. Henbest (1946, p. 134) discovered *Endothyra baileyi*, a foraminifer which is an index fossil of the Spergen limestone, and A. K. Armstrong collected a suite of fossils of Mississippian age (R. H. Flower, oral communication). Because there are few exposures in the Santa Fe area, the lower limestone member of the Sandia formation has been included with the Pennsylvanian sedimentary rocks on the maps.

Approximately 212 feet of rocks of the Magdalena group was measured in the gorge of Little Tesuque Creek south of Bishops Lodge; the section is presented in Part 5. East of Rancho Elisa (center of W½ sec. 9, T. 17 N., R. 10 E.) the lower gray limestone member of the Madera limestone is thinner than along Little Tesuque Creek and is overlain by brown coarse-grained arkosic sandstones and gray limestones of the upper arkosic limestone member. These beds are sharply folded, faulted, and partly covered.

About 400 feet of rocks of the Magdalena group are exposed in the east-facing scarp bordering Aztec Springs Creek (NW¼ sec. 16, T. 17 N., R. 10 E.). The lower part of the section, composed chiefly of carbonaceous and ferruginous shale and thin-bedded limestone, is mostly buried under talus. Most of this section is part of the upper clastic member of the Sandia formation; the lower limestone member is present only locally along Aztec Springs Creek. The cliff-forming beds of the scarp are made of the lower gray limestone member of the Madera limestone. Arkosic sandstones and limestones of the arkosic limestone member of the Madera limestone occur near the crest of the ridge.

The upper clastic member of the Sandia formation is thick north of the Santa Fe River (secs. 17, 19, 20, T. 17 N., R. 10 E.), where shale beds are quarried to make burnt clay products.

The Sandia and Madera Formations and their members are defined as lithologic units. Near Santa Fe, and also in the areas to the north along the west side of the Sangre de Cristo Mountains and to the southeast and east from Lamy to Pecos and along the Pecos River, these units vary greatly in thickness and in lithologic character. The thin section (less than 500 feet) of the Magdalena group near Santa Fe may be the lithologic equivalent of the Sandia formation to the east along the Pecos River, where Read and others (1944) measured 370 feet of the upper clastic member. However, to the southeast near Lamy and 4 miles north of Glorieta, the upper clastic member of the Sandia formation is only 105–130 feet thick, and the lower gray limestone member of the Madera limestone includes many beds of clastic rock. The latter two sections are similar in composition and thickness to the section of the Magdalena group near Bishops Lodge. Brachiopods from limestone in the Magdalena group near Bishops Lodge were reported by Professor P. K. Sutherland, University of Oklahoma (oral communication, Mar. 19, 1959), to be of Atoka age and identical with those from faunas collected from the upper clastic member of the Sandia formation along the Pecos River. This evidence suggests that the strata called the Madera limestone by the writer are a time-equivalent lime facies of the upper clastic member of the Sandia formation 15 miles to the east; otherwise, the Sandia-Madera contact must cross fossil-zone lines.

### PERMIAN AND MESOZOIC ROCKS

Formations of the Permian, Triassic, and Jurassic systems are not exposed in the Santa Fe area, and Cretaceous rocks are found only as isolated outcrops in the southwestern part of the area. However, along Galisteo Creek, south of the Santa Fe area, a fairly complete section of Permian and Mesozoic formations (fig. 8) has been mapped (Read and Andrews, 1944; Read and others, 1944; Stearns, 1953a; Disbrow and Stoll, 1957). Regional studies suggest that the area of the present Sangre de Cristo Mountains was occupied by the Uncompahgre highland during late Pennsylvanian and Permian time (Brill, 1952). In every period of the Mesozoic era sediments were deposited in north-central New Mexico (McKee, 1951; Reeside, 1944). Therefore, west of the present mountain front in the Santa Fe area a complete section of Permian through Cretaceous rocks was probably deposited, but some may have been removed by erosion before the accumulation of younger sediments.

Mudstone, sandstone, quartzite, argillite, and crystalline limestone crop out in the southwestern part of the Turquoise Hill quadrangle and are mapped as Cretaceous sedimentary rocks. Although exposures are limited and in many places the sediments were altered by igneous activity during the Tertiary period, the lithology of the sediments as compared with that of known Cretaceous rocks to the southwest, and the presence in two places of heavy-ribbed pelecypod shells, possibly *Inoceramus*, suggest a Cretaceous age.

### PRE-SANTA FE TERTIARY ROCKS

Sedimentary and volcanic rocks of early to middle Tertiary age are well exposed in the southwestern part of the Santa Fe area and form scattered outcrops along the mountain border and at the south edge of the area. These rocks are part of the "bedrock floor" that forms the La Bajada constriction (Kelley, 1952) along the southern end of the Santa Fe embayment of the Rio Grande trough.

Details of field and laboratory study are adequately presented in reports by Stearns (1953a, b), Disbrow and Stoll (1957), and Sun and Baldwin (1958); therefore, only a summary will be given here.

The following discussion of the pre-Santa Fe Tertiary rocks is organized according to the geographic areas of exposure, because correlation of volcanic units between the several areas of outcrop is not established.

### CIENEGA AREA

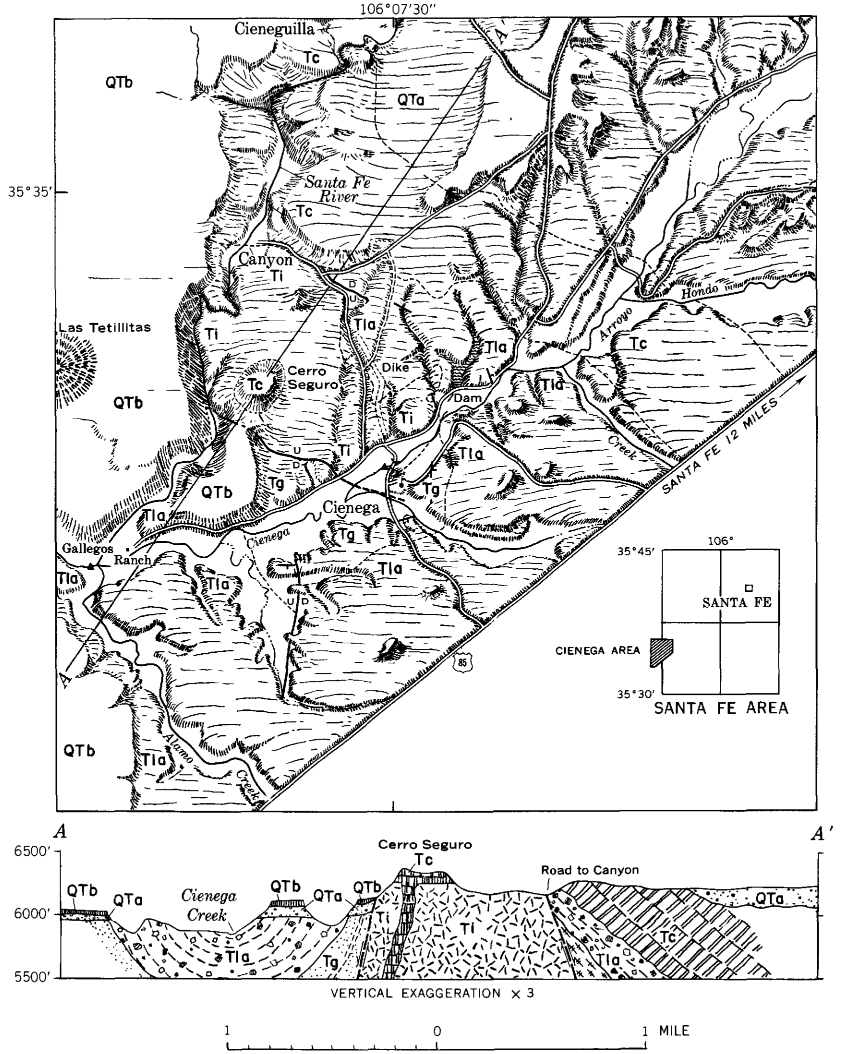
In the Cienega area (fig. 9), at the west edge of the Turquoise Hill quadrangle, an intrusive monzonite is surrounded by the Galisteo formation, volcanic flows and breccias, and the Cieneguilla limburgite of Stearns (1953b). The following summary is based on work by Sun and Baldwin (1958).

#### GALISTEO FORMATION

The Galisteo formation was named by Hayden (1869) and first studied in detail by Stearns (1943). At Cienega it is a pale-reddish-brown to grayish-orange sandstone and mudstone containing some conglomeratic beds. The beds dip away from a central area of monzonite in an arc of outcrops south and southwest of the intrusion. A section of the Galisteo measures 1,300 feet and is nearly complete, although the base of the measured section is separated from monzonite by a fault sliver of mudstone of Cretaceous(?) age. The Galisteo formation accumulated as an alluvial deposit in a basin of Laramide origin; petrified wood and some Duchesne River (Eocene or Oligocene) vertebrate fossils have been collected from the upper part of the formation (Stearns, 1943). Along Galisteo Creek, the Galisteo formation rests unconformably on the Mesaverde formation (Upper Cretaceous), but along the Santa Fe River a few miles west of Cienega it rests on the upper part of the Mancos shale (Disbrow and Stoll, 1957, pl. 1).

#### VOLCANIC FLOWS AND BRECCIAS

Volcanic flows and breccias form three units, about 1,000 feet in total preserved thickness. The earliest is a series of andesite breccias, which are exposed south and southwest of the monzonite and which rest with gradational contact on the Galisteo formation. East and southeast of the monzonite is a sequence of about 500 feet of brownish-gray calcic latite flows and breccias, which are chemically similar to the monzonite. The calcic latite contains phenocrysts of plagioclase ($An_{50}$) and, locally, augite. Vesicles are present in the flows at the west end of the dam shown in the center of figure 9. The calcic latite rests on an eroded surface of monzonite. Just east of the dam, the orange to gray breccias of glassy latite rest on an uneven surface of the calcic latite. Phenocrysts in the glassy latite include plagioclase ($An_{23-40}$) and biotite, and some augite or hornblende.




EXPLANATION

Ancha formation, QTa; basalt flows, QTb; Cieneguilla limburgite of Stearns, 1953b, Tc; latitic to andesitic flows and breccia, Tla; intrusive rocks, Ti; Galisteo formation, Tg

**Figure 9.**—Map and cross section showing rock units of Cienega area, New Mexico.

All the breccias contain blocks as much as a foot across, and many contain blocks measuring 5 or 10 feet. The breccias are massive and generally unsorted, suggesting a lava or mudflow origin, in contrast with the water-laid origin Stearns (1953b) mentions for the breccias at Espinaso Ridge, 14 miles south of the Cienega area. The Galisteo formation and the conformably overlaying andesite breccias were evidently domed by the intrusion of monzonite, but the calcic latite and glassy latite are younger than the monzonite.

#### INTRUSIVE ROCKS

The monzonite, which forms some of the higher hills of the Cienega area and is probably continuous in the subsurface with the monzonite of Las Tetillitas to the west, is a porphyritic rock that contains phenocrysts of plagioclase (oligoclase to andesine), augite, and biotite. The groundmass forms about one-half the rock and probably consists of albite or orthoclase.

A dike of hornblende andesite forms two knobs near the Cienega school and extends northward across both the monzonite and the calcic latite. This dike may be older than the glassy latite.

#### CIENEGUILLA LIMBURGITE OF STEARNS

The Cieneguilla limburgite, named by Stearns (1953b), is best exposed along the Santa Fe River between Canyon and Cieneguilla, where it dips northeast and is 600 or 700 feet in exposed thickness. It consists of a series of dense, fine-grained black rocks, in the form of thick flow units and some interbedded tuff breccias, and is composed mostly of augite and olivine. The limburgite caps Cerro Seguro, where it contains inclusions of monzonite, and Cerro de la Cruz (Calvary Butte of Stearns); both of these may be plugs or feeders. Stearns mentions other occurrences outside the Santa Fe area. The limburgite rests on the glassy latite, apparently with erosional unconformity. Near the mouth of the canyon of the Santa Fe River, limburgite flows are overlain conformably by the Abiquiu(?) formation of Stearns (1953a).

### ARROYO HONDO

A sequence of sedimentary and volcanic rocks 568 feet thick is exposed in Arroyo Hondo; it rests unconformably on Precambrian rocks and is overlain with slight angular unconformity by the Bishops Lodge member of the Tesuque formation. Three subdivisions can be made:

1. Siltstone, sandstone, and conglomerate, deep-red-brown, consisting of fragments of Precambrian rocks; 48 feet.
2. Red crossbedded conglomerate and sandstone, containing abundant volcanic pebbles; lower and upper parts consist of sandstone, siltstone, and shale; 368 feet.
3. Andesitic flows and interbedded pyroclastic rocks; 152 feet.

This sequence is illustrated in figure 10. The sequence can be traced in scattered exposures for a mile north of Arroyo Hondo, at which place the tuffaceous or volcanic sediments of the Bishops Lodge member extend eastward to the Precambrian. Erosion prior

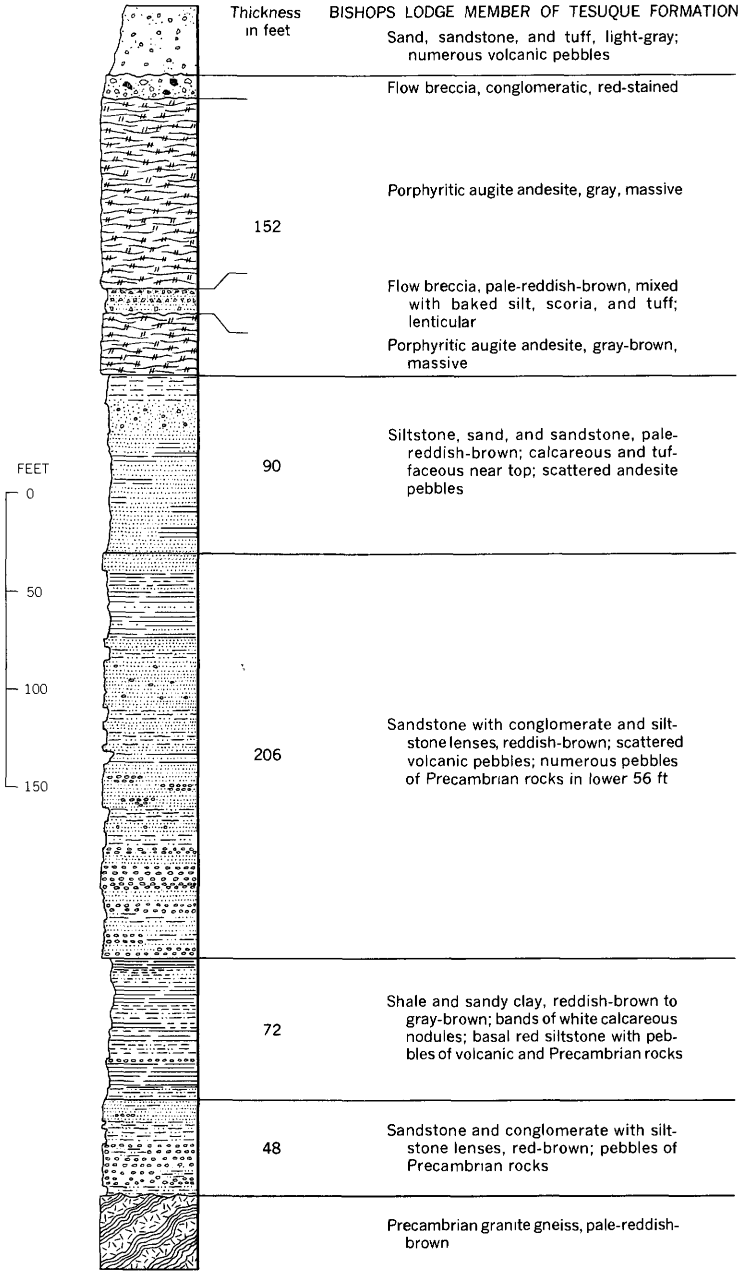



FIGURE 10.—Pre-Tesuque rocks of Arroyo Hondo, secs. 12 and 13, T. 16 N., R. 9 E. (unsurveyed).

to the deposition of the Tesuque probably removed the tilted volcanic strata north of this locality.

#### SOUTH BORDER OF THE MAP AREA

Along the south border of the Seton Village quadrangle, at the north end of the Kentucky Ridge of Stearns (1953a) in sec. 26, T. 15 N., R. 9 E., an augite andesite dike and a massive intrusive body (or flow) crop out in a gully. Just south of the map area the dike cuts a tuffaceous sandstone that may belong to the Bishops Lodge member or to the earlier volcanic sequence. Volcanic breccias are exposed in the streambed adjacent to the dike.

#### SOUTHWEST CORNER OF THE MAP AREA

In the southwest corner of the Santa Fe area, south of U.S. Highway 85, there are many knobs and hills, which are part of the Tertiary complex of the Cerrillos. Although some breccias are present, most of the rocks are intrusive. Augite monzonite forms the northern tip of the Cerrillos, the central part of Turquoise Hill, and the knob one-half mile southeast of Turquoise Hill. Augite latite containing conspicuous plagioclase phenocrysts forms most of the knobs of this area and all but the central part of Turquoise Hill. Trachytic rocks form Bonanza Hill.

#### AGE AND CORRELATION

The Galisteo formation is regarded as Eocene and Oligocene(?) in age. Near La Bajada, at the mouth of the lower canyon of the Santa Fe River, the Abiquiu(?) formation of Stearns (1953a) rests on flows of his Cieneguilla limburgite (Stearns, 1953b, p. 448). Stearns (1953a) tentatively correlates his Abiquiu(?) formation with the Abiquiu tuff of Smith (1938) 60 miles to the north, where the tuff underlies the beds containing the Santa Fe fauna of the transition zone of the Miocene and Pliocene. Thus the age of the Abiquiu(?) formation of Stearns (1953a) is suggested as middle Miocene. From the above discussion it is inferred that the volcanic rocks of the Santa Fe area are Oligocene and Miocene in age.

Stearns (1953b, p. 430–432) correlates the red beds of Arroyo Hondo with scattered exposures of similar rocks in the area extending north to Santa Fe. Smith (1938, p. 943) correlates the red beds of Arroyo Hondo with his El Rito formation. Red sedimentary rocks near Bishops Lodge that Smith correlates with his El Rito formation are here considered part of the Tesuque formation. Stearns (1953b, p. 430–432) suggests that the sequence along Arroyo Hondo was formed during the transition from deposition of the Galisteo to volcanic accumulation, the transition being protracted because of the distance from volcanic centers. In the present report, the sediments that were derived from volcanic materials are mapped (pls. 1, 4) as the Galisteo(?) formation.

The transitional interval between the Galisteo formation and the overlying volcanic breccias is found in the Cienega area as it is in several places to the south (Stearns, 1953b), although locally there is an angular unconformity between the two (Disbrow and Stoll, 1957, p. 12), because of deformation by intrusions. Stearns (1953b) and Disbrow and Stoll recognized more than one stocklike intrusion in the Cerrillos, the older being fine-grained rock containing hornblende and the younger being equigranular rock containing augite. Although Stearns included all the latitic breccias and flows in his Espinaso formation, and considered that the intrusions in general followed the extrusive activity, Disbrow has subdivided the breccias and correlated each with the several contemporary intrusive bodies he had mapped. The monzonite in the Cienega area is correlated with the youngest period of igneous activity of the Cerrillos (Disbrow and Stoll, 1957, pl. 1).

### SANTA FE GROUP

The Santa Fe marls were named by Hayden in 1869 (see part 5) in referring to poorly consolidated sediments north of Santa Fe and between Santa Fe and Galisteo Creek, but Hayden's designation was vague and based only on reconnaissance study. In more recent years the Santa Fe has become identified as the basin-filling materials of the Rio Grande trough, but the term has been used both in a restricted sense and as an all-inclusive term, even in the same report. In their geologic studies of the trough in the northern part of New Mexico, Bryan and his students (Stearns, 1953a, fig. 6) have restricted the term Santa Fe to rocks correlated with or believed to be equivalent to the formations in the Espanola Valley bearing the classic Santa Fe fauna of late Miocene and early Pliocene age. Farther south in the Rio Grande trough, however, nearly all the basin fill has been mapped as Santa Fe, although the meager faunal collections suggest a late Pliocene or Pleistocene age for much of the fill.

It is proposed in this report, with informal agreement from a dozen geologists who have been concerned with the late Cenozoic geology of the Rio Grande trough, that the term Santa Fe be raised to group status, and that all the basin fill, whether Tertiary or Quaternary, be included in the Santa Fe group. Broad usage of the term Santa Fe group is an advantage in areas where the basin fill is not, or cannot be, subdivided. In those areas where subdivisions have been established by detailed mapping, local formation and member names may be applied until the basin fill is well enough understood that the correlation of units can be demonstrated.

Therefore, the Santa Fe group is here considered to be a broad term including sedimentary and volcanic rocks related to the Rio Grande trough, with a range in age from middle(?) Miocene to Pleistocene(?). The lower limit is here placed above the latitic and limburgitic flows and breccias exposed in the Cienega area. It is placed at the base of the volcanic sediments [Stearns' Abiquiu(?) formation] that are exposed along the Santa Fe River about 5 miles west of Cienega (Stearns, 1953a, pl. 1). The upper limit is here considered to include all but the terrace deposits and alluvium of present valleys; thus, the Santa Fe group includes the sediments that mantle remnant and buried graded surfaces (previously lumped together as the "Ortiz surface").

In the Santa Fe area, the Santa Fe group consists of the following units (see also figs. 19, 20):

Basalt flows }<br>Basalt tuff } intertoned with upper part of Ancha formation<br>*Ancha formation<br>*Tesuque formation, formerly the Santa Fe formation in restricted sense; included as minor units are:<br>Olivine basalt flows near Bishops Lodge<br>*Bishops Lodge member

The Tesuque formation consists principally of pinkish-tan silty sandstone, which forms the bulk of the Santa Fe group. Two minor units, olivine basalt flows and the volcanic sediments of the Bishops Lodge member, are included in the basal part of the Tesuque formation. However, in this report, references to the lithology of the Tesuque formation are generally to the nonvolcanic pinkish arkosic sandstones. The Ancha formation is a sand-and-gravel blanket resting on tilted and beveled beds of the Tesuque formation. Basalt tuff and basalt flows, which intertongue with the upper part of the Ancha formation, are here excluded from the Ancha formation although included in the Santa Fe group.

### TESUQUE FORMATION

The Tesuque formation of middle(?) Miocene to early Pliocene age, here named for the town of Tesuque, 5 miles north of Santa Fe (fig. 2), consists of several thousand feet of pinkish-tan soft arkosic, silty sandstone and minor conglomerate and siltstone (fig. 14). It is not possible to assemble a type section of the formation because structural complications probably exist in these beds in the Santa Fe area, good exposures are scattered, and recognizable horizons are absent. An arbitrary type section can be given as being along the north boundary of T. 17 N., extending 9 miles westward from

* Named in this report.

Tesuque Creek (NE¼ sec. 5, T. 17 N., R. 10 E.) to a point three-fourths of a mile east of the Buckman Road (NE¼NW¼ sec. 2, T. 17 N., R. 8 E.). The Tesuque formation is well exposed also in the "badlands" in the vicinity of Tesuque and Pojoaque, between the Sangre de Cristo Mountains and the Rio Grande; with the possible exception of the upper part, almost all the formation is exposed in that area.

In the Santa Fe area, the Tesuque formation is generally exposed north of the Santa Fe River, and it is best exposed along the north edge of the Santa Fe area. The Tesuque, which represents the greater part of the Santa Fe group in the Santa Fe area, rests with at least local angular unconformity on the volcanic rocks of Oligocene and Miocene(?) age and is overlain with angular unconformity by the Ancha formation. Although near its base the Tesuque includes sediments derived from Tertiary igneous rocks, it consists principally of debris from Precambrian rocks.

The color of the Tesuque formation ranges from grayish orange to moderate reddish orange and light brown. The usual pinkish color is due largely to the predominance of reddish grains of microcline. Crossbedding is common, and molds of desiccation cracks have been noted on the under surfaces of sandstones that rest on siltstones. Cementation by calcium carbonate is common, and in many specimens the cement is crystalline. The conglomerate, which is coarse, is common near the mountain front but less common farther west, partly because in general the lower beds are exposed only near the mountains. Clay is present only in very small amounts, but silt and very fine sand form a large proportion of the unit. The sand in many of the sandstone beds is fairly well sorted. Of the 19 samples studied by W. M. Bundy, curves are shown for four that represent common lithologic types (figs. 11 and 12). A summary of the laboratory procedure is presented in the appendix.

The Tesuque formation is composed predominantly of fragments of Precambrian rocks—red feldspar, granite, quartz, schist, gneiss, and quartzite. Most of the material probably came directly from the Precambrian rocks to the east, although some of it may represent reworking of pre-Tesuque sediments. Locally, near remnants of Pennsylvanian rocks, limestone fragments are common or even predominant. The cement is quite possibly derived from solution of limestone of the Magdalena group.

Thin sections of samples *A*, *B*, and *C* (figs. 11 and 12) show that the grains are angular to subangular. Calcite cement fills some or all of the pore space between the sand grains. For the most part, the crystalline units of calcite are about the size of the sand grains in samples *B* and *C*, although a few crystal units are the size of

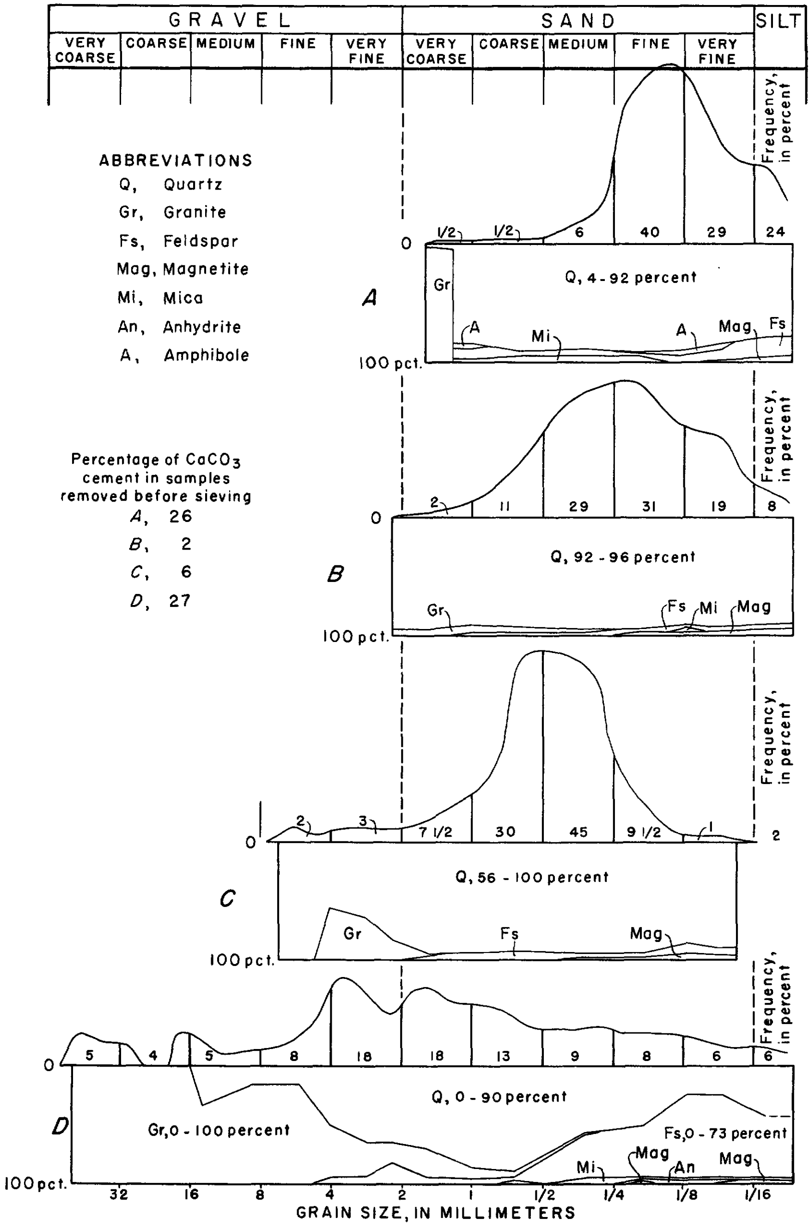



FIGURE 11.—Frequency curves and variation diagrams of four samples of common rock types in the Tesuque formation.

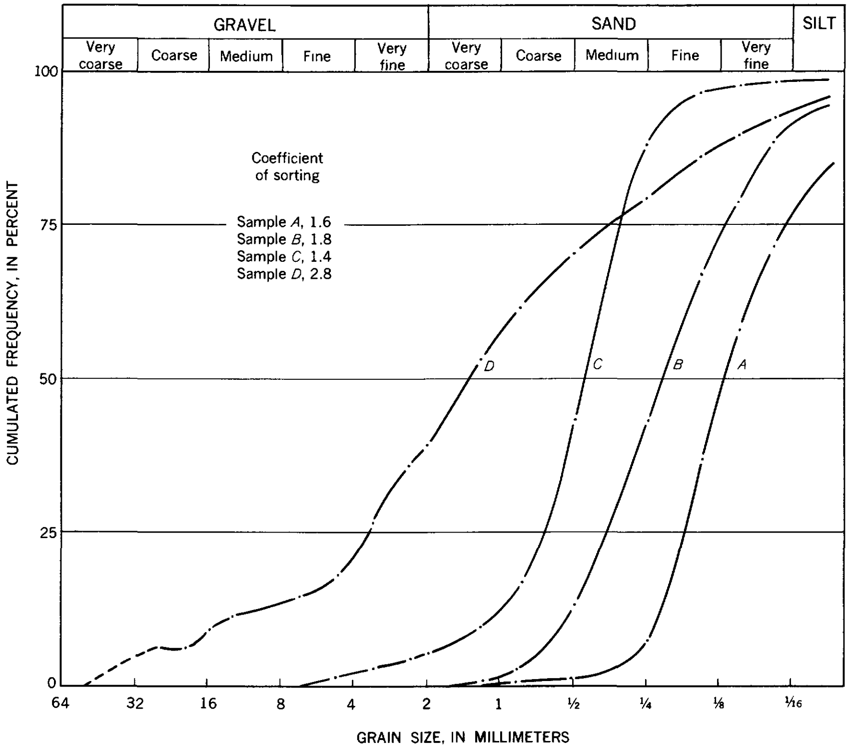



FIGURE 12.—Cumulative frequency curves of four samples of the Tesuque formation.

5 or 6 grains; it is reflections from these latter, larger units that give the glittering appearance in hand specimen. In one hand specimen, a unit of crystalline calcite measures several millimeters in diameter. In sample *A*, the calcite is in part almost microcrystalline, and the silt particles between the sand grains apparently impeded the development of larger crystals. Feldspar grains in general are completely unaltered.

Denny (1940a) described the Santa Fe formation in the Espanola Valley. The center of Denny's area is about 20 miles north of the Santa Fe area and extends south to within 3 miles of the area. Several lithologic differences exist between the Santa Fe formation as described by Denny and the correlative Tesuque formation of this report. Intraformational (channel) breccias are not found in the Santa Fe area but are fairly common farther north, and other types of channel deposits sparsely present in the Santa Fe area also become more obvious northward. Fine-grained sediments—sandstone and siltstone—appear to be more abundant in the Espanola Valley area, though they are characteristic also of the Tesuque formation. Tuffaceous beds are reported to be distributed sparsely throughout the sediments in the Espanola Valley; they are perhaps more common east of U.S. Highway 285. In the Santa Fe area such sediments are restricted to the eastern border and lower part of the Tesuque formation.

The volcanic-derived Bishops Lodge member and the olivine basalt flows (fig. 13) are two mappable units which occur near the base of the Tesuque formation.

#### BISHOPS LODGE MEMBER

The Bishops Lodge member of the Tesuque formation is here named for Bishops Lodge (fig. 4), 4 miles north of the city of Santa Fe. It consists of light-gray sandstone and silt derived from gray intermediate volcanic rocks, and locally it contains weathered pebbles of porphyritic andesite. Blocky, massive tuff beds 2–11 feet thick are locally interbedded with the siltstone and sandstone beds. Moderately coarse conglomerate occurs in a gully south of the Santa Fe River, northeast of Talaya Hill (NW¼ sec. 29, T. 17 N., R. 10 E., unsurveyed); the boulders of andesitic to latitic rocks are strongly weathered. In most localities the Bishops Lodge member is gradational with the arkosic sediments typical of most of the Tesuque formation, and so it is considered a member of the Tesuque formation; however, it is locally underlain and overlain unconformably by the arkosic sediments.

The Bishops Lodge member crops out discontinuously from Arroyo Hondo north to the edge of the area; outcrops are most numerous north of the Santa Fe River and are abundant in the vicinity of Bishops Lodge. The outcrops form a narrow belt near the base of and close to the present eastern limit of the Tesuque formation. The member is lenticular, possibly as a result of contemporaneous erosion. Thicknesses are: 50–120 feet, north of Tesuque Creek; and 500 feet, near Bishops Lodge; 110 feet, just north of the Santa Fe River; and 530 feet, in Arroyo Hondo. The type section measured near Bishops Lodge is illustrated in figure 13.

#### OLIVINE BASALT FLOWS

Approximately 140 feet above the Bishops Lodge member an olivine basalt flow is interbedded with arkosic sandstone in the Tesuque formation (fig. 14). The center of extrusion of the flows apparently was in the SW¼NW¼ sec. 5, T. 18 N., R. 10 E., 6½ miles north of Bishops Lodge, where about 25 feet of dark-green weathered olivine basalt is exposed in the hills north of the village of Chupadero. The upper part of the flow is vesicular and contains amygdaloids of calcite. The basal part is a massive olivine basalt containing plagioclase ($An_{50}$).

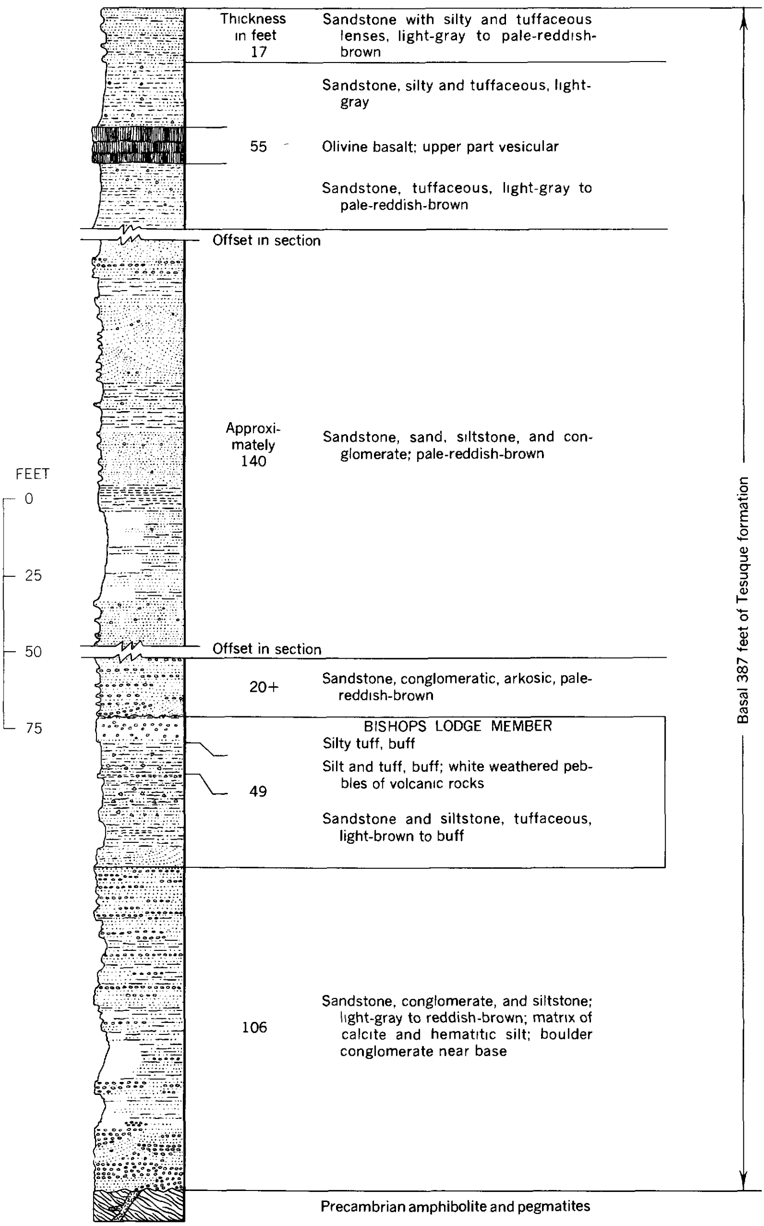



FIGURE 13.—Basal part of the Tesuque formation, showing the type section of the Bishops Lodge member and an olivine basalt flow, S½ sec. 32, T. 18 N., R. 10 E. (unsurveyed).

FIGURE 14.—Typical exposure of the Tesuque formation; olivine basalt flow (dark) interbedded near base of formation. Seven miles north of Bishops Lodge.

Two thin olivine basalt flows separated by about 15 feet of tuffaceous sand occur west of Bishops Lodge. Discontinuous outcrops of the olivine basalt occur near the mountain front, northward from the divide between the Santa Fe River and the Rio Tesuque. The outcrops of olivine basalt are discontinuous, partly because of erosion during Tesuque time and partly because of faulting. A section measured in the hills just west of Bishops Lodge is illustrated in figure 13.

### ANCHA FORMATION

The Ancha formation, consisting of gravel, sand, and silt, is here named for exposures along Canada Ancha, in the northwestern part of the Agua Fria quadrangle. A part of a typical section, measured in a cut below the basalt-capped cliff at the north edge of the area, is illustrated in figure 15. This exposure is typical of the arkosic gravels that make up the Ancha formation in this vicinity. The Ancha rests with angular unconformity on the Tesuque formation, but good exposures of the basal part of the Ancha formation are rare even in the northwestern part of the area, and the contact between the Ancha and Tesuque could be mapped only by means of careful, detailed work.

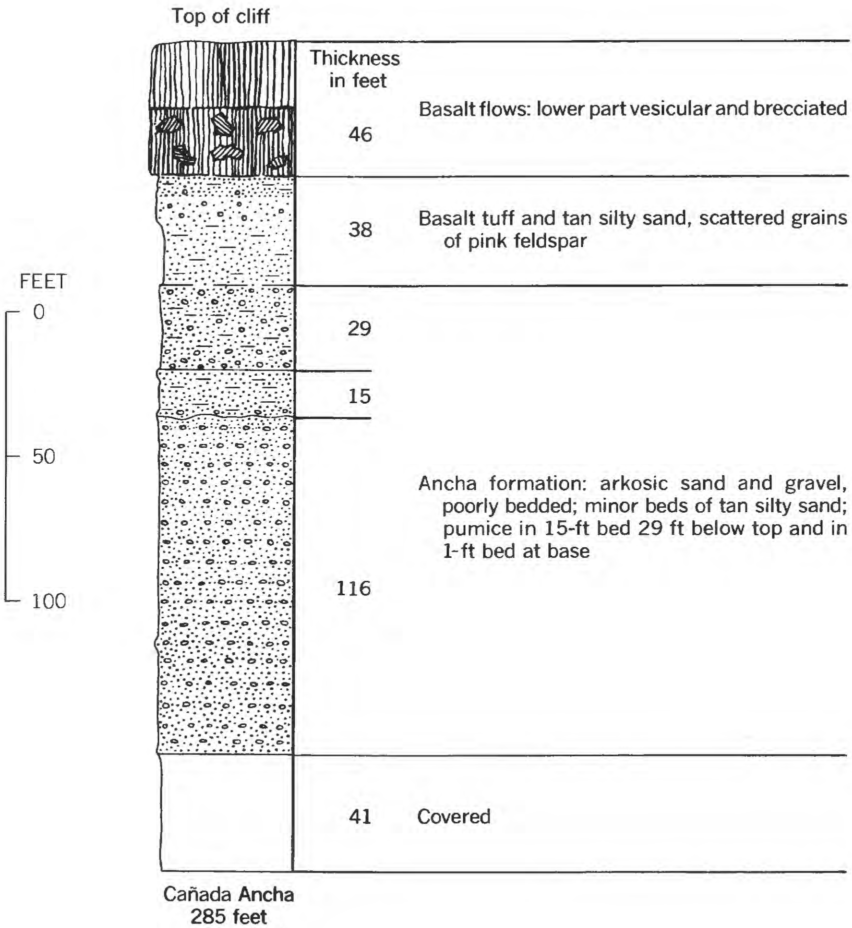



FIGURE 15.—Partial section of the Ancha formation and basalt units, E½ sec. 32, T. 18 N., R. 8 E. (unsurveyed).

Distinction between the Tesuque and Ancha formations is difficult, because there is considerable overlap in lithologic types. However, the contact was mapped on the basis of several characteristics that appear to be valid in the Santa Fe map area:

| *Tesuque formation* | *Ancha formation* |
|---|---|
| Beds are tilted 5° or more. | Beds essentially horizontal; may dip as much as 2° in some localities. |
| Mostly sandstone; minor siltstone and conglomerate. | Gravel and coarse sand abundant. |
| Sorting is good in most beds. | Sorting is generally poor. |
| Many beds are cemented to form ledges. | Few cemented beds. |
| Cement is commonly glittering and crystalline. | Cement is aphanitic. |

No single characteristic except the first is sufficient to demonstrate the formation to which sediments in a given outcrop should be assigned. Actually, however, the contact was mapped largely on the distribution of loose pieces of fairly well sorted sandstone having a glittering appearance. In the present arroyos, sandstone blocks of the Tesuque formation are found only within a few hundred feet of the outcrops, and so mapping on the basis of the float is fairly reliable. In localities where the Tesuque strata are not tilted appreciably, the contact between the Ancha and Tesuque is most difficult to determine. Observations made during a reconnaissance suggest that north of the map area the Tesuque is not tilted appreciably, and, although the Ancha formation probably extends into the Buckman area northwest of the Santa Fe area, such correlation is only tentative.

In the northwestern part of the area and also beneath the Airport surface, the Ancha formation is composed in large part of gravel, and slopes developed in this material are commonly steep and gullied. South of the Airport surface, on the other hand, the formation consists mostly of sand and silt, with only minor gravel. The character of the formation is illustrated by curves of samples *E–H*, figures 16 and 17. Sample *E* represents the finer grained material of the southern part of the Santa Fe area. Thin beds of caliche occur in some parts of the area, but in general the sediments are poorly consolidated to unconsolidated.

Particles of volcanic ash and a few diatoms were noted under the microscope in samples of the Ancha formation collected near the center of the Santa Fe area. The diatoms were found in a sample of the silt that can be seen as white bands on a knob below and just north of the Municipal Airport (SE¼ sec. 9, T. 16 N., R. 8 E.).

Massive beds of dense to powdery calcium carbonate occur in the southwest corner of the map area. In particular, these may be observed on the dirt road southeast of Cerro de la Cruz, and in the deep gullies north of the Marshall Bonanza mine. The limey beds are up to 5 feet thick and are covered in places by 5 or 10 feet of slope wash. About 20 feet of limey material is found in the gully draining northeastward into Alamo Creek, just northwest of U.S. Highway 85, in the southwest corner of figure 9. In this exposure there is a lower zone of nearly pure dense limestone overlain by conglomeratic sandstone having a calcareous matrix. These limey deposits are developed in the Ancha formation immediately above its contact with underlying impermeable rocks of the "bedrock floor." The calcium was probably leached from the nearby Tertiary igneous rocks and was concentrated by evaporation in the soil profile of old valley slopes.

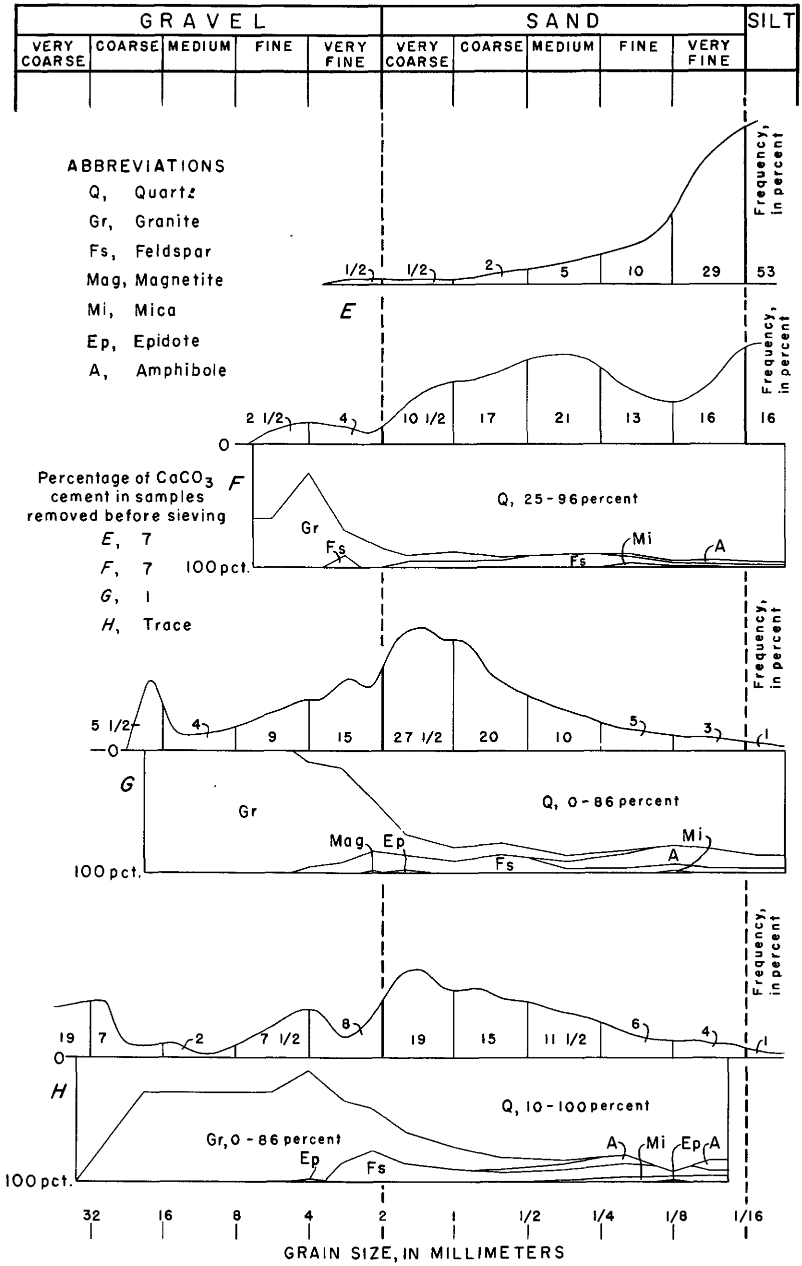



FIGURE 16.—Frequency curves and variation diagrams of four samples of rock types common in the Ancha formation.

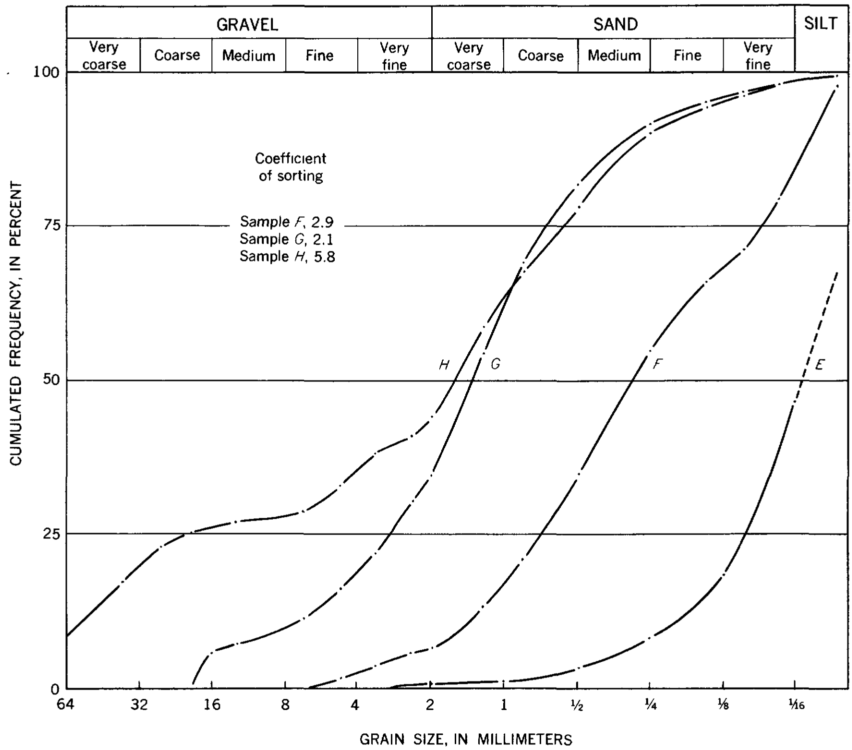



FIGURE 17.—Cumulative frequency curves of four samples of the Ancha formation.

In the southwestern part of the Turquoise Hill quadrangle some alluvium has been derived locally from the Cerrillos or from the outlying knobs. This alluvium is here included in the Ancha formation because it could not be mapped separately, even though the Ancha formation is derived mostly from the Precambrian rocks of the Sangre de Cristo Mountains.

Stratigraphic relations of the Ancha formation are sketched in figure 19. The lower and upper limits of the Ancha are graded surfaces, both previously called the "Ortiz surface." The Ancha rests on an erosion surface that bevels the tilted beds of the Tesuque formation, and its upper limit is another graded surface, remnants of which form the broad divides between arroyos. In the western part of the area, the upper part of the Ancha formation intertongues with flows and tuffs of basalt. These basaltic units belong in the Santa Fe group but are excluded from the Ancha formation. A buried graded surface is indicated at the base of the basalt tuff. Although no fossils have been collected from the Ancha formation, a late Pliocene or Pleistocene age is inferred from physiographic relations. The formation blankets most of the Santa Fe area. Geophysical studies suggest that the formation is 100–200 feet thick in the south-central part of the area. In the northwestern part of the area, the thickness of the formation is estimated to be at least 300 feet, on the basis of the interval between the projected top of the Tesuque formation and the base of the basalt tuff and basalt flows.

### LAVA FLOWS

The lava mesa that lies between the Santa Fe area and White Rock Canyon has not yet been mapped in detail, and the present study included only a brief reconnaissance across the mesa and near Buckman. The interpretations of relations are, therefore, not conclusive and are presented only because of their bearing on interpretation of events in the Santa Fe area.

The lava mesa is composed of two main topographic units and also, presumably, of two main geologic units. Standing several hundred feet above the main level of the mesa are several high, dissected mesas; these are believed to represent earlier flows. The early flows are tentatively considered as part of the Santa Fe group but distinct from the Ancha or Tesuque formation, with one of which they presumably intertongue.

Basalt flows that cap both the basalt tuff and the Ancha formation underlie the main level of the mesa, and they are excluded from the Ancha formation, with which they intertongue. They are, however, included in the Santa Fe group.

#### EARLY FLOWS

The earlier flows form the high, dissected mesas that make up the Cerros del Rio (fig. 2). These mesas reach altitudes of about 7,300 feet, several hundred feet above the main level of the lava mesa. A tip of one of the high mesas appears at the west edge of the Agua Fria quadrangle. A mile or so north of the mapped area, another high mesa extends east to the cliff along Canada Ancha; here, the basalt flows intertonguing with the upper part of the Ancha formation appear to lap against the thicker mass of the early flows. This relation and the limited dissection of the basalt flows indicate that the high, dissected mesas represent an earlier phase of igneous activity, which was presumably taking place during the deposition of the Tesuque or Ancha formation.

Basaltic andesite makes up at least a part of the volcanic rocks of the high mesas. The few specimens collected are medium dark gray and aphanitic, and contain phenocrysts of plagioclase and of augite or hornblende. Chemical analysis "V" of Wells (1937, p. 34) probably represents a sample of these earlier flows.

### BASALT TUFF

Basalt lapilli tuff underlies the basalt flows and intertongues with the Ancha formation throughout an area that extends several miles east of the flows, particularly north of the Santa Fe River. The tuff is about 40 feet thick along the cliff in Canada Ancha. West of the Municipal Airport and somewhat farther north (secs. 8 and 17, T. 16 N., R. 8 E.) the tuff is appreciably thicker, measuring 60 to 80 feet. The cinder pit at the west edge of the area, in sec. 17, is developed in the flank of a cinder cone that was buried by the flows and is now being exhumed. South of Cieneguilla the amount of basalt tuff is small and the material is mixed with gravel of the Ancha formation, derived from the east.

The tuff immediately underlies the flows north of Cieneguilla, except for a few places where gravel derived from the east forms a 10- to 20-foot lens between the two. In general the tuff overlies the sediments of the Ancha formation, but locally beds of the Ancha formation lie above the tuff. This is particularly true in the west-central part of the Agua Fria quadrangle, where 60–80 feet of sediment in the Ancha formation derived from the east rests on the basalt tuff and basalt flows.

In single outcrops under the cliff-forming basalt the tuff is exposed for distances of several hundred feet, and in such exposures the tuff unit rests on a surface that has about 20 feet of relief. Locally the dip of the tuff is 10° or more, probably representing initial deposition on the irregular surface. The tuff lenses materially reduce the irregularities, and the upper surface of the tuff is more nearly even.

East of the cliff, particularly in the Agua Fria quadrangle, the tuff appears as dark patches on the aerial photographs, and on the ground the dark particles are readily recognized. The tuff evidently rests on a surface that existed during one fairly short interval. This surface slopes S. 70° W. about 120 feet per mile, according to the present distribution and altitudes of the contact at the base of the tuff. In the northwestern part of the area the tuff lies across the Ancha-Tesuque contact.

The tuff is thin bedded and remarkably even bedded; cross-bedding was noted in only a few outcrops. The finely vesicular basalt fragments form persistent layers an inch or more in thickness. These layers occur in beds 1–10 feet thick; the beds in turn are interbedded with massive, poorly sorted tan silt and fine sand that contain particles of volcanic glass. Similar silt occurs as a matrix in some beds of tuff. Pink feldspar grains form a few percent of the sediments, being less abundant near the top. Fragments of rotten pumice are moderately abundant near the base of the tuff

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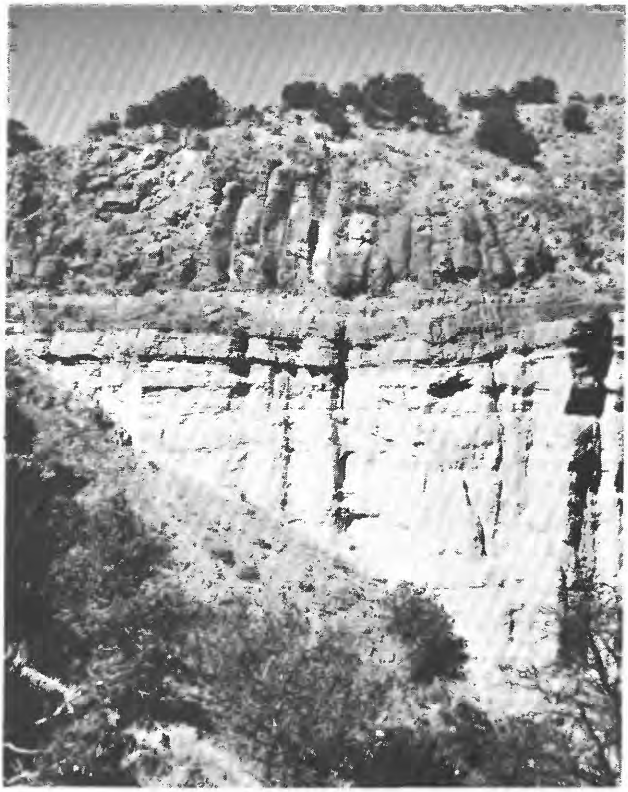

FIGURE 18.—Columnar basalt flow and basalt tuff (dark) overlying the Ancha formation (light). East flank of Mésa de los Ortiz southeast of Otowi Bridge, S½ sec. 19, T. 19 N., R. 8 E. Note the two men at the base of the cliffs on the left slope.

interval in some places. A typical section is presented in figure 15, and an excellent exposure is shown in figure 18.

The basalt tuff was deposited mostly by direct fall but perhaps in part by water. The even bedding and essentially pure composition indicate the former; but scattered grains of pink feldspar, though they may have been ejected from the same vents, may have been admixed by sheetwash or some similar means. To the east of the cliff the tuff contains more grains of quartz and pink feldspar, suggesting reworking near the margin. South of Cieneguilla the tuff is intermixed with the material of the Ancha formation derived from the east.

### BASALT FLOWS

Flows of medium-dark-gray basalt underlie much of the area of the lava mesa—all the mesa within the map area. Although outcrops are commonly poor on the mesa, the bordering cliffs provide areas of exposure. Individual flow units were not distinguished in the cliff, but the pattern of scattered outcrops in the northwestern part of the map area suggests that there are three or more flows. Vertical jointing is fairly common, though in places the joints are curved and irregular. The rock is aphanitic to very finely crystalline and contains phenocrysts of plagioclase and olivine.

The thickness of the basalt, as exposed along the Santa Fe River and Canada Ancha, averages about 50 feet; although the flow at Cienega, east of Gallegos ranch (fig. 9), is only 20 feet thick, in places the basalt appears to be 100 feet thick. The basalt flows are correlative with the next-to-youngest of the five basaltic units mapped along White Rock Canyon by R. L. Griggs (written communication); the flows designated as early flows in this report are the middle unit of Griggs.

A detailed description of the basalt is given by Sun and Baldwin (1958).

Stearns (1953a, pl. 1) indicates two north-trending faults in the vicinity of La Bajada. These faults are covered by basalt flows of Mesa Negra but are in line with two sets of fairly recent centers of basaltic eruption. It is inferred that the feeders of the flows trend northward beneath the lava mesa, roughly parallel to the axis of the Rio Grande trough. If so, the feeders probably are a partial barrier to the westward movement of ground water from the Santa Fe area.

The original eastern limit of the basalt flows was probably less than 1 mile east of the present limits. Basalt tuff, which was deposited almost immediately before the flows were extruded, is still preserved on ridgetops 4 miles east of the basalt-capped cliff in the northwestern part of the area, and so there has been little erosion of the ridges in this area since the time of the flows. The flows diverted the westward drainage and defined the present course of Canada Ancha and the lower course of the Santa Fe River.

The flows and underlying basalt tuff rest on the Ancha formation. Locally, as in the western part of the Agua Fria quadrangle, near the former Pankey Ranch headquarters, 60–80 feet of the Ancha formation rests on the basalt tuff and flows.

### BASALTIC ALLUVIUM

Some locally derived slope wash and earlier alluvium are present on the lava mesa. Their total thickness is probably about 20 feet; they were derived from the lava flows and cinders. For the most part the unit consists of tan silt and sand, but it includes some cindery material, which is fairly abundant just north of the former headquarters of the Pankey ranch; this material may be original cinder fall rather than reworked material. The alluvium is on top of the lava flows and so is fairly recent, perhaps correlative with

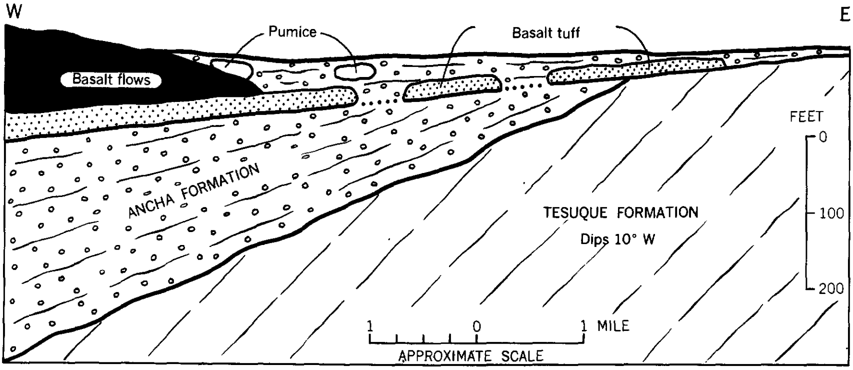


FIGURE 19.—Relations of post-Tesuque units and graded surfaces in northwestern part of the Santa Fe area, New Mexico. Graded surfaces shown by heavy black lines. Dips steepened by vertical exaggeration.

the thin uppermost beds of the Ancha formation north of the Santa Fe River. Some of it may be windblown.

### GRADED SURFACES

Prior to and during deposition of the Ancha formation three or more graded surfaces[2] were developed, two of which are buried and the third of which is preserved as a physiographic surface on divides between arroyos (fig. 19). The third is actually a modification of the second. The first two were formed by erosion, and the third is apparently the result of both erosion and deposition. Were it not for the basalt tuffs, which rest on the second surface, the second graded surface would not be recognizable. Many other surfaces almost certainly existed but are not recognizable.

#### PRE-ANCHA SURFACE

The Ancha formation rests on a surface of erosion that bevels the tilted and faulted beds of the Tesuque and pre-Tesuque rocks. The outcrop pattern of the Ancha-Tesuque contact in the northwestern part of the Santa Fe area is digitate and thus provides good control on the shape of the pre-Ancha surface over a broad area. Scattered exposures of the basal contact of the Ancha formation occur near the mountains from Santa Fe south to Seton Village, along the south border of the Seton Village quadrangle, and a few hundred feet outside the southeast corner of the area. Nearly continuous exposures in the southwestern part, particularly in the Cienega area, complete the geologic information on the pre-Ancha surface. Geophysical evidence has added measurably to the control. Plate 5

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[2] The "Ortiz surface" of Bryan and his students is actually compound (Stearns, oral communication), and the graded surfaces associated with the Ancha formation can be considered correlative with the compound "Ortiz surface".

shows a reconstruction of the pre-Ancha surface, which was modified by erosion during Ancha time along the present trend of the Santa Fe River. The map thus is an inferred geologic and generalized topographic map of the Santa Fe area if the Ancha formation were removed. The control is not adequate for a map that is accurate in detail, but the broad features appear to be valid. For example, it is not possible to determine whether the pre-Ancha surface is convex or concave upwards, but it is established that this surface slopes west-southwestward at about 100 feet per mile. The trend of the contours is at an angle to the mountain front but is nearly parallel to inferred structures.

The contours indicate the presence of two major ancient valleys, one along the present trend of the Santa Fe River and the other along the north edge of the map area. This second valley, a feature of the pre-Ancha surface, is indicated by the basalt tuff, which in sec. 3, T. 17 N., R. 8 E., is underlain by an estimated 200 or 300 feet of the Ancha formation deposited in the valley, whereas 2 miles to the south, in sec. 15, the tuff rests directly on the Tesuque formation. The buried valley along the present Santa Fe River, on the other hand, was probably formed during Ancha time. Thickening of the basalt-tuff unit northwest of the Municipal Airport indicates that this valley of the ancestral Santa Fe River existed until the outpouring of basalt flows, and geophysical evidence suggests that the base of the Ancha formation is some 150 feet below the present channel of the Santa Fe River in the Agua Fria quadrangle. In the Santa Fe quadrangle the buried channel may lie somewhat south of the broadest terrace, under remnants of the Airport surface, inasmuch as outcrops of the Tesuque formation are scattered along the present channel of the Santa Fe River.

### PRE–BASALT-TUFF SURFACE

In the northwestern part of the area, basalt tuff rests on a surface that cuts across the Ancha-Tesuque contact. This surface slopes S. 70° W. about 120 feet per mile and was formed during Ancha time. If the tuff could be found and mapped in other than the vicinity of the basalt cliff it would be a valid basis for subdividing the Ancha formation, the bulk of which probably accumulated before the basaltic eruption. With present data, the Ancha can be so subdivided only where there are outcrops of the tuff.

The ancestral Santa Fe River flowed westward on the pre–basalt-tuff surface, as indicated by the increased thickness of the tuff west and northwest of the Municipal Airport. The thickness of the tuff here is some 60–80 feet, and there is much interbedded gravel derived from the mountains, suggesting that along this drainage line the tuff was in part reworked and mixed with Ancha sediments by the ancestral Santa Fe River. The valley shown on plate 5 probably was eroded during, instead of before, Ancha time.

### PHYSIOGRAPHIC SURFACES

Three surfaces formed a part of the present landscape: the Plains surface, the Airport surface, and the Divide surface (fig. 5). These surfaces now exist only as remnants on divides between arroyos.

The Airport surface is between the areas occupied by the other two surfaces and so obscures their relations. It is the youngest of the three, forming a broad, shallow valley. The shape and altitude of the two older surfaces, suggest that they were once continuous.

The Plains surface is south of the Santa Fe River and is developed entirely on the Ancha formation. It slopes west-southwestward with a gradient of 140 feet per mile near the mountains and 50 feet per mile in the center of the Turquoise Hill quadrangle. Arroyos draining in the same direction have cut broad, shallow valleys 60–80 feet deep, leaving digitate remnants of the surface. No gravel veneer is present. In the southwestern part of the Santa Fe area the surface north of the Cerrillos slopes northward toward Alamo Creek with a gradient decreasing from 200 to 80 feet per mile. This surface, now being dissected, is cut mostly on locally derived alluvium and is about 60 feet above Alamo Creek by projection.

North of the Santa Fe River is the Divide surface, which is broadly convex to the west, being higher in the middle and sloping southwest or northwest on the flanks. The divide itself has a west-southwestward gradient decreasing from 130 to 90 feet per mile. Near the former Pankey ranch headquarters the surface merges in a gentle saddle with the eastward-sloping surface of the lava mesa. The present drainage, particularly in the area north of the divide, is fine textured, and so reconstruction of the original surface is difficult.

The Divide surface is underlain in some localities by a gravel veneer 5–10 feet thick. Where the basalt tuff is present, in the western part of the area, the surface is developed commonly on the tuff or on sediments above the tuff. The surface and the underlying tuff lie across the contact between the Tesuque and Ancha formations in secs. 1 and 2, T. 17 N., R. 8 E. West of this contact the surface is developed on the Ancha formation; to the east, on the Tesuque formation.

The Airport surface, which forms a belt about 3 miles wide, follows the course of the Santa Fe River west-southwestward from the city to the edge of the lava mesa, where the river turns southward to Cienega. The gradient is about 77 feet per mile near the Old Municipal Airport and 40 feet per mile southwest of the present

Santa Fe Municipal Airport. The surface is underlain by gravel that is fairly thick, and the gravel-capped buttes just east of Cienega (fig. 9) are probably remnants of the surface. The gravels have been included in the Ancha formation and are probably the youngest strata of the formation in the area. The gravels underlying the surface, and the course of the surface, indicate that this was a valley floor of the ancestral Santa Fe River.

The border between the Airport surface and the Plains surface is undissected in only a few places, one being in the W½ sec. 26, T. 16 N., R. 8 E. The Airport surface appears to have a gentler gradient than the other surfaces, for it is perhaps 100 feet below the Plains surface at Santa Fe, yet its remnants project to the same altitude as the Plains surface in the Cienega area.

In the report area, the lava mesa has an eastward gradient of about 80 feet per mile and the eastern limit has an altitude of about 6,400 feet.

### CORRELATIONS WITHIN THE SANTA FE GROUP

Nomenclature of, and possible correlation within, the Santa Fe groups are indicated in figure 20. Many localities in which fossils were found are not identified exactly in terms of stratigraphic units, and so correlation must be made on the basis of lithologic character, intertonguing, and general stratigraphic position of the units. The Santa Fe group in the general vicinity of the Santa Fe area consists of two principal units: (a) the Tesuque formation, a thick sequence of pinkish-tan arkosic sediments containing in its lower part some thin flows of olivine basalt and a layer of sand and silt derived from volcanic material—the Bishops Lodge member; and (b) an upper blanket—the Ancha formation—which hitherto has been thought of as pediment gravel.

The flows of olivine basalt near the base of the Tesuque formation are possibly correlative with the Cieneguilla limburgite of Stearns (1953b).

The Bishops Lodge member of the Tesuque formation has a stratigraphic position similar to other volcanic-derived sedimentary rocks in the region. Some 40 miles north-northwest of Santa Fe, Smith (1938) mapped 500–1,200 feet of water-laid tuff and volcanic conglomerate as the Abiquiu tuff. Cabot (1938) named the water-laid Picuris tuff, which he mapped in discontinuous exposures from Picuris south some 40 miles to Santa Fe. These exposures include the material here referred to as the Bishops Lodge member, but the latter name is proposed for the Santa Fe area because the stratigraphic relations of these volcanic-derived sedimentary rocks are not yet clearly demonstrated. Farther south, Stearns (1953a) placed

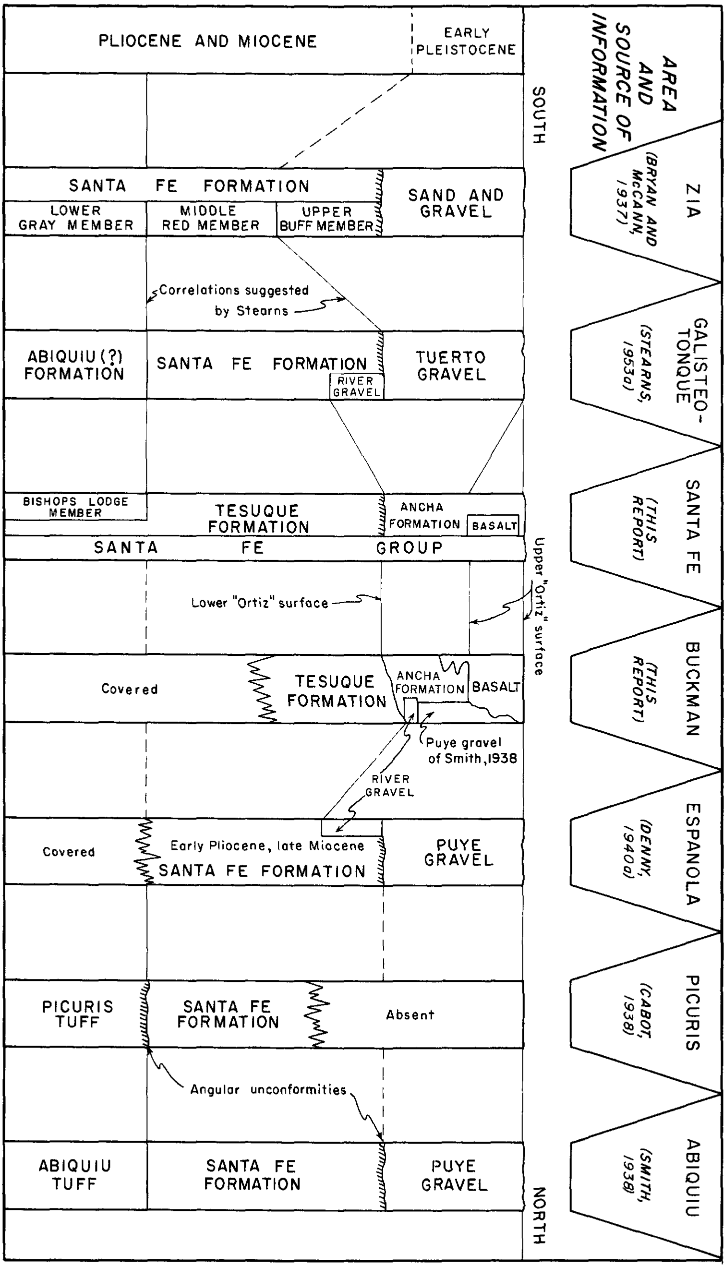


FIGURE 20.—Nomenclature of the Santa Fe group in north-central New Mexico.

in his Abiquiu(?) formation some 1,400 feet of gray-white arkosic sedimentary rocks of the Galisteo-Tonque area, correlating with the Abiquiu tuff of Smith (1938) "only upon similarity of stratigraphic position and upon the presence of tuffs in the La Bajada escarpment." Stearns (1953a, p. 496) further suggested the possibility that the lower gray member of the Santa Fe formation of Bryan and McCann's (1937) is correlative with his Abiquiu(?) formation.

The Tesuque formation can be traced directly into the Santa Fe formation as used by Denny in the Espanola Valley, although the precise upper and lower limits cannot be followed. The uppermost beds of the Tesuque formation are probably concealed under the lava flows of the lava mesa and under the Ancha formation. Cabot (1938) and Smith (1938) have made similar correlations of their Santa Fe formation with the sedimentary rocks described by Denny (1940a) in the Espanola Valley. Stearns (1953a) has correlated the Santa Fe formation as he used it in the Galisteo-Tonque area with the sedimentary rocks of the Espanola Valley, and he further suggests (1953a, p. 499) that it is generally equivalent to Bryan and McCann's (1937) middle red member of the Santa Fe formation in the Rio Puerco area.

The Ancha formation has not been correlated by detailed mapping with sedimentary rocks in adjacent areas, but, if the writer's tentative correlations are correct, certain events in the Rio Grande trough have taken place somewhat more recently than has been generally believed. Reconnaissance along Canada Ancha and in the northern part of White Rock Canyon, near Buckman, suggests that the Ancha formation intertongues to the north with the Puye gravel of Smith (1938). In this area it is difficult to distinguish the Ancha from the Tesuque formation, but the writer is reasonably certain that 100 feet or more of the Ancha is present between the Tesuque formation and the overlying mesa-forming basalt.

Thus, the Ancha formation may be correlative with the prominent river gravels of Denny (1940a, pl. 4, fig. 1; and pl. 1, sections *G–H*). Also, at least some, and probably most, of the lavas interbedded in the sedimentary rocks west of Buckman and downstream intertongue with the Ancha formation. The prominent river gravels and at least some of the lavas were placed in the Santa Fe formation by Bryan and Denny.

To the south, the Ancha formation is equivalent to the Tuerto gravels of Stearns (1953a). His Tuerto gravels rest on an erosion surface that bevels tilted beds of his Abiquiu(?) formation; by inference, the surface bevels beds equivalent to the Tesuque formation. In places the gravels are 150 feet thick and the upper surface appears to be another erosion surface, formed by regrading of the depositional surface of the Tuerto gravels (Stearns, oral communication). The "Ortiz surface" of Bryan (1938) is thus actually compound, representing a sequence of erosion, deposition, and probably erosion again. Similarly, in the Santa Fe area, the Ancha formation rests on a surface of erosion, which bevels the tilted beds of the Tesuque formation, and the Ancha in turn was eroded before the basalt tuff was deposited. Deposition and erosion during Ancha time later modified the uppermost surface.

An angular unconformity exists between Bryan and McCann's (1937, fig. 8) upper buff member of the Santa Fe formation and the overlying sand and gravel which Wright (1946, p. 404, 406, pl. 3, fig. 1) interprets as a local unconformity that disappears to the south: Wright states that "the beds of gravel and sand interfinger with the main unit of the upper buff member." He adds (1946, p. 411) that the river gravels can be traced into Bryan and McCann's upper buff member, but whether they also include material older than the upper buff is not demonstrated. Stearns (1953a, p. 499) suggests that "the upper buff member and associated river deposits may represent only late Pliocene time." It is here suggested that the upper buff member of Bryan and McCann (1937) and the river gravels are correlative with the Ancha formation and the Tuerto gravels of Stearns (1953a). (See fig. 20.)

The Ancha formation may be correlative with the Servilleta formation as used by Montgomery, which rests on tilted strata of the Santa Fe formation and is interbedded with basalt flows near the Picuris Range (Montgomery, 1953, p. 53; see also Atwood and Mather, 1932, pl. 22 A).

## ORIGIN OF THE SANTA FE GROUP

The Santa Fe group is largely a complex of alluvial fans that accumulated in the Rio Grande trough. The variations in lithology and structure of the several parts of the Santa Fe group are due to differences in source material, relief, and other factors. The principal control of geography and sedimentation, however, was by tectonic movements; igneous activity played a minor role.

The source of the volcanic sediments near the base of the Santa Fe group appears to be igneous rocks of Oligocene and Miocene(?) age, although the olivine basalt flows and some tuffs resulted from contemporary volcanic activity. According to Stearns (1953a, p. 494), Butler (1946) concluded that a fan of the Abiquiu tuff of Smith (1938) radiated from contemporaneous centers of volcanism on the Taos Plateau, north of the Abiquiu area. In support of this idea, it should be noted that one unit of the Bishops Lodge member evidently accumulated by direct fall. On the other hand, most of the published descriptions indicate that the "tuffaceous" sediments were actually derived by erosion of igneous rocks or are streamlaid tuffs, and this is consistent with most of the observations in the Santa Fe area. Thus the volcanic detritus could have been derived by erosion of the earlier formed Tertiary igneous rocks, many of which were not originally tuffs. Stearns (1953a, p. 493) states that the nontuffaceous sediments of his Abiquiu(?) formation could be material reworked from the Galisteo or Espinaso (Stearns, 1953b) but that the tuffs near La Bajada were probably carried by streams from the Taos Plateau.

The Bishops Lodge member cannot be associated with a specific source. One unit, previously mentioned, may have been formed by direct fall of ash coming from a distant volcano, but most of the material may have been carried by streams from outcrops of earlier Tertiary igneous rocks. Stearns (1953a, p. 494) suggests that the [pre-Tesuque] volcanic sediments in Arroyo Hondo were carried in by northwestward-flowing streams. However, the coarse conglomerate in a gully just south of the Santa Fe River and east of Talaya Hill must have had a fairly local source, possibly some of the andesitic flows exposed southwest of Talaya Hill.

The Tesuque formation in general is composed of the strata that are "typical" of the Santa Fe group in the Espanola–Santa Fe area. These are moderately well sorted, highly crossbedded alluvial deposits which were derived largely from the Precambrian rocks to the east. Denny (1940a) noted the presence of channeling and intraformational breccias. The Santa Fe was originally thought to be a lake deposit, because of the "marls," but Johnson (1903) demonstrated that the Santa Fe formation, as he described it in the Cerrillos area, is an alluvial deposit. It might be noted here that the sediments on which Johnson based his argument are actually part of the Ancha formation rather than the thicker, deformed Tesuque formation. Denny (1940a) suggests that some of the finer grained sediments in the Espanola Valley are of eolian origin, and such might apply also to some few beds in the Tesuque formation in the Santa Fe area. Other origins might be postulated for single beds or lenses in the Tesuque formation, but by and large the formation is properly considered to be rapidly deposited alluvium.

The Rio Grande trough is generally believed to have been formed by block faulting, although in its early stages it may have been formed by warping. The basin-fill material in the Santa Fe area was probably derived from the Sangre de Cristo Mountains and carried westward into the basin. The feldspar grains are fresh, indicating that the rate of erosion was greater than the rate of chemical weathering in the highlands. The rock fragments near the mountains are commonly coarse, suggesting that relief was considerable. The variety and abundance of fauna collected in the Espanola Valley indicate that the climate was favorable for many kinds of mammals.

As no playa-type deposits of thin-bedded silts are known in the area, none of the sediments in the Tesuque formation here were deposited near the center of the basin. Nevertheless, the present through-flowing drainage may not have existed at that time; no river gravels derived from outside this region have been noted in the Tesuque formation in the Santa Fe or the Buckman area. Denny (1940a, p. 691) inferred from the texture of the sediments that the eastern limit of the Santa Fe group in the Espanola area was perhaps as far east as the present summit of the Sangre de Cristo Mountains. The eastern limit in the Santa Fe area cannot be reconstructed, but there is no stratigraphic evidence to indicate that the Tesuque formation once extended farther east than its present limits.

The Ancha formation was derived from Precambrian rocks and from the Tesuque formation, although some material may have come from Pennsylvanian sedimentary rocks. In the vicinity of the Cerrillos, the material mapped as the Ancha formation was derived in part from Tertiary igneous rocks and possibly in part from sedimentary rocks of Mesozoic age. The lithology and sedimentary structures of the Ancha formation suggest that several kinds of origin were involved. The gravels beneath the Airport surface were probably deposited in shifting stream channels, and this may be true of the gravels in the Ancha in the northwestern part of the area. The coarse material near the mountains resembles that of alluvial fans. The silts and sands over the south part of the area are alluvial deposits which may contain reworked windblown material. No evidence of lake beds is known, even near the Airport where the Santa Fe River was temporarily dammed by lava flows before it was diverted to the south.

## AGE OF THE SANTA FE GROUP

The age of the Santa Fe group ranges from middle(?) Miocene through a part of the Pleistocene(?). No fossils have been collected from this group in the Santa Fe area, and the age assignment is proposed on the basis of the physiographic relations of the Ancha formation and of the age of faunas collected from Tesuque equivalents in the Espanola Valley.

Abundant faunal collections have been made in the Santa Fe marls of Hayden (1869) in the Espanola Valley. Cope (1884, p. 308) concluded that the marls represent "a member of the Loup

Fork division of the Miocene Tertiary." Frick (1926, fig. 1c) originally suggested middle Miocene age. Subsequent studies by Matthew (1909, p. 115–118), Osborn (1918, fig. 5, p. 9; p. 25), and Simpson (1933, fig. 6, p. 87; p. 109) are in general agreement that the fauna of the Espanola Valley occupies the transition zone between the Miocene and Pliocene (upper Barstow and lower Clarendon). In his published monographic studies on several mammalian groups, Frick (1930a, 1933, 1937) has refrained from making specific statements about the stratigraphic position or range of the fauna, because of "uncompleted researches on several contemporaneous groups" (1937, p. 6), but he also is apparently in general agreement with the late Miocene and early Pliocene age (1937, p. 7–8) suggested for the fauna collected in the Espanola Valley.

In none of the reports are the faunas associated precisely with stratigraphic units, but it is reasonably certain that they are restricted to the Tesuque formation above the level of the Bishops Lodge member and its equivalents. By inference, the Bishops Lodge member is probably middle Miocene in age. Allowing time for deformation and erosion of the Tesuque formation, the Ancha formation is possibly late Pliocene or Pleistocene in age, and the basalt tuff and flows are probably early Pleistocene.

Farther south in the Rio Grande trough, fossils have been collected from the Santa Fe formation. At the north end of the Ceja del Rio Puerco, Bryan and McCann (1937, p. 809) found fossils in their middle red member that are "characteristic of" or "compatible with the known Santa Fe fauna." In the same region Wright (1946, p. 413) collected from his upper buff member fossils that could be of the age of the Santa Fe fauna or could be latest Pliocene. South of Belen, Denny (1940b, p. 93) reported late Pliocene fossils in the Santa Fe formation as he used the name. According to Needham (1936), basin-fill deposits near Socorro contain fossils which in one place are probably late Pliocene and in another possibly Pleistocene. In all these reports, the Santa Fe formation is not necessarily equivalent to the typical Santa Fe strata of the Espanola Valley. Wood's summary (1941, pl. 1) of the range of the Santa Fe formation, from the middle of the late Miocene into late Pliocene, should be considered to refer to a broad usage of the name Santa Fe formation.

## PUMICE

Deposits of pumice have been found in a belt extending southeastward through the center of the Santa Fe area; some of the exposures are in small test trenches and pits. The largest pits are a mile south of the former Pankey ranch headquarters, at the north edge of sec. 28, T. 17 N., R. 8 E., and are indicated by the "gravel pit" symbol on the topographic sheet of the Agua Fria quadrangle. In these pits the pumice rests on a basalt flow, and several deposits between there and the west edge of the area rest on alluvium that in turn rests on basalt. In the west half of the area there is little or no overburden on the pumice, but the deposits to the southeast toward Arroyo Hondo are overlain by as much as 50 feet of the Ancha formation. The pumice fragments, which range in diameter from ½ to 2 mm, are fresh and are associated with a sand of angular to subangular quartz and orthoclase grains. In the SE¼NE¼ sec. 18, T. 16 N., R. 9 E., a thickness of 20 feet of pumice was measured, and in two other places nearby, 7 feet or more of pumice is exposed. About 12 feet of pumice is present just north of Arroyo Hondo in the southwest corner of sec. 7, T. 16 N., R. 10 E. The occurrences in the northeastern part of the Turquoise Hill quadrangle are overlain by a tan silty sand which contains fragments of reworked pumice.

The pumice fragments and mineral grains are similar to the pumice and mineral grains exposed near the junction of the Los Alamos and Bandelier National Monument highways; the latter pumice underlies immediately the rhyolitic welded tuff of the Pajarito Plateau (Kelley, 1948). The deposits in the Santa Fe area probably were transported through the air and deposited by direct fall, although there may have been some local reworking. Although this pumice forms lenticular deposits in both the Ancha formation and the basalt alluvium, it is here excluded from the Santa Fe group because of its different origin and is instead tentatively associated with the volcanic units of the Valles caldera.[3]

## POST-SANTA FE DRAINAGE AND SEDIMENTS

### DIVERTED DRAINAGE

Three instances of drainage diversions, possibly resulting from aggradation, postdate the formation of the Airport surface. The headwaters of Arroyo Hondo once flowed northwestward onto the Airport surface, but either aggradation at the edge of the exposed Precambrian rocks, which raised the channel floor sufficiently, or else capture caused the stream to turn westward into its present course, which is now superposed from the Ancha formation onto the westward-dipping pre-Ancha sedimentary and volcanic rocks. These westward-dipping rocks are responsible for the irregular

[3] Field conferences, particularly with Messrs. C. S. Ross and R. L. Smith, furnished invaluable background material on areas west of the Rio Grande, upon which this and other conclusions on relations of the Santa Fe group were based.

course near the mountains. Several reaches of the stream are along the strike of the pre-Tesuque volcanic sediments.

The diversion of the headwaters of Arroyo de los Chamisos may have taken place in two steps. The original course of the arroyo is inferred to have been east of Talaya Hill into an ancient Santa Fe River, along the Chamisos fault. Slight aggradation may have diverted the course to the west side of Talaya Hill—but still toward the Santa Fe River—where the stream cut a fanlike surface on the Tesuque formation. The second diversion occurred after the beginning of the present cycle of downcutting. Now, Arroyo de los Chamisos is on the south side, and the Santa Fe River on the north side, of the resistant gravel-filled channel of the ancestral Santa Fe River.

A third case of diversion is that of the Santa Fe River below Cieneguilla (fig. 9). The buttes of gravel between Cienega and the highway are interpreted as remnants of the Airport surface, indicating that the surface and the main channel of the river were east of Cerro Seguro. However, the Santa Fe River has now cut a canyon across the hardest rocks of the area, the monzonite and limburgite, and this secondary or diverted course developed either because aggradation east of Cerro Seguro was sufficient to raise the channel level above the level of an outlet west of Cerro Seguro, or because of capture by a tributary.

### TERRACE DEPOSITS

Terraces are well developed along the Santa Fe River. The terrace deposit whose surface is less than 5 feet above the arroyo bed has been mapped as part of the alluvium. The next terrace above the river, 10–15 feet above the arroyo floor, is mapped as the "low terrace" and extends with some gaps from Santa Fe to Cieneguilla. It is preserved on both sides of the arroyo.

The third terrace, 20–30 feet above the arroyo, is mapped as the "middle terrace," and it similarly extends from Santa Fe to the base of the Lava Mesa, and possibly to Cieneguilla. The terrace is nearly 1 mile wide and is preserved mostly on the south side of the arroyo. In the Agua Fria quadrangle the terrace is 15–20 feet below the Airport surface, but eastward it merges with that surface at the city limits. In the mountains also the middle terrace is 20–30 feet above the Santa Fe River. The "high terrace," 45–60 feet above the river in the mountains, is not recognized west of the mountains.

One of the interesting features of the terraces along the Santa Fe River is the high ridge that forms the streamward edge of several terraces. This feature is best shown by the contours on the middle terrace, north of the Municipal Airport. The ridge here is at least 5 feet higher than the main level of the terrace and is protected by gravel.

Although the terraces were mapped as geomorphic surfaces rather than stratigraphic units, they are undoubtedly underlain by terrace deposits. The upper few feet of sediment under the terraces is composed of moderately coarse gravel. This gravel can be seen north of the Municipal Airport, where the road crosses the western edge of sec. 10, T. 16 N., R 8 E. Other exposures can be seen along the Santa Fe River in the western part of the Santa Fe quadrangle.

The middle and high terraces are particularly well developed near the junction of Tesuque and Little Tesuque Creeks. The lower of the two, mapped as the middle terrace, is 90–115 feet above the creek, and the upper, mapped as the high terrace, is 150–160 feet above the creek. The ratio of elevations of the two terraces above Tesuque and Little Tesuque Creeks is 100:155, and this ratio is close to that of the middle and high terraces in Santa Fe Canyon, which is 30:50. The terrace deposits of Tesuque Creek are cross-bedded sand and silt containing gravel lenses, the upper 15–35 feet consisting largely of poorly sorted, very coarse gravel, and boulders up to 5 feet in diameter. The terrace deposits are probably related to contemporaneous glaciation in the mountains.

Remnants of low terraces, 10–20 feet high, occur along most of the larger valleys in the mountains. In the canyon of Arroyo Hondo, the lower terrace is 15–40 feet above the present stream, and the upper set of terraces is about 80 feet above the valley. These terraces appear to be tilted to the east. In the upper part of Arroyo de los Chamisos, terraces that occur 20–40 feet above the stream channel are continuous with the local alluvial plain, which slopes toward Santa Fe Canyon east of Talaya Hill. This plain represents the former course of Arroyo de los Chamisos, now abandoned.

Terraces 5–15 feet above the streams are found along many of the arroyos tributary to the Santa Fe River, west of the mountains. These are not well developed and are difficult to recognize and correlate for more than about 1 mile, and so they have been mapped in only a few places. Commonly, a wide arroyo, occupying the entire valley floor gives way downstream to an arroyo channel incised 5 feet or more below the valley floor; still farther downstream the channel is widened, and as a result the terraces are largely removed; even farther downstream the terraces are gone and a wide arroyo bottom again exists. Such a situation is present on a larger scale in the extreme northwest corner of the Turquoise Hill quadrangle, where the broad Arroyo Calabasas, draining southward into the Santa Fe River at the base of the lava mesa, is graded to the low terrace of the Santa Fe River. These alternating incised and broadened arroyo floors are not completely understood, but they are probably related to local patterns of vegetal cover and storm intensity. Antevs (1952) discussed similar features.

### ALLUVIUM

Alluvium, as mapped in plates 1–4, is essentially restricted to the most recent alluvial wash and valley fill. It includes gravel in those valleys having steep gradients and appreciable headwater drainage area, fill in the arroyos, and sand and silt in short, minor tributaries. In order to simplify the mapping, slope wash has been included with the alluvium where it merges with the valley fill. The thickness of "fill" in short tributaries is usually greater than the depth of the gullies that have cut into the fill, which is commonly 5 feet and in places 10 or 15 feet.

The present dissection has developed asymmetric ridges in much of the plain of the Santa Fe area. The west-trending ridges commonly have a relatively steep south-facing slope with thin or spotty vegetal cover, whereas the north-facing slope is gentler and usually covered with more vegetation.

### EOLIAN SEDIMENTS

Windblown sand and silt form an irregular blowout-and-dune topography in the southwestern part of the Turquoise Hill quadrangle. Most of the eolian deposits are restricted to the area south and east of Turquoise Hill itself, but some dune ridges are mapped northeast of Cerro de la Cruz. The deposits lap up onto the Plains surface but are largely on the present dissected surface. They are evidently quite recent in age and possibly resulted from wind erosion initiated by farming operations around now-abandoned homesteads.

### COVER

An attempt has been made to indicate areas of cover in the western half of the area (pls. 2, 3). Where no outcrops are present but the identity of the covered unit has been established, a pale hue of the color representing that unit is used. Single outcrops, and areas where outcrops are abundant, are indicated by full color. A few areas that are covered by talus, or that are where the position of contact of the underlying formations is not known and topography does not serve as a clue, are shown merely as "cover" (pls. 2, 3). Where the covered Tesuque-Ancha contact is dashed in the Agua Fria quadrangle (pl. 2), the surface of this contact was contoured and projected to the land surface.

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## STRUCTURE

### REGIONAL SETTING

The geologic structures in the Santa Fe area are the result of deformation during the four main stages: (a) the long and complex Precambrian history; (b) the Laramide orogeny; (c) the igneous intrusions of middle Cenozoic time; and (d) the development of the Rio Grande trough, in late Cenozoic time.

The Santa Fe area is on the east border of the Rio Grande trough. This trough, a linear structural and topographic depression caused by faulting during late Cenozoic time, extends southward from southern Colorado through much of New Mexico. Lindgren (1910, p. 25) recognized the structural nature of the depression, but Bryan (1938, p. 199 et seq.) was the first to begin a systematic study. He and his students mapped large areas in the trough (see Stearns, 1953a, fig. 6) from 1936 to about 1946. More recently, Kelley (1952, 1954) has undertaken detailed study of representative parts of the trough. Kelley and Silver (1952, p. 170–171) suggested that the structural features of the Rio Grande trough originated in a zone of shearing adjustment between the Colorado Plateau and the Great Plains, and that these features are a modification of Basin and Range structure.

Both Bryan and Kelley have shown that the Rio Grande trough is complex in detail, containing basins, embayments, and constrictions of structural origin. Kelley's "La Bajada constriction" limits the Santa Fe embayment of the Espanola basin on the south; the constricting element traverses the southwestern part of the Santa Fe area and consists of pre-Tesuque sedimentary and igneous rocks. Thus, the Santa Fe area is situated both on the eastern border of the trough and on the southern border of an embayment.

The west border of the Sangre de Cristo Mountains is on the west flank of the Canoncito axis (Read and others, 1944), the westernmost of several south-plunging axes of the south end of the eastern prong of the Southern Rocky Mountains. The Canoncito axis is modified appreciably by the vertical faults that form the west base of the mountains (Cabot, 1938). These faults have a northward trend but in detail consist largely of sets of faults en echelon.

The upfaulted mass of the Sangre de Cristo Mountains forms the east border of the Rio Grande trough in the latitude of Santa Fe, and lower to middle Cenozoic sedimentary and igneous rocks form the southwestern part of the map area. The remainder of the area is occupied by upper Cenozoic basin-filling sedimentary rocks and lava flows.

Inasmuch as the Ancha formation forms a blanket over most of the Santa Fe area, structural details in the older rocks are obscure. Along Galisteo Creek, where the Ancha formation has been removed, Stearns (1953a, pl. 1) mapped open folds and high-angle faults that deform the pre-Tesuque rocks (pre-Santa Fe of Stearns). Stearns has also mapped the Los Angeles fault system, which trends southwest from the boundary between the Sangre de Cristo Mountains and Glorieta Mesa. Movement on this major fracture zone was down on the northwest side, and it probably occurred after deposition of the Tesuque formation. The structural pattern northwest of the fault zone is markedly different from that southeast. The structural pattern northwest of the fault zone, which is dominated by faults trending north-northwest, appears to continue north as far as the Santa Fe River.

## SANTA FE AREA

The structure of the Santa Fe area will be discussed under the following topics: Features within the mountains, the mountain border, the southwestern part, the plains, and the area north of the Santa Fe River.

The structure of the rocks beneath the Ancha formation is important both to an understanding of the development of the Rio Grande trough and to an evaluation of ground-water conditions. (See pl. 5.) The entire surface beneath the Ancha formation, as shown, did not necessarily exist prior to deposition of the Ancha, for such features as the ancestral course of the Santa Fe River may have been formed during Ancha time (p. 64). Most of the inferred faults are probably post-Tesuque and pre-Ancha in age. The inferences are based on data collected in geologic, topographic, hydrologic, and geophysical studies. The hydrologic and geophysical studies are discussed in later parts of this report, and only their conclusions will be drawn upon in the present analysis of structure.

The thickness and distribution of the Tesuque formation and the thickness of the Ancha formation are estimated from geophysical and structural data and therefore are discussed in this section.

### MOUNTAINS

Structures in the Precambrian rocks range from small-scale features of foliation and fracture cleavage to larger features, such as joints, faults, dikes, veins, and breccia zones. These structures are in general alined in one of two preferred directions. South of the Santa Fe River the two major strikes of the structural features are N. 35°–45° W. and N. 24°–51° E. North of the Santa Fe River, the major features strike either N. 0°–20° W. or N. 15°–30° E., although some structural features have trends similar to those south of the river.

Brecciated zones are abundant in the red granite. In the Seton Village quadrangle they are approximately parallel to the mountain front, but north of the Santa Fe River the breccia masses trend eastward. Where the Hyde Park Road enters the canyon of Little Tesuque Creek, breccia is exposed in a pinnacle (fig. 7). Higher on the slope to the north, Pennsylvanian sedimentary rocks rest directly on the breccia but are nearly horizontal and unbrecciated. The Pennsylvanian rocks are broken and dropped to the west in two successive steps along normal faults, and the westernmost plate is tilted steeply to the west and faulted down against Precambrian granite.

Normal faults are characteristic of the area, but in some places they change along the strike into reverse faults. Thrust faults may be more common than shown on the maps, but the nature of the Precambrian rocks makes it difficult to recognize the presence of, or displacement of, many probable faults, especially those that are pre-Tesuque in age. A thrust fault in Precambrian rocks is exposed in the canyon of Arroyo Hondo 600 yards west of U.S. Highway 85; it strikes N. 45° W., dips 26° N.E., and is marked by a breccia zone. This fault is taken to be a point along the inferred Hondo fault, described below.

Sedimentary rocks of the Magdalena group rest unconformably on Precambrian rocks and have been deformed by sharp folding and some faulting. Except for a few scattered exposures, the Magdalena group is exposed in the foothills north of the Santa Fe River in isolated north-trending synclines whose limbs dip an average of 20° and a maximum of 54°.

The abrupt southward termination of rocks of the Magdalena group at the Santa Fe River indicates that the block south of the river was elevated along what is here called the Santa Fe River fault. This fault trends east-northeast and serves as the boundary between two sets of minor structures in the Precambrian rocks, as noted above. The Santa Fe River fault also separates two distinct sets of border faults, as will be noted below. If the Santa Fe River fault were projected westward some 19 miles, it would form the north limit of the pre-Tesuque rocks that are exposed along La Bajada escarpment and in the lower canyon of the Santa Fe River. The trend of this projected fault would be approximately parallel to the Los Angeles fault system of Stearns (1953a), 15 miles to the south. It is possible that the Los Angeles fault system and the Santa Fe River fault have structurally isolated the intervening block; along both faults the downthrow is to the north, and both are probably post-Tesuque in age. However, geophysical data do not suggest major vertical displacement (more than a few hundred feet) along the Santa Fe River fault. The gravity study, which is best suited to delineate the larger features, was restricted to the area south of the Santa Fe River, but existence of a major fault nearby, increasing the volume of dense material, might be expected to have some recognizable effect on the gravity observations; such an effect was not observed. Thus the main displacement may have been restricted largely to the mountains.

### MOUNTAIN BORDER

The west limit of exposed Precambrian rocks in the Santa Fe area approximates a line trending north-northwest from the southeast corner of the Santa Fe area to Seton Village; from here north, the limiting exposures form a north-trending line that is offset eastward near Arroyo Hondo and again at the Santa Fe River. Several kinds of evidence indicate that the uplift of mountains took place along faults trending north-northwest, and that this belt of faults has shaped the mountain front north to the Santa Fe River. Reasons for inferring the presence of each fault and for the exact location shown on plate 5 are presented below. The most important evidence is the subparallel alinement of several valleys trending north-northwest in the Precambrian rocks.

#### SETON VILLAGE FAULT

The Seton Village fault, approximately along the west margin of Precambrian exposures, is inferred from several lines of data. Rocks of the Magdalena group, which crop out a short distance south of Seton Village, dip 41° E. Somewhat farther south, seismic station 18 and resistivity station 122 both indicate a depth of about 200 feet to basement rock (Precambrian?), yet these stations are only 500 and 100 feet, respectively, from exposures of Precambrian rock. Topographic contours outline a line of small knobs at the western limit of exposures. Therefore, a fault is inferred along this topographic line, just east of the geophysical stations and the rocks of the Magdalena group. The displacement is downward on the west side. The fault is named for Seton Village, which is a few hundred feet west of the projection of the inferred fault.

#### HONDO FAULT

Northeast of the Seton Village fault, on the east side of the low hills, a long valley trends north-northwest. A major fault in the basement rocks is inferred to have fixed the position of this valley. This fault, named in this report the Hondo fault, appears to be represented at Arroyo Hondo by the thrust fault in the Precambrian described on page 70; exposures downstream from the Precambrian are sufficiently abundant to indicate that no major fault cuts the post-Precambrian, pre-Tesuque rocks along Arroyo Hondo. Geophysical studies indicate a fault between seismic stations 23 and 24. The Hondo fault is projected northward beyond Arroyo Hondo to the west side of sedimentary rocks derived from the volcanic material deposited prior to Tesuque time (Galisteo? formation). The Hondo fault (pl. 5) is southwest of the axis of the valley. The displacement is downward on the west side. On the southwest side of the valley the structures in the Precambrian rocks commonly trend N. 25° E., whereas on the northeast side of the valley the structures trend approximately N. 50° E.

#### PIEDRAS NEGRAS FAULT

The northwest-trending straight valley of Piedras Negras Canyon and the offset of the west margin of exposed Precambrian rocks seem to indicate the presence of a fault, named in this report the Piedras Negras fault. The fault is projected to the northwest to separate two areas of outcrop of pre-Tesuque volcanic sedimentary rocks (Galisteo? formation). The northeast block is downthrown, and thus the Piedras Negras and Hondo faults form the sides of an uplifted block, or horst, which causes the Precambrian rocks to extend northwestward just north of Arroyo Hondo.

#### CHAMISOS FAULT

The straight valley of the headwater reach of Arroyo de los Chamisos appears to indicate the presence of a fault, named in this report the Chamisos fault. The fault can be projected along its north-northwest trend to pass on the east side of Talaya Hill and join the exposed fault between rocks of the Magdalena group on the west and downfaulted Tesuque sediments on the east, just north of the Santa Fe River. The fault can be projected a short distance farther north to separate the tuffaceous sediments northwest of the outcrop of rocks of the Magdalena group from the similar sediments that crop out farther east. The Chamisos fault is offset in the same direction as the Piedras Negras fault, the northeast side being dropped. The Chamisos fault thus explains most of the offset of the mountain front at the Santa Fe River. This fault is the northeasternmost of the set of faults trending north-northwest.

#### CERRO GORDO FAULT

The Cerro Gordo fault separates sedimentary rocks of the Tesuque formation on the west from rocks of the Magdalena group and Precambrian rocks on the east. From the Santa Fe River, at the west side of Cerro Gordo, the fault extends northward 2 miles.

The fault is probably continuous with the one that lies just south of the Santa Fe River and appears to end southward against the Chamisos fault. If the Cerro Gordo fault continues northward more than 2 miles from the Santa Fe River, it must veer west of the sedimentary contact between Tesuque strata and the rocks of the Magdalena group; however, it may die out 2 miles north of the river, to be replaced by the north-trending faults which have been found farther east in the northeast corner of the Santa Fe quadrangle.

### CIENEGA AREA

The pre-Tesuque rocks of the southwestern part of the Santa Fe area represent part of the La Bajada constriction of Kelley (1952). Although no structural information can be obtained in the Santa Fe area southeast of U.S. Highway 85, certain structural features of the Cienega area (fig. 3) northwest of the highway are worth mentioning.

The Galisteo formation forms an arcuate pattern for about 140° around the southeast to southwest sides of a mass of monzonite and evidently was domed by its intrusion. The sandstones of the upper part of the Galisteo formation are interbedded with the lower part of the first volcanic unit. The second and third volcanic units appear to be later than the original intrusion of monzonite, for their structure suggests that they do not "wrap around" the monzonite; also, two outcrops suggest that the second unit rests on an eroded surface of the monzonite. The Cieneguilla limburgite of Stearns (1953b) is certainly later than the intrusion, because its outcrops occur in a fairly straight band trending northwest, it dips to the northeast, and monzonite fragments occur in the limburgite on Cerro Seguro.

The southwest border of the monzonite is a normal fault along which the Galisteo formation has been dropped against the monzonite; uplifting of the monzonite mass along the fault probably was responsible for the northeast dips of the limburgite and the volcanic breccias. A second, less well documented fault trends northwest along the north border of the monzonite, but its displacement probably is less than that of the other fault.

Just southwest of the monzonite a syncline is developed in the first volcanic unit and plunges gently toward the west-northwest. Intrusion of the monzonite arched the overlying rocks, forming the northeast limb of the syncline. The west limb is part of a regional structure, the eastward dipping "Galisteo monocline" of Stearns (1953a, pl. 1). The Galisteo monocline is the west half of the Galisteo structural basin and is dated as pre-Abiquiu(?) by Stearns (1953a, p. 487, fig. 7).

Faulting in the Cienega area is younger than the limburgite flows and is also probably younger than the Abiquiu(?) formation of Stearns (1953a), for near the mouth of the canyon of the Santa Fe River both the Abiquiu(?) and the limburgite are tilted westward (Stearns, 1953a, pl. 1). Whether the faulting is pre-Tesuque or post-Tesuque cannot be established in the Cienega area. Outcrops near the Cerrillos are too poor to indicate whether there is deformation other than that associated with the intrusion.

#### CIENEGA FAULT

The pre-Tesuque rocks of the Cienega area are possibly bounded on the east by a fault that trends north-northwest and is downthrown on the east—an inferred fault that is here named the Cienega fault. Details of this eastern border fault are not available, because the Ancha formation conceals the bedrock geology and geophysical traverses did not extend eastward across the possible fault. Geologic evidence for the Cienega fault consists in large part of the north-northwest alinement of the eastern limit of outcrops of pre-Tesuque rocks; an alinement that is at a considerable angle to the northwest strike of the limburgite. This fault is on the projection of one of the faults mapped by Stearns (1953a, pl. 1) farther south, who shows that the downthrown block is to the west in that locality; a reversal of throw along the strike of the fault therefore must be assumed.

### PLAINS

Inasmuch as the Ancha formation forms a veneer over most of the Santa Fe area, geophysical evidence as to the structure of the sub-Ancha rocks is in large part unsupported by geologic evidence, and even the areas of geophysical control are limited. Two matters are determinable to some degree: the southward extent of the Tesuque formation and the thickness of the Ancha formation.

#### DISTRIBUTION OF THE TESUQUE FORMATION

The Tesuque formation, which is well exposed north of the Santa Fe River, is absent along the south border of the area. A few miles south of the area, along the scarp of Galisteo Creek, the Ancha formation rests directly on tilted beds of pre-Tesuque rocks (Stearns, 1953a, pl. 1). Just south of the Santa Fe River, scattered exposures of the Tesuque formation occur in gullies near the mountains. The southernmost exposures are along Arroyo Hondo, within 1½ miles of the Precambrian outcrops, although a small outcrop just south of the Seton Village quadrangle (NE¼ sec. 34, T. 15 N., R. 9 E.) is tentatively assigned to the Tesuque formation. The available evidence, therefore, indicates that the Tesuque formation thins southward; probably the thinning was caused by northward tilting and pre-Ancha erosion.

The position of the southern limit of the Tesuque, which is important to the understanding of ground-water conditions, is estimated from both seismic and well data. Well 15.9.17.133a [4] encountered hard red siltstone, probably the Galisteo formation, at 130 feet, whereas well 15.8.13.242, 1½ miles to the west-northwest, penetrated coarse sand and gravel from 151 to 190 feet. The Tesuque formation is absent in the first well mentioned but may be represented by the coarse sand and gravel in the other. Well 15.8.2.211 penetrated sand and some gravel down to 210 feet, which is interpreted as the Ancha formation, underlain by sand and silt of the Tesuque formation down to 675 or 715 feet. From 715 to the bottom of the hole at 795 feet, particles of volcanic rocks indicate either pre-Tesuque rocks or rocks of the basal part of the Tesuque formation.

Data from seismic stations 20 to 22 and 13 to 15 indicate a layer having a seismic velocity intermediate between the 2,500 feet per second typical of the Ancha formation and the 9,000–11,000 feet per second typical of the pre-Tesuque rocks. This intermediate layer, whose seismic velocity is about 8,000 feet per second, is interpreted as saturated Tesuque formation; it is absent at seismic station 19. Profile *A–A′* (fig. 54) shows that the intermediate layer thickens northward from the zero point between seismic stations 19 and 20, and this agrees with the south limit of the Tesuque formation as suggested by the well data mentioned above. Seismic station 15 located a fault, and another fault is indicated between stations 12 and 13; these two faults are taken as the limit of an unfaulted block of the Tesuque formation.

The west limit of the Tesuque formation is not determinable with present data, but the formation probably extends westward to the inferred Cienega fault. The formation does not crop out in the dissected area around Cienega, but, inasmuch as the Ancha formation covers the inferred Cienega fault, no outcrops would be expected. Flattening of the gradient between the 6,100- and 6,200-foot water-level contours (pl. 6) suggests either that the Ancha formation is thicker in the western part of the Turquoise Hill quadrangle or that the Tesuque formation is present below it. Geophysical traverses in this part of the Santa Fe area are restricted to the west side of the Cienega fault. At resistivity stations 75 and 83, a layer of similar material at depths of 200 and 300 feet, respectively, is inferred to be the Ancha formation, although the lower

[4] See explanation of well-numbering system, p. 101.

part of the layer could be horizontal beds of the Tesuque formation. The steep water-level gradient south of Seton Village and just west of the mountains suggests that the permeable, unconsolidated sediments are thin and, therefore, that the Tesuque formation is absent there.

### PRE-TESUQUE ROCKS

Neither geologic nor geophysical information is adequate for subdividing the pre-Tesuque rocks where they lie beneath the Ancha formation. A magnetic high, which coincides with a ground-water high, and an inferred structural high occur in the south-central part of the Santa Fe area (fig. 53). Seismic profile *B–B′* (fig. 54) indicates much minor faulting, which is not illustrated on plate 5. Several faults are indicated on plate 5 where they cross geophysical profiles, but most of these are based on evidence from single stations. The fault indicated seismically at station 15, however, has been projected north between resistivity stations 61 and 62 to explain the fact that to the east in profile *E–E′* (fig. 55) the resistivity data form one pattern, whereas to the west the pattern is different. The direction of this inferred post-Tesuque fault is parallel with the inferred basement faults, and the fault can be projected to cross the Santa Fe River at Cieneguita spring.

### NORTH OF SANTA FE RIVER

North of the Santa Fe River the Tesuque formation composes most of the "basin fill" west of the mountains. The sediments are tilted west and are broken by north-trending faults. In the western part of the area north of the river, the Ancha formation clearly rests with angular unconformity on the Tesuque formation. Indeed, the same relation can be noted in the few small exposures of the Tesuque formation extending south of the river to Arroyo Hondo.

In the Agua Fria quadrangle the Tesuque formation has an average strike of N. 20° E. and dips about 10° W. In the eastern part of the quadrangle the direction of dip is less regular and the angle is somewhat steeper. The attitude of beds differs from one outcrop to the next, and even from one bedding plane to another in the same outcrop. This variation is due in large part to the initial cross-bedding, but in part it can be ascribed to later faulting.

The presence and importance of post-Tesuque faulting are difficult to estimate, because there are no key horizons in the Tesuque formation, except in the lower part, and exposures are intermittent. A few north-trending high-angle faults were noted in individual outcrops but could not be traced across country.

The thickness of the Tesuque formation cannot be estimated with confidence because the structure is not known. If it is assumed that there has been no faulting, the 8-mile outcrop width and the average dip of about 10° indicate that the formation may be at least 7,000 feet thick. The thickness would be increased by the stratigraphically higher beds that are buried under the Ancha formation and the lava mesa. However, this assumption of thickness can be questioned, not only because some faulting is known to have occurred, but also because of a peculiar occurrence of quartzite of Pennsylvanian(?) age in the northeast corner of the Agua Fria quadrangle. The presence of the quartzite suggests that basement rocks have been faulted to the surface. The maximum thickness of the Tesuque formation east of the area of upfaulting is believed to be 4,000 feet or less, which should be a maximum for the Santa Fe area as a whole.

The location of the quartzite exposures is shown in figure 21. At each of seven places is a pile of quartzite blocks as much as 15 feet across. The angular to subangular blocks are apparently not in place, and they lie 30–100 feet below the higher ridges. The quartzite is of sedimentary origin and consists of brown to gray well-

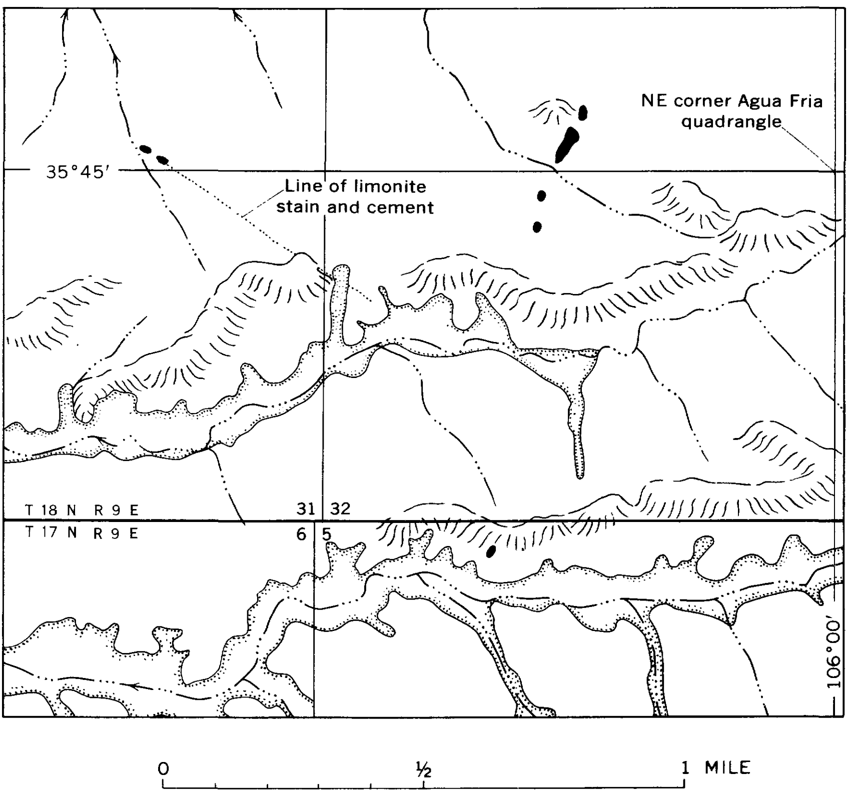


FIGURE 21.—Sketch map of northeast corner of Agua Fria quadrangle, showing location of piles of quartzite blocks of Pennsylvanian(?) age (black areas).

sorted silica-cemented quartz sand with pebbly lenses and scattered pebbles. The pebbles are predominantly siliceous—quartz, quartzite, and chert—but a few pieces of schistose quartzite were seen. Lithologically the quartzite closely resembles Pennsylvanian sedimentary quartzite exposed northeast of Santa Fe; no other known rock in the area bears any resemblance. No other rock types are present in these boulder piles. Probably all the piles in the map area have been found, but no attempt was made to discover any north of the area shown in figure 21.

The Tesuque formation is stained dark brown and in places is a true ferruginous sandstone along a band that trends S. 60° E. from the two northwesternmost piles of boulders. The band may represent a fault. A hundred feet or so east of the southernmost pile of boulders is a fault in the Tesuque which strikes N. 13° E. and dips 65° E.; the northeasternmost piles are about on the projection of this fault.

The blocks were not transported by ice or water to their present positions. The nearest exposures of quartzite are some 5 or 6 miles to the east, and the intervening area is underlain by the Tesuque formation. The blocks are large and all are lithologically alike; therefore, it is most unlikely that they were carried from the mountains by any human or geologic agent. One is forced to accept the conclusion that the quartzite piles represent talus from "basement" rocks; and, hence, that the basement rocks have been raised as much as 3,500 feet along faults (3,500 feet is the projected thickness of the Tesuque formation from the mountains west to the quartzite, on the assumption that there has been no repetition of beds as a result of faulting).

The meager data on precise location of faults in the Santa Fe area permit several different explanations of the quartzite occurrence. A line from the fault at seismic station 15 (pl. 5) can be projected between resistivity stations 61 and 62 (separating two sets of dissimilar resistivity patterns) past Cieneguita spring to the quartzite area. Similarly, the Seton Village fault can be projected north to this area. Also, the quartzite could have been raised along a north-trending fault that is not yet recognized. Although no interpretation is made on plate 5 as to the location of the faults, the scattered boulders of quartzite probably represent an upfaulted block.

The age of this inferred faulting is possibly pre-Tesuque, the block having been a hill—buried under the Tesuque formation—that only now is being exhumed, revealing boulders of an ancient talus. Some faulting took place during or after Tesuque time, but it is difficult to determine such faulting in this area because of poor outcrops and lack of mappable horizons.

## STRUCTURAL SUMMARY

Deformation prior to the Pennsylvanian period, probably during the Precambrian, is recorded by foliation and brecciated zones in the Precambrian rocks. Laramide deformation may be recorded by folds in rocks of the Magdalena group. Igneous intrusion during Oligocene and Miocene(?) time in the southwestern part of the area was responsible for some deformation, particularly for the doming of the Galisteo formation at Cienega. Most of the structural features of the Santa Fe area are, however, associated with the development of the Rio Grande structural trough from middle Miocene(?) perhaps into Pleistocene time, and most of the present topographic expression of structure was probably caused by faulting in late Pliocene and early Pleistocene time.

The accumulation of the thick basin-filling sediments of the Tesuque formation is an indication of uplift of the mountains relative to the trough. This vertical movement probably occurred along faults trending north-northwest and due north along the mountain border, and the displacement on individual faults probably diminishes and dies out northward. Early stages of the uplift perhaps were responsible for the deformation of the pre-Tesuque volcanic sedimentary rocks at Arroyo Hondo, erosion near the mountains removing much of these rocks while the Tesuque sediments were being deposited farther west. Movement along the border faults may have continued moderately throughout Tesuque time, and much more severe final movement plus northward tilting probably ended Tesuque deposition. Erosion prior to the deposition of the Ancha formation produced a plain sloping west-southwestward toward an ancestral Rio Grande, and it removed much of the Tesuque formation from the southern part of the area. In addition, there may have been uplift of the block between the Los Angeles fault system and the Santa Fe River fault, and there was almost certainly uplift of the wedge-shaped block bounded by the Cienega, Santa Fe River, and Rosario faults (Stearns, 1953a, pl. 1), forming the Bajada constriction.

The Ancha formation was deposited on the westward-sloping surface. Pleistocene(?) basalt flows issued from centers on the lava mesa. As the flows built up the land surface, an eastward-sloping plain was formed in the eastern part of the lava mesa.

## ECONOMIC GEOLOGY

The Santa Fe area can be divided into three parts, each having a different set of mineral resources. The southwest corner of the area is a part of the Cerrillos mining district, from which zinc and lead and some silver and copper have been mined sporadically since 1879, and from which turquoise worth several million dollars was mined prior to about 1905. Precambrian rocks along the east border include no known mineral resources, for the pegmatites, though abundant, are barren of commercially desirable minerals. However, rocks of the Magdalena group, in the northeast corner, contain coal, clay, and shale and at least one deposit of manganese. The remainder of the area, underlain by sediments of the Santa Fe group, contains sand and gravel, pumice, and scoria. None of the mineral resources of the Santa Fe area, with the exception of sand and gravel, clay, and perhaps scoria, are being exploited commercially. Talmage and Wootton (1937) refer to several nonmetallic deposits near Santa Fe.

## METALLIC DEPOSITS

A manganese deposit on the Hill property is located 3 miles northeast of Santa Fe, in the SW cor. sec. 9, T. 17 N., R. 10 E. (Wells, 1918, p. 57–58). An abandoned stope cuts about 40 feet into sandstone and shale of the upper clastic member of the Sandia formation of the Magdalena group, along a zone of breccia that contains numerous fragments of limestone. The faulted beds dip about 40° to the east. According to Wells (1918), the ore is largely in soft shale as a replacement along bedding planes. In part, the ore consists of nodules forming irregular pockets containing a few hundred pounds. The exploratory work had won less than a ton of ore, which, however, was of excellent grade and consisted chiefly of pyrolusite and psilomelane. The property was idle when Wells visited it in 1918 and apparently has not been worked since. The stope was in fair condition in 1951 but only traces of limonite, pyrolusite, and psilomelane could be seen. Much quartz and some calcite were observed in the breccia. Any ore that might have been present had been removed.

Veins containing manganese minerals are associated with the breccias of calcic latite in the Cienega area. Prospect pits and outcrops are found 1,000 feet northwest of the dam (fig. 9) and 1,300 feet south of the dam. According to Verne Byrne, who operates the Pennsylvania mine in the Cerrillos, core tests were made at Cienega in 1941, but no other information on the reported tests could be obtained. X-ray analysis of samples of vein material collected just west of the dam indicated the presence of pyrolusite in a matrix of quartz, hematite, and some montmorillonite; the matrix is pink.

According to Disbrow and Stoll (1957, p. 43–51), sporadic mining in the Cerrillos mining district, which extends into the southwest corner of the Santa Fe area, has continued from 1879 to the present, and there is evidence that metal mining was carried on before the Indian revolt in 1680 and again after the return of the Spaniards in 1692. The major period of mining activity was in the early 1800's, but no production figures are available. However, a reported 25,843 tons of ore of zinc, lead, and silver, and some copper and gold, was produced between 1909 and 1952. The metalliferous deposits occur as narrow sulfide veins associated with intrusive monzonite masses of Tertiary age. In the past, small tonnages of oxidized copper and zinc ores have been mined. The chief primary ore minerals include sphalerite, galena (with silver), chalcopyrite (with gold), and pyrite. Gangue minerals include quartz, carbonate minerals, and some barite, opal, and chalcedony. Hydrothermal solutions have altered the wall rock for distances of 1–10 feet from the veins, forming sericite and, at greater distances, chlorite. "The veins have been partly oxidized and leached to depths of 50–150 feet" (Disbrow and Stoll, 1957, p. 49), and the ore has been enriched at depth by deposition of oxidized ore minerals. The only metalliferous mine of the Cerrillos district in the Santa Fe area is the Marshall Bonanza mine.

The Marshall Bonanza mine, the shaft of which is in the SE¼ sec. 20, T. 15 N., R. 8 E., supplied a few cars of ore between 1900 and 1906 and 21 tons of copper ore in 1917. The Bonanza Trust Co., which leased the property in 1947, reconditioned the mine and shipped a modest amount of ore in 1948–49; "the mine has been idle since 1950" (Disbrow and Stoll, 1957, p. 51). The recent shipments averaged 7.4 percent lead, 0.6 percent copper, and minor amounts of silver and gold; a zinc content of 18.2 percent was reported for 1948. The shaft, reported to be 220 feet deep, served drifts at a depth of 160 feet, from which the vein was stoped upward to the bottom of the oxidized zone, 120 feet below the surface. The vein, which strikes N. 30° E., is less than 2 feet wide at the surface and was reported to be 3 feet thick in the drifts. "Much water" was present below the drifts. The vein is composed of altered porphyry and quartz; ore on the dump consists of quartz, ankerite, and rhodochrosite, with specks and bands of sphalerite, galena, and pyrite. Malachite and psilomelane also are present.

## NONMETALLIC DEPOSITS

The turquoise deposits of Turquoise Hill, sec. 21, T. 15 N., R. 8 E., which have not been worked since about 1905, occur in monzonite porphyry, which intruded Jurassic(?) and Cretaceous sedimentary rocks. In the vicinity of the workings the monzonite is extensively altered, largely toward sericite, so that in places the feldspar phenocrysts are scarcely visible. The workings are concentrated on the southwest and southeast knobs and include shafts, adits, open pits, and prospect trenches and pits. A dike exposed in the long trench on the southeast knob contains blebs of turquoise near its center. No other turquoise in place was noted in the writer's brief examination of the workings in 1951. According to Northrop (1942, p. 313–327) the American Turquoise Co. holdings on Turquoise Hill yielded more than $2 million worth of gem material before 1915, and there was a higher proportion of high-grade turquoise than in any other deposit in the United States; the mining activity may have gone on for centuries. The reader is referred to Northrop's summary of the history of turquoise in New Mexico and to the extensive bibliography in his report. See also the description by Disbrow and Stoll (1957, p. 44, 46).

Quartz microcline pegmatites are numerous in the Precambrian rocks but relatively few are zoned. Most of the pegmatite dikes are less than a foot thick and less than 100 feet long at the surface. Muscovite, albite, brown garnet, and black tourmaline, in crystals less than half an inch across, are associated with some of the pegmatites. Quartz veins are abundant and have been the channels for solutions that have tourmalinized local bodies of schist and gneiss. Only the above-listed minerals were observed by Kottlowski in 1951–52 in the many prospects along pegmatites and quartz veins.

Limestone of the Magdalena group has been quarried northeast of Santa Fe for road metal, flagstone, and burnt lime. The New Mexico State Penitentiary operates a small pot kiln to make lime for the local market. In general, dimension stone is not available because of fractures and impurities in the limestone beds. However, some stone walls and buildings in Santa Fe have been constructed from limestone and sandstone.

The State Penitentiary intermittently operates a brick and tile plant for the local market, quarrying clay from deposits in the Sandia formation north of the Cerro Gordo road (secs. 17, 19, and 20, T. 17 N., R. 10 E.). Adobe clays, which are in general clayey loams, are used throughout the area, as in all of New Mexico, for building construction. Suitable deposits occur in the Santa Fe area as slope wash in minor valleys.

Sand and gravel for construction, fill, and highway maintenance occur in sufficient quantities to meet future demands. The sand is not pure, as it contains much feldspar, but the material is adequate for local use. Most of the sand and gravel used for construction in Santa Fe is obtained from the channel fill of the Santa Fe River and Arroyo de los Chamisos; the material is trucked to a central location for screening into the desired sizes. A large volume of material, mostly sand, is available in the larger arroyos although deposits having the desired range in size of coarser portions may be more difficult to locate. In certain areas, particularly beneath the

Airport surface in the northern and western parts of the Turquoise Hill quadrangle, the Ancha formation consists of sand and gravel that is suitable for highway construction and fill. Curves F, G, and H (figs. 16 and 17) illustrate the range in size of three samples, H representing a sample collected from beneath the Airport surface.

Deposits of pumice are distributed in a belt extending southeastward across the Santa Fe area and are correlated with the volcanic activity of the Valles caldera. The deposits vary in thickness, the maximum noted being 20 feet. A sand of quartz and orthoclase is associated with most of the pumice deposits. Test stripping and trenching of several deposits appeared to have been the limit of development as recently as 1951, although a few pits may have supplied a truckload or two. More details on the occurrence are given above under pumice (p. 63). The deposits in the Santa Fe area appear to be too small to be exploited successfully.

Basalt lapilli tuff has been quarried from a cinder pit at the west edge of the area (W½ sec. 17, T. 16 N., R. 8 E.). Here the basalt tuff consists of fresh cinders forming a cinder cone, which was later buried by a basalt flow. In the immediate area there is a large volume of fresh and well-sized material. However, the remaining deposits of basalt tuff in the area are too thin, inaccessible, and impure to merit consideration for commercial development.

Lenses of subbituminous coal occur in the upper clastic member of the Sandia formation (Magdalena group) of Pennsylvanian age in the northeastern part of the Santa Fe area, but the deposits are small, impure, and not of commercial value. Past production has been small and sporadic. Some coal was mined about 500 yards south-southeast of Rancho Elisa (SE¼SW¼ sec. 9, T. 17 N., R. 10 E.). The coal bed, which dips 44° E., is lenticular and as much as 5 feet thick; much bone coal and laminated carbonaceous shale are present. The underground workings are not accessible, but it is estimated that at least several hundred tons of coal and shale have been removed. A limekiln nearby used both coal and limestone from rocks of the Magdalena group. This is probably the area mentioned by Blake (1859) where a small amount of coal was mined. Along Aztec Springs Creek (center sec. 16, T. 17 N., R. 10 E.), a thin bed of coal and black shale fills depressions in the surface of Precambrian rocks. Several stopes and drifts were excavated, but very little coal was mined. Coal mines along the Pecos River, about 12 miles to the east-southeast, are apparently in the same stratigraphic horizon as those near Santa Fe. Gardner (1910, p. 451) gives the following analysis of coal in the Cowles mine: moisture 0.83 percent, volatile matter 22.47 percent, fixed carbon 51.86 percent, ash 24.84 percent, and sulfur 2.78 percent. The coal is classified as a medium-volatile bituminous coal of high sulfur and ash content (Am. Soc. Testing Materials classification).

## GEOLOGIC HISTORY

### PRE-TERTIARY

The oldest rocks in the Santa Fe area are represented by schist and gneiss of the older foliated complex. The mineral composition of the several kinds of rocks suggests that they were once sandstone and mudstone, deposited in shallow seas, and some basic and intermediate igneous rocks. Almost complete alteration of the original rocks resulted from metamorphism, more than one epoch of which may have occurred. Small bodies of gray granite intruded the foliated complex and formed injection gneiss near the contact. Dioritic intrusions formed similar small bodies. The last main event of Precambrian time was intrusion by a batholithic mass of red granite, and accompanying metamorphism and deformation; pegmatites and other dikes and veins were formed at this stage. Stresses produced foliation in the red granite, and the granite was later brecciated. At the end of Precambrian time, the area was part of an extensive landmass.

The history of the Paleozoic and Mesozoic eras in the Southwest is summarized on the isopach maps presented by McKee (1951). Rocks of Cambrian through Silurian ages are absent in northern New Mexico, and possible Devonian and Mississippian rocks are represented only by the thin and discontinuous lower limestone member of the Sandia formation (McKee, 1951, p. 484, footnote). Thus northern New Mexico, much of Colorado, and parts of Arizona and Utah may have been an extensive landmass through much of early and middle Paleozoic time, and certainly were one in Late Mississippian and Early Pennsylvanian time. Rocks of early Paleozoic age are found in southern New Mexico and elsewhere around the borders of the landmass.

During Magdalena time, fluctuations of an invading sea were accompanied by elevation of the Uncompahgre–San Luis highlands. The highlands trended south into the northwestern part of Santa Fe County (Brill, 1952, pl. 3). Shallow-water and shoreline sediments were deposited on the weathered surface of the Precambrian rocks. East of Santa Fe, sediments of the arkosic limestone member of the Madera formation accumulated in appreciable thicknesses. According to McKee (1951, pl. 2), the Pennsylvanian rocks in the Santa Fe area originally ranged from 0 to 2,500 feet in thickness and thickened eastward, although only 400 feet of Pennsylvanian was measured near Bishops Lodge. Permian and Triassic sediments lapped progressively northward onto the land mass of northern New Mexico. Jurassic and Upper Cretaceous sediments were deposited in the Santa Fe area and are exposed just south of the Santa Fe area along Galisteo Creek. Most of the post-Pennsylvanian rocks in the Galisteo area are nonmarine. The Mancos shale of Late Cretaceous age represents the last marine invasion of northern New Mexico.

Thrusts and folds associated with the Laramide orogeny of Late Cretaceous or early Tertiary time were superimposed on structures that dated back to Precambrian and Pennsylvanian orogenies. The folding and some faulting of the Pennsylvanian rocks in the northeast corner of the Santa Fe area probably resulted from the Laramide deformation, although specific field evidence in the map area is inconclusive.

## PRE-SANTA FE TERTIARY

The mountains that were formed in Laramide time outlined basins in which nonmarine sediments and volcanic rocks accumulated. The Galisteo formation of Eocene and Oligocene(?) age was deposited in a basin that presumably included all the Santa Fe area. The formation thins to the northwest (Stearns, 1943, p. 308–309). The Galisteo formation is an alluvial deposit that accumulated in a moderately humid climate in an area of "through-flowing, perennial streams." With the start of Oligocene and Miocene(?) volcanic activity in the Cerrillos, the Cienega area, and the Ortiz Mountains, drainage lines were deranged and deposition of the Galisteo formation gave way to accumulation of volcanic rocks.

The Oligocene and Miocene(?) igneous rocks of the Cerrillos and Cienega area are near-surface complexes. Intrusion of monzonite accompanied and was followed by extrusion of latitic to andesitic flows and flow breccias. In several parts of the Cerrillos it is not possible to determine where an intrusive mass becomes extrusive, and extensive alteration is a further impediment to distinguishing extrusive from intrusive rocks (Disbrow, A. E., oral communication, 1951). On reaching the surface the magma flowed out, carrying blocks of earlier formed volcanic rocks and forming the volcanic breccias. Farther away from the Cerrillos center the breccias have stream-laid characteristics. The extent of the flows must have been considerable, for they can be traced along the north side of Galisteo Creek some 9 miles east of the Cerrillos. Near Arroyo Hondo, sediments containing volcanic pebbles probably were deposited by northward-flowing streams; andesite flows from an unknown center then covered the sediments.

At Cienega, meanwhile, the intrusive monzonite domed the Galisteo formation and an early unit of breccias, and extrusion of two more flow and breccia units followed the intrusion. Limburgite flows and tuffs, which possibly came from a vent on Cerro Seguro, accumulated on an uneven surface eroded on the earlier igneous rocks. Mineralization of the Cerrillos and of Turquoise Hill was probably due to a late stage of the Oligocene and Miocene(?) igneous activity.

The pre-Santa Fe sedimentary and volcanic rocks were warped down to form the Galisteo structural basin, a broad syncline plunging northeast (Stearns, 1953a). The Galisteo "monocline" of Stearns is exhibited in the Cienega area by the northeast dips of the several volcanic units and is actually the western limb of the Galisteo structural basin. The fault along the southwest border of the monzonite at Cienega is possibly a secondary structural feature which developed when the Galisteo structural basin was formed. The warping of the Galisteo structural basin probably accounts for the angular unconformity between the Tesuque formation and the underlying volcanic sediments at Arroyo Hondo.

## SANTA FE TIME

Uplift, which began in the Miocene epoch, initiated the erosion that led to the accumulation of the sediments of the Santa Fe group. Streams began to erode actively, and the first materials transported and deposited were the tuffaceous products of the Oligocene and Miocene(?) igneous activity, giving rise to the Bishops Lodge member of the Tesuque formation and its correlatives. Stearns (1953a, fig. 8) illustrated the Abiquiu basin of deposition, the center of which was apparently near La Bajada, a few miles southwest of the Santa Fe area. The tuffaceous sediments of the Santa Fe area were probably derived from fairly local areas, although much of the Abiquiu(?) formation may have been carried from the Taos Plateau (Stearns, 1953a, fig. 8). Contemporaneous volcanic activity, indicated by a few beds of pure tuff and the basalt flows near Bishops Lodge, may have been merely the last stages of the main activity preceding Santa Fe time; the olivine basalt flows are possibly related to the Cieneguilla limburgite. Once the products of igneous activity had been removed from the rising mountains, large areas of Precambrian rocks were reexposed, most of the overlying sediments having been removed before the end of deposition of the Galisteo formation. Lithologically the rapidly accumulating sediments thus became characterized by first-cycle fragments of quartz and pink feldspar from the Precambrian granites and gneisses. A wide variety of mammals have been found in beds equivalent to the Tesuque formation in the vicinity of Pojoaque and Espanola.

Deformation in the Santa Fe area was probably intermittent from the beginning of Tesuque time [middle(?) Miocene] until the middle or late Pliocene, major faulting marking the beginning and end of the deposition of the Tesuque formation. Deformation was controlled by the Santa Fe River fault and the Los Angeles fault system. These two faults or fault zones, in each of which the downthrow is to the northwest, evidently isolated the intervening block, which then responded independently to the forces that formed the Rio Grande structural trough. This block, which includes the Santa Fe area south of the Santa Fe River, was broken into strips by faults trending north-northwest, and it was along the latter faults that most of the uplift of the present Sangre de Cristo Mountains was accomplished. Displacement on individual faults probably diminishes northward, judging from their en echelon pattern. Geophysical studies indicate that the main basement fault lies 1½ miles west of the present mountain front, but other faults probably have as much displacement. Just as the Precambrian rocks of the Sangre de Cristo Mountains were uplifted along these faults, so the Bajada constriction, which forms the south end of the Santa Fe embayment of the Rio Grande trough (Kelley, 1952), consists of pre-Santa Fe rocks raised along other faults trending north-northwest. The intervening structural trough south of the Santa Fe River, a minor feature of the Rio Grande trough, is superposed approximately on top of the Galisteo structural basin. The Los Angeles fault system cuts across the structural basin (Stearns, 1953a, pl. 1) and so is younger. The fault pattern north of the Santa Fe River fault appears to be different and thus to belong to another isolated block, as yet undefined.

Post-Tesuque displacement is indicated on many of the faults of the Santa Fe area. Tesuque strata are faulted down along the Cerro Gordo and Chamisos faults, and the inferred westward projection of the Santa Fe River fault separates Tesuque rocks on the north from pre-Tesuque strata on the south near La Bajada (Stearns, 1953a, pl. 1). Post-Tesuque deformation resulted in the westward and northward tilting of the Tesuque formation, and possibly the block south of the Santa Fe River was raised along the Santa Fe River fault. The scattered quartzite exposures in the northeast corner of the Agua Fria quadrangle may represent "fossil" talus on top of a block that was faulted up either at the beginning of or during Tesuque time and that is now being exhumed by erosion.

Pre-Ancha erosion formed a graded surface sloping west-southwestward about 100 feet per mile. The contours trend oblique to the present mountain front, possibly as a result of the southward slope of a master stream. The surface was probably continuous southward with the surface beneath the Tuerto gravels of Stearns (1953a) around the Ortiz Mountains, the lower part of the compound "Ortiz surface." The pre-Ancha surface was not completely graded, for knobs and hills of pre-Tesuque rocks stood above this surface in the southwestern part of the area and in the Cerrillos. The Tesuque formation was eroded from most of the southern part of the block between the Santa Fe River and Los Angeles faults, suggesting either uplift of this block or northward tilting. The approximately 200 feet of unconsolidated sediments at seismic station 18, only a few hundred feet west of exposed Precambrian rocks, may indicate that a fault scarp of pre-Ancha time was not planed off before deposition of the Ancha formation.

During erosion of the Santa Fe area, there was presumably aggradation in the basin farther west, and these deposits finally were thick enough to lap eastward into the Santa Fe area as the Ancha formation. Deposition continued, and the piedmont slopes (the Plains and Divide surfaces) probably had little relief. An ancient course of the Santa Fe River passed west-southwestward across what is now the lava mesa toward what is now the Rio Grande. The buried channel of this ancient stream, according to resistivity studies, may have been 200 feet below the present surface, being located beneath the terrace and Airport surface in the eastern part of the area and beneath the present stream channel in the western part. The channel may have formed on the pre-Ancha surface approximately along the Santa Fe River fault. Deposition of the Ancha formation was not continuous, and there may have been several periods of general erosion. One of these erosional periods is indicated by the surface under the basalt tuff, which is the only recognizable time horizon within the Ancha formation. Basalt tuff, mixed with gravel from the east, filled the former channel of the Santa Fe River at the west edge of the area, and the basalt flows which were then extruded onto the west-sloping surface completely diverted the westward drainage. Some creeks were turned northward, where they joined the Rio Grande near Buckman. The Santa Fe River flowed southward, then westward at the saddle between flows from the north and south.

The basalt flows at Cienega formed a static base level for the Santa Fe River during much of the Pleistocene. To the east the river deposited much gravel to fill in its former channel. The supply of water, presumably greater than the present supply, may have come from melting of mountain glaciers (Ellis, 1935). Most of the deposition took place in the western part of the area, and thus the gradient was less than before the basalt was erupted. Deposition around Cienega continued until the stream was raised to the level of the basalt and began to flow west, its course being east of Cerro Seguro. The buttes of gravel between Cienega and the highway are interpreted as remnants of the Airport surface, the depositional surface of the aggrading stream. The present course of the Santa Fe River, west of Cerro Seguro, is almost certainly a secondary or diverted course, formed by capture or by building up the Airport surface to a level higher than the outlet across the flow rocks and monzonite west of Cerro Seguro.

A similar diversion resulting from aggradation or capture is postulated for the upper courses of Arroyo Hondo and Arroyo de los Chamisos. The present courses of the Santa Fe River and Arroyo de los Chamisos appear to be along the lateral limits of the coarser gravel fill under the Airport surface, the coarse gravel being slightly more resistant than the flanking sandy gravels.

After the basalt flows had diverted the drainage, but before present dissection began, explosions during the Pleistocene from the Valles caldera cast pumice over part of the Santa Fe area. Subsequent modification of the Plains surface by intermittent streams has resulted in deposition of as much as 40 or 50 feet of materials, included with the Ancha formation, above the pumice.

### POST-SANTA FE TIME

Downfaulting of the Santo Domingo valley (Kelley, 1952) along the Rosario fault (Stearns, 1953a, pl. 1) evidently accelerated erosion by both the Santa Fe River and the Rio Grande, the latter carving the gorge of White Rock Canyon to a depth of 1,000 feet, while the former cut headward to form the 400-foot-deep canyon below Cieneguilla. Once the rocks forming the local base level had been breached at Cienega, the present erosion of the Santa Fe area began. The terraces along the Santa Fe River may be associated with the intermittent character of erosion related to cycles of Pleistocene glaciation in the higher parts of the Sangre de Cristo Mountains.

# PART 3—WATER RESOURCES

By Zane Spiegel

## INTRODUCTION

### HISTORY OF WATER USE IN THE VICINITY OF SANTA FE

#### EARLY USE OF WATER

For centuries the Santa Fe area has been a desirable place in which to live, because of its climate and its readily available supply of water for crops and domestic use. Rodriguez, one of the earliest Spanish explorers, reported four Indian pueblos along the Santa Fe River in his account of an expedition to northern New Mexico in 1581–82 (Hammond and Rey, 1927). These pueblos may have been near La Bajada, at Cieneguilla, at Agua Fria, and at the present site of Santa Fe (S. A. Stubbs, Laboratory of Anthropology, Santa Fe, oral communication). As all these pueblos were on stretches of the Santa Fe River where ground water emerged as springs, it appears that the Indians considered such small perennial flows to be better suited to their needs than the sometimes larger but more variable flows of surface water in the Santa Fe River. In spite of the many developments and uses of the water of the Santa Fe River since the Spanish conquest, the springs downstream from Santa Fe at Cieneguilla, Cienega, and La Bajada still supply sufficient water for the irrigation of small farms at those places. Springs at Agua Fria and Cieneguita have practically dried up. (See p. 173.)

There is no definite archeological evidence that the Indians of these pueblos practiced irrigation. It is believed that their scanty crops of corn, beans, and squash were grown in moist areas adjacent to the springs, or in bottomland areas subject to occasional inundation from the river (S. A. Stubbs, oral communication). This inference is supported by the observation that all the known pueblos in the vicinity of Santa Fe are situated near natural cienegas (marshy areas) or springs, usually far from the mountains near which streamflow is most dependable.

Another indication that artificial irrigation was not practiced by the Indians in this part of the Rio Grande drainage area is furnished by Villagra, who accompanied the Onate expedition in 1598. Writing of the arrival of the expedition at the Pueblo of San Juan, on the east bank of the perennial Rio Grande above the mouth of Rio Chama, Villagra stated in his journal (Villagra, 1610) that the

Indians feared the loss of their crops because of the lack of rain. One of the first projects of the Spanish after they were established in San Juan was the construction of irrigation ditches.

Ruins of other, earlier pueblos and smaller communities dating back to 1250 or before have been found along the Santa Fe River (S. A. Stubbs, oral communication). It is known that many of these sites were not occupied continuously, and it may be that prolonged droughts, resulting in the diminution of ground-water storage and the consequent reduction or cessation of flow of some springs and of the Santa Fe River, with consequent failure of crops and water supply, caused evacuation to more favorable locations.

Twitchell (1925, p. 17–20) concluded that the area that is now Santa Fe was not visited by the very early Spanish explorers, and that Don Gaspar Castano de Sosa may have been the first, in 1590. He concludes also that the first Spanish settlement at Santa Fe, near the present plaza, was made about 1609 when Onate, the first Governor, moved the capital of Nuevo Mejico from its first location at San Juan (established 1598) to San Gabriel (established 1601), and then to Santa Fe. Some of the pueblos along the Santa Fe River were reported to be inhabited at this time.

Probably one of the factors in the choice of this location for the new capital, although not specifically mentioned in history, was the presence of the former cienega, a marshy area watered by perennial springs, just east of the present plaza. Apparently the springs were more desirable to the Spanish also than was the larger but more variable surface flow in the Santa Fe River, which was used later when ditches were constructed and the irrigation of lands expanded upstream and downstream.

In 1610 the new settlement, named La Villa Real de la Santa Fe de San Francisco de Assisi, became the capital of the province of Nuevo Mejico. It was a small community; in 1617 (Twitchell, 1925, p. 62) the total Spanish population was reported at 48 soldiers and colonists. It is quite probable that these colonists built the first irrigation ditches in the area.

Santa Fe continued to grow under the Spanish government, except in the period 1680–92, when the Indians revolted and the Spanish were driven back to Mexico. Apparently, the Spanish had not yet begun to use wells by 1680, for the siege by the Indians included cutting off the ditch supplying water from the springs and river, which added to the hardships of the colonists.

Some excerpts from the writings of R. E. Twitchell (1925, p. 51–52) are given on the following pages to illustrate the natural ground-water conditions in the Santa Fe plaza area. References are made in the excerpts to the cienega east of the plaza, to several springs that had their source in or near the cienega, and to the Rio Chiquito, which represented the combined outflow of the cienega and springs.

* * * The main plaza of the villa then had, for its eastern limits, a line drawn north and south almost in keeping with the present enclosure of the Church property, except in this that the road turned in front of the old Church instead of turning to the southeast, as it does at the present time, proceeded southward, across the Rio Chiquito (a stream which had for its source the big spring in the present garden of the Archbishop, and continued westerly, almost parallel with the Rio Santa Fe, to a confluence with the latter about a half a mile farther west). * * * All that part of the villa lying immediately above and below and on both sides of the present Court House of Santa Fe County, and on the site and to the east of the Sisters' Hospital building, was a meadow or cienaga, the cultivated lands lying east of the slope of the cienaga, along the foot of its slope from a point near the rear of the property now belonging to Solomon Spitz, on Palace Avenue, and extending in a southeasterly direction toward the Rio Santa Fe, several springs were located which supplied the water by which the marshy hay-growing locality was created, and which also supplied water to the Church and convent which stood at the eastern end of the plaza mayor. * * * At the foot of this slope, and beginning at a point in the Rio Santa Fe, above the source (spring) of the Rio Chiquito and below the mouth of the Arroyo de los Saises, was a small irrigation ditch or acequia, which supplied water to the convent garden, to the settlers whose lands were immediately adjoining, and extended through the lands now the property of the Sisters of Charity and down the present Palace Avenue, and prior to the revolution in 1680, and also until very recent times, supplied the dwellers in the palacio real and its capacious inner plaza and garden in the rear with water for domestic and irrigation purposes. It was this source of water supply which was cut off by the Indians during the last days of the siege of Santa Fe. Before the revolt the acequia passed along the south facade of the palacio real.

About 1850, according to Twitchell (1925, p. 329), the Rio Chiquito, a small stream,

* * * used to flow down the present Water Street and united with the Rio Santa Fe at a point near Guadalupe Church. It had its rise in a large spring in what is today known as the Bishop's Garden * * *

One of the first water disputes recorded in New Mexico history is described by Twitchell (1925, p. 52). In this dispute, in 1715, the right of a soldier, Diego Arias, to pond water of the cienega was disputed by landowners upstream from the pond. The decision was that the pond had no harmful effect on spring flow above the pond, and the pond was declared legal.

An excerpt from a letter quoted by Twitchell (1925, p. 59), dated July 17, 1716, describes one of the first wells in the city of Santa Fe.

* * * He[5] also had a well dug in the patio 4 varas[6] wide and 40 varas in depth, with a curb of earth and stone, which is partly destroyed. At present it has no water but it has a wooden bucket * * *

[5] The governor at the Palace of the Governors.

[6] One vara is equivalent to 32–43 inches, usually 33.

Little is known of the agricultural development under the Spanish, or even later under the Mexican government, except that it was reported as early as 1716 that the runoff of the Santa Fe River in dry years was insufficient to irrigate all the cultivated acreage. A map of Santa Fe prepared in 1768 (Urrutia, 1768) shows two main irrigation ditches, one on each side of the river.

Other Spanish settlements were established in the vicinity of Santa Fe wherever sufficient water for irrigation existed. A list of these taken from Candelario (1929, p. 282–284) is given in the following table:

TABLE 3.—*Dates of establishment of settlements near Santa Fe, N. Mex.*

| Year | Settlement | Location |
|---|---|---|
| 1715 | Cienega | On Cienega Creek. |
| 1730 | Alamo | Probably on Alamo Creek. |
| 1698 | Cieneguilla | Along the Santa Fe River. |
| 1698 | Los Palacios | Along the Santa Fe River. |
| 1740 | Pino | Along the Santa Fe River. |
| 1730 | Pueblo Quemado | Along the Santa Fe River. |
| 1740 | Tesuque | On the Rio Tesuque. |

Use of water for irrigation at Cienega and Tesuque probably expanded slowly as the number of colonists increased. However, no large reservoirs were constructed. The extent of development of water for irrigation in these two places probably has been nearly static for many years. Most of the other areas are still inhabited, and still for the same reason—a dependable domestic or irrigation water supply, much of which emerges as springs. The population of three areas—Tesuque, Santa Fe, and the adjacent community of Agua Fria—have increased to such an extent that artificial ground-water development by wells and infiltration galleries has been necessary, especially in dry years, to supplement the natural domestic supplies from streams and springs. Wells have been necessary in all areas to provide sufficient potable water for domestic use.

Santa Fe had reached a population reported as 6,000 when New Mexico came under Mexican rule in 1821 (Twitchell, 1925, p. 150). An attempted conquest of Santa Fe by an expedition from Texas was successfully resisted in 1841, but Kearny's expedition in 1846 was not resisted, and New Mexico became a territory of the United States. New Mexico was admitted to Statehood in 1912.

The extent of irrigation in the Santa Fe area before 1893 is not known. Estimates of acreages irrigated in the area in 1893 are given by Hinton,[7] and in several later years by Yeo;[8] an accurate measurement was made in 1913–14 by the State Engineer.[9] It appears probable that many variations have occurred, influenced by political, cultural, and economic factors as well as climatic variations. The irrigated areas other than those along the Santa Fe River itself have probably had no overall change over scores of years, except that an infiltration gallery and two storage reservoirs, having a total capacity of 18-acre-feet, were built on the Rio Tesuque in 1925 for irrigation near Tesuque Pueblo, just north of the Santa Fe area. A small reservoir for irrigation water was built on Arroyo Hondo, but it was completely filled with sediment within a few years. A second reservoir was planned, but the dam failed during construction and the project was abandoned.

Use of the Santa Fe River for irrigation has changed greatly, especially in the past 20 years. Residential areas have been extended into the heart of the former irrigated tracts; many farmers have changed to other occupations; and the flow of the Santa Fe River has been diverted in increasing amounts for public supply. Irrigation to some extent has merely been shifted from one tract to another since the early days, for, although the irrigation of areas watered by the old ditches has largely ceased, feed crops southwest of the city limits are now watered by treated sewage effluent. On the infrequent occasions when excess surface flow of the Santa Fe River is available, some of the old ditches are cleaned and used to supply water for lawns and gardens. Most of the old ditches still exist, but in general they are in poor condition.

### STORAGE AND USE OF SURFACE WATER

The rapid growth of the population of Santa Fe from 1870 to 1880, in anticipation of operation of the railroad, made it evident that the community would have to provide a better water supply than that afforded by scattered private wells, the uncontrolled Santa Fe River, and the irrigation ditches passing through the town. Such a supply was obtained in 1881 by the construction of Stone dam on the Santa Fe River at the mouth of the canyon, about 2½ miles east of the plaza. This dam created a reservoir, of 25-acre-foot capacity, which was connected to a new distribution system by

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7 Hinton, R. V., 1893, Irrigation in areas near Santa Fe and irrigation in Mesilla and Rincon valleys: *extracted* in Yeo, H. W., 1928, Report on irrigation in the Rio Grande Basin in Texas above Ft. Quitman and in New Mexico during 1907, 1920, and 1928: New Mexico State Engineer Office [unpub. ms.], v. 1, p. 51–58 and v. 3, p. 165–170.

8 Yeo, H. W., 1928, Report on irrigation in the Rio Grande Basin in Texas above Ft. Quitman and in New Mexico during 1907, 1920, and 1928: New Mexico State Engineer Office [unpubs. ms.], v. 1, p. 51–58 and v. 3, p. 165–170.

9 Miller, L. S., and Carroll, S. S., 1919, Report on Santa Fe Hydrographic Survey: New Mexico State Engineer Office [unpubs. ms.], 110 p., 40 pls.

a 10-inch pipeline. In the following years the capacity of the reservoir was diminished beyond usefulness by accumulated deposits of sediment. In 1894 a higher dam, known as Twomile dam, was built farther downstream. Its spillway crest was at the same altitude as that of Stone dam, and the reservoir thus created had a capacity of 406 acre-feet. A channel was provided alongside the reservoir to bypass unwanted, sediment-laden flows.

In 1895 a hydroelectric powerplant, utilizing water from the reservoir behind Twomile dam, and two earthen storage basins were constructed about 1¼ miles below the dam. The original capacity of these basins, which received tail water from the powerplant, is not known, but the larger one, subsequently lined with brick and concrete and still in use, has a capacity of 16.4 acre-feet. The powerplant was operated nightly to furnish electric power to the town. A small storage basin having a capacity of 2 acre-feet was built on Atalaya Hill to furnish water at adequate pressure to residences built on the higher land south of the river.

A power ditch, 8,800 feet long, was completed up the canyon in 1902 to a point about 1½ miles above Twomile dam for the purpose of diverting water at the higher elevation and delivering it by pipeline to the hydroelectric plant, thus providing at the plant a static head of 271 feet.

Detailed studies of the use of water were made during the Santa Fe Hydrographic Survey (op. cit.). It was reported that 1,267 acres of irrigated land was furnished 5,701 acre-feet of water in the 1914 irrigation season, a diversion of 4.5 acre-feet per acre. It was reported also that the annual domestic use from the public system was 1,742 acre-feet, or 223 gallons per capita per day.

Shortly after the service basin was lined in 1923, the water and light company began a series of tests to determine the rate of water consumption. At the outset the service basin was carefully calibrated and in each test thereafter all water used was withdrawn from the basin. In a 15-month period from June 1923 to August 1924, 126 tests were made, and it was later found that the total consumption in 1924 was 1,815 acre-feet or 591 million gallons (209 gallons per day per capita), of which 1,120 acre-feet was for domestic use and 695 acre-feet was for irrigation of lawns and gardens. This extremely large consumption was undoubtedly due to the fact that the water was not metered; water was first metered to the consumers in 1931.

Unusually low streamflow in 1922, 1923, and 1925, combined with a normal increase in demand, caused shortages of supply that demonstrated the need for increased storage facilities for the system. This need was met in 1926 by the construction of Granite Point dam, about 4 miles east of Twomile dam, with a reservoir capacity of 561 acre-feet.

After 1930 the population increased rapidly. To meet the fast-growing demand for water it again became necessary to provide additional storage for the water system. This was accomplished in 1935 by increasing the height of Granite Point dam and spillway, which increased the capacity of the reservoir to 650 acre-feet. In 1943 Nichols dam was constructed about four-fifths mile upstream from Twomile dam. This created a reservoir of 796-acre-foot capacity, with 4 feet of flashboards in the spillway.

After the outbreak of World War II, the U.S. Army began the construction of Bruns General Hospital, a large establishment of many buildings including a powerplant and a laundry. In order to assure a supply for the hospital, as well as for the city, work was begun on the long-planned additional enlargement of Granite Point dam, which would increase the capacity of the reservoir to a total of 2,908 acre-feet, with 4 feet of flashboards in the spillway. At the dedication of the dam in 1947 the name was changed to McClure dam in honor of the late Thomas M. McClure, State Engineer of New Mexico from 1933 to 1946.

The changes in population, water use, and reservoir capacity at Santa Fe since 1880 are summarized in figure 22. The total storage capacity provided by the various reservoirs and basins in 1947 is shown in table 4.

TABLE 4.—*Surface-reservoir capacity on the Santa Fe River, N. Mex.*

| | *Acre-feet* |
|---|---|
| Twomile reservoir | 406 |
| Settling basin | 16 |
| Atalaya reservoir | 2 |
| Nichols reservoir | 796 |
| McClure reservoir | 2, 908 |
| Total | 4, 128 |

## USE OF GROUND WATER

Ground water has been used in the Santa Fe area for agriculture or domestic use as long as man has been known to inhabit the area. At first the natural springs were used, but later small diversion and storage works were built. Beginning about 1716, wells were dug and drilled for domestic and stock supplies. Infiltration galleries for irrigation water from the Rio Tesuque and the Santa Fe River came into use after 1925, but the one in the Santa Fe River (G–17.9.23.300) was abandoned in 1945 because of diminished flow and was replaced by a drilled well (17.9.23.312) in 1946. (See p. 101 for explanation of numbers of springs, wells, and infiltration

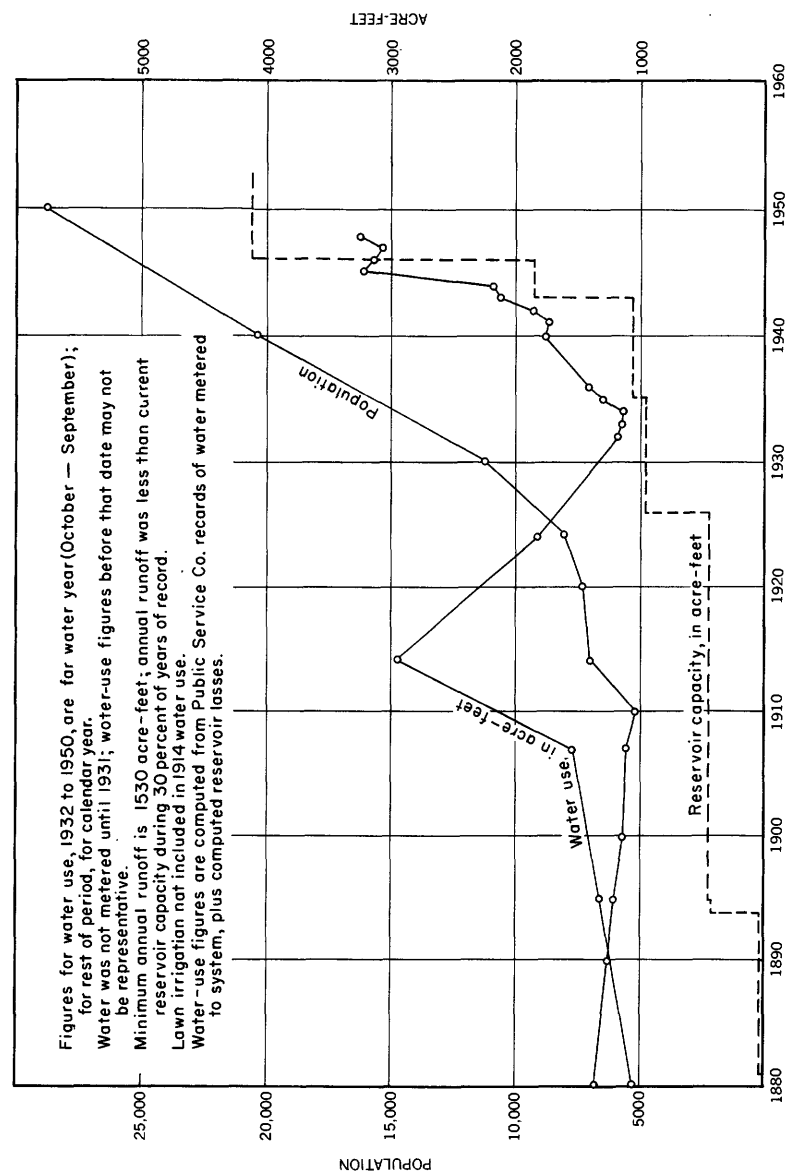


FIGURE 22.—Water use, reservoir capacity, and population, Santa Fe, N. Mex.

galleries.) Well 17.9.28.423 was drilled in 1947 and has since been used for washing gravel. Well 17.9.27.211 was drilled in 1948 and has since been used for irrigation. Three wells were drilled for public supply in Santa Fe in 1946 as a consequence of a severe water shortage. Two of the wells, along with four others drilled later, were used to augment the surface supply from October 1950 until the spring of 1952, when an adequate surface supply was again assured by a heavy winter snowpack. The drought also encouraged drilling of a large number of private and institutional wells for lawn and garden irrigation. The Indian School tested an old unused well (17.9.27.411), found it adequate, and began using it for irrigation in 1951. The School for the Deaf also had a well drilled for irrigation (17.9.26.232) in 1951, but the school had a second well drilled to replace it in 1952 (17.9.26.142).

By the end of 1952 there were 10 large-capacity wells in use or usable in secs. 22, 23, 26, 27, and 28, T. 17 N., R. 9 E. Four of these wells are used for irrigation 6–8 months of the year, and another is used throughout the year. At present the public-supply wells are used only in drought periods, but eventually some pumping from these wells may be required each year.

### WATER-RESOURCES INVESTIGATIONS

The first known study of water resources in the Santa Fe area listed the acreage irrigated near Santa Fe; later estimates were given by Yeo. (See footnote, p. 95.)

A detailed hydrographic survey of the Santa Fe River was made in 1913–14 by the State Engineer of New Mexico (see footnote, p. 95) at the request of 305 petitioners to determine rights to the surface flow of the Santa Fe River. The acreage irrigated and the water used during 1914 were determined, and a large-scale map of the irrigated area and ditches was made with a land-surface contour interval of 2 feet.

The U.S. Geological Survey began measuring the flow of the Santa Fe River in May 1910 and has measured the flow intermittently since that time. The flow of Rio Tesuque, Acequia Medio, and Mitchell ditch has been measured by the Survey since March–June 1936.

A study of the flood-discharge potential of the Santa Fe River was made by the National Park Service.[10] This study included a survey of the boundary of the drainage basin, measurement of the areas of 10 water-producing areas above Alto Street in Santa Fe, and a profile of the stream.

[10] Veale, J. H., 1938, Report on a hydrologic survey to determine the maximum flood expectancy of Santa Fe River, Santa Fe, New Mexico: National Park Service [memo. rept.], Region 3.

A study of irrigation by the United Pueblos made by the U.S. Indian Service[11] includes some data on and interpretations of streamflow and precipitation near Santa Fe.

Preliminary statistical computations of the water yield of the upper Santa Fe River have been made by G. L. Hardaway (oral communication) of the Regional Forest Service Office in Albuquerque, and additional studies of water yield in similar areas of the upper Rio Grande were begun in January 1952 by the Southwestern Forest and Range Experiment Station, Upper Rio Grande Section, Albuquerque, N. Mex. (E. J. Dortignac, oral communication).

In July 1946 the office of the U.S. Geological Survey in Albuquerque was notified of a water shortage in Santa Fe. The base flow of the Santa Fe River was insufficient for summer requirements, and storage was very low, although reservoir-storage capacity had been increased from 1,832 acre-feet in 1943 to 4,128 acre-feet by that time. C. R. Murray of the Survey made a brief reconnaissance of ground water in the Santa Fe area in July 1946 in cooperation with the State Engineer of New Mexico. At that time three test wells were being drilled for supplemental supply. One of these, on Sierra Vista Street, was considered unsatisfactory and was abandoned at 155 feet. A second well on Hickox Street (17.9.26.222, table 17) was completed and tested by the driller in August 1946 but yielded only 75 gpm. The third, on Alto Street (17.9.23.332), was more satisfactory, yielding 550 gpm. Pumping tests of this well were were made in November 1946 and February 1947. However, heavy rains in August 1946 brought reservoir storage to a safe level and alleviated the water shortage for the time being. Lack of funds and the end of the shortage ended the investigation. The record drought in 1950 and 1951, along with the continued increase in water use, again made necessary a brief ground-water investigation by the U.S. Geological Survey in November 1950 and March 1951, but lack of funds and personnel prevented an adequate investigation until July 1951. Four additional wells were drilled by the Public Service Co. of New Mexico for municipal supply during this period, and many wells of smaller capacity were drilled by individuals in and near Santa Fe to augment existing supplies.

Largely as a result of the severe drought, the present cooperative investigation of the geology and water resources of the Santa Fe area was begun in July 1951 by the U.S. Geological Survey and the New Mexico Bureau of Mines and Mineral Resources in cooperation with the State Engineer of New Mexico.

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[11] Hodges, P. V., 1938, Report on irrigation and water supply of the Pueblos of New Mexico in the Rio Grande basin: U.S. Bureau of Indian Affairs, United Pueblos Agency, New Mexico [unpub. ms.].

Methods of investigation involved an inventory of wells and springs, surface storage, and runoff of the area. Water levels in wells were measured with a steel tape wherever possible, but the owner's or driller's reported depth to water was used where measurements were not feasible and where such reports were considered reliable. The altitude of the measuring point was determined from the topographic map or by instrument. The altitude of the water level at each well or spring was then computed and plotted on the map, and contours were drawn at suitable intervals. The water-table contours are shown on plate 6, which is a map showing the general availability of water in the Santa Fe area. Pumping tests and accurate water-level measurements gave some preliminary quantitative data on the transmissibility and storage coefficients of the more important aquifers. Analysis of stream flow and quality of water made by the Geological Survey provided additional quantitative information.

## WELL-NUMBERING SYSTEM

In New Mexico the system of numbering water wells, as used in most areas by the U.S. Geological Survey, is based on the common subdivisions in sectionized land. The well number, in addition to designating the well, locates its position to the nearest 10-acre tract in the land net. The number is divided into four segments by periods (fig. 23). The first segment denotes the township north or

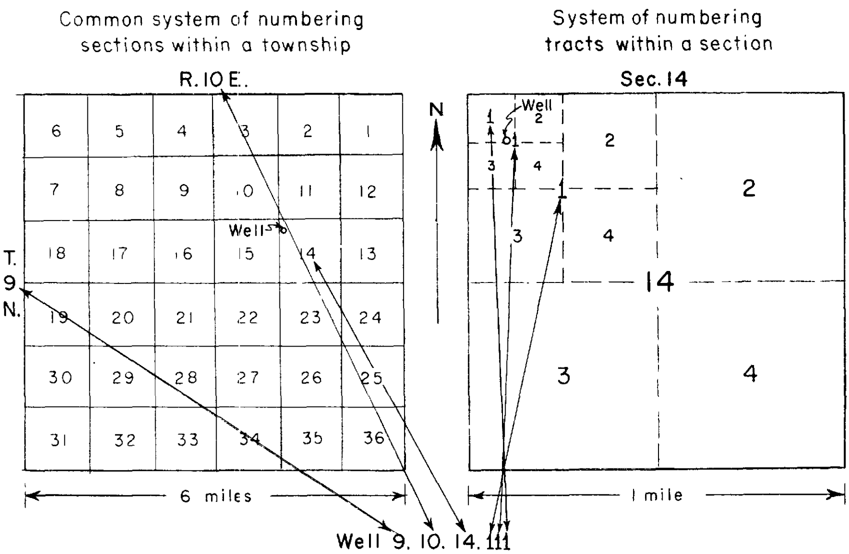


**FIGURE 23.—Methods of numbering sections within a township and tracts within a section.**

south of the New Mexico base line; the second denotes the range east or west of the New Mexico principal meridian, the third denotes the section, and the fourth denotes the location within the section. In unsurveyed areas, the positions of sections were determined by projecting the section lines from adjacent sectionized land into the unsectionized areas. These projected lines are shown dotted or are omitted on maps in this report.

The fourth segment of the number, which consists of three digits, denotes the particular 10-acre tract in which the well is situated. For this purpose, the section is divided into four quarters, numbered 1, 2, 3, 4, in the normal reading order, for the northwest, northeast, southwest, and southeast quarters, respectively. The first digit of the fourth segment gives the quarter section, which is a tract of 160 acres. Similarly, the quarter section is divided into four 40-acre tracts numbered in the same manner, and the second digit denotes the 40-acre tract. Finally, the 40-acre tract is divided into four 10-acre tracts, and the third digit denotes the 10-acre tract. Thus, well 9.10.14.111 in Santa Fe County is in the NW¼NW¼NW¼ sec. 14, T. 9 N., R. 10 E. If a well cannot be located accurately to a 10-acre tract, a zero is used as the third digit, and if it cannot be located accurately to a 40-acre tract, zeros are used for both the second and third digits. If the well cannot be located more closely than the section, the fourth segment of the well number is omitted. When it becomes possible to locate more accurately a well in whose number zeros have been used, the proper digit or digits are substituted for the zeros. Letters a, b, c, . . . are added to the last segment to designate the second, third, fourth, and succeeding wells in the same 10-acre tract.

In the text of this report, but not in the tables, a G or S precedes the location number of an infiltration gallery or spring, respectively. The well-numbering system is used also to locate some of the stream-gaging stations.

## GROUND-WATER PRINCIPLES

### BASIC CONCEPTS

All the water in the vicinity of Santa Fe and east of the Rio Grande originates from precipitation upon the land surface west of the divide between the Rio Grande and the Pecos River. An estimated 75–95 percent of the precipitation, varying inversely with the altitude, is returned to the atmosphere by evapotranspiration in the area, and the remaining 5–25 percent becomes the surface-water and ground-water supply available for use within the Santa Fe area (see the section "Hydrologic cycle"). Part of the surface water runs off directly, but the remainder has a complex history. Infiltration into soil and channel alluvium, penetration under the influence of gravity beyond the reach of plant roots, and subsurface movement through pore spaces in the saturated zone in the earth are phases of this history with which this section of the report is concerned. Surface runoff cannot be completely separated from subsurface water; and it will be shown in later sections that in the Santa Fe area, as elsewhere, surface water, ground water, precipitation, evapotranspiration, and intermediate phases are intimately related.

The accumulation of water in the ground, its movement, its appearance at the surface as springs, and its availability for withdrawal by wells are not governed by chance or by supernatural means, but by well-known physical principles, and by the distribution, character, and origin of the rocks near the earth's surface.

In order for water to occur in the ground, there must be open spaces in rocks or soil for it to occupy. If water is to move through the ground, as it must in order for it to enter wells or appear as springs, not only must there be spaces in the rocks for it to occupy, but these spaces must interconnect. They must also be large enough to permit adequate movement of the ground water. The relative size, volume, and degree of connection of these interstices determine the potential rates of movement of the water they contain.

These spaces are of two general types. The more important type in the Santa Fe area, as in most areas, consists of the spaces or pores between the particles of a sedimentary rock. These pores exist because the particles are not fitted together perfectly by the geologic processes which deposit sediments. The number and size of pores are related to the range and proportion of sizes (sorting) of the particles. The total pore volume is potentially largest when all the particles are of the same size, as in a uniform sand bed, although relative pore volume (porosity) varies to some extent with the arrangement of the particles and is dependent also on depositional processes. The porosity and permeability may be more uniform parallel to bedding planes in water-laid sediments than across them, and for that reason water may tend to move preferentially parallel to the bedding planes.

The second type of opening is spaces in consolidated rocks caused, or at least initiated, by structural forces acting on the earth's crust, or, in igneous rocks, by cooling and contraction. Both types, with some of the many possible variations, are illustrated in figure 24.

Joints, other fractures, and openings along bedding planes that are not enlarged by solution commonly yield only small quantities of water to individual wells or springs, as the size and total volume of such spaces generally is small, and the movement of water through

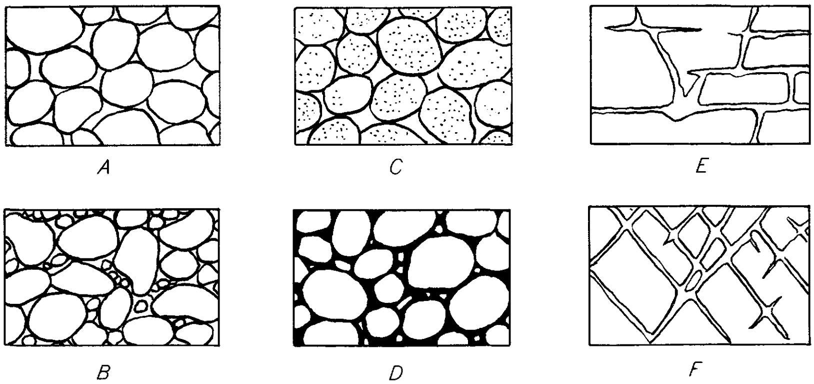


FIGURE 24.—Types of pore spaces. *A*, well-sorted sedimentary deposit having high porosity; *B*, poorly sorted sedimentary deposit having low porosity; *C*, well-sorted sedimentary deposit consisting of pebbles that are themselves porous, so that the deposit as a whole has a very high porosity; *D*, well-sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter in the interstices; *E*, rock rendered porous by solution; *F*, rock rendered porous by fracturing.

them is slow. However, the aggregate spring flow from many such openings may be appreciable, and such discharge adds to the surface flow of the mountain streams near Santa Fe.

The primary or original interstices may be modified by geologic processes that act after the rocks are deposited. These modifications are classed as follows:

1. Reduction of porosity:
   a. Deposition of fine-grained and colloidal particles, or precipitation of mineral cementing agents (such as calcium carbonate, silica, and iron oxide) carried by water passing through interstices.
   b. Compression or compaction of sediments and rocks, which closes fracture openings and decreases intergranular porosity.
   c. Chemical weathering or decomposition of a permeable rock or sediment in place, resulting in swelling of mineral grains owing to hydration, and thus to a decrease in porosity.
2. Increase of porosity:
   a. Solutional enlargement of openings, especially in limestone, gypsum, and calcite-cemented rocks.
   b. Chemical weathering or decomposition of impermeable rocks, involving removal of some components by solution.

Whether an increase or decrease in porosity will occur is determined by the type of materials present, the chemical character of the circulating water, and the climatic history of the area; these factors affect the direction and rate of the chemical and physical reactions continually taking place in the ground. Probably the most important modification in the Santa Fe area has been the deposition of calcium carbonate cement between sand grains, which has decreased the porosity and converted unconsolidated sediments to consolidated rocks. The reverse process, solution of limestone, generally beginning along joint or bedding planes, has caused the small bodies of limestone of Pennsylvanian age near Santa Fe to become more permeable. In some areas, such as the Roswell artesian basin of southeastern New Mexico, cavernous limestones are the most permeable aquifers. Except for solution channels in limestone and gypsum, and flow tunnels in lava rocks, underground "streams" and "lakes" do not exist.

### DEFINITIONS AND ABBREVIATIONS

The following is a list of the principal hydrologic terms used in this report, with brief definitions and comments:

*Aquifer.*—Saturated rock that will yield water to wells or springs in usable amounts.

*Artesian conditions.*—The conditions in which an aquifer is overlain and underlain by confining beds, and in which the piezometric (pressure-head-indicating) surface, or head of water in the aquifer, is higher than the top of the aquifer. They are generally prevalent wherever the dip of a confining bed is greater than the hydraulic gradient in the aquifer. Where the head is higher than the land surface, a flowing artesian well can be obtained.

*Base flow.*—That part of surface streamflow derived from groundwater discharge. Base flow varies with water levels in contributing aquifers, but the variations are generally small compared to the average discharge of the stream.

*Capillary fringe.*—The belt of the zone of aeration just above the zone of saturation in which some or all of the capillary interstices are filled with water held above the zone of saturation by capillarity acting against gravity.

*Coefficient of storage.*—The volume of water an aquifer releases or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. In water-table aquifers the coefficient of storage is less than the porosity, as some water is retained in the pore spaces against the force of gravity when sediments are drained.

The coefficient of storage in artesian systems is represented by a reduction in water level, or artesian head, and a squeezing out of water by elastic deformation, rather than by an actual dewatering of the rocks. Reduction in storage capacity in artesian aquifers occurs when the artesian head is reduced by well discharge, and the aquifer and its contained water are compressed by the weight of overlying rocks. The coefficient of storage under artesian conditions is much smaller—often hundreds of times smaller—than under water-table conditions. Therefore, the initial rate of spread of the cone of depression (see following definition) in an artesian aquifer is much faster than in a water-table aquifer.

*Cone of depression.*—Discharge of a well lowers the water level, or head, in the well and in the surrounding aquifer, thus producing a cone of depression in the water table or piezometric surface, the cone being more pronounced than that in a body of surface water when water is pumped out of it through a pipe because flow in ground-water reservoirs is impeded by friction in the water-bearing bed. The shape and size of the cone are determined by the rate and length of pumping and by the transmissibility (see beyond), coefficient of storage, and boundary conditions (location of areas of recharge, natural discharge, and changes in rock type) of the aquifer, but the rate of expansion of the cone is determined only by the transmissibility and coefficient of storage.

*Confining bed.*—A rock unit that is less permeable than an adjacent water-bearing bed, and that impedes movement of ground water into or out of the aquifer.

*Hydraulic gradient.*—The ratio of the decrease in head to the flow distance, usually measured in feet per mile. Henry Darcy (1856) verified experimentally that the rate of movement of water at any point through a given sand is proportional to the hydraulic gradient at that point.

*Infiltration.*—The downward percolation of water from precipitation or from streams into the soil or rocks.

*Perched water.*—The water in a zone of saturation underlain by a less permeable zone, and underlain in turn by a zone of aeration.

*Permeability.*—Ability of a unit thickness of a rock or sediment to transmit water, expressed quantitatively by the coefficient of permeability, or the number of gallons of water that can pass in 1 day through a 1-square-foot cross section of the material at right angles to the direction of flow under a hydraulic gradient of unity at 60°F. The field coefficient of permeability is the same except that it is measured under local conditions, such as temperature, rather than at 60°F. Permeability, as expressed in terms of water at 60°F, is thus a function of the physical characteristics of the rocks or sediment.

*Piezometric surface.*—The term commonly used to denote an imaginary surface that everywhere coincides with the static water level in an aquifer—the surface to which the water from a given aquifer will rise under its full head. Also called pressure-head-indicating surface, potential-indicating surface, or potentiometric surface.

*Porosity.*—The ratio of the volume of void spaces (filled with air or water) to the total volume of a rock.

*Recharge.*—The water added to ground-water storage, derived under natural conditions from infiltration of rainfall or streamflow.

*Rejected recharge.*—Surface flow or precipitation on a recharge area that does not enter an aquifer because the aquifer in the recharge area is already full. The water table in the aquifer must be at the surface in places in the recharge area for water to be rejected. If the cone of depression of a discharging well or wells extends into the recharge area, some water that otherwise would have been rejected may be taken into the aquifer.

*Seep.*—In this report the term "seep," used as a noun, describes a small amount of ground-water discharge, usually represented by moist rock or alluvium, where no appreciable surface flow is apparent. As a verb, in proper usage, it is a variously used term implying several different concepts of movement of water in both saturated and unsaturated materials.

*Semiperched water.*—The water in a zone of saturation separated from permeable materials below by less permeable materials. Water levels in the semiperched zones are higher than those in the main zone of saturation, but no zone of aeration is present between them.

*Specific capacity.*—The discharge rate of a well divided by the drawdown, usually expressed as gallons per minute per foot of drawdown in a specified time, such as 24 hours. It is an approximate measure of the productivity of a well. For most wells, the drawdown at moderate discharges differing from those already observed can be computed if the specific capacity is known, as the drawdown is generally proportional to the discharge for equivalent pumping times. Well construction and development influence specific capacity. Therefore, specific capacity is not a property of the aquifer alone.

*Streamline.*—Line perpendicular to lines of ground-water potential (water-level contours), representing the direction of movement of a parcel of ground water. This term is used in its mathematical sense and is not related to surface shapes or bodies of water.

*Transmissibility.*—The ability of an aquifer to transmit water, expressed by the coefficient of transmissibility. The coefficient of transmissibility, in gallons per day per foot, is equal to the field coefficient of permeability multiplied by the thickness of the saturated aquifer, in feet.

*Underflow.*—In this report, flow of ground water in the Recent fill of a stream channel.

*Water-level contour.*—Line connecting points of equal altitude on the water table or piezometric surface. Ground water moves down-gradient perpendicular to water-level contours.

*Water table.*—The upper surface of the zone of saturation except where that surface is formed by an impermeable body. It is represented by the water level in nonartesian wells.

*Zone of aeration.*—The portion of the ground not saturated with water under hydrostatic pressure.

*Zone of saturation.*—The zone in which the interstices of the rocks are completely saturated with water under hydrostatic pressure. More detailed discussions of these and other terms are given in the following publications, among others:

Meinzer, 1923a, b, 1939, and 1942.
Wenzel, 1942.
Theis, 1935 and 1940.
Tolman, 1937.
Jacob, 1950.

The following abbreviations and symbols are used in this report:

acre-ft = water discharge, or volume, in acre-feet (the volume of water required to cover 1 acre to a depth of 1 foot). Equal to 43,560 cubic feet, or 325,850 gallons.

cfs = water discharge in cubic feet per second; a unit of discharge equivalent to about 449 gallons per minute. A discharge of 1 cfs for 1 day is equivalent to 1.98 acre-feet.

gpm = gallon(s) per minute.
gpd = gallon(s) per day.
mgd = million gallon(s) per day.
ppm = part(s) per million.
$T$ = coefficient of transmissibility.
$S$ = coefficient of storage.
$t$ = time, in any specified unit.
$s$ = drawdown, in feet.
$Q$ = discharge, in gallons per minute.

## CHEMICAL QUALITY OF WATER

### ORIGIN OF DISSOLVED CONSTITUENTS

Water obtained from wells and springs, although initially derived from rain or snow, which is nearly pure water, always carries dissolved constituents. These include oxygen, carbon dioxide, and other gases dissolved in passage through air and soil; and mineral matter dissolved from the soil, unconsolidated sediments, and consolidated rocks through which the ground water passes. The base flow of surface streams represents largely the discharge of ground water, and the quality of such base flow is indicative of its source. Surface flow that originates directly from runoff after precipitation usually has a smaller proportion of dissolved minerals, so that surface water at high discharge rates usually is lower in mineral content than the base flow. Exceptions to this general rule may occur where runoff washes over and dissolves salt accumulations resulting from evaporation of soil moisture or ground water.

The mineral content of ground water is dependent upon the following factors:

1. Amount of gases and minerals dissolved during precipitation and surface flow.
2. Amount of gases and minerals dissolved during passage of water through surface soil. This is dependent on the chemical content of the water in stage 1 above, type and decomposition rate of organic material contained in the soil, surface:volume ratio of sedimentary grains composing the soil, and degree of concentration of natural water by evapotranspiration, in which pure water is discharged.
3. Chemical and mineralogical composition of rocks and sediments through which the underground water passes en route to a point of discharge. Ground water passing through sedimentary rocks may dissolve parts of either the original sedimentary grains or the cementing material. As calcium carbonate is a common cementing material, many sedimentary rocks yield water high in calcium bicarbonate.
4. The rate of flow of water through the soil, sediments, and rocks. The longer water remains in contact with the minerals of the materials through which it passes, the more nearly chemical equilibrium is approached with respect to the minerals with which the water is in contact. If movement is sufficiently slow the water may become nearly saturated with the rock components.
5. The temperature of the water. Generally, the warmer the water the greater its dissolving power.

The chemical quality of water, as much as the quantity available, determines its usefulness for different purposes. The chemical quality of ground water from a particular well or spring may change but little, but the quality of water from different wells may be markedly different. On the other hand, surface water varies markedly in quality from time to time at the same point, according to the source of the water and the rate of discharge.

General standards of quality and required characteristics of water for various uses are outlined in the following references:

| | |
|---|---|
| Public supply and private domestic use. | U.S. Public Health Service, 1946 and 1950. |
| Irrigation | U.S. Dept. Agriculture, 1954, Agricultural Handbook 60. |
| Industrial uses | Moore, 1940. Liquon, 1950. |

### EXPLANATION OF ITEMS IN THE TABLE OF WATER ANALYSES

Samples of water from representative public and private water supplies were collected during and previous to the investigation and were analyzed in the laboratory of the U.S. Geological Survey, Albuquerque, N. Mex. The results are shown in table 5. Chemical analyses are concerned with the mineral content of water and not its sanitary condition. The bacteriological quality of water should be assured before the water is used for domestic purposes especially in areas near a source of pollution.

All known water supplies in the vicinity of Santa Fe contain less dissolved solids than the maximum suggested in the Public Health Service standards for drinking water (500 ppm). The hardness of nearly all the ground-water supplies of the area ranges from moderate to very high. Silica is generally present in such quantities as to make the water unsuitable for boiler use without treatment. The selected water analyses should be compared to the standards and requirements outlined in the above-mentioned references for determination of the suitability of the water for specific uses in industry.

The methods of analysis used are those summarized by Collins (1928) and the American Public Health Association (1946), and others adopted by the U.S. Geological Survey.

The chemical constituents are reported in the table in parts per million, by weight. One part per million (1 ppm) is a unit weight of the constituent in a million unit weights of the water. The following discussion of the various constituents reported in a typical chemical analysis of water has been adapted from several U.S. Government publications dealing with the subject.

*Silica* ($SiO_2$).—Silica forms a large percentage of the mineral matter in all rocks, the weighted average for all rocks being 59 percent (Clarke, 1924, p. 34). Although silica is relatively insoluble, some silica is dissolved by all ground water, and especially by water whose pH is high.[12] Ground water in the Santa Fe area

[12] The pH is a measure of the acidity or alkalinity of water. It may be defined as the logarithm of the reciprocal of the hydrogen-ion concentration. Waters having pH values below 7.0 are increasingly acid; those having values above 7.0 are increasingly alkaline. The waters of the Santa Fe area are neither excessively acid nor excessively alkaline; therefore, pH values are not given in this report.

TABLE 5.—*Chemical analyses of waters from sources near Santa Fe, N. Mex.*

[Location numbers correspond to those in tables 17 and 18. Analyses by U.S. Geological Survey; chemical constituents in parts per million]

| Location No. | Date of collection | Specific conductance (micromhos at 25°C) | Silica ($SiO_2$) | Calcium (Ca) | Magnesium (Mg) | Sodium and potassium (Na+K) | Bicarbonate ($HCO_3$) | Sulfate ($SO_4$) | Chloride (Cl) | Fluoride (F) | Nitrate ($NO_3$) | Dissolved solids | Hardness as $CaCO_3$ | Percent sodium |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S15.8.5.114 | 8- 1-51 | 305 | 28 | 35 | 7.5 | 27 | 174 | 15 | 13 | 0.2 | 0.6 | 212 | 118 | 33 |
| 16.8.1.321 | 7-24-51 | 460 | 19 | 64 | 6.7 | 13 | 106 | 41 | 44 | .2 | 30 | 270 | 187 | 13 |
| 16.8.10.422 | 8-13-51 | 214 | 17 | 30 | 4.3 | 7.8 | 124 | 3.5 | 2.2 | .2 | 1.2 | 127 | 92 | 16 |
| 16.8.12.312 | 11-21-52 | 224 | | | | | | | 4 | | 1.6 | | 94 | |
| S16.8.20.312 | 10-10-51 | 258 | 20 | 41 | 3.3 | 7.8 | 134 | 12 | 3.5 | .2 | 5.4 | 159 | 116 | 13 |
| 16.8.24.333 | 8- 1-51 | 283 | 24 | 40 | 5.1 | 14 | 145 | 15 | 5.0 | .2 | 11 | 185 | 121 | 20 |
| S16.8.28.241 | 10-10-51 | 230 | 24 | 34 | 2.0 | 15 | 128 | 8.8 | 2.0 | .2 | 9.8 | 159 | 93 | 26 |
| 16.9.1.431 | 9-12-51 | 508 | 30 | 60 | 19 | 24 | 258 | 37 | 18 | .5 | 3.4 | 319 | 228 | 19 |
| 16.9.3.134 | 1- 2-52 | 296 | 20 | 52 | 4.0 | 9.4 | 141 | 31 | 10 | .2 | 5.1 | 201 | 146 | 12 |
| .321 | 1-16-52 | 701 | 19 | 106 | 6.8 | 36 | 186 | 160 | 30 | .2 | 10 | 460 | 292 | 21 |
| 17.8.1.212 | 9-19-51 | 480 | 21 | 60 | 5.9 | 31 | 162 | 27 | 10 | .2 | 81 | 316 | 174 | 28 |
| 17.9.22.441 | 6- 7-51 | 311 | 15 | 46 | 7.0 | 6 | 130 | 5.5 | 12 | 0 | 30 | 207 | 144 | 7 |
| 17.9.23.322 | 6- 7-51 | 350 | | | | | 170 | | 8.5 | | | | | |
| .332 | 11-22-46 | 477 | | | | | 225 | | | | | | | |
| .332 | 11-26-46 | 476 | | 83 | 5.8 | 4.6 | 220 | 29 | 17 | .1 | 7.3 | 255 | 231 | 4 |
| .332 | 2- 9-47 | 504 | 18 | | | | 214 | 26 | 17 | | | | | |
| 17.9.24.122 | 8-20-51 | 417 | | | | | | | | | 2.7 | | | |
| .123 | 8-20-51 | 747 | | | | | | | | | 12 | | | |
| .124 | 9-11-51 | 157 | | | | | 68 | | 8.0 | | 2.5 | | | |
| .124a | 9-12-51 | 398 | | | | | 176 | | 12 | | 18 | | | |
| 17.9.26.222 | 6- 7-51 | 453 | | | | | 192 | | 16 | | | | | |
| 17.9.27.143 | 9-11-51 | 354 | 17 | 52 | 5.1 | 7.6 | 123 | 30 | 8.0 | .6 | 27 | 208 | 150 | 10 |
| .211 | 8- 3-51 | 457 | 19 | 78 | 5.6 | 11 | 223 | 21 | 10 | .2 | 28 | 283 | 218 | 10 |
| S17.9.28.422 | 1-15-53 | 370 | 20 | 60 | 6.8 | 10 | 188 | 21 | 10 | .2 | 11 | 231 | 178 | 11 |
| 17.9.28.423 | 7-24-51 | 322 | 17 | 52 | 3.8 | 11 | 159 | 14 | 9 | .2 | 14 | 199 | 145 | 14 |
| G18.9.24.344 | 11- 2-51 | 434 | 20 | 76 | 9.5 | 3.9 | 264 | 12 | 4 | .4 | 1.6 | 257 | 228 | 4 |
| 18.10.31.413 | 8-19-51 | 387 | 19 | 38 | 8.5 | 37 | 217 | 17 | 8.0 | .5 | 3.8 | 239 | 130 | 39 |
| 19.7.36.424 | 9-19-51 | 251 | 30 | 4.0 | 1.3 | 53 | 134 | 10 | 4 | .2 | 4.1 | 173 | 16 | 88 |
| (1) | 9-19-42 | 87 | 11 | 8.2 | 2.2 | 3.5 | 36 | 4.9 | 1.6 | .1 | .1 | 58 | 30 | 20 |
| (1) | 6- 9-43 | 72 | 11 | 8.0 | 2.4 | 4 | 30 | 6.3 | 1.7 | .2 | .2 | 49 | 30 | 17 |

[1] Santa Fe public supply from Santa Fe River.

commonly contains 15–30 ppm of silica. Surface water in the mountain streams generally has about 10 ppm of silica. Silica contributes to the formation of boiler scale and hard deposits on turbine blades, but it is not ordinarily troublesome for domestic uses.

*Iron* (Fe).—Although iron is a minor constituent of most rocks, it is objectionable in the small amounts present in many ground waters, especially in areas where iron-rich igneous and metamorphic rocks or iron-cemented sandstones are prevalent.

More than 0.3 ppm of iron may be objectionable for domestic use, because of taste or staining of plumbing fixtures, utensils, and laundry. On exposure to air, water containing soluble ferrous iron becomes turbid with insoluble reddish ferric hydroxide. Water initially low in iron, such as water from the Santa Fe River, may dissolve some iron from pipes. Ground and surface waters in the Santa Fe area generally do not contain much iron.

*Calcium* (Ca).—Calcium is present in all rocks, especially in rocks such as limestone (calcium carbonate), dolomite (calcium and magnesium carbonate), gypsum (calcium surfate), calcite-cemented sandstones, and igneous rocks high in calcic feldspar (basaltic and intermediate volcanic rocks). Granite is relatively low in calcium, as are uncemented sediments derived from it. Calcium and magnesium are the principal constituents that cause hardness in water, and are largely responsible for the formation of boiler scale. Calcium is the predominant cation (positively charged ion) in ground water of the Santa Fe area.

*Magnesium* (Mg).—Magnesium is commonly present in large amounts only in ground water from dolomitic rocks and other rocks high in magnesium. The effects of magnesium in water are similar to those of calcium.

*Sodium* (Na) *and Potassium* (K).—Sodium and potassium are chemically somewhat similar and are found in practically all waters, the sodium generally in concentrations several fold larger than the potassium. Moderate quantities of sodium and potassium have little effect on the usefulness of water for most purposes, but highly mineralized waters that contain a large proportion of sodium salts (high percent sodium) may be unsatisfactory for irrigation. Water in the Santa Fe area is generally low in these constituents.

*Bicarbonate* ($HCO_3$).—When the gas carbon dioxide is dissolved in water it enables the water to dissolve compounds of calicum, magnesium, iron, and other common constituents of rocks. Bicarbonate in moderate concentrations in water does not affect its use for most purposes. Bicarbonate is the predominant anion (negative charged ion) in all the waters in the Santa Fe area.

*Sulfate* ($SO_4$).—Sulfate is dissolved from many rocks and soils but in especially large quantities from gypsum (calcium sulfate), from many beds of shale or clay, and from the oxidized sulfides of iron. Sulfate in water that contains much calcium or magnesium causes hard scale to form in boilers and may increase the cost of softening the water. In general sulfate is low in water in the Santa Fe area, although it is likely that water from deep wells in the southern part of the area would be high in sulfate.

*Chloride* (Cl).—Some chloride is present in nearly all rocks, but generally in very small quantities, especially in igneous and metamorphic rocks. However, most chloride compounds are extremely soluble. The chloride ion is not usually precipitated or exchanged for other ions, and therefore in ground water it tends to increase in the direction of water movement. Some sediments contain a large amount of chloride salts. Sodium chloride is a common constituent in sewage, and therefore any appreciable pollution of ground waters is generally marked by an increase in the chloride content of the water. Bacteria may be removed in passage through the ground, but the chloride ion is not removed. In general the chloride content of the ground water in the Santa Fe area is low.

*Fluoride* (F).—Fluoride is present in most ground waters in the western United States. The principal source of fluoride is believed to be igneous rocks, including juvenile water emanating from cooling igneous rocks.

A concentration of about 1 ppm of fluoride in drinking water greatly lessens the incidence of decay of the permanent teeth when the water is drunk habitually by children, but fluoride in excess of 1.5 ppm in drinking water may cause mottling of the enamel of the teeth of children who use the water during the period of calcification of the teeth (Dean, 1936). Surface and ground waters near Santa Fe are low in fluoride; the concentration is commonly about 0.2 ppm.

*Nitrate* ($NO_3$).—Nitrate in most unpolluted ground water or surface water is usually small in quantity. Concentrations greater than about 10 ppm, especially when associated with high chloride, may indicate contamination with sewage or other organic matter. Concentrations of nitrate in water exceeding 44 ppm have been associated with cyanosis in infants (Maxcy, 1950, p. 265). Of 26 samples analyzed from the area, 10 samples contained 10–30 ppm, and 1 sample, 81 ppm.

*Dissolved solids.*—The reported quantity of dissolved solids (sum) is the sum of the determined constituents, bicarbonate being converted to carbonate by dividing by 2.03. Values for parts per million are converted to tons per acre-foot by multiplying by 0.00136.

Drinking water should not contain more than 1,000 ppm of dissolved solids and preferably not more than 500 ppm, according to U.S. Public Health Service drinking-water standards. All the waters utilized in the Santa Fe area contain less than 500 ppm of dissolved solids.

*Hardness.*—Hardness is the charatceristic of water that receives the most attention with reference to domestic and industrial use. It is usually recognized by the quantity of soap required to produce lather. Hard water is objectionable also because of the formation of scale in boilers, water heaters, radiators, and pipes, with a resultant decrease in the rate of heat transfer, possibility of boiler failure, and loss of flow. Water that has a hardness of less than 60 ppm is usually rated as soft, and its treatment for reduction of hardness is seldom justified. Water having a hardness between 60 at 120 ppm is rated as moderately hard. This degree of hardness does not seriously interfere with the use of water for most household uses, but laundries and some other industries may find it profitable to soften the water. When the hardness exceeds 120 ppm, the water is considered hard (above 200 ppm, very hard) and softening is desirable for many uses of the water.

Hardness is caused almost entirely by calcium and magnesium. Iron, manganese, aluminum, barium, strontium, and free acid also cause hardness, but these dissolved materials are not usually found in appreciable quantities in natural waters. Surface waters in the mountains near Santa Fe are soft. Most of the ground waters in the Santa Fe area, however, are moderately hard to hard, and some are very hard.

*Specific conductance.*—The specific conductance of a water is a measure of its capacity to conduct a current of electricity, and is currently reported by the Geological Survey in micromhos (millionths of a reciprocal ohm) at 25°C. The conductance varies with the temperature, concentration, and proportions of the different minerals in solution. The specific conductance of a water is a rough measure of the concentration of the dissolved solids. More accurate approximations of the concentration can be made from conductance measurements if the proportions of the constituents are approximately known.

*Percent sodium.*—The value reported for percent sodium is obtained by dividing the equivalents per million of sodium by the sum of the equivalents per million of the principal cations (calcium, magnesium, sodium, and potassium) and multiplying by 100. To convert parts per million to equivalents per million, the concentration of the constituents in parts per million is divided by the equivalent, or combining, weight of the constituent. The equivalent weight in turn is found by dividing the molecular weight of a constituent by its chemical valence. Percent sodium then represents the proportion of sodium to the principal basic constituents in the water on a chemically equivalent basis.

Water having a high percent sodium (more than about 50 percent), when used for irrigation, may cause the soil to become less permeable to water and difficult to till, but the addition of gypsum to the water or soil will often permit the use of water having a high percent sodium. Discussions of the quality of irrigation waters are given by Wilcox (1948a and 1948b) and the U.S. Department of Agriculture (1954); the effect of irrigation on the quality is discussed by Gatewood and others (1950). Ground water in the Santa Fe area generally has a low percent sodium.

## GEOLOGY AND GROUND WATER

### SUMMARY OF GEOLOGY AND REGIONAL GROUND-WATER MOVEMENT

The rocks near Santa Fe that make up the framework for movement of water underground are summarized in table 6, beginning with the youngest. In terms of geologic age and structural history these units may be grouped as shown in table 7.

These rocks are also grouped into five major hydrologic units on the basis of their hydrologic properties and distribution (see right-hand column of table 7). Their distribution is largely the result of major structural movements in late Cenozoic time, associated with the formation of the Rio Grande trough (p. 68).

Rocks of hydrologic units 1 and 2 (table 7) are resistant to erosion and have low permeability, and they form the basic framework of the structure, topography, and hydrology. Plate 5 shows the distribution and structure of these rocks as inferred from geologic, hydrologic, and geophysical data.

The Sangre de Cristo Mountains, consisting largely of Precambrian rocks (hydrologic unit 1, table 7 and plate 6) cut by major faults, dominate the east margin of the Rio Grande trough in this latitude. Because of their altitude they receive more rainfall than the basin areas, and they are therefore the major source of runoff in the vicinity of Santa Fe. The ground water in easily accessible parts of the mountains does not occur under conditions favorable for large-capacity wells, and even small domestic supplies are difficult to obtain. However, heavy winter snow packs at high altitudes and temporary water retention in fractured Precambrian rocks and in soil, alluvium, and glacial drift favor perennial streamflow and high water yields per unit area.

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TABLE 6.—*Summary of geologic units in the Sante Fe area, New Mexico*

| Age | Unit | | Thickness (feet) | Description | Water-bearing characteristics |
|---|---|---|---|---|---|
| Recent | Eolian deposits | | 0–15 | Windblown sand and silt. | Generally not saturated. Usually permeable and conducive to infiltration of precipitation and recharge to ground water in underlying units. |
| Recent and Pleistocene | Cover | | 0–10 | Slope wash consisting largely of silty sand and some pebbles and talus. | Permeability low; generally not saturated. |
| Recent and Pleistocene | Alluvium | | [1] 0–20 | (a) Channel sand and gravel of major streams. | Permeability high. Supplies water to shallow wells and infiltration galleries; generally saturated only only where underlain by relatively impermeable phases of the Tesuque formation or less permeable older rocks. Water of generally good quality but hard in places. |
| | | | | (b) Flood-plain sand, silt, and clay. | Locally yields small supplies to dug wells. |
| | | | | (c) Silty sand and gravel fill of small valleys and arroyos. | Usually not saturated, except near springs or seeps emerging from underlying rocks. |
| Pleistocene | Terrace deposits | | [1] 0–100 | Same as (a) and (b) above, but commonly containing many large rounded boulders. | Lowest terrace gravels saturated in locations similar to (a) above. Suitable in places for artificial-recharge flooding. |
| Pleistocene(?) | Santa Fe group | Basalt flows and tuff; dikes | [2] 20–100 | Thick flows of columnar basalt underlain by cinders; dikes. | Generally not saturated except at or near level of Rio Grande, west of Sante Fe area. Tuffaceous basalt probably very permeable. |
| Pleistocene or late Pliocene | Santa Fe group | Ancha formation | 0–300+ | Silt, sand, and gravel, generally uncemented. | Saturated only where underlain by relatively impermeable phases of Tesuque formation or older rocks. Usually water bearing near Sangre de Cristo Mountains. Yields small to moderate supplies locally, but may yield large supplies west of State Highway 10. |
| Early Pliocene to middle(?) Miocene | Santa Fe group | Tesuque formation | 0–4,000+? | Predominantly pinkish-tan silty to conglomeratic sand and sandstone. Some phases in lower third(?) are uniform sand, uncemented. | Dependable for small supplies; prospects for large supplies good in uniform-sand phases. |
| | | Basalt flow | 0–25 | Amygdaloidal basalt, deeply weathered. | Permeability probably very low. |
| | | Bishops Lodge member | 50–530 | Gray silty and clayey sand and conglomerate derived from intermediate volcanic rocks. | Permeability generally very low. |

| | | | | |
|---|---|---|---|---|
| Miocene and Oligocene(?) | Cieneguilla limburgite of Stearns (1953b) | 700 | Thick flows and feeders of limburgite interbedded with agglomerate, breccia, and conglomerate. | Permeability low but usually sufficient for small stock or domestic supplies. Water occurs only in fractures. |
| | Intrusive rocks | | Intermediate igneous rocks, closely jointed in places. | |
| | Extrusive rocks | 1,000± | Latitic to andesitic flows and breccias | |
| Oligocene(?) and Eocene | Galisteo formation | 900–4,300 | Pebbly sandstone, well-sorted and moderately cemented; red siltstone and silty sandstone. | Permeability generally low in Santa Fe area. |
| Cretaceous | Mesaverde formation [3]<br>Mancos shale [3]<br>Dakota sandstone | Unknown | Sandstone, limestone, and mudstone, poorly exposed in Turquoise Hill. | Unknown. |
| Jurassic, Triassic, and Permian | Undifferentiated | Unknown | Not known to crop out in the area, but probably exist in subsurface in southwestern and western parts, at least. | Unknown. |
| Pennsylvanian | Madera limestone | | | Where thick limestone beds are at low altitudes or in synclines, they may yield small to moderate quantities of hard water. |
| | Upper arkosic limestone member | | Gray limestone, arkosic sandstone, and shale | |
| | Lower gray limestone member | | Gray limestone | |
| | Sandia formation | | | |
| | Upper clastic member | | Carbonaceous and variegated shale, thin-bedded limestone. | |
| | Lower limestone member | 0–51 | Gray limestone, present only locally | |
| Precambrian | Igneous and metamorphic rocks | | Red granite, amphibolite, gray granite, schist, and gneiss. | "Basement" rocks, generally impermeable, extremely hard to drill. In outcrop area, yield small supplies to shallow wells from fractures, especially in valleys or near faults. Springs emerging from fractured zones yield water of good quality and supply part of base flow of mountain streams. |

[1] Estimated thickness.
[2] Thickness in White Rock Canyon, 1,200 ft.
[3] Remnants may be present at borders of intrusive masses. See p. 32, 33 and pl. 3.

TABLE 7.—*Summary of geologic units and events in the major physiographic units*

| Age | | Geologic unit | Geologic events | Hydrologic and physiographic unit in which found |
|---|---|---|---|---|
| Recent and Pleistocene | | Eolian deposits, cover Alluvium, terrace gravel | Climatic changes, successive erosion cycles with little tectonic activity. | (5) Stream valleys. |
| Pleistocene and Pliocene(?) | Santa Fe group | Lava flows, dikes, and pyroclastics | Sedimentation and extrusion of thin, widespread volcanic units, masking older structure. | (4) Lava mesa. |
| " | Santa Fe group | Ancha formation | Severe faulting, especially at margins of Rio Grande trough. | |
| Pliocene and Miocene | Santa Fe group | Tesuque formation | Subsidence of Rio Grande trough accompanied by deposition of thick terrestrial basin-filling sediments derived principally from Precambrian rocks on uplifted margins. | (3) Piedmont slope. |
| Miocene and Oligocene(?) | | Cieneguilla limburgite of Stearns (1953b)<br>Intrusions<br>Latite flows, pyroclastics, breccia | Early stages of trough subsidence and filling were characterized by deposition of material derived from volcanic deposits and by local volcanic activity. Extrusion of basic flows and breccias.<br>Intrusion and extrusion of intermediate rocks. | (2) Cienega and Cerrillos areas. |
| Oliogocene(?) and Eocene | | Galisteo formation | Development of isolated basins of deposition; sediments largely derived from Paleozoic and Mesozoic sedimentary units; moderate relief. | |
| Cretaceous | | Undifferentiated rocks | Extensive marine deposits in shallow seas. | |
| Pennsylvanian | | Magdalena group | Widespread marine and nonmarine deposition controlled by oscillating shorelines; generally low relief. Broad, low positive areas controlled sedimentation. | (1) Sangre de Cristo Mountains. |
| Precambrian | | Precambrian rocks | Sedimentation, intrusion, metamorphism. | |

The intrusive rocks of the Cerrillos and the Cretaceous and lower Tertiary sedimentary and volcanic rocks in the southern part of the area (hydrologic unit 2, table 7) are the center of a radial drainage net of ephemeral arroyos. Some ground water is available from these rocks, but they are more important for their control of the movement of ground water in overlying, more permeable late Cenozoic sedimentary rocks. The intrusive rocks have helped retard erosion of a structurally high bedrock floor of pre-Santa Fe impermeable rocks east of Cienega and the Cerrillos. The Mesozoic and lower and middle Tertiary rocks composing the bedrock floor crop out in the escarpment on the north side of Galisteo Creek, where they are overlain unconformably by the Ancha formation. The Ancha directly overlies them also in exposures south of Gallina Arroyo, except where a small patch of the Tesuque formation south of the Seton Village quadrangle (sec. 34, T. 15 N., R. 9 E.) overlies the Galisteo formation. The inferred geology beneath the Ancha formation is shown on plate 5.

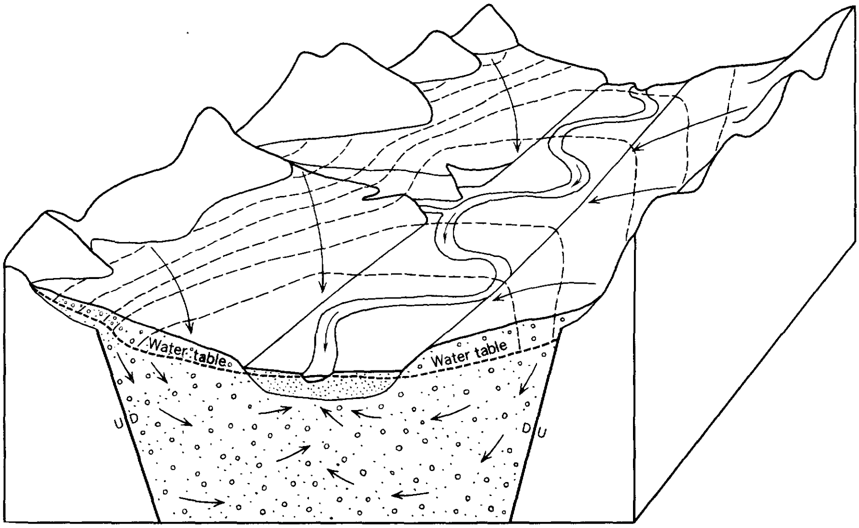


FIGURE 25.—Block diagram showing relation of ground-water flow to the Rio Grande trough. Heavy arrows indicate general direction of movement of ground water. Dashed lines represent contours on the water table.

Geologic and hydrologic conditions in parts of the Rio Grande trough approach the idealized conditions of a simple bedrock trough filled with unconsolidated sediments of uniform thickness and permeability and bounded by sources of recharge. Figure 25 shows the pattern of water-table contours in such an idealized trough. However, the Rio Grande trough in the Santa Fe area departs appreciably from these idealized conditions; therefore, the actual pattern of water-level contours in the unconsolidated fill of the trough (pl. 7) also departs appreciably from the idealized pattern.

The Tesuque formation (hydrologic unit 3, table 7) overlies rocks of unit 2 under most of the piedmont slope north of Gallina Arroyo; in the Santa Fe area it is the major aquifer. Its present distribution is due largely to post-Tesuque faults which have dropped it in generally northwest-trending fault blocks, thus preserving it from erosion. The contours in plate 6, drawn on the basis of water levels in the Tesuque formation, indicate that the general movement of ground water is westward and northwestward. (See pl. 7, fig. 31, p. 151). Discharge from the Tesuque and Ancha formations is localized in the Cienega area because of the presence at shallow depth of an upfaulted block of the bedrock, but north of the Santa Fe River ground water in the Tesuque formation is diverted to the northwest by dikes (part of hydrologic unit 4, table 7) and by the pre-Santa Fe bedrocks of the Cerrillos-Cienega area.

In addition to the major anomalies in the water-table contours caused by the principal hydrologic-geologic features, several minor anomalies are present in and near the southern and western parts of Santa Fe:

1. Contours in secs. 22 and 27, T. 17 N., R. 9 E. (pls. 6, 7), diverge—that is, the hydraulic gradient flattens—as the result of the presence of a zone of high permeability in the Tesuque formation, along the Santa Fe River near the western city limits. Wells of high yield have been drilled in this area. The material of high permeability is uncemented, well-sorted medium sand.

2. The 6,600- and 6,700-foot water-table contours along and north of the Santa Fe River converge in the western part of Santa Fe, probably because of the presence of an uplifted block of a red silty fine-grained facies of the Tesuque formation (exposed in the stream channel by excavations in 1951) which impedes movement of ground water from the more coarsely sandy phase to the east.

3. A small area of shallow perched water which lies in the vicinity of Siringo Spring, sec. 3, T. 16 N., R. 9 E., and extends northwestward to the Santa Fe River, appears to be caused by local recharge to the Ancha formation, which is inferred to be overlying a phase of the Tesuque formation of low permeability at this locality. Three other similar small areas appear to reflect the same conditions.

4. The 6,800- and 6,900-foot water-table contours north of Arroyo Hondo converge because faults cut the Tesuque formation and cause conditions similar to those described in anomaly 2 above. Anomalies 2 and 3 above are probably related to the fault zone suggested by the topography southeast of Seton Village.

The zone of saturation in the Ancha formation is thin or absent in most of the area where the formation overlies the bedrock floor, and ground water there occurs only in the slightly permeable bedrock. Locally the topography of the bedrock floor controls the accumulation and movement of ground water in the overlying Ancha formation. In most of the areas south of Gallina Arroyo the ground water in the pre-Santa Fe rocks, and locally in the Ancha formation, moves generally southwest, discharging to the heads of arroyos fringing the north side of the Galisteo Creek valley. North of Gallina Arroyo the bedrock floor dips northwestward and is overlain by the Tesuque formation. In this area the Ancha is not generally saturated, except where perched water occurs above less permeable zones of the Tesuque formation, or above older rocks.

## GEOLOGIC UNITS AND THEIR WATER-BEARING PROPERTIES

### PRECAMBRIAN ROCKS

Although crystalline Precambrian rocks are inferred to exist under the entire area, in general they are buried deeply by younger sediments and igneous rocks, except in the mountains and foothills in the eastern part of the area investigated, where they are either exposed at the surface or are covered by thin layers of younger rocks.

The area drained by the Santa Fe River above Santa Fe is wholly within the area of outcrop of Precambrian rocks, and the principles discussed in this description are applicable also to those areas of Precambrian rocks.

The Precambrian rocks have a relatively small volume of primary pore space to store or transmit water. However, ground water may be contained in openings caused by weathering, or in openings caused by structural deformation of the rocks, such as faults and joints. Such openings are nearly always small and constitute a very small percentage of the total volume of the rock. Although the different types of Precambrian rocks react somewhat differently to structural movements and to chemical and mechanical weathering, both permeability and storage capacity are generally low in these rocks. In areas in which they crop out or are accessible beneath thin cover they are usually a source of only small water supplies; where they are buried deeply they are not considered an aquifer at all.

As deep weathering of the crystalline rocks occurred before overlying Pennsylvanian sediments were deposited, a weathered zone may exist locally below the Pennsylvanian rocks in favored areas where the Pennsylvanian rocks and the weathered zone have not been removed by later erosion. Such weathered zones may yield small quantities of water to wells. Precambrian rocks were exposed in parts of the mountain areas during the deposition of the Tesuque formation, but in those localities where the contact of the Tesuque and Precambrian is exposed, the Precambrian rocks are only slightly weathered. Post-Tesuque weathering occurred concurrently with the late Pliocene and Pleistocene cycles of erosion and deposition, when the drainage system was essentially the same as at present.

*Ground-water recharge and movement.*—Rain or snowmelt that enters crevices or weathered portions of the Precambrian rocks moves generally downward to the zone of saturation. Movement of the water in crevices and weathered rock is generally toward the major drainage lines. Water-table gradients in the Precambrian rocks are high because of the low permeability, relatively large recharge entering the rocks quickly through the permeable soil, steep gradient of the base of the zone of appreciable permeability, and rough topography. However, as the mountain drainage basins are narrow, ground water reaches the streams relatively quickly, as shown by the marked decline in flow of such streams within a few months after periods of recharge (see fig. 49).

*Discharge.*—Discharge of ground water from the Precambrian rocks occurs largely through springs that emerge from fractures in the rocks, generally at or near valley bottoms. The aggregate discharge of these springs represents a portion of the base flow of the streams in the mountains, as described in the sections on surface water. Because of the small unit storage capacity of crystalline rocks, the drainage of water from them that supports the prolonged discharge of springs results in large declines of ground-water levels below the peak levels of spring, even at some distance from the areas of discharge.

*Utilization.*—The Precambrian crystalline rocks in this area are far more important as sources of springs and surface streamflow than as sources of ground water available to wells. At present the natural discharge of some individual springs in this area is used for domestic supplies. (See table 18.) Springs along Tesuque Creek (17.10.5.211) and Arroyo Hondo (16.9.13.224) emerge above stream level at points where westward movement of ground water in fractures in the crystalline rocks is blocked by overlying westward-dipping Tertiary sediments of low permeability. The water from many smaller springs, such as S–17.10.28.314 and S–17.10.29.232, which flow from fractures in the crystalline rocks, either is used locally by plants or percolates into the ground downstream. Part of the flow of these springs could be developed for useful purposes without directly affecting the flow of the major streams near Santa Fe, but at the sacrifice of the native vegetation using the water.

Wells drilled into the Precambrian rocks in some areas have been unsuccessful in obtaining water. If a well in crystalline rocks does not encounter open fractures or weathered zones below the water table, little or no water may be obtained. As rocks weather only near the land surface, weathered zones will not be encountered at depth in the crystalline rocks, except rarely along fractures of unusual extent.

Generally, in this area, wells in valleys are more successful than those on ridges, as valleys are often coincident with fault zones or zones where joints are closely spaced, whereas ridges are generally formed of more massive rocks. Locally, however, the valley-forming faults may dip under the ridges and yield water to wells there. Plates 1 and 4 indicate some of the more important fracture zones of this type. Wells drilled along the strike of these fractures may yield more water than wells drilled at random locations. Although joint and fault openings may extend deeper than weathered zones, they generally decrease in size and number with depth because of the weight of the overlying rocks; thus, in general, little or no water will be obtained at depths of more than a couple of hundred feet.

Generally wells in the Precambrian rocks of the area yield 1–10 gpm. Wells that intersect faults may furnish water at higher discharge rates, but only if pumped intermittently. Storage tanks may be desirable even for small domestic water systems in these areas, in order to provide sufficient reserve for periods of peak use. The pumping of small quantities of water for long periods of time, and the use of large storage tanks, may provide an adequate water supply in many areas in which larger pumping rates would lower the water level in a well excessively.

The depth to the water table in the area of outcrop of the Precambrian rocks is highly variable because of the considerable topographic relief and the steep water-table gradients. Valley sites are topographically as well as hydrologically more favorable for successful wells at shallow depths. In larger valleys the alluvium may yield water, obviating the necessity of drilling into the underlying hard Precambrian rocks.

Water from the Precambrian rocks is generally low in both hardness and dissolved solids.

### MAGDALENA GROUP

Rocks of the Magdalena group, which includes strata of Pennsylvanian and possibly Mississippian age, are exposed in several places along the west edge of the Sangre de Cristo Mountains. The total area of outcrop of these rocks in the Santa Fe area is about 4 square miles. Plates 1 and 4 show that the outcrops are isolated, and that the largest single outcrop covers about 1 square mile.

No Pennsylvanian rocks are known to exist between the east edge of the map quadrangles and the crest of the range in this latitude. The subsurface extent of these rocks is incompletely known but is thought to be small immediately west of the mountains, for the following reasons:

1. Even in the outcrop areas, large portions of these rocks have been removed by erosion.

2. Fragments of Pennsylvanian rocks are common in younger formations, indicating that at least some of these older rocks were reworked during the Tertiary and Quaternary, especially in the eastern part of the area investigated.

3. Well logs indicate that rocks of the Magdalena group are generally thin or absent below the Tertiary sediments along the mountain front.

Farther west of the mountain front, rocks of the Magdalena group, if present, are probably at depths greater than 1,000 feet. The occurrence of boulders from Pennsylvanian(?) strata in secs. 31 and 32, T. 18 N., R. 9 E., described on page 77, suggests that locally

Pennsylvanian rocks may be near the surface even in the structurally low Rio Grande trough, and that the block fault system exposed in the margins extends into the trough proper. Regional studies indicate that a highland existed during Late Pennsylvanian time in the west half of the Santa Fe area (Brill, 1952), and therefore no Upper Pennsylvanian rocks are present there.

In general the rocks of the Magdalena group in this area are not good aquifers. Shale and well-cemented sandstone predominate and in general do not yield sufficient water even for ordinary domestic needs. The thick limestone beds in the Magdalena group are possibly water bearing. The permeability of these beds is dependent upon the solutional enlargement of cavities along joint and bedding planes. Such openings are not particularly well developed in this area. The limestone strata most favorable for ground-water occurrence in the Magdalena group are in the lower limestone member of the Sandia formation, which is discontinuous in the Santa Fe area, and in the lower gray limestone member of the Madera limestone. Limestone beds in the upper arkosic limestone member are generally thinner and interbedded with shale and well-cemented sandstone and arkose.

In general, the development of solution channels in the limestone beds is likely to be greatest near the areas of greatest ground-water recharge and discharge. Solutional enlargement therefore should be best developed along the present valleys, wherever the limestone is structurally depressed, as in the Santa Fe River valley in secs. 19 and 20, T. 17 N., R. 10 E., in a tributary valley in sec. 16, T. 17 N., R. 10 E., and in the valley of Little Tesuque Creek just above Bishops Lodge. Elsewhere along these main drainage courses, the limestone has been removed by erosion.

*Ground-water recharge and movement.*—Recharge to the Magdalena group is by infiltration of rainfall and snowmelt into openings in the bare rock and overlying soil, and by infiltration of streamflow on the floors of some arroyos and canyons draining higher country. Generally the water table or piezometric surface slopes toward the larger streams such as the Rio Tesuque and the Santa Fe River, and ground-water discharge from the limestone furnishes a small part of the flow of these streams. Appreciable recharge is contributed to limestone beds by Little Tesuque Creek above Bishops Lodge during the spring runoff and infrequent summer rainstorms, as the water table there is below the arroyo bed, and Little Tesuque Creek visibly loses as much as 1 cfs where it crosses the limestone.

*Discharge.*—Natural discharge of ground water from the Magdalena group occurs through springs and seeps in arroyos that dissect the outcrop areas. These springs emerge from solutionally enlarged openings along the fracture planes in limestone in the Santa Fe River and its two northern tributaries. Ground water may be discharged from the limestone to channel alluvium as well as directly to the streams, and to the Tesuque formation where it overlies Pennsylvanian rocks in Tesuque and Little Tesuque Creeks.

*Utilization.*—Rocks of the Magdalena group are not present over sufficiently large areas to be a source of large quantities of water for public supply or irrigation. Also, these rocks are unfavorable for large ground-water development because of their low average storage coefficient and permeability. Locally, sufficient water may be available for intermittently pumped wells of moderate yield (perhaps 25–50 gpm) but generally only small domestic or stock supplies are available. Locally, the proximity of perennial streams, which could recharge the limestone strata once a cone of depression was formed by pumping, would in part compensate for the small extent of the aquifer, so that moderately large amounts of water are probably available in the two limestone areas described on page 29. However, pumping from this aquifer will reduce or stop the flow of springs from the limestone and eventually decrease the total surface flow downstream. Heavy pumping in such local areas during extended droughts may partly deplete the stored water, lower the water levels, and lessen the spring and stream flow downstream; but the ground-water reservoirs presumably would be at least partly replenished during the spring runoff, especially in the valley of Little Tesuque Creek. In the isolated synclinal blocks of Pennsylvanian rocks (secs. 16, 19, and 20, T. 17 N., R. 10 E.) small supplies of ground water can be obtained from wells penetrating limestone beds near the axis of the syncline. The flow of the few small springs and seeps emerging from fractures in the limestone would probably be lessened by pumping from these beds.

Water from limestone is generally very hard, and it is to be expected that water from the Magdalena group will be similar in this respect to that from other limestone rocks.

## PERMIAN AND MESOZOIC ROCKS

Sedimentary rocks of Permian and Mesozoic age crop out south of the Santa Fe area along Galisteo Creek, and they probably underlie much of the Santa Fe area. They are hydrologically unimportant in the Santa Fe area because of their generally low permeability. Although permeable Permian rocks may exist at great depth under the Seton Village and Turquoise Hill quadrangles, there are no known areas where they can discharge freely into adjacent rocks, and consequently they may contain highly mineralized water.

### LOWER AND MIDDLE TERTIARY ROCKS

The thick sequence of lower and middle Tertiary rocks is composed of units of varied lithology, but all are characterized by low permeability. Together with the Mesozoic rocks they compose a bedrock floor that controls the accumulation and movement of ground water in overlying sediments.

In the Agua Fria quadrangle and in parts of the Turquoise Hill, Seton Village, and Santa Fe quadrangles the pre-Santa Fe Tertiary rocks and the older consolidated rocks are too deep to influence ground-water movement and occurrence, except near the front of the Sangre de Cristo Mountains. Water levels in the thick Tesuque formation are controlled by factors discussed in later sections.

#### GALISTEO FORMATION

The Galisteo formation within the area investigated is exposed only in valleys, and in relatively few localities there. The principal exposures are along Cienega Creek in the vicinity of Cienega. The Galisteo formation in the mountain areas, if deposited, was removed by erosion. Nearly everywhere else in the area, the Galisteo formation may be present below middle Tertiary extrusive rocks or younger sedimentary rocks and lava flows; but, if present, it is at great depth in the two northern quadrangles. In the southern parts of the southern quadrangles the Galisteo formation probably underlies much of the Ancha formation of the piedmont slope.

Although the Galisteo formation is saturated with water up to or above stream grade wherever it is known to exist in the area investigated, the permeability of the strata is very low. In the zone of saturation, water fills those parts of the interstices between sand and silt grains not filled by mineral cement. As the intergranular spaces are small, and the uncemented spaces still smaller, the Galisteo formation is a poor aquifer in the Santa Fe area. Probably the greatest importance of the Galisteo formation to the hydrology of the Santa Fe area is its role as a principal unit of the bedrock floor below the Ancha formation on the plains south of Santa Fe.

*Ground-water recharge and movement.*—Recharge to the Galisteo formation in the Santa Fe area probably occurs largely by downward seepage from the saturated zone of the overlying Ancha formation. As the details of structure of the Galisteo formation are not known in most of the area, the movement of its contained water is not known and artesian conditions may exist locally in the more permeable sandstone beds. It is possible that some recharge into the Galisteo formation in its outcrop area may move downdip (northwest) into the Santa Fe area, but water-table contours south of

Gallina Arroyo suggest that the ground-water movement is generally southwestward.

*Discharge.*—Ground water in the Galisteo formation discharges to springs on the north escarpment of Galisteo Creek, into seeps and springs on Cienega Creek, and by slow movement at depth toward the lower Santa Fe River and Galisteo Creek. The discharge is probably very small compared to that from the overlying, more permeable Tesuque and Ancha formations.

*Utilization.*—It is generally not advisable to attempt development of even small water supplies from the Galisteo formation until all other possible sources have been considered. The overlying Ancha or younger sediments generally yield sufficient water for stock and domestic needs, except in the areas outlined on plate 6. In these areas the contact of the Ancha formation with the Galisteo formation is above the regional water table and no water will be found in the Ancha formation. A reported test on well 15.9.17.133a indicates that the Galisteo formation does not yield sufficient water even for stock supplies. Sufficient water for stock or domestic supply might be obtained locally from sandstone beds in the thick Galisteo formation in some localities south and southwest of the Santa Fe area, as well as along Cienega Creek at the west edge of the Turquoise Hill quadrangle. In such places test wells should be located far enough downdip from the lowest outcrop of coarse sandstone beds as to intersect the sandstone beds below adjacent stream grades or below the level of local springs.

### EXTRUSIVE ROCKS

The principal exposures of the extrusive rocks of the area are along Cienega Creek and its tributaries near Cienega. Both these rocks and the Galisteo formation have been removed by erosion nearly everywhere from the mountain and foothill parts of the area investigated, except in Arroyo Hondo canyon in sec. 18, T. 16 N., R. 10 E. Scattered outcrops immediately south of the area investigated, as well as the results of geophysical studies, indicate that these rocks, in addition to the Galisteo formation, are probably present below the Ancha formation in the southern parts of the Seton Village and Turquoise Hill quadrangles (pl. 5).

Although ground water in the extrusive rocks occurs only in fractures, rather than in intergranular spaces as it does in the Galisteo formation, the overall patterns of recharge, movement, and discharge are similar. The extrusive rocks also are part of the bedrock floor discussed on page 126.

*Ground-water recharge and movement.*—Recharge to the extrusive rocks, as to the Galisteo formation, probably occurs largely by downward movement from the saturated zone of the overlying, more permeable Ancha formation. Lateral movement is slow because of the low permeability of the rocks and probably about in the same directions as in the saturated zone of the Galisteo formation.

*Discharge.*—Ground water is discharged from the extrusive rocks to springs in arroyos draining the north escarpment of Galisteo Creek, and into seeps and springs on Cienega Creek and the Santa Fe River. The discharge is probably very small compared to that from the overlying Tesuque and Ancha formations.

*Utilization.*—As the extrusive rocks consist largely of nonvesicular flows and indurated breccias, their hydrologic characteristics are similar to those of other consolidated rocks, such as the Precambrian rocks in the Sangre de Cristo Mountains (p. 121). Fracture openings such as joints and faults may yield sufficient water to supply small stock or domestic wells, but where younger formations are present, testing of them may be warranted before wells in the extrusive rocks are attempted. In localities such as some of the valleys in the vicinity of Cienega, the extrusive rocks may be the only rocks present for several hundred feet below the surface. In such places small quantities of water might be obtained from these rocks. As in other crystalline rocks, however, fractures generally decrease in size and number with depth, so that drilling to great depths is generally not advisable. In some localities, such as the uplands north, south, and east of Cienega, the base of the Ancha formation is above the water table; therefore, the extrusive rocks are the only possible sources of water supplies at moderate depths. The most favorable well sites are those at which the well may intersect the zone of saturation in fractured zones of the extrusive rocks below the stream grades. In general, the extrusive rocks probably are more favorable for successful wells than are the predominantly clayey and silty sandstone beds of the underlying Galisteo formation, but they probably are not as permeable as some of the sandstone beds in the Galisteo formation.

### INTRUSIVE ROCKS

The major outcrops of intrusive rocks in the area investigated are at the north tip of the Cerrillos. These rocks intrude the extrusive rocks and older formations near the Jarrett ranch headquarters (vicinity of sec. 8, T. 15 N., R. 8 E.) and at Cienega. Their surface outcrops in the latter places may be due largely to upfaulting. Geophysical studies suggest that other intrusive bodies may be covered by the Ancha formation.

As the rocks cut by the intrusives are probably no more permeable than are the intrusive rocks themselves, the direct effect of the intrusives on ground-water movement in older rocks is probably slight. Although the intrusives do not cut the Ancha formation, locally they have an indirect effect on ground-water movement in the Ancha formation. The intrusive rocks are harder and more resistant to erosion than most of the rocks they cut; hence, they have remained as hills standing above the pre-Ancha erosion surface. The intrusive rocks northeast of the Jarrett ranch headquarters form a bedrock dam to ground-water flow in the overlying Ancha formation. A partially exhumed gap, eroded in the intrusive body before the Ancha formation was deposited, allows ground water in the Ancha formation east of the intrusive remnants to pass through and emerge as springs and seeps on Bonanza Creek and Alamo Creek (southwest of Santa Fe).

*Ground-water recharge and movement.*—Recharge to the intrusive rocks is by direct precipitation on the outcrop area, downward percolation of water from the overlying Ancha and younger sediments, and inflow from older rocks. Ground water in the intrusive rocks moves from the high outcrops toward the nearby drainage courses, such as Alamo and Galisteo Creeks. The interstices through which the water moves are joints and faults. Hence, the principles of ground-water occurrence are similar to those outlined generally for the Precambrian rocks (p. 121). Movement is slow, water-table gradients are high, and the water table is near the surface in most of the lower areas. Although the potential yields of wells are small, deep shafts and extensive workings of the mines and prospects in the area encounter water in moderately large quantities because of the large number of fractures intersected. Technically, mine drainage should not be difficult, although the continuous pumping necessary to dewater deep workings might be an economic problem. Pumping continuously for long periods would eventually dewater surrounding rocks and decrease the amount of pumping needed to maintain a given lowering of water level. Pumping from sumps probably would be more effective than that from wells because of the great extent of existing workings. However, wells could be drilled in the sumps to provide additional drawdown locally. In general, the effects of such pumping are similar to the effects of pumping ordinary wells, but the storage coefficients and transmissibilities are likely to be low and the cones of depression to be steep sided.

*Discharge.*—Ground water from the intrusive rocks locally discharges into overlying Ancha and younger sediments, and into alluvium in the deeper valleys such as those of Alamo and Cienega Creeks in areas near the upland outcrops of the intrusives. The total discharge from the intrusive rocks is probably small compared to that from the overlying Ancha formation.

*Utilization.*—Water from the intrusive rocks is generally suitable in quality for stock and human consumption, though it is somewhat hard. Quantities of water sufficient only for ordinary domestic or stock use are obtained from wells in these rocks, but, even so, yields from these rocks are probably higher than from adjacent shales and siltstones of Cretaceous and early Tertiary age.

#### CIENEGUILLA LIMBURGITE OF STEARNS

The Cieneguilla limburgite of Stearns (1953b) is known to exist in the Santa Fe area only at the extreme west edge of the Turquoise Hill quadrangle. South of these outcrops it has probably been removed by erosion in Santa Fe and post-Santa Fe time; but it may exist below the Quaternary gravels and basalt cap of the lava mesa west of the Santa Fe River, and below the Ancha formation north of Cienega. Because of its small areal extent within the area investigated and its low permeability, the formation is of little practical importance as an aquifer. It may extend beneath the Ancha across the northern parts of T. 15 N., Rs. 8 and 9 E., where it may form part of the pre-Santa Fe bedrock floor.

Its role in forming the floor of the zone of saturation in the overlying Ancha formation is well illustrated in the small tributary to Cienega Creek in sec. 5, T. 15 N., R. 8 E., and in the Santa Fe River valley below Cieneguilla. In both these localities the position of the impervious limburgite below the Ancha causes ground water in the Ancha to discharge through springs and seeps to the surface streams.

*Ground-water recharge and movement.*—Although some precipitation may occasionally enter the limburgite directly, most of the recharge occurs by downward leakage from the overlying Ancha formation.

*Discharge.*—Ground water from the limburgite probably discharges to the west, toward the Rio Grande valley, either by outflow to overlying sediments or directly to the surface.

*Utilization.*—As the low permeability, low storage coefficient, and small areal extent of the limburgite make it a poor source of ground water, the zone of saturation of the overlying Ancha formation is a more promising source than the limburgite. Where no water is available from the Ancha formation, as is probably the case in the vicinity of sec. 31, T. 16 N., R. 8 E., wells in the limburgite should encounter water at and below the general level of Cienega Creek and the Santa Fe River, but the yields may be insufficient even for ordinary stock and domestic supplies.

## SANTA FE GROUP

### TESUQUE FORMATION

The major part of the Tesuque formation consists of reddish brown and pinkish-tan silty sand and gravel derived largely from the granite and gneiss of the Sangre de Cristo Mountains to the east. Near the base of the formation is an interbedded gray unit of tuff, clay, silt, and conglomerate 50–530 feet thick. This unit, the Bishops Lodge member, is poorly sorted, contains a large proportion of silt, is firmly compacted, and consists of particles derived predominantly from gray intermediate volcanic rocks. This sequence is overlain by several thousand feet of firmly compacted silty and gravelly sand and fine-grained sandtsone which crop out in the hills northwest of the Santa Fe River. These sediments above the Bishops Lodge member compose the undifferentiated major portion of the Tesuque formation. An estimated 900 feet of moderately well sorted, nearly uncemented sand, present in the silty basal portion of the Tesuque formation upstream from Cieneguita, may represent an ancient, unusually persistent stream channel.

*Ground-water recharge and movement.*—A large proportion of the recharge to the Tesuque formation probably occurs by infiltration of the perennial flow and frequent flood flow and snowmelt runoff of Tesuque and Little Tesuque Creeks, the Santa Fe River, and Arroyo Hondo, and of occasional flood flows of many other arroyos. The more porous and permeable Ancha formation, and terrace, flood plain, and channel deposits in the valleys, play a large part in retaining and spreading surface flow over a large area, so as to facilitate infiltration into the underlying Tesuque formation. Because of the generally steep slopes characteristic of its outcrop area, any appreciable direct recharge from rainfall on the Tesuque formation or overlying materials probably occurs only in years of heavy, well-distributed rainfall, such as 1941.

Contours on the piezometric surface of the Tesuque formation (pls. 6, 7) show ridges under Tesuque Creek, the Santa Fe River, and Arroyo Hondo, indicating recharge from these three sources. Some quantitative estimates of surface flow, recharge, and discharge of the Tesuque formation are given in the sections on the hydrologic cycle, pages 153–203.

Water that enters dipping beds and lenses of the Tesuque formation moves generally downward parallel to the bedding, because the permeability of these sediments is greatest parallel to the bedding. After reaching the zone of saturation, water then moves mainly in the direction of the slope of the piezometric surface, which in the area north of the Santa Fe River is generally northwestward in the general direction of the dip of the Tesuque formation. As

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the Tesuque formation dips westward and northwestward to areas of discharge along the Rio Grande, more steeply than the slope of the piezometric surface, water must move across the dipping beds in order to discharge, even though the permeability across beds of the Tesuque formation is low. The steep gradients of the piezometric surface of the Tesuque formation (50 to more than 100 feet per mile) are due mainly to the movement of water across, rather than parallel to, the dipping beds, and thus do not generally indicate the transmissibility of individual beds.

*Discharge.*—Ground water in the Tesuque formation north of the Santa Fe River discharges principally to the Rio Grande. However, because of certain geologic complexities, some ground water discharges at places other than the Rio Grande channel. These areas of natural discharge include springs and seeps at Cieneguita, Agua Fria, and Canoncito in the deep canyon near the mouth of Canada Ancha. In all these areas, that portion of the spring flow which is not evaporated or transpired returns to the Tesuque formation downstream from the springs.

The discharge at Cieneguita is probably the result of impedance of ground-water flow through the permeable sand section of the Tesuque formation by compact red conglomeratic silt which crops out in the channel of the Santa Fe River just below the west limit of Santa Fe. The native growth of cottonwoods, the emergence of ground water, and the shallow water table in the Tesuque formation upstream—all indicate the existence of the partial barrier. Probably some ground water leaks through the barrier at depth, as well as flowing down the channel cut into it. Downstream from the barrier the ground-water discharge probably returns to the Tesuque formation, as the water table there is deep again. Similar conditions prevail at Agua Fria, where also the ground water in a sandstone of the Tesuque formation flows across a barrier. The overflow emerges in the Santa Fe River channel because it is the lowest possible overflow line in the area. Similar springs occur in the Rio Tesuque valley north of the Santa Fe area.

Much nearer the Rio Grande, the dike feeder for the thick lava flow that forms the north bluff of a canyon of Canada Ancha, in sec. 12, T. 18 N., R. 7 E., blocks the westward flow of ground water in the Tesuque formation, causing it to emerge in Canoncito Spring (18.7.12.244) in the channel of Canada Ancha. Water from the spring, forming a short perennial stream, disappears by downward percolation downstream from the dike, and eventually discharges to the Rio Grande. Nearly continuous seeps and springs along the Rio Grande, and invisible accretion to the flow of the river itself, probably represents the larger part of the natural discharge from the Tesuque formation north of the Santa Fe River.

Water that enters the Ancha formation south of the Santa Fe River percolates downward into the Tesuque formation, where the Tesuque is present, and moves through the Tesuque formation toward the Cienega discharge area. In this area the ground water emerges through the overlying Ancha formation and discharges into the valley of the Santa Fe River at Cieneguilla, and into Cienega Creek and its tributaries in the Cienega area. Quantitative details of this discharge are discussed under "Hydrologic cycle."

Pumping of many domestic and stock wells and of some public-supply and irrigation wells in the Santa Fe area constitutes an appreciable artificial discharge from the Tesuque formation. Details of this artificial discharge and its quantitative aspects are given on pages 143–203.

*Utilization.*—In general, the Tesuque formation has only a moderate permeability; but as it is areally extensive, is very thick, has a relatively large recharge potential, and contains at least one unit of moderately high permeability; it is an important aquifer. Nearly everywhere in the mapped area the Tesuque formation is a better aquifer than the underlying older rocks and will yield at least sufficient water for ordinary domestic use. However, the more clayey or silty phases are not likely to yield sufficient water even for an adequate domestic supply, except to very deep wells having large pumping drawdowns. Only one phase is known to be adequate for large supplies (pl. 6 and p. 131). The more permeable phases of the Tesuque formation are in general sandy and poorly cemented. These poorly cemented strata require special well construction and development to prevent or reduce the entrance of sand into the well.

Except for a few large-capacity wells, the pattern of ground-water withdrawal from the Tesuque formation involves many small-capacity wells widely scattered in and around Santa Fe. This pattern represents what is probably the best possible way to achieve conservative use of ground water from a moderately permeable aquifer, for it leads to recovery of a large quantity of water without excessive local lowering of water levels.

The development of large-capacity wells for long-continued use is possible only in the permeable phase of the Tesuque formation (pl. 6). As this phase of the Tesuque formation is, at present, the only practical source for a supplementary municipal water supply for Santa Fe in dry years, it is probable that water levels locally will be lowered appreciably with future pumping, especially as several irrigation wells also are pumping from the same ground-water reservoir. Future recharge of excess surface water to the permeable phase of the Tesuque formation could lessen the decline of water levels appreciably, but it is probable nevertheless that lowering of the water level by future pumping will be somewhat greater than the lowering that resulted from the pumping during the 1950–51 drought. As the transmissibility, storage capacity, leakage and boundary effects, and geometry of the ground-water reservoir in the Tesuque formation in the Santa Fe area cannot be determined in detail from the data presently available, no quantitative estimates of future water-level lowering can be made, but some qualitative conclusions are given in the section on the effects of pumping (p. 178–180).

*Chemical quality of ground water.*—Water from wells in the Tesuque formation is of good quality, though hard. Dissolved solids (table 5) generally range from 175 to 320 ppm. Calcium and bicarbonate are the predominant constituents. The hardness is somewhat more variable than the dissolved solids, ranging generally from 121 to 232 ppm. In general, water in the more permeable parts of the formation appears to be softer than water in the less permeable parts.

Results for hardness and dissolved-solids content of waters from the Santa Fe group are plotted against the conductance in figure 26. The relation of the concentration of dissolved solids and the conductance is essentially linear in the range of concentrations present

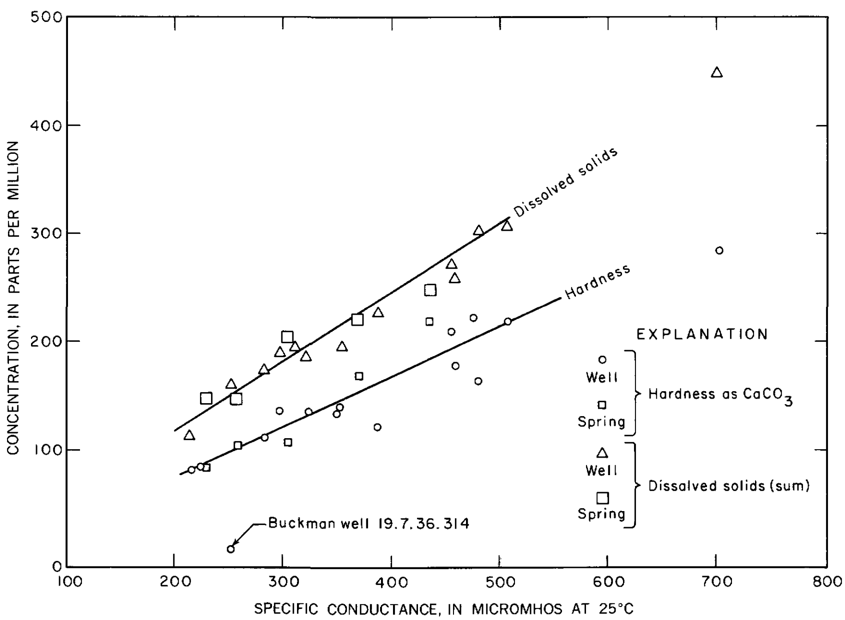


FIGURE 26.—Relation of specific conductance to dissolved solids and hardness, Santa Fe area, New Mexico. Waters are from springs and wells in the Tesuque and Ancha formations (see tables 5, 17, and 18).

in the Santa Fe area. An estimated figure for the dissolved solids, in parts per million, may be obtained by multiplying the conductance by the factor 0.6. The error is less than 10 percent. The small scattering of points in figure 26 is due largely to variation of the proportions of minor constituents. Scattering of the points for hardness is greater because hardness is not so closely related to conductance as is total concentration; therefore, the hardness cannot be estimated accurately from the conductance. The large departure from the curve of the point representing the hardness of the flowing artesian water at Buckman is probably due to exchange of calcium for sodium ions at depth, inasmuch as the well is near the discharge area of the Tesuque formation and water here is probably moving upward from deeper Tesuque strata into strata yielding water to the well. The abnormally high water temperature (60°F) for this locality is a further indication that the water comes from an appreciable depth.

## ANCHA FORMATION

The Ancha formation covers more than two-thirds of the area mapped and probably once was much more extensive than it is now. Parts of the Cerrillos and the Sangre de Cristo Mountains probably were never covered by sediments of the Ancha formation; however, they may have been, in part, the sources of these sediments. At the extreme west edge of the Agua Fria quadrangle, the Ancha formation is overlain by basaltic tuff and a basalt flow that originated in the Cerros del Rio to the west. Along the Santa Fe River and Rio Tesuque and Tesuque Creek, the Ancha formation is covered by Quaternary terrace gravels and channel deposits. Nearly everywhere in the Santa Fe area the Ancha formation is covered with a veneer of soil, slope wash, and alluvium laid down in several cycles of deposition.

The occurrence of ground water in the Ancha formation is controlled largely by differences in permeability between the Ancha and pre-Ancha formations. The pre-Ancha formations are grouped, according to their permeability, into those having moderate permeability (Tesuque formation) and those having only slight permeability (pre-Tesuque formations). All the known pre-Tesuque rocks underlying the Ancha formation are much less permeable than the Ancha formation as a whole, although some zones in the Ancha formation also may have a low permeability. Therefore, in the areas in which the Ancha formation is underlain directly by any of the pre-Tesuque formations, conditions are for the most part favorable to the accumulation of ground water in the overlying Ancha formation. Details of the extent of pre-Tesuque rocks beneath the Ancha are probably not necessary to an understanding of ground-water occurrence in the Ancha formation, because all these rocks have a much lower permeability than the Ancha formation. However, where these rocks occur beneath the Ancha, the topography of the "bedrock floor" is the major factor controlling the thickness of the zone of saturation in the Ancha formation. Insufficient reliable geologic, hydrologic, and geophysical data are available in this area to determine the details of the sub-Ancha topography, but the general form of this buried surface is shown in plate 5.

*Ground-water recharge and movement.*—Ground-water recharge into the Ancha formation is largely by infiltration from the perennial flow and flood runoff of arroyos that drain the lower foothills of the Sangre de Cristo Mountains and the erosion surfaces on the Ancha formation. To a lesser extent the formation is recharged by direct infiltration of rainfall into the aquifer in wet years. Direct recharge per unit area to the Ancha formation is likely to be greater than to the Tesuque formation because the Ancha formation is more permeable, has a sandy soil cover, and has much less surface relief. Quantitative data on the recharge to the Ancha formation are given on p. 153–203.

Contours of water levels in the Santa Fe group (pls. 6, 7) indicate that ground water moves from the eastern edge of the Ancha formation, where a large part of the recharge occurs, toward Alamo Creek, Cienega Creek, and tributaries of Galisteo Creek. Infiltration of local precipitation and runoff from the Cerrillos contributes additional ground-water recharge, which also moves toward the discharge areas in directions perpendicular to the water-level contour lines. The boundaries of the ground-water units are indicated on figure 31. These boundaries doubtless are controlled in part by highs on the bedrock floor underlying the Ancha formation.

The gradient of the water table in the Ancha formation decreases westward from more than 100 to less than 50 feet per mile. Water-table gradients are the reflection of the recharge rate, permeability, and cross section of flow. As the width of the cross section of flow remains relatively constant, the decrease in the water-table gradient from east to west must be due to increase in thickness of the Ancha formation or underlying Tesuque formation westward and (or) to greater permeability of the Ancha formation to the west. Geophysical data suggest that the Tesuque formation is present below the Ancha formation in the area of low water-level gradients in the Turquoise Hill quadrangle. This area, therefore, appears to be favorable for the development of large ground-water supplies.

*Discharge.*—Ground water discharges from the Ancha formation to Galisteo, Alama, and Cienega Creeks, and to the Santa Fe River. This discharge includes evapotranspiration from extensive seep areas along Cienega and Alamo Creeks, as well as flow from individual springs. As evaporation and transpiration rates in the winter months are low, the average discharge rate in the winter can be considered to be the average annual discharge rate from the Ancha formation. The winter surface flow of the Santa Fe River in sec 1, T. 16 N., R. 8 E., represents the aggregate westward discharge of all the Ancha formation south of the streamline in the latitude of Cieneguilla (pl. 6, fig. 4) and northwest of the streamline of Gallina Arroyo. Quantitative estimates of the unit ground-water discharge from this part of the Ancha formation are given on pages 189–192.

The areas of ground-water discharge from the Ancha formation are controlled by the depth of incision of arroyos into or through the Ancha formation, the topography of the bedrock floor in the vicinity of these incisions, and the lithology of the Ancha. Springs emerge where pre-Ancha valleys, cut into the bedrock floor, have been exposed along the sides of post-Ancha valleys. Where these post-Ancha valleys are cut below the water table in the Ancha, springs and seeps emerge into the valley floors and lower side slopes.

*Utilization.*—In the areas in which ground water is shown to occur in the Ancha formation (pl. 6, area 3b and parts of area 3a), stock and domestic supplies generally are easily obtained, although entrance of fine sand into wells may be troublesome. The section on well construction and development (p. 203) indicates methods of preventing or reducing the entrance of sand into wells. It is important to know the depth to the base of the Ancha formation in these areas. Where the Ancha formation overlies the pre-Tesuque rocks of the bedrock floor, the contact generally is easily determined from well logs, as the underlying materials in general are harder and darker in color than the materials of the Ancha formation. However, in many places where the Tesuque formation is present below the Ancha it is difficult to distinguish the Ancha from the Tesuque, even in outcrops (p. 46). It is particularly difficult to distinguish the formations by drill logs or drill cuttings. The approximate base of the Ancha has been inferred by electrical resistivity and seismic surveys (pl. 5) to be at the point where resistivity curves or seismic velocities at adjacent probe points become inconsistent. Selecting the approximate base of the Ancha by this method is possible even where the Tesuque formation underlies the Ancha because the Tesuque generally dips at an appreciably steeper angle than the Ancha formation, and different beds of the Tesuque "crop out" at different points on the pre-Ancha surface.

Although the withdrawal of small supplies of water from widely scattered wells in the Ancha and Tesuque formations has had no noticeable effect on the natural spring discharge to the Santa Fe River and its tributaries, future development of larger yield wells, particularly near the springs, will eventually reduce this natural discharge by an amount proportional to the development. However, many years might elapse before the effects could be measured.

### LAVA FLOWS

Although lava flows cover about 15 square miles near the west borders of the Agua Fria and Turquoise Hill quadrangles, they are not known to contain zones of saturation. Apparently the thick, columnar flows are sufficiently jointed and permeable to allow water to percolate downward to the underlying sediments. The depth to water is great in the areas covered by the lava flows because the land surface rises westward toward the Cerros del Rio, whereas the water table slopes westward and northwestward toward the Rio Grande. Reported depths to water in several wells passing through the lava flows (pls. 6, 7) indicate that feeders of the flows do impede direct movement of ground water to the river and divert the ground water around to the north and possibly to the south. Although it is possible that the flows locally uphold perched water bodies, no such conditions have been observed, nor are any high-level springs known on the east bluffs of White Rock Canyon. Therefore, water levels under the lava mesa generally must be very deep.

### POST-SANTA FE SEDIMENTS

#### TERRACE DEPOSITS

The sediments that are present beneath most terraces are lithologically similar to the Recent alluvium in the present stream channels and flood plains, although they locally contain coarser gravel and larger boulders than are common in the present channels. These terrace sediments, where present, occur as thin sheets that overlie the older rocks. They are hydrologically important near the mountain front, where they generally overlie the lower part of the Tesuque formation. There the streams have cut relatively wide valleys into the easily eroded but moderately permeable lower strata of the Tesuque (fig. 27). The lowest terrace gravels along the Santa Fe River are particularly interesting, for these gravels were the source of the springs utilized in early Santa Fe history (pp. 91–95).

Recharge to the terrace sediments occurs largely by infiltration from the Santa Fe River west of sec. 19, T. 17 N., R. 10 E., where the present channel locally does not cut to the base of older terrace deposits, and by local rainfall elsewhere. The basal part of the Tesuque formation has low permeability where it underlies the terraces in parts of secs. 24 and 25, T. 17 N., R. 9 E., and vicinity; consequently, water is perched or semiperched in the permeable

FIGURE 27.—Terrace gravels unconformable on conglomeratic and silty sandstone of the Tesuque formation. Santa Fe River near the Alto Street well, NW¼SW¼ sec. 23, T. 17 N., R. 9 E. View to north, showing westward dip of Tesuque in left side of photograph.

terrace sediments. The old springs in the vicinity of Cienega Street in Santa Fe probably represented discharge of the water in terrace-gravel lenses that were interbedded with impermeable carbonaceous swamp deposits. These deposits were exposed during excavations for the St. Vincent's Hospital addition at Palace Avenue and Cienega Street, in 1951. This area previously had been partly drained by trenches dug to the Santa Fe River and backfilled with boulders. In this and similar areas, ground water in the thin terrace sediments can be developed by means of large-diameter wells or infiltration galleries (horizontal wells), although continued increase in the diversion of water from the Santa Fe River may allow less recharge, with consequent failure of shallow wells and reduction of underflow.

### ALLUVIUM

The deposits of the lowest terrace are included with the Recent alluvium of the present stream channel of the Santa Fe River, although the surface-water level in the present stream channels is generally far below the lowest terrace surface (pls. 1–4). Careful examination of this lowest terrace and its historical record indicates that, at times of extreme flood, the lowest terrace is involved in the channel shifting and scour of the present cycle of erosion and deposition.

Further, buried channel fill below this flood-plain surface is still connected with the present channel both physically and hydrologically, and, where saturated, these deposits contain shallow semi-perched ground-water bodies along the Santa Fe River. In these areas, the water table in the underlying Tesuque formation is as much as 50 feet, or even more, below the land surface.

Recent alluvium is present in all the stream channels of the area. The Recent alluvium bears water along most of the course of the Rio Tesuque, Tesuque and Little Tesuque Creeks, and the Santa Fe River, and along the upper reaches of Arroyo Hondo, Canada de los Alamos, and some small tributaries of the Santa Fe River. Alluvium beneath the bottom lands of the lower Santa Fe River and alluvium along the lower courses of tributaries of the Santa Fe River in the Cienega area also bear water downstream from the points of discharge of ground water from the Ancha and Tesuque formations. The occurrence of water in the Recent alluvium depends on the following factors:

1. Permeability of underlying materials.
2. Amount of recharge available.
3. Permeability and transmissibility of the Recent alluvium.
4. Thickness of the alluvium.
5. Gradient of the stream valley.

In general, the thickness of alluvium is proportional to the size of the stream valley and drainage area, as the deposits are largely laid down in channels scoured during floods. The depth of scour depends on the relation of stream discharge, sediment load, and stream gradient (Leopold and Maddock, 1953), but no data on these points are available for this area.

*Ground-water recharge and movement.*—Recharge to the alluvium results largely from infiltration of flood flows in the ephemeral streams and of the perennial flow of spring-fed streams such as the Rio Tesuque and tributaries, the Santa Fe River, Arroyo Hondo, and Canada de los Alamos. Alluvium in tributaries of the Santa Fe River near Cienega receives recharge from perennial springs. In the areas where recharge is perennial, the water level in the alluvium probably is fairly constant, but in the areas where the recharge is from seasonal or flood flows the water levels probably fluctuate considerably.

In the larger arroyos and stream channels the alluvium is generally thick and permeable and has a large infiltration capacity. The rate at which water can be absorbed by these channels has not been measured, but the loss of flow by infiltration from the Rio Tesuque and its tributaries has been estimated from streamflow records (fig. 51 and p. 196–197).

The storage capacity of the stream-valley alluvium in the Santa Fe area is small—usually not much larger than the annual inflow; hence, the alluvium may nearly dry up in droughts, whereas very large ground-water reservoirs, such as the Ancha and Tesuque formations, are affected only slightly by ordinary droughts.

Water in the Recent stream alluvium moves downstream as underflow. Where the Recent alluvium overlies less permeable strata west of the mountain front, the lower part of the alluvium remains saturated even though water levels in the underlying strata are lower than water levels in the alluvium—that is, the water in the alluvium is semiperched, and it recharges the underlying strata. At localities where the alluvium is underlain by permeable strata, such as along most of the arroyos south of the Santa Fe River and west of the outcrops of Precambrian rocks, all or most of the underflow may move downward into the underlying strata, leaving the alluvium unsaturated most of the time. In some of the smaller arroyos, zones of saturation may exist only in wet seasons even where the alluvium lies on less permeable rocks.

*Discharge.*—Ground water in the Recent stream alluvium is discharged to underlying formations, to surface streams, and (by evapotranspiration) to the air. Loss to underlying formations probably constitutes the largest single type of discharge. It is also the largest source of recharge to the older, more extensive aquifers. It is not possible, however, with present available data, to measure or even estimate the amount of water recharged to and discharged from the alluvium.

*Utilization.*—The development of large supplies of ground water by means of wells in the Recent alluvium in even the larger valleys within the Santa Fe area is not generally feasible, because of the small areal extent and thickness of the alluvium. Also, the small storage capacity does not generally provide sufficient reserve for adequate supplies during drought years, when water is needed most.

Locally, water from Recent stream alluvium can be collected by means of infiltration systems of pipes trenched below the low-water level of water-bearing alluvium. Two such systems are in use by Tesuque Pueblo, in the Rio Tesuque just north of the Santa Fe area. A third, which was reported to have drained water from alluvium in the Santa Fe River channel in sec. 26, T. 17 N., R. 9 E. for orchard irrigation, was reported by the owner to have failed in 1945 and was replaced by a well. As nearby large-capacity wells were not yet in use by that time, and the increased surface-storage facilities on the upper Santa Fe River had not yet been completed, the cause of failure of the infiltration system was probably the severe drought of 1945 and the accumulated effects of changes in the pattern of diversion of streamflow which had been occurring for some years previously. Although the Tesuque Pueblo system is outside the Santa Fe area, discussions of records of the Tesuque Pueblo infiltration system are included in the section on the Rio Tesuque because these are the only data available on such systems, and the discharge of ground water from the alluvium there is closely related to the occurrence of ground water in the adjacent Santa Fe area. The rate of discharge from the infiltration system into Mitchell ditch bears a close relation to precipitation, the streamflow upstream, and the growing season, and probably also to pumping from wells in the valley.

Generally there is no surface indication of either the permeability or the thickness of the water-bearing alluvium, and in broad valleys such as those of the Santa Fe River and the Rio Tesuque, the present channel may not coincide with the deepest part of channels eroded during previous floods. Because of the mode of origin of the sediments, the permeability of the Recent alluvial deposits changes greatly within short distances, both horizontally and vertically. The topography of the bedrock floor is the controlling factor on the occurrence of ground water, provided that the bedrock floor is relatively impermeable and recharge is adequate to maintain a zone of saturation in the alluvium.

Presumably, the deepest channels in the older alluvium should contain the coarsest, most permeable sand and gravel channel fills, whereas fine-grained flood-plain deposits should occur beneath the somewhat higher areas bordering the old channels. Therefore, exploration for shallow ground-water supplies could be conducted logically by test drilling, by digging test pits or trenches, or by geophysical exploration to determine the bedrock topography in the vicinity of prospective well sites. The deepest channels not only have more permeable alluvium, but also have the thickest zones of saturation and allow greater water-table lowering during droughts.

Where the permeability of the alluvium is low and the saturated thickness is small, dug wells are probably better than small-diameter drilled wells during normal years. However, as wells can ordinarily be dug only a short distance below the water table in permeable materials, only a slight lowering of the water table is required to dry up such wells. Many shallow dug wells in Recent alluvium of the Santa Fe area went dry during the extended 1950–51 drought. As drilled wells can be put down any required distance below the water table, drilled wells of sufficient depth are more dependable in drought periods. The depth below the water table to which a well should be drilled depends on the permeability of the aquifer, the desired pumping rate, the drawdown of the water level in the well caused by pumping at that rate, and the thickness of the water-bearing alluvium. If possible, the well should be drilled to a depth below the water table equal to at least two or three times the drawdown in the initial test, in order to allow for future declines caused by pumping.

#### EOLIAN SEDIMENTS AND COVER

Eolian (windblown) sediments are thin and occur in isolated patches in the Santa Fe area. Generally they are moderately permeable but have no zone of saturation. Eolian deposits commonly form excellent recharge areas, however, as a relatively large proportion of the precipitation can percolate downward through the uniform dune sand to a depth that is beyond the reach of transpiring plants. Eolian sediments, nevertheless, are probably of little consequence to the occurrence of ground water in the Santa Fe area.

## HYDROLOGIC CYCLE

Hydrology is the study of water—its properties, distribution, and movement. The hydrologic cycle consists of three interrelated phases of movement of water: in the atmosphere, on the ground, and beneath the surface of the ground, as illustrated in figure 28. The hydrologic cycle embraces the sciences of meteorology, hydrology, and oceanography.

Air masses circulate over the earth in a pattern determined by many complex factors. While air masses are in contact with the oceans they absorb water evaporated from the ocean surface. Most of the precipitation upon land areas is derived from the moist maritime air masses. In the summer the moist air masses that reach the Santa Fe area come principally from the Gulf of Mexico; in the winter the moist air masses are largely from the Pacific Ocean.

Only a small part of the precipitation upon the land surface in the Southwest runs off directly into drainageways, thence into rivers, and ultimately to the oceans from which it came. Surface runoff is relatively large when rainfall intensities are high, as in summer thunderstorms, but small or nonexistent when small amounts fall or when the intensity is lower than the infiltration capacity of surface materials. The largest part of the precipitation (up to an estimated 96 percent in the Santa Fe area, according to altitude) is returned to the atmosphere by evapotranspiration, but some water absorbed by the surface soil, alluvium, or rock crevices is able to escape evapotranspiration. This water recharges the ground-water bodies. Whenever the infiltration capacity of the surface materials is exceeded, runoff of water into surface drainage channels can occur.

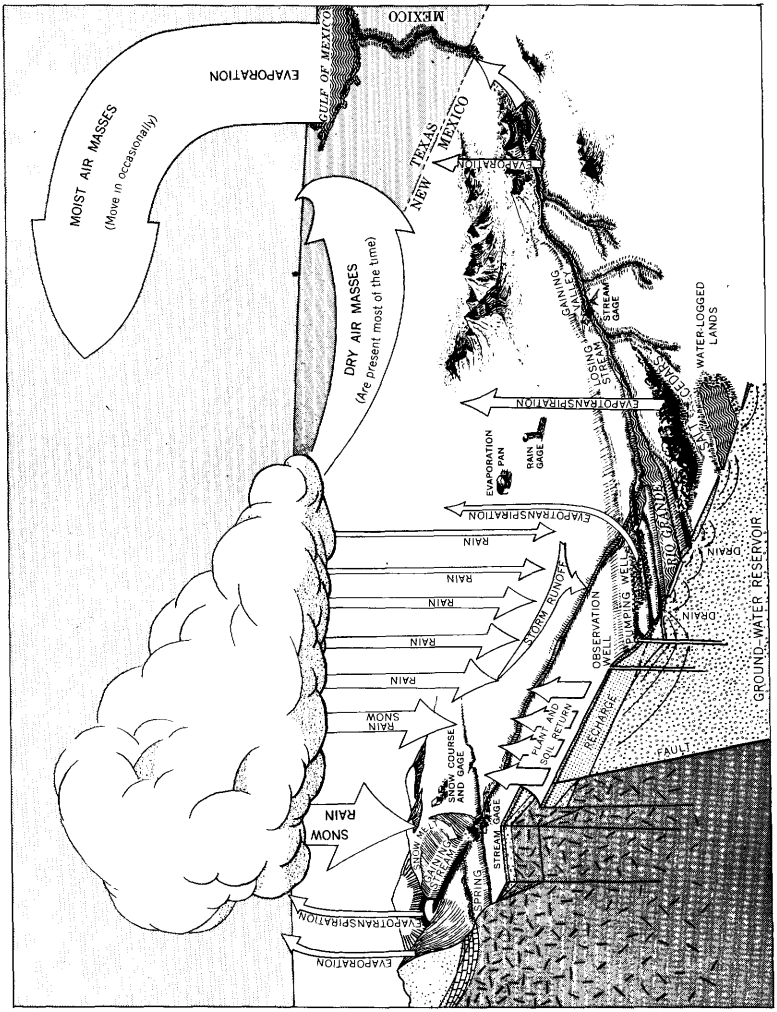


FIGURE 28.—Hydrologic cycle in the upper Rio Grande drainage basin, New Mexico. (Courtesy of New Mexico State Engineer Office.)

Ground water moves laterally in directions controlled by the relative location and elevation of recharge and discharge areas and the character and structure of the aquifer. If the recharge from precipitation moves through shallow, generally temporary saturated zones of small extent and discharges to adjacent streams quickly, it is considered a part of the direct runoff. It is sometimes called "subsurface storm flow." Recharge to deeper, more extensive aquifers takes a longer time to reappear as spring or stream flow and is then called ground-water runoff. Ground-water runoff from the principal aquifers in the Santa Fe area constitutes the base flow of the streams. Except for snowmelt and releases from reservoirs, it constitutes the entire flow in dry weather. Variations in the amount of ground-water discharge to streams are smaller than variations in the discharge of surface water to streams by direct runoff. Base flow is difficult to compute with accuracy, as representative daily records of precipitation within the drainage basin above the stream-measurement point are required, as well as records of daily discharge.

The hydrologic cycle in the vicinity of Santa Fe may be divided into two main phases: (a) precipitation, runoff, recharge of ground water, evapotranspiration, ground-water movement, direct runoff, snowmelt, and ground-water discharge in the surface-water and ground-water basins of streams in the Precambrian rocks of the Sangre de Cristo Mountains, and (b) precipitation on and recharge of ground-water basins in the remainder of the Santa Fe area from rain and snowmelt and by surface runoff from the adjacent Sangre de Cristo Mountains, evapotranspiration, ground-water movement in extensive aquifers, and surface- and ground-water discharge to the Rio Grande and to the valleys of its major tributaries in the Santa Fe area. Small-scale "subcycles" exist locally within each of these two main phases.

In later sections, the course of water in each of the surface-water and ground-water basins in phase "a" will be traced and followed through phase "b" to what constitutes the end of the cycle insofar as the Santa Fe area is concerned—the atmosphere and the Rio Grande. Major differences in geology and altitude between these mountain and plains areas produce significant differences in all the components of each phase, in the total water yield of each, and in the proportions of surface and ground water composing the total yield. These differences will be discussed in following sections, as listed in table 8.

The data in table 8 were derived from tables 10 and 11, and from accompanying discussions; they are highly generalized.

TABLE 8.—*Phases of the hydrologic cycle in the Santa Fe area, New Mexico*

| Season and component of hydrologic cycle | Mountain phase (altitude 7,500–12,409 feet) | Plains phase (altitude 6,000–7,500 feet) |
|---|---|---|
| Annual: | | |
| Precipitation (average). | Ranges with altitude, 16–58 inches; mostly in winter. | Ranges with altitude, 10.5–16 inches; about one-half in the summer months. |
| Vegetation | Forest | Grassland, scattered juniper and pinyon. |
| Total runoff | Ranges with altitude, 7–27 percent of precipitation (64–370 acre-feet per square mile, largely snowmelt). | 4 percent of precipitation (25–34 acre-feet per square mile, almost entirely ground water). |
| Summer (*June–Sept.*): | | |
| Precipitation (average). | Ranges with altitude, 7.2–22 inches, mostly in thunderstorms, but less intense than in plains phase. | Ranges with altitude, 5–7.2 inches, mostly in short, high-intensity thunderstorms in July and August. |
| Evaporation rate | Moderate | High. |
| Total runoff per unit area. | Low, except in extremely wet years, or when heavy winter snows remain late into spring and summer. | Runoff is principally ground water; see below. Most of direct runoff occurs after thunderstorms in July and August. Surface runoff passing entirely through area less than 1 percent of precipitation. |
| Soil moisture | Deficient, especially in late summer | Deficient. |
| Evapotranspiration | High (most of the 14.4–19.1 inches that does not run off) because of heavy vegetation, despite moderate evaporation rate. | High (most of the 12.5–14.4 inches that does not run off) because of high evaporation rate. |
| Infiltration | High because of absorbent forest soils and surface mulch. | Probably moderate on sandy soils, low on clayey soils. |
| Ground-water recharge. | Low because of high plant usage of soil moisture (the bulk of the 14.4–19.1 inches is evapotranspired annually, mostly in summer). | Recharge occurs principally in extremely wet years; some from flood runoff in most years. |
| Winter (*Oct.–May*): | | |
| Precipitation (average) | Ranges with altitude, 8.8–35.2 inches; mostly snowfall. | Ranges with altitude, 5½–8.8 inches; partly rain, partly snow. |
| Evaporation rate | Very low | Low. |
| Snowpack | Above 10,000 feet accumulates from November to March or April, melts March–June. From 7,500 to 10,000 feet snowpack varies from month to month and is negligible in some years. | Snow on ground for few days at a time only after storms. |
| Runoff per unit area | High. Most of annual runoff occurs in late winter, spring, and early summer from melting snow. | Runoff is principally ground water. Direct runoff negligible in most years. |
| Soil moisture | High | High to moderate. |
| Infiltration | In cold weather, negligible at high altitudes, occasionally below 10,000 feet; in spring, extremely high, especially above 10,000 feet. | Unknown. |
| Ground-water recharge. | Extremely high in spring, but water largely discharged into streams within short distance. | Direct recharge occurs only after extremely heavy precipitation. Average winter recharge is negligible. |

## PRECIPITATION

In this region two types of storms generally produce precipitation. During the summer, frequent thunderstorms, which develop in moist tropical air masses from the Gulf of Mexico, result in isolated downpours or a series of local heavy showers. The thunderstorm activity of the Santa Fe area is apparently influenced by the altitude and position of the Sangre de Cristo Mountains. In the winter the region is invaded by polar air masses and tropical Pacific air masses, as well as tropical continental masses, and is also traversed by extratropical storms. The interaction of these wintertime masses, strongly aided by the altitude and position of the Sangre de Cristo Mountains—the southern extension of the Rocky Mountains—causes precipitation, usually in the form of snow, especially above an altitude of 6,000 feet.

In the Santa Fe area the only long records of precipitation available have been collected in or near the city of Santa Fe. The longest precipitation record is that for the city of Santa Fe, which was started in 1850 by medical officers of the U.S. Army. The data are fragmentary for the first few years, but since September 1852 the record is continuous except for the year 1862, when Santa Fe was taken by the Confederate Army, the years 1866, 1867, and 1883–4, and several months in 1941, 1942, and 1944.

In 1941 the U.S. Weather Bureau discontinued the precipitation station at Santa Fe, altitude about 7,000 feet, and established one at the Municipal Airport about 6 miles southwest of Santa Fe, at an altitude of 6,675 feet. A few years later the station was moved to the new Municipal Airport about 9½ miles from Santa Fe, at an altitude of 6,312 feet. The station at Santa Fe was reestablished in 1942. All available records of the precipitation in Santa Fe and at the airports were compiled for this investigation from U.S. Weather Bureau records.

Records of precipitation were collected by the U.S. Forest Service at Granite Point ranger station (Santa Fe Canyon precipitation station), a few hundred feet upstream from the canyon stream-gaging station on the Santa Fe River. The records, totaling 13 years, were collected during two separate periods. Precipitation records currently being collected at Elk Cabin, upstream from Granite Point and 1,000 feet higher, also were compiled for this report. However, these two stations and the Santa Fe precipitation station are too close geographically, and too low in altitude, to serve as a basis for defining the distribution of precipitation over the upper Santa Fe River basin, which ranges in altitude from 7,718 to 12,409 feet.

Because of the lack of precipitation stations at various altitudes in the immediate vicinity of Santa Fe, records of precipitation were assembled from locations where the topography and exposure are similar to those at the same altitudes in the Santa Fe area, in order to supplement the records taken in and near Santa Fe. A number of precipitation records at stations in north-central New Mexico, having altitudes between 5,000 and 10,200 feet, were studied. Most of the records from places west of the Rio Grande and some on the east were eliminated from consideration because of a difference in exposure to air masses or because some met the criteria for but one of the two type of seasonal storms. The stations finally selected as being indicative of precipitation near Santa Fe are listed in order of altitude in the following table.

655033 O—62——11

TABLE 9.—*Precipitation at selected stations in north-central New Mexico*

[Data from U.S. Weather Bureau, Climatic summary of the United States. Station elevations in part corrected since dates of publication]

| No. | Location | | Years of record | Periods of record | Altitude (feet) | Mean precipitation | | |
|---|---|---|---|---|---|---|---|---|
| | Place | County | | | | June–Sept. | Oct.–May | Annual |
| 1 | Anchor mine | Taos | 10 | 1911–20 | 10,200 | 13.73 | 20.43 | 34.16 |
| 2 | Rea Ranch | Torrance | 8 | 1912–19 | 9,200 | 11.62 | 16.58 | 28.25 |
| 3 | Bateman Ranch | Rio Arriba | 22 | 1909–30 | 8,900 | 9.49 | 13.95 | 23.44 |
| 4 | Red River | Taos | 25 | 1906–30 | 8,676 | 9.90 | 12.63 | 22.53 |
| 5 | Taos Canyon | do | 22 | 1909–30 | 8,400 | 8.95 | 11.14 | 20.09 |
| 6 | Tres Piedras | do | 31 | 1889–90<br>1896–98<br>1905–30 | 8,076 | 7.68 | 8.58 | 16.25 |
| 7 | Truchas | Rio Arriba | 22 | 1909–30 | 8,000 | 8.01 | 7.79 | 15.80 |
| 8 | Santa Fe Canyon | Santa Fe | 13 | 1910–16<br>1923–28 | 8,000 | 8.36 | 9.33 | 17.69 |
| 9 | Santa Fe | do | 81 | 1850–1930 | 7,013 | 7.19 | 7.08 | 14.27 |
| 10 | Taos | Taos | 38 | 1889–96<br>1901–30 | 6,950 | 5.85 | 7.15 | 13.00 |
| 11 | Estancia | Torrance | 26 | 1904–21<br>1923–30 | 6,140 | 6.88 | 6.35 | 13.30 |
| 12 | Espanola | Rio Arriba | 33 | 1895–1902<br>1905–29 | 5,590 | 5.00 | 5.05 | 10.05 |
| 13 | Albuquerque | Bernalillo | 60 | 1850–79<br>1889–90<br>1892–1930 | 5,196 | 4.33 | 3.73 | 8.06 |
| 14 | Bernalillo | Sandoval | 13 | 1889–92<br>1895–1901<br>1923–24 | 5,050 | 3.75 | 4.41 | 8.16 |

For each of these stations the data for the June–September, the October–May, and the annual periods were plotted against the corresponding altitude on a semilogarithmic chart, as shown on figure 29. The general alinement of the points representing the altitude-precipitation relations for the period October–May is very good for data of this type. The prevailing storms during this period originate from Pacific maritime masses and the plotting shows that most of the locations have similar exposure to such storms. The principal deviations from the alinement are Tres Piedras (no. 6), Truchas (no. 7), and Albuquerque (no. 13). Tres Piedras is on the lee or east slope of the San Juan Mountains, west of the Rio Grande, and is in the rain shadow of the prevailing storms. Truchas is in an open plain. The Albuquerque station is about 14 miles west of the highest part of the Sandia Mountains.

During the period June–September the altitude-precipitation relations are more erratic. The high precipitation shown at Estancia (no. 11) is due to exposure to Gulf tropical air masses, which move up the Pecos Valley from the southeast more frequently than they move into the Rio Grande Valley.

The correlation curves shown in figure 29 were determined graphically. They represent the relation of mean precipitation to altitudes from 5,000 to 12,000 feet. Extrapolation of the annual curve

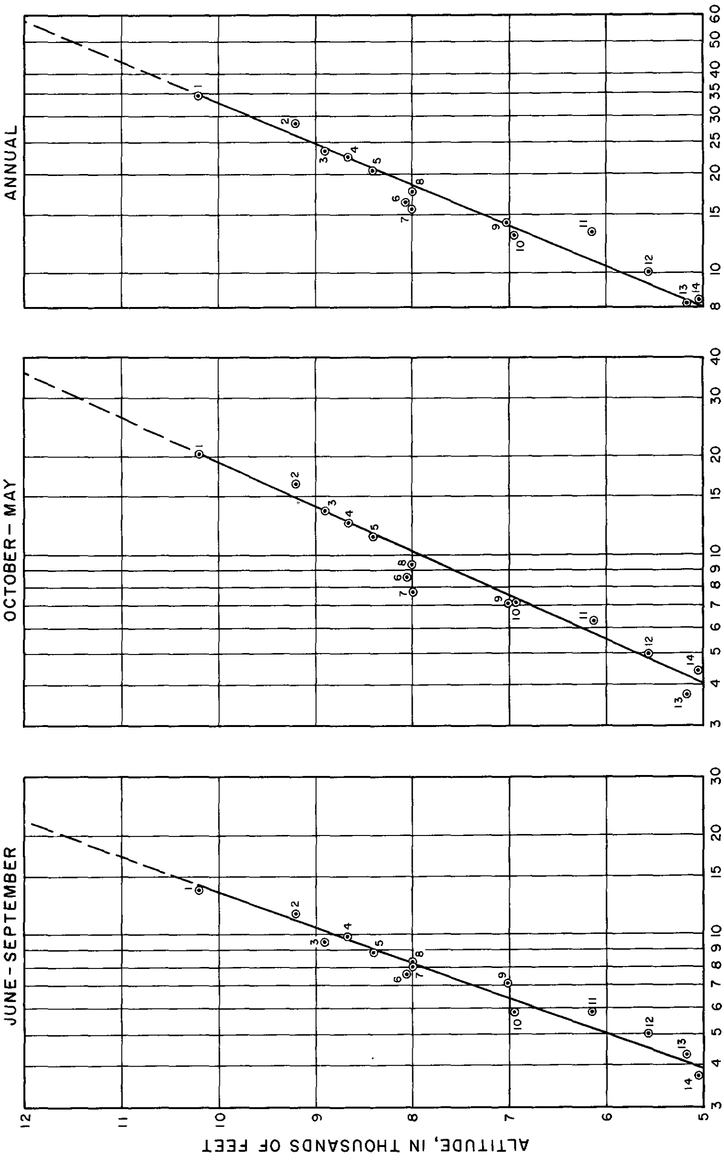


FIGURE 29.—Relation of precipitation to altitude in north-central New Mexico. Numbers at points represent stations listed in table 9.

suggests that precipitation on higher parts of the Sangre de Cristo Mountains is probably about 58 inches.

## SURFACE WATER

By E. L. BARROWS and ZANE SPIEGEL

### SURFACE-WATER BASINS

The Rio Grande is the master stream of the area. Although it does not flow through the Santa Fe area, instead forming the western border of the area as defined for this report, surface-water and ground-water contributions to the Rio Grande from the latitude of Santa Fe are a part of the overall water economy of New Mexico. The Santa Fe River, which drains about 160 square miles or 66 percent of the Santa Fe area, is the most important stream within the Santa Fe area. Canada Ancha drains 22 square miles of the Agua Fria quadrangle, and some northern tributaries of Galisteo Creek drain 55 square miles of the Seton Village quadrangle. The Rio Tesuque and its tributaries, however, which drain much of the high mountains near Santa Fe, are second to the Santa Fe River in importance to the economy of the Santa Fe area, even though they drain only 9 square miles of the Santa Fe area. Surface-water basins and their areas in the vicinity of Santa Fe are shown on figure 30.

### STREAMFLOW RECORDS

Many records of streamflow in the vicinity of Santa Fe have been collected for varying periods of time. These records are contained in many published and unpublished papers issued by the U.S. Geological Survey and the State Engineer of New Mexico. Tables 19 and 20 index the published data.

Time was not available for complete evaluation of all the existing streamflow records of the Santa Fe area, but the most important records are discussed in the following sections. Since 1926 the flow at the station on the Santa Fe River has been controlled by McClure dam (completed in 1926; raised in 1935 and again in 1947). Records of the discharge of Santa Fe River collected at several sites near Santa Fe have been reviewed and revised where necessary in connection with a project for compilation of records through September 30, 1950. For the purpose of this report, these records were adjusted for storage changes and evaporation, and the resulting computed natural flows are shown in table 21.

As it is difficult to compute or evaluate the annual water yields of ground-water basins from the meager ground-water data available for most of the Santa Fe area, the quantitative study of water yield in the following sections of this report has been done on the basis of surface-water records. The delineation of ground-water

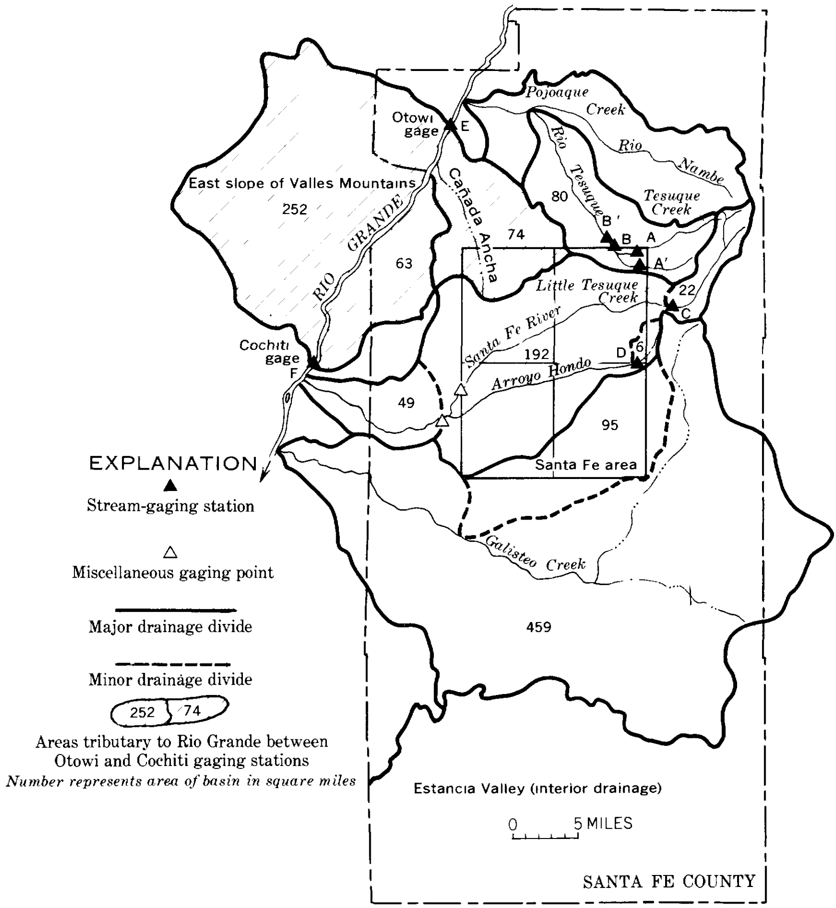


**Figure 30.**—Surface drainage areas near Santa Fe, N. Mex. Letters by stream-gaging stations are indexed in table 19.

reservoirs, however, makes it possible to make preliminary estimates of the annual recharge of ground water per unit area in the vicinity of Santa Fe, and to determine qualitatively the effects of ground-water and surface-water development on the natural water equilibrium.

## GROUND-WATER BASINS

Three ground-water units are recognized within the area investigated (pl. 7, fig. 31). These units, respectively the northern unit, Cienega unit, and southern unit, are defined on the basis of the conclusion that the ground-water reservoirs contributing to each of the three areas of ground-water discharge (which, respectively, are along the Rio Grande, the Santa Fe River, and Galisteo Creek) can be defined by drawing streamlines of ground-water flow separating

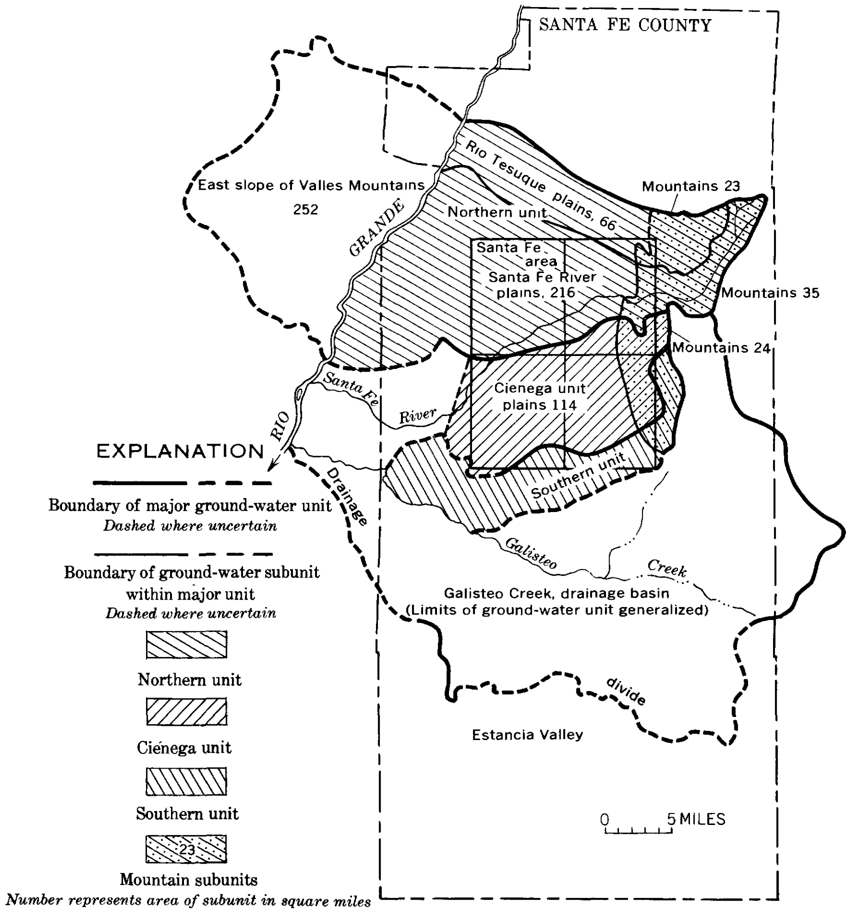


FIGURE 31.—Ground-water units near Santa Fe, N. Mex.

the three main discharge areas. The bounding streamlines are extended eastward across the plains perpendicular to the water-level contours to the points where they meet the ground-water divides in the mountains. Ground water entering aquifers within each of the basins moves perpendicular to the water-level contours to the respective major discharge areas without crossing the bounding streamlines drawn on plates 6 and 7, and figure 31. These boundaries are not generally defined by bedrock divides on the plains (although they may be locally), and thus could be shifted by future pumping. The boundaries are defined by topographic divides in the mountains. Although ground water in the respective basins is assumed not to cross the bounding ground-water streamlines, surface drainage (Santa Fe River) from the northern unit does cross the Cienega ground-water unit, and probably provides some recharge to it.

Portions of both the mountains and the plains are represented in each ground-water unit. The geology and ground-water movement are generally similar throughout the mountainous part of each unit, except for the larger amount of glacial materials in the higher valleys, and from unit to unit. However, the rocks and structure of the plains differ considerably from one to another of the three ground-water units, resulting in important differences in the directions of ground-water movement and the areas of ground-water discharge.

## QUANTITATIVE RELATIONS

### SANTA FE RIVER

#### UPPER DRAINAGE AREA

By E. L. BARROWS and ZANE SPIEGEL

##### STREAM MEASUREMENTS

Stream gaging on the upper Santa Fe River, or that reach above Santa Fe (published as Santa Fe Creek prior to October 1953), began when a staff gage was established on the Don Gasper Street bridge in Santa Fe on May 31, 1907. The data obtained were fragmentary, and although estimates of flow from June 1907 to April 1910 were made and published, these estimates must be considered only approximate. After April 1910 the station was practically abandoned, although it was not actually discontinued until November 1912. As it was located below Twomile reservoir and below diversions for the city water supply and several irrigation ditches, and as there are no records of changes in storage or of diversions, the runoff record for this station is of little practical value.

On August 29, 1910, a station was established in the canyon at Monument Rock, 7 miles above the Don Gasper Street bridge and above all diversions. This station existed until August 7, 1911, but, owing to the paucity of data in the latter part of the period, only the records of flow from September to December 1910 were computed and published (see table 19).

A new station, equipped with an automatic water-stage recorder, was established in the Santa Fe River Canyon on April 24, 1913. The site was 5 miles east of Santa Fe, 1.5 miles above Twomile dam, and 0.25 mile above the Santa Fe Water and Light Co.'s power ditch. This station was operated until the recording gage was destroyed by vandals in November 1930. The drainage area above this station was 22 square miles. When the station was reestablished in 1931 it was moved 1.5 miles upstream to a site 0.3 mile below Granite Point (now McClure) dam, which had been constructed in 1926. The altitude of the reestablished station is about 7,718 feet, and the drainage area of the basin above the station is 18.2 square miles.

Before Granite Point dam (now McClure dam) was built, the flow passing the gaging stations represented natural discharge ("virgin flow"). After construction of the dam, however, the flow of the stream was controlled by the operation of the dam, and the flow was reduced by evaporation from the surface of the impounded water. As no records of changes in the amount of storage in the reservoir are available for the period 1926–31, the recorded flow at the stations could not be adjusted for reservoir operation during this period. Although the records for some individual months in these years may not represent virgin flow accurately, the annual discharge during the period is substantially correct, because the reservoir capacity was only 561 acre-feet. The recorded flow after 1931 has been adjusted for reservoir operation and evaporation to obtain a computed natural flow. The adjusted runoff, by months, is shown in table 21. The values of evaporation, by months, used in computing the evaporation losses from the reservoirs are shown in figure 39.

#### PRECIPITATION AND WATER YIELD

The topographic map of the Santa Fe sheet shows the mountainous portion of the drainage basin in sufficient detail to permit computation of the areas at various altitudes. The areas between 7,718 feet (the altitude of the present gaging station) and the divides are shown in the first two columns of table 10.

From the areas in each altitude zone and the relation of altitude and precipitation (fig. 29), the areal distribution and average amount of precipitation on the drainage basin were estimated. The data and the results of the computations are given in table 10.

TABLE 10.—*Estimates of average annual precipitation on the upper Santa Fe River drainage basin*

| Altitude (feet) | Area (acres) | Mean precipitation | | | | Volume of water supplied to basin | | |
|---|---|---|---|---|---|---|---|---|
| | | Oct.-May | | June-Sept. | | Oct.-May | June-Sept. | Total |
| | | (inches) | (feet) | (inches) | (feet) | acre-ft | acre-ft | acre-ft |
| 7,718- 8,000 | 290 | 9.9 | 0.82 | 7.9 | 0.66 | 200 | 200 | 400 |
| 8,000- 9,000 | 4,360 | 12.0 | 1.00 | 9.3 | .77 | 4,400 | 3,400 | 7,800 |
| 9,000-10,000 | 3,360 | 16.4 | 1.37 | 11.8 | .98 | 4,600 | 3,300 | 7,900 |
| 10,000-11,000 | 2,200 | 22.5 | 1.88 | 15.1 | 1.26 | 4,100 | 2,800 | 6,900 |
| 11,000-12,409 | 1,450 | 32.8 | 2.73 | 20.0 | 1.67 | 4,000 | 2,400 | 6,400 |
| Total | 11,660 | | | | | 17,300 | 12,100 | 29,400 |
| Percent | | | | | | 59 | 41 | 100 |

The computed precipitation is equivalent to about 26 inches over the drainage basin. The water yield by surface runoff, including ground-water discharge into the streams, averages 6.9 inches, or about 27 percent of the precipitation (table 11). This table shows

TABLE 11.—*Annual average water yield of drainage basins near Santa Fe, N. Mex.*

| Drainage basin | Area | | Estimated average precipitation (inches) | Years record | Annual average water yield [1] | | | | Altitude (feet) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | (sq mi) | (acres) | | | (acre-ft) | (inches) | Percent of precipitation | acre-ft per sq mi | Minimum in basin | Maximum in basin | Average |
| Santa Fe River [2] | 18.2 | 11,660 | 26 | 38 | 6,706 | 6.9 | 27 | 370 | 7,718 | 12,409 | 9,700 |
| Tesuque Creek [2] | 11.8 | 7,460 | 21 | 14 | 2,800 | 4.5 | 21 | 238 | 7,100 | 12,050 | 8,750 |
| Little Tesuque Creek [2] | 7.2 | 4,600 | 19 | 5 | 906 | 2.4 | 13 | 126 | 7,450 | 11,329 | 8,700 |
| Arroyo Hondo [2] | 6.7 | 4,290 | 17 | 9 | 535 | 1.5 | 9 | 80 | [3] 7,250 | 9,121 | [3] 8,200 |
| Santa Fe River [4] | 8.8 | 5,620 | 18 | ---------- | 680 | 1.5 | 8 | [5] 80 | 7,348 | 9,431 | 8,100 |
| Foothills, Cienega ground-water unit | 17.1 | 15,300 | 17 | ---------- | [6] 1,100 | [3] 1.2 | 7 | [5] 64 | ---------- | ---------- | [3] 7,500 |
| Cienega area, total | 137.8 | 88,000 | 15 | 1 | [7] 4,700 | .6 | 4 | 34 | ---------- | ---------- | [3] 6,700 |
| Plains, latitude of Cienega | 114 | 73,000 | 13 | ---------- | 3,100 | .5 | 4 | 27 | 6,000 | 7,000 | [3] 6,500 |
| Plains and badlands, latitude of Santa Fe | 282 | 179,000 | 13 | ---------- | [8] 7,050 | .5 | 4 | [5] 25 | 5,300 | 7,500 | [3] 6,000 |

[1] Values adjusted to 38-year average discharge of the Santa Fe River.
[2] Above present or most recent gaging station.
[3] Estimated.
[4] Below present gaging station and above Twomile Dam.
[6] Assumed values.
[5] Excluding Arroyo Hondo.
[7] Ground-water discharge only.
[8] Excluding contribution of mountain area and direct surface runoff.

also that, although about 8.5 square miles of drainage area is tributary to the Santa Fe River below the present gaging station and above the lowest city reservoir, this area contributes only about a tenth of the total runoff above the lowest reservoir.

The flow of the Santa Fe River is sustained by ground-water discharge from glacial deposits and from soil, weathered zones, and fractures in the Precambrian rocks of the Sangre de Cristo Mountains. As the ground-water accretion to the stream, or base flow, varies with water levels in the ground-water reservoirs tributary to the stream, base flow is a variable amount. Although the snowmelt runoff in April, May, and June is responsible, on the average, for approximately half the annual surface runoff, and substantial parts of the precipitation for the remainder of the year are discharged as direct runoff, base flow probably contributes 20–25 percent of the average annual runoff, 100 percent of the flow in long dry periods within the year, and as much as 60 percent of the total runoff in drought years. Ground-water accretion is thus the stabilizing factor that maintains flow during dry periods.

Three major locales of ground-water bodies are the source of this base flow of the Santa Fe River: (1) near-surface soil, weathered zones, and alluvium; (2) thick glacial deposits at high altitudes, mostly above 10,000 feet; and (3) the deep zone of saturation in fractured crystalline rock. These ground-water reservoirs are connected hydrologically with each other in most places. Although the shallow zones of saturation and the soil zone are important in controlling the amount of future infiltration and direct runoff from precipitation, and in augmenting the total ground-water discharge during wet periods, probably only the deeper zones of saturated, fractured crystalline rocks and the glacial deposits at high altitudes provide substantial base flow in prolonged dry periods. During wet periods the surface soil, weathered zones, and near-surface alluvial and glacial deposits absorb rainfall and runoff and have zones of saturation. Water from these saturated zones is then discharged to small tributaries of the Santa Fe River and to the river itself. These saturated zones also supply water to many small seeps, springs, and intermittent tributary streams, as well as recharge to the underlying main zone of saturation in places. They are thin and probably discharge most of their water within a short time after the end of wet periods, as is indicated by the rapid decline in base flow during the first 2 months after the end of wet periods. Thus, ground-water depletion, or decline in base streamflow, in mountain areas is probably not a simple process analogous to drainage of saturated soil by linear drains, but is determined by the combined rates of decline of discharge from the three types of ground-water reservoirs. The declines in discharge are in turn controlled by the rates of decline of water levels in the ground-water bodies.

Snowmelt, resulting from warmer weather beginning in March, is responsible for the great increase in streamflow in the spring. (See figs. 39 and 49.) Maximum runoff normally occurs in May because of rapid melting of snow at the high altitudes at that time (and possibly partly because by May the snow and underlying soil and aquifers are saturated with water from earlier melting of snow), and ground-water accretion to the main streams is probably large. By late June the snowmelt runoff is usually completed; and, because of normally low precipitation in June, high water use by vegetation, and low soil-moisture content, streamflow usually drops to a summer minimum in July. The usual high precipitation in the area in July and August is responsible for the high flow in late summer—usually August or September—in years when precipitation is in excess of the amount required to replenish soil moisture. The time and amount of the late-summer high flow depend largely on the summer precipitation, but also on the previous spring runoff and the ground-water levels and soil-moisture content at the beginning of the rainy season. The late-summer flow usually is especially large when the preceding spring runoff has been large, as a large spring runoff generally means that high ground-water levels and soil-moisture content will persist into the summer.

A decline in flow during the fall and winter is due to the normally low precipitation during that period and the fact that most of the precipitation at high altitudes from November to April is in the form of snow, most of which is not released until April, May, and June. The minimum flow occurs most frequently in January because, on the average, it is the driest and coldest month; minimum flows may occur in February or December, however. Extremely cold weather may result in freezing of some of the smaller source springs as well as part of the surface flow, accounting in part for the minimum flow in January.

### CORRELATION OF PRECIPITATION AND RUNOFF

As precipitation is the source of all runoff, some correlation should exist between the two. However, because of the different climatological conditions causing precipitation in the vicinity of Santa Fe, two different relations can be discerned, one for the winter period extending from about October to May and one for the warm period of summer storms from June to September. The winter storms provide precipitation that accumulates as snowpack, which melts from early spring to June as the increasing warmth reaches progressively higher altitudes. Although summer storms occasionally cause some precipitation in June, precipitation normally is light in that month.

The consistency of records of Santa Fe precipitation from October to May and of natural runoff of the Santa Fe River, October–June, was tested by plotting the accumulated totals of precipitation and runoff by years against each other (double mass curve). The result is shown in curve A, figure 32. A fairly sharp decrease in general slope is indicated on the curve at about 1925 or 1926.

No precipitation records reflecting exactly the conditions existing in the Santa Fe River drainage basin over long periods are available, although precipitation data are currently being collected at Truchas, at Santa Fe Lake, and in the upper Rio Tesuque basin. Truchas, on a high mesa extending westward from the mountains, and Winsors ranch in the Pecos River drainage basin, east of the high west prong of the Sangre de Cristo Mountains, have precipitation records from 1914 to date. The accumulated October–May precipitation data for both these stations are plotted against the October–June flow of the Santa Fe River in curves B and C in figure 32. Curve B is somewhat smoother than curve A. The break in slope at about 1925 is sharpest in curve C.

The precipitation gages for all three of these stations have been moved from time to time. Prior to March 1922 the Santa Fe gage was in several different locations and possibly diffierent exposures near the plaza. From then to May 1941 it was at the Post Office building one block east of the plaza. The consistency of the precipitation records for all three stations is verified by the double mass curves in figure 33. Although the curve for Winsors ranch shows a minor deviation, the portions of the curve before and after the deviation are parallel.

The longest record of natural flow on a neighboring stream is the record for Pecos River near Cowles from 1911 to 1919. The station near Cowles was moved to Irvin ranch, near Pecos, after 1919. The Pecos River drainage basin is east of the high western spur of the southern Sangre de Cristo Mountains and probably is protected to some extent from the Pacific maritime air masses in the winter. The record of flow of Pecos River at Irvin ranch in the period 1920–50 is compared with that of the Santa Fe River by means of the double mass curve in figure 34.

The excessive runoff from Santa Fe River during 1921 was caused by a storm on August 14, 1921. The runoff in August 1921 was 27 percent of the total for the year.

### CLIMATIC CYCLES, VEGETATION, AND RUNOFF

The records of precipitation and streamflow discussed in this report represent only the conditions existing during the period of record. Climatic cycles in the past have been studied by various means, but no attempt is made here to determine such cycles, although it

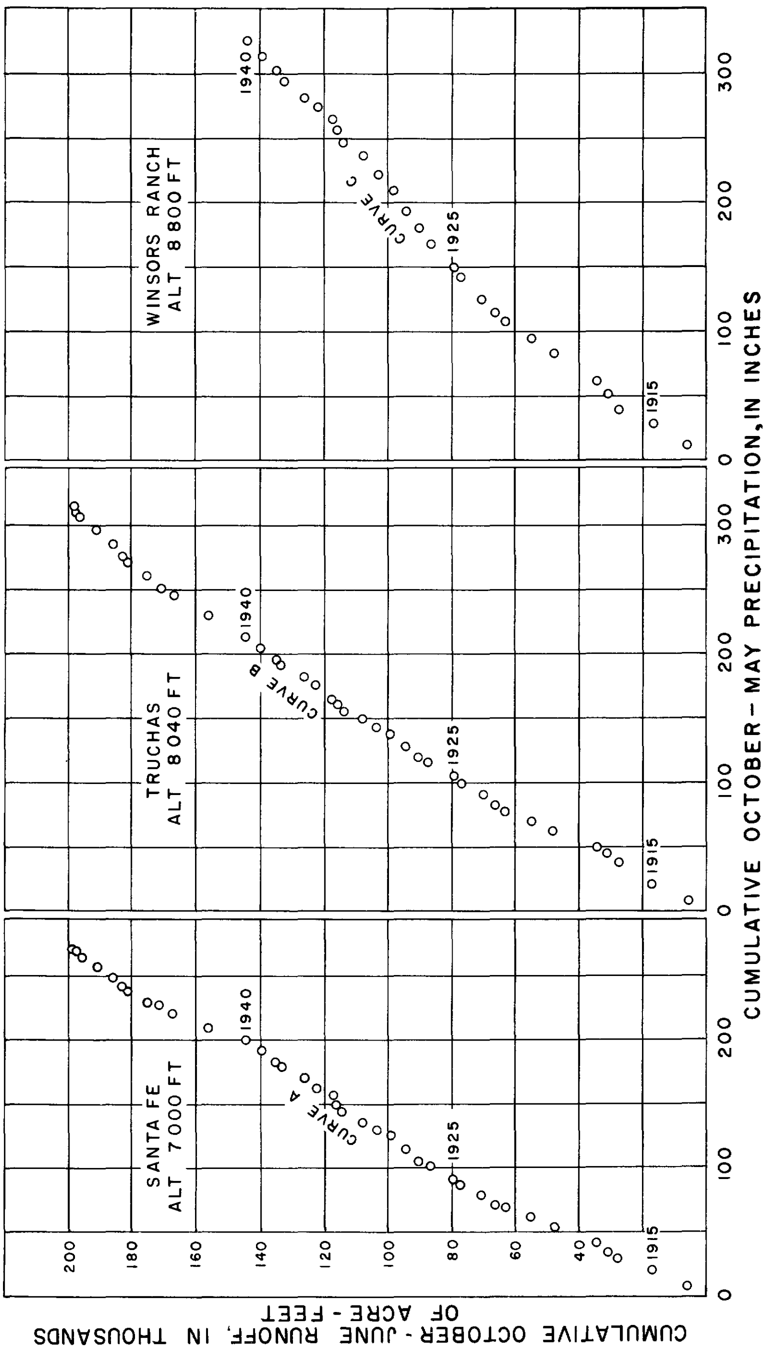


Figure 32.—Precipitation and runoff near Santa Fe, N. Mex.

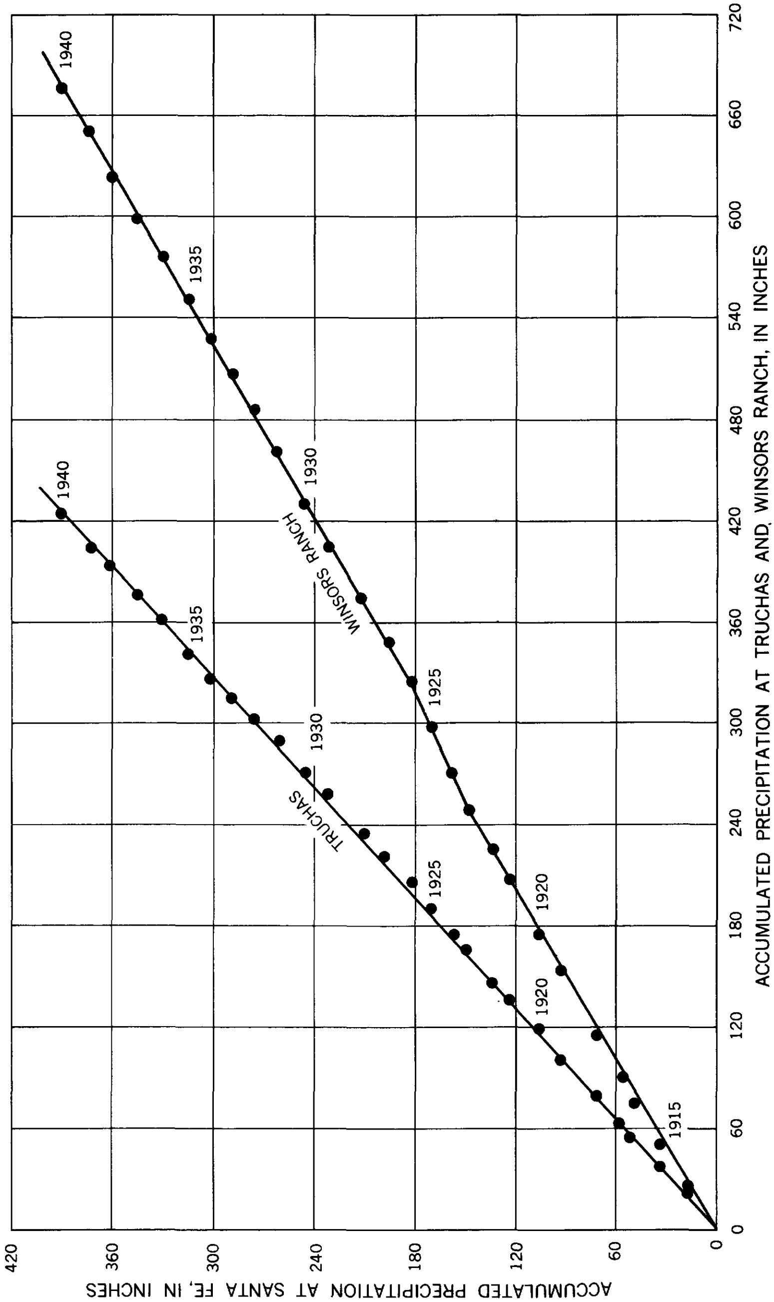


FIGURE 33.—Precipitation near Santa Fe, N. Mex.

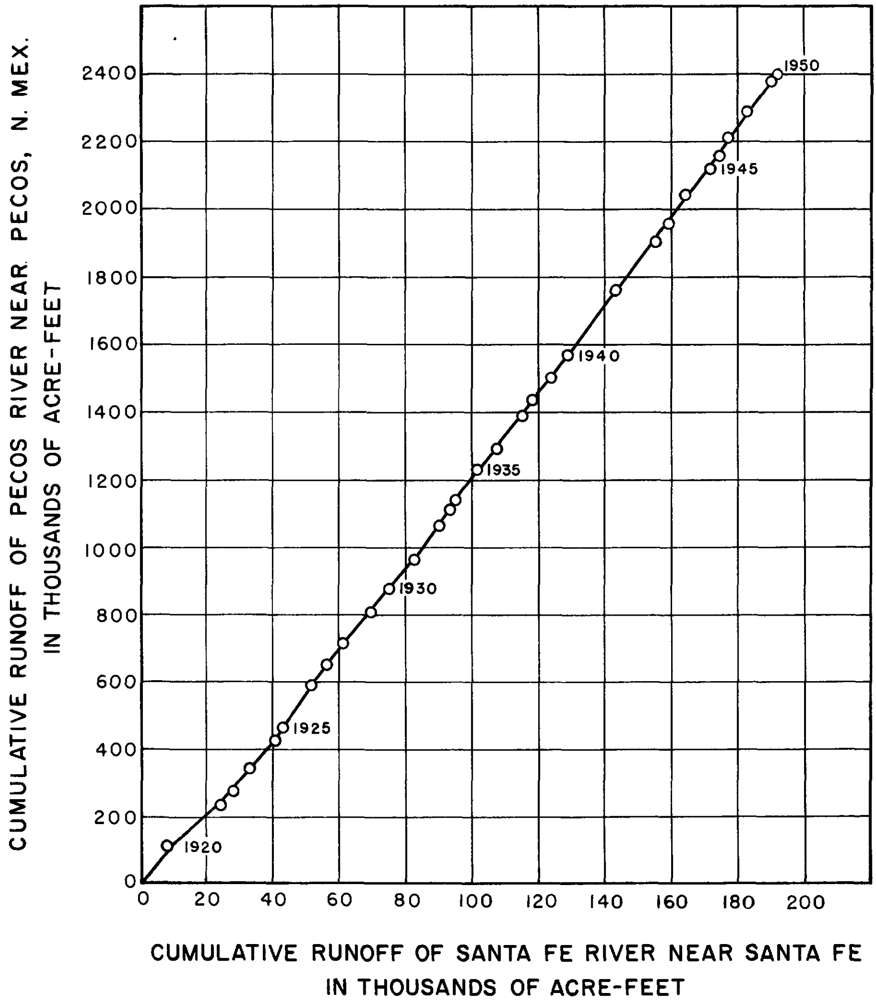


FIGURE 34.—Cumulative runoff of Santa Fe River and Pecos River, N. Mex., 1920–50.

is recognized that climatic fluctuations within the period of record have been large, and that the period of record may not be a true sample of the long-term climate. There is at present no way of predicting future climatic variations, but it is assumer here that the range of future climate will not differ from that in the past. It should be recognized that a change in precipitation causes a change in runoff that is proportionately greater than the change in the precipitation.

Changes in the vegetation of the upper Santa Fe River canyon have occurred as a result of the restriction of grazing in the canyon above Twomile reservoir in 1916, and the closing of that part of the canyon to all use in 1926 in order to improve the sanitary quality of water. Changes in the vegetation in the valley bottom have been observed by the Forest Service, and have been recorded by a series of photographs taken at 5-year intervals from identical positions.[13] The changes are of two types: (a) substantial increase in growth of grass, shrubs, and deciduous-tree seedlings along the valley floor and in meadow and marsh areas, and (b) minor increase of forest undergrowth—grass, shrubs, and tree seedlings.

Both types of increased plant growth have resulted from the elimination of grazing, trampling, and manmade fires. Both probably decrease the total runoff by the amount of additional water transpired and intercepted. Direct use of water by vegetation has probably increased most in the valley-floor areas, by the increased growth of type a, above. The runoff is decreased further by the increased capacity of the soil for holding moisture, induced by heavy vegetation. Water stored as soil moisture in amounts less than the field capacity does not contribute directly to either runoff or groundwater discharge, though it contributes indirectly to both, in that the more soil moisture is retained the less precipitation is required before runoff or recharge begins.

As the increase in vegetative cover in the Santa Fe River canyon has probably increased the infiltration and moisture-retention capacity of the soil, this type of moisture storage and use is probably greater during periods of low to moderate precipitation than it was under former conditions of heavy grazing. In dry years, increased soil storage of moisture from infrequent rains reduces the runoff from the drainage basin by the additional amount retained in soil-moisture storage; the water is evaporated and transpired during long intervening dry periods. However, in very wet years, when the soil is saturated much of the time, both runoff and recharge can occur readily and can be reduced only by the amount of soil moisture consumed by the increased plant growth itself.

Unfortunately, no continuous streamflow records are available for a long period prior to the closing of the basin to grazing, and it is not possible to determine the magnitude of any changes in water yield that might have been caused by increased vegetal growth or other factors. Probably some decrease in water yield has occurred, at least in dry years, but the decrease may be small. However, the benefits of increased soil stability may outweigh a small use of water by increased vegetation cover. Reservoirs not endangered by excessive sediment are invaluable, especially where additional good reservoir sites are not available.

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[13] Files of the U.S. Forest Service, Santa Fe, N. Mex.

Research on the effect of vegetation and soil conditions on water yield is being done by the Upper Rio Grande Research Center of the U.S. Forest Service, Albuquerque, N. Mex. Similar studies were described by Rich (1951). Much more study of the history and records of the Santa Fe River is necessary to reach valid conclusions on the effects of vegetal changes on the water yield of the drainage basin.

FLOW CHARACTERISTICS OF THE SANTA FE RIVER

It is possible to establish an approximate relation between magnitude of discharge and the recurrence interval of such discharges by means of a graph on a specially designed chart. Although the chart is used principally for plotting peak flood flows, it can be used also for plotting the total flow during any period. As the capacity of McClure reservoir is equivalent to a large proportion of the annual discharge of the Santa Fe River above the gaging station, annual discharge is used on the frequency plot (fig. 35) rather than the

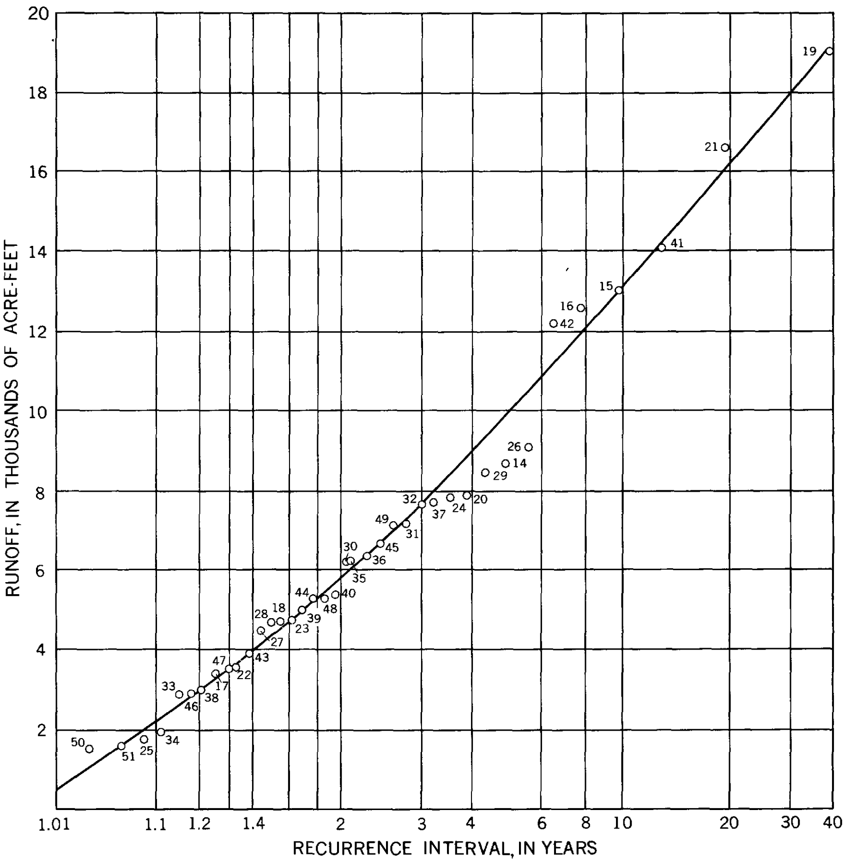


FIGURE 35.—Recurrence intervals of yearly discharges of Santa Fe River, N. Mex. (1914–51). Small figures indicate years of record (19 omitted).

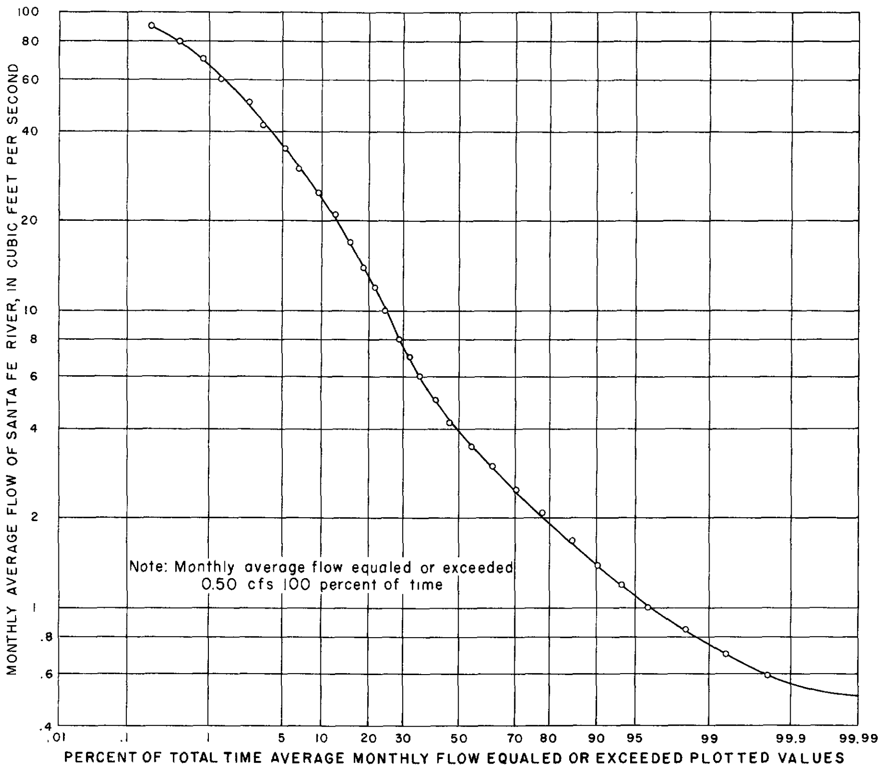


FIGURE 36.—Duration curve of monthly flow, 1914–51, Santa Fe River, N. Mex.

discharge for a shorter period. If the annual discharges are listed and numbered in order of magnitude, beginning with the highest, the plotting position or abscissa of each point (the recurrence interval $p$) may be determined from the formula $p = \frac{N+1}{M}$, where $N$ is the total number of annual discharges and $M$ is the relative magnitude of the discharge. The discharge itself is the other coordinate (fig. 35).

A flow-duration curve—a curve showing the percentage of time during which a given rate of flow was equaled or exceeded throughout the entire period of record—is shown in figure 36. Although it is customary to develop such curves on the basis of daily flows, in this instance mean monthly flow in cubic feet per second was used, as variations among daily flows are smoothed out in the reservoirs. The data for the curve were obtained by dividing the total range of mean monthly flows into intervals and listing for each interval the number of months when the flows equaled or exceeded the lower limit of the interval. The number of months when the flow was at least that of the lower limit of the interval was divided by the total number of months to obtain the percentage of time.

Figure 37 shows the lowest runoff in the Santa Fe River to be expected during periods of any given length up to 108 months. For example, the lowest runoff to be expected in any period of 20 consecutive months, according to the graph, is 2,000 acre-feet. The flows establishing the points on the curve for 30 and 36 months occurred between 1932 and 1935; all others have occurred since 1943. The curve is useful for computing the auxiliary supply needed to meet any given future demand during a drought up to 9 years long.

### AVAILABLE YIELD

The annual natural discharge of the Santa Fe River, as computed for the station below McClure dam (table 21), shows large fluctuations, from a minimum of 1,530 acre-feet in the 1950 water year to 18,990 acre-feet in the 1919 water year. The total water yield above Santa Fe is somewhat greater than these figures because of inflow to the two reservoirs below the gaging station. The inflow below the gaging station may not always be proportional to the natural flow above the reservoir and is, in general, much more variable. The unmeasured increment from the 8½ square miles tributary to this stretch of the river is estimated to average approximately 680 acre-feet per year, equivalent to about 10 percent of the discharge past the gage (table 21). Additional surface flow from springs and storm runoff below the reservoirs is also available, in part, to recharge the ground-water reservoir along the Santa Fe River at and below Santa Fe. However, evaporation from the three reservoirs when filled to capacity is about 350 acre-feet per year, and evapotranspiration loss from the 80–100 acres of cottonwood, willow, and alder below McClure dam may be as much as 300 acre-feet annually.

The large discharges in the first few years after the beginning of the record are particularly important in interpreting average discharge available in various periods; in fact, 6 of the 8 highest annual discharges recorded occurred during the first 13 years (table 21 and fig. 38). The remaining 2, the 3d and 6th highest, occurred in 1941 and 1942. Because of this concentration of high flows in a few years, the mean annual discharge for the first 13 years is 8,704 acre-feet. For the remaining 25 years, even including the high flows of 1941 and 1942, the mean discharge is about 5,700 acre-feet. The mean and median annual discharges for the period of record are 6,706 and 5,800 acre-feet, respectively.

However, such computations of the average flow of the Santa Fe River may be misleading, inasmuch as the runoff in wet years is greater than the combined diversion and storage capacity (fig. 38) of water above Santa Fe. As the total reservoir capacity is about 4,000 acre-feet and the present annual use also is about 4,000 acre-feet, it is apparent that, at the present rate of use, the natural runoff

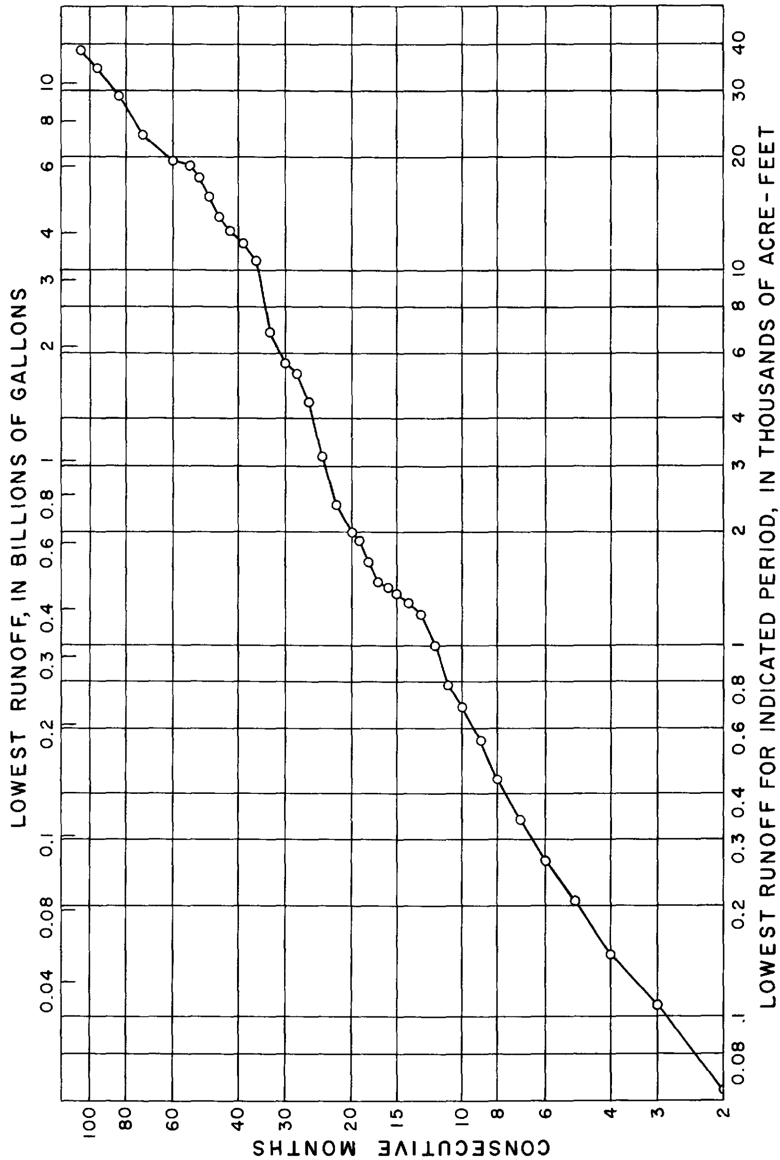


FIGURE 37.—Lowest runoff for indicated period, Santa Fe River, N. Mex. (Period of record, 1914–51).

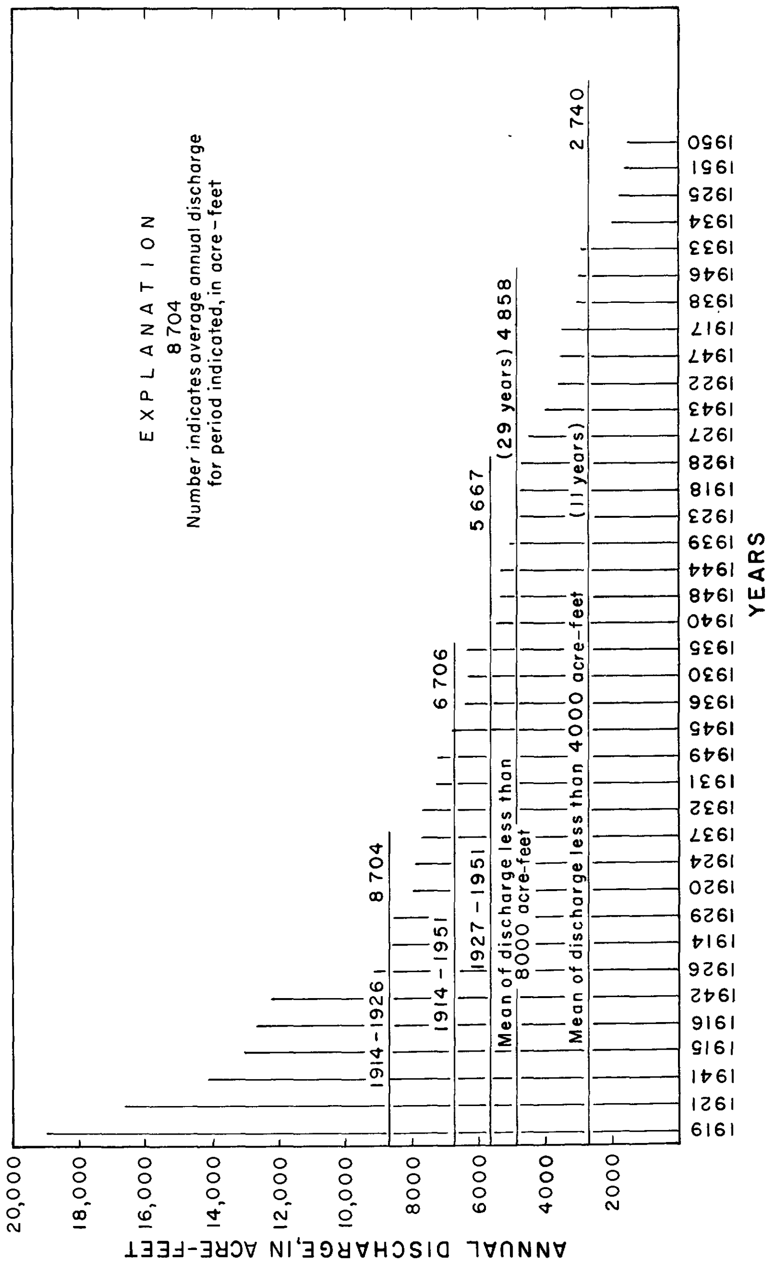


FIGURE 38.—Annual discharge, 1914–51, of Santa Fe River below McClure dam, N. Mex., by magnitude.

above 8,000 acre-feet in any year must spill past the reservoirs. During such years the usable runoff of the Santa Fe River is therefore only 8,000 acre-feet.

During a sequence of very dry years all the runoff can be used, but in a sequence of wet years, when storage is at a high level, much spill may occur and the usable runoff may be little more than the annual city use. On the basis of limitations of 8,000 acre-feet during occasional wet years, 4,000 acre-feet during successive wet years, and actual flow during dry years, the average annual usable supply can be computed to be about 4,800 acre-feet.

During long droughts both surface-water storage and ground-water storage contributing to surface flow of the Santa Fe River are depleted. In such periods the large ground-water storage reservoirs in the plains areas near Santa Fe can be of maximum usefulness. Provision can easily be made for replenishing these ground-water reservoirs with surplus surface flow from the mountains during the infrequent wet years. (See p. 187.)

### WATER REQUIREMENTS OF SANTA FE

Water requirements in Santa Fe have increased markedly in recent years. According to records of the Public Service Co. (fig. 22), public use increased from 1,650 acre-feet in 1940 to 3,011 acre-feet in 1945, an increase of more than 80 percent. The use declined somewhat with the deactivation of Bruns Hospital, but increased again with postwar expansion of the population, influenced by nearby Los Alamos. Despite restriction of use because of a severe water shortage, the 1951 per capita consumption was about 110 gallons per day (annual use, 3,350 acre-feet), compared to 75 gallons per day per capita in 1940 (annual use, 1,650 acre-feet).

The distribution of water use by months varies somewhat from year to year, especially in summer when irrigation demands are influenced by precipitation. Figure 39 shows the average percentage of surface-water supply and demand, by months, determined by averaging these factors for the period 1945–48, for comparison with the distribution of precipitation, runoff, and evaporation for the respective periods of record. The minimum cumulative monthly discharges in the period of record, for terms of 1 to 108 months, are shown on figure 37.

### WATER-SUPPLY FORECASTING

Forecasting streamflow and runoff has become an important phase of the activities of the U.S. Geological Survey, U.S. Weather Bureau, Corps of Engineers, and the Forest Service and Soil Conservation Service of the U.S. Department of Agriculture. In recent years, much interest in these forecasts has been aroused by

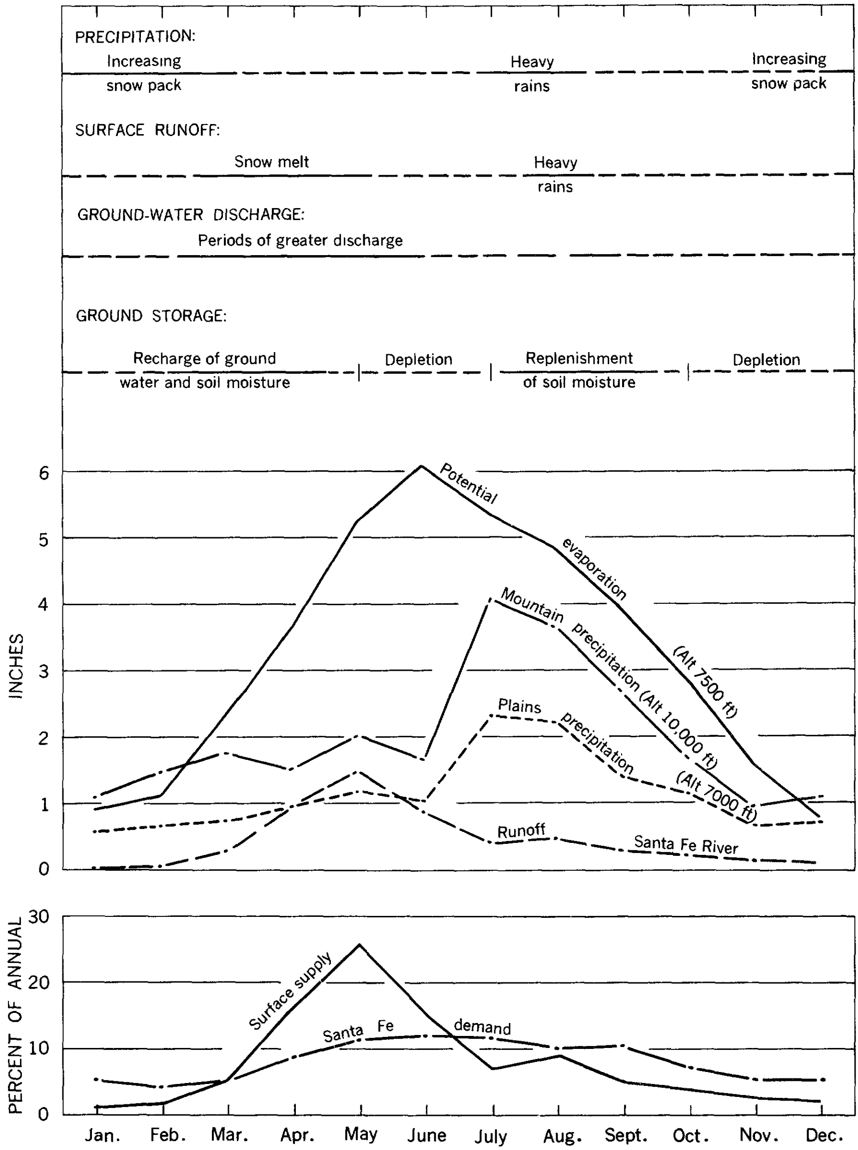


FIGURE 39.—Monthly average precipitation, evaporation, and surface-water supply and demand for periods of record, Santa Fe, N. Mex.

the realization of the aid that accurate forecasting can give in guiding the operations of municipal reservoirs, powerplants, and irrigation, flood-control, and multipurpose water projects all over the country, especially in the Western States, New England, and Pennsylvania. The forecasts at present are based primarily on statistical analysis of past streamflow records (gathered largely by the

Geological Survey), aided by correlation with precipitation records gathered by the Weather Bureau and with snow-course data collected by several agencies. Many methods of predicting streamflow have been evolved and refined. All methods require study of continuous records, preferably 10 years or more long. Unfortunately, adequate basic hydrologic data are not available for all areas. The accumulation of such basic data is imperative, not only for water-supply forecasting in connection with existing uses but also for the intelligent planning of future development and control works. Most of the correlations and predictions to date have been made by statistical treatment of past records of precipitation, snowfall, snow cover or snow-water content, and runoff. Even in areas where data of this type are adequate, close correlations and accurate predictions of runoff have not been achieved, because of the effects of other variables (Stanley and Kennedy, 1947, p. 779), even with such refinements as weighting the snow-water content in accordance with differences in moisture content with altitude, and inclusion of antecedent precipitation.

Therefore additional variables must be considered in forecasting, if greater accuracy is to be achieved. The most important variables, other than snow-water content, distribution of snowpack (water-content basis), and spring precipitation, are soil-moisture deficiency, ground-water levels, and base-flow conditions. Meteorologic phenomena such as rates of melting, evaporation, and sublimation (evaporation of ice and snow) also are probably important, especially in the mountains.

Hydrologists are beginning to realize the importance of the effects of soil moisture and ground-water storage and depletion upon the relations of precipitation and streamflow. Some suggested and applied considerations of the role of ground water and soil moisture to runoff are given in the following papers, among others: Croft (1946), Cross (1949), Harrold (1934), Huff (1944), Jacob (1943, 1944), Merriam (1942, 1948), Paget (1946), Piper (1948), Schiff and Dreibelbis (1949), and Thomas (1949a). Piper's paper (1948) makes the following suggestions for improving runoff forecasts: (1) more snow courses, (2) air-photo reconnaissance of snow distribution, (3) more soil-moisture courses, (4) observation wells, and (5) determination of ground-water depletion rates and their relations to antecedent precipitation. Peterson's discussion (1948) of a pair of points in Piper's paper (1948) pertaining to the Pacific Northwest power pool pinpoints the need for and value of precise predictions of streamflow.

The papers by Merriam outline the results and value of experiments in forecasting the minimum possible flow of the Susquehanna

River, for power generation, on the basis of observations of ground-water levels by the U.S. Geological Survey and cooperating State agencies.

Jacob (1943, 1944) summarizes the earlier methods for correlation of precipitation and ground-water levels and develops mathematically a method previously suggested by Leggette (1942), using plots of cumulated departure from progressive monthly precipitation averages to correlate with and predict ground-water levels. This statistical method appears to be applicable to predictions of the small natural fluctuations in ground-water level in the Ancha formation south of the Santa Fe River, if continuous water-level records become available in the future. A variation of this approach could be used to correlate precipitation with base flow of the Santa Fe River and Tesuque Creek, using data currently available. However, if continuous water-level records become available in the future, correlation of precipitation and ground-water levels with runoff would be more useful.

It should be possible to develop, on the basis of the methods described in the papers listed above, a satisfactory method of forecasting the runoff in the Santa Fe River each spring. These forecasts could guide the release and storage of surface water, and the pumping and recharge of ground water, for the municipal water supply of Santa Fe so as to utilize fully the good-quality surface water and to use as little as possible of the harder ground water. Such a study ideally would require a program of measurement of snowfall, snow cover, snow-water content, soil moisture, and water levels in properly selected wells or springs in glacial drift, and accurate measurement of flow above McClure reservoir and at other places on the Santa Fe River.

The depth of water in a storage-precipitation gage near Santa Fe Lake has been measured twice a year, usually in early June and in early October, since its installation in 1947. When it was visited in June 1948 it had overflowed. The present data collected from this gage are of no value as a basis for forecasts.

Before reliable forecasts of flow can be made, an adequate program of collection of the additional hydrologic data must be set up, although preliminary tests of the adequacy of present methods of forecasting can be made with present data. The data needed for accurate forecasting could be provided by installing two recording precipitation gages of the storage type at altitudes of about 9,500 and 10,500 feet and converting the gages at Elk Cabin and Santa Fe Lake to gages of the same type. All gages should be read regularly at monthly intervals. Observations of the depth and water content of the snowpack at selected locations representative of several altitudes should be made during the spring. A gaging station, constructed to permit year-around operation, should be established on the Santa Fe River just above the backwater of McClure reservoir. Similar gaging stations should be installed on the Santa Fe River below Santa Fe Lake at an altitude of about 11,000 feet, above Elk cabin at about 9,000 feet, and below Twomile reservoir at about 7,300 feet, in order to determine the proportion of runoff from different altitudes. Soil-moisture and water-level records also should be collected.

## MIDDLE VALLEY

### HISTORY OF SURFACE-WATER USE IN RELATION TO GROUND WATER

A brief review of the history of water use in the upper and middle parts of the Santa Fe River basin (the reach above Cieneguilla) is useful here to relate present conditions to the natural hydrologic equilibrium. A description of the geologic and hydrologic aspects of the principal aquifers in the valley is given on pages 115–143. Additional discussion of the important ground-water reservoir above Cieneguita (see fig. 4) is given in the following section.

No surface storage facilities existed on the Santa Fe River prior to 1881, and probably no diversions were made prior to settlement by the Spaniards. The perennial flow from the upper basin ran uncontrolled through what is now the heart of Santa Fe. This perennial flow diminished downstream by infiltration into the channel gravels and into the permeable beds of the Tesuque formation to the west, especially in the stretch of the river above Cieneguita. No data are available on the infiltration capacity of the stretch of the river between the mouth of the upper canyon and Cieneguita, but in the next section some inferences are drawn from data on a somewhat similar stretch of Rio Tesuque.

Partial ground-water barriers at Cieneguita and Agua Fria at times cause the appearance of springs, which are the overflow of ground water from moderately permeable, sandy phases of the Tesuque formation. The major barrier of intrusive igneous rocks and other lower Tertiary rocks below Cieneguilla causes ground water to discharge from the Cienega ground-water unit and from the area along the Santa Fe River. The basalt-dike feeders of the Cerros del Rio and the northwest dip of the Tesuque formation result in a northwestward diversion of ground water in the Cienega unit. (See pl. 7, fig. 31.)

As the flow of the river prior to settlement by the Spanish was neither stored nor diverted, the normal and low flows above Cieneguita were probably larger than after settlement. Therefore flows greater than the infiltration capacity of the river bed, resulting in direct runoff as far as Cieneguilla and into the Rio Grande, probably occurred more frequently.

As irrigation was developed and increased, more ditches were constructed and more water was diverted, so that the natural flow of the river through what is now Santa Fe became less and less. The early agricultural practices constituted an excellent form of artificial recharge of a part of the diverted water to the underlying aquifers because of ditch leakage and extensive water spreading. Despite the consumptive use by the irrigated fields, probably a larger proportion (possibly 30–50 percent) of the streamflow reached the zone of saturation after irrigation began than did under natural conditions. Figure 40 illustrates the extent of the system of diversion in 1914. The diversion of water to irrigate 1,267 acres along the Santa Fe River in that year was estimated to have been about 5,700 acre-feet, according to Miller and Carroll,[14] a quantity larger than that used at present by the entire city water system. However, the runoff of 8,680 acre-feet during the water year 1914 was well above the average, especially during the summer, and irrigation applications that year were probably greater than normal. Previous, less accurate estimates of irrigated acreage along the middle stretch of the Santa Fe River by H. W. Yeo[15] are 5,760 acres in 1893 and about 3,500 acres from 1894 to 1896. The Santa Fe River valley in those days must have been much like the Rio Tesuque and Nambe valleys of today—broad, terraced valleys covered with green fields and dotted with farm homes and buildings.

Under the nearly ideal conditions for recharge such as existed in the older irrigation systems, the springs at Cieneguita and formerly at Agua Fria apparently were much larger and more dependable than they are now. During the past 40 years more and more of the flow of the upper Santa Fe River has been diverted into the city distribution system. A graphical summary of the increase in storage and use is given in figure 22. Figure 40 shows the change in place of irrigation use and return near Santa Fe.

### RECHARGE OF SURFACE WATER TO GROUND-WATER RESERVOIRS

The reach of the Santa Fe River between the mountain front (where the base of the Tesuque formation crops out) and the west city limits of Santa Fe is about 4 miles in length. In proportion to the loss of flow in a similar but shorter reach of the Rio Tesuque (p. 194–197, fig. 52), about 8 cfs should be the maximum sustained loss of flow in this reach of the Santa Fe River under natural conditions, and about 4 cfs would be the "optimum" loss rate. That is, a flow of about 4 cfs at the mountain front would be completely

[14] Miller, L. S., and Carroll, S. S., 1919, Report on Santa Fe hydrographic survey: New Mexico State Engineer Office [unpub. ms.], 110 p., 40 pls.

[15] Yeo, H. W., 1928, Report on irrigation in the Rio Grande basin in Texas above Ft. Quitman, and in New Mexico during 1907, 1920, and 1928: New Mexico State Engineer Office [unpub. ms.], v. 1, p. 51–58 and v. 3, p. 170.

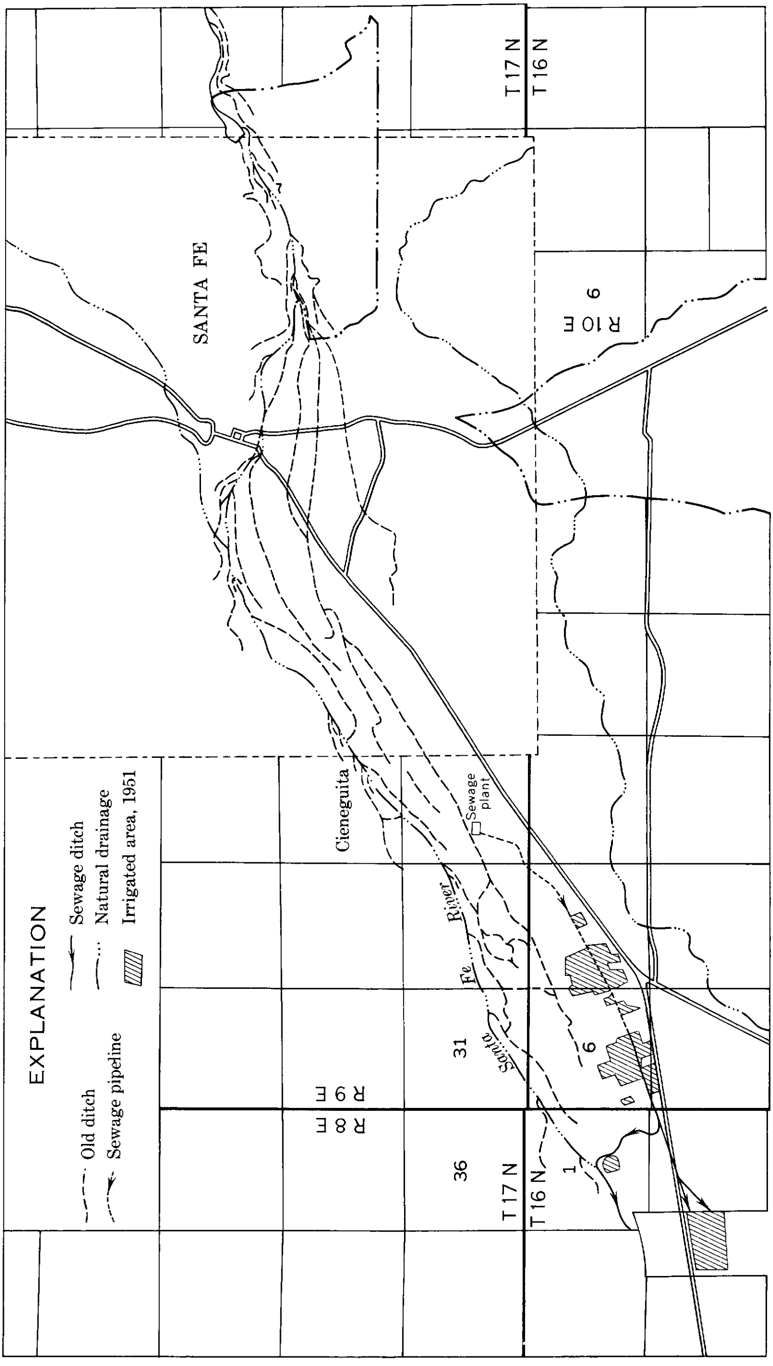


FIGURE 40.—Irrigation ditches along Santa Fe River, N. Mex. Location of old ditches is taken from L. S. Miller and S. S. Carroll.

absorbed by the channel materials, and eventually recharged to the underlying Tesuque formation in this reach of the Santa Fe River.

As the surface reservoirs above Santa Fe now divert and store about 4,000 acre-feet per year, in many years (fig. 38) all runoff from the upper part of the Santa Fe River basin is diverted. However, in some wet winters, such as that of 1951–52, runoff in excess of storage capacity, in addition to the normal runoff from springs, snowmelt, and rain downstream from the reservoirs, does recharge ground water in the Tesuque formation. In most years the reservoir spill rate probably will not exceed the estimated "optimum" rate of infiltration, 4 cfs, and thus most of the reservoir spill may be recharged to the Tesuque formation. Springs and snowmelt downstream from the reservoirs maintain a small flow ranging from an estimated 0.1 to more than 1 cfs past the Delgado Street bridge through the winter months when evapotranspiration is low. All this runoff is usually absorbed in the stretch of the river between Delgado and Alire Streets. If the flow were to average as much as 0.5 cfs for 6 months, an annual total of about 180 acre-feet would be recharged to the underlying aquifers. Storm runoff in the summer frequently exceeds the infiltration capacity of the channel, and at such times some runoff passes the Cieneguita area. However, in the summer, the base streamflow below the reservoirs is consumed, apparently by evapotranspiration, in the stretch of the river between Camino Cabra and College Avenue.

Much of the summer use of water in Santa Fe is for lawn and garden irrigation, and the amount of water that filters into the underlying aquifers from such use is probably less than that from farm irrigation. The areas of lawn irrigation are relatively small and are scattered over the entire city, but are more concentrated in a few neighborhoods such as the Federal Plaza and the Casa Alegre subdivision. Many homes in Santa Fe are not connected to the city sewage systems, and waste water and sewage is discharged into cesspools or septic tanks. Much of this water also percolates downward to the zone of saturation. However, most of the waste water from domestic use is collected by the city sewage system and delivered by gravity flow to the city sewage plant at the southwest city limit.

Treated sewage effluent from the city is conducted through a closed concrete conduit for about 4 miles generally southwest, parallel to U.S. Highway 85. From the end of the conduit, the sewage effluent flows in an open ditch to the municipal golf course, where it is used for the irrigation of about 100 acres of lawn grass. Between the end of the conduit and the golf course about 400 acres (1951) of feed crops are irrigated by laterals from the main ditch.

The area irrigated under this system is shown on figure 40, together with the extent of ditches along the Santa Fe River in 1914.

Figure 40 shows the change in the location of irrigated areas since 1914, and thus the change in the location of areas of artificial recharge to the ground-water reservoir of the middle valley. Many of the old ditches are still used in wet years such as 1952, when the reservoirs spilled; but the amount of water spread at present by the old ditch system is small compared to that spread by the system using sewage effluent. Where the sewage ditch crosses the Airport road (sec. 12, T. 16 N., R. 8 E.), a branch ditch carries the excess effluent to the Santa Fe River below Agua Fria. Some of this water is used for irrigation below Agua Fria, but most is discharged into the channel of the Santa Fe River, where at maximum flow it is completely absorbed within 1½ miles of the point of entry into the channel.

Probably 30–50 percent of the sewage effluent is recharged to ground-water reservoirs by irrigation during the growing season, but probably nearly 100 percent of the flow is recharged to these reservoirs by infiltration along the Santa Fe River below Agua Fria during the winter months. On the whole, then, probably more recharge is occurring at present than occurred in the past, but in different places. Quantitative data on the amount of sewage effluent discharged is not available.

Increased use of surface water by the city in the future will probably increase the amount recharged to ground-water reservoirs by irrigation return and ditch or channel loss south and west of Agua Fria, thus amplifying the present effects of change in place of irrigation.

### APPROXIMATE YIELD OF THE GROUND-WATER RESERVOIR ABOVE CIENEGUITA

Although the data available at present are insufficient to determine accurately the total ground-water storage and annual recharge of the ground-water reservoir, some approximations are made in table 12, together with comparisons to the surface-water storage facilities on the Santa Fe River. It is tentatively concluded that the potential withdrawal from wells existing as of 1951 (4,650 acre-feet) would exceed the total potential recharge by more than 1,000 acre-feet annually. In addition to the potential withdrawal for city supply as of 1951, irrigation wells in the area in 1953 had a net "withdrawal potential" of about 500 acre-feet annually. Thus, if maximum withdrawal were to be made from the wells existing in 1951, the potential annual recharge would be exceeded by more than 1,500 acre-feet. Table 11 indicates that ground-water supplies of more than 11,000 acre-feet annually are available perennially in or near the Santa Fe area (4,700 acre-feet in the Cienega ground-water

TABLE 12.—*Comparison of surface-water and ground-water reservoirs near Santa Fe, N. Mex.*

| Storage reservoirs | | | |
|---|---|---|---|
| Surface water (upper Santa Fe River) | | Ground water (Western part of Santa Fe area) | |
| **1. Storage and use (in acre-ft)** | | | |
| (a) Present storage | 4,128 | (a) Present storage | 128,000+ (per sq. mi.). |
| (b) Present annual use | 4,000 | (b) Potential withdrawal, 1951 (largely from storage). | 4,650. |
| (c) Probable future supply by additional storage. | Variable, depending on economic feasibility, but assumed to be zero because good storage sites are not available. | (c) Approximate natural discharge that can be diverted to well discharge. | 1,000. |
| | | (d) Potential supplement to natural recharge by artificial recharge. | 2,500. |
| | | (e) Total available for increment to storage (c+d). | 3,500. |
| When storage is at maximum (4,128 acre-ft) discharge cannot be controlled. | | Storage can be increased (d, above) in appreciable amount by artificial recharge. | |
| **2. Annual inflow** | | | |
| (a) Ranges from 40 to 450 percent of total storage, and averages 6,706 acre-ft. However, the usable annual inflow averages only 4,800 acre-ft. (See p. 168.) | | (a) Variations large, but annual natural inflow probably less than 1 percent of total storage. | |
| **3. Reservoir parameters** | | | |
| (a) Reservoir-capacity curves in files of Public Service Co. and State Engineer of New Mexico. | | (a) Areal extent, not well defined by present data. Saturated thickness variable, assumed average 1,000 ft. Transmissibility, average estimated at approximately 30,000 gpd/ft. Specific yield, unknown (assumed 20 percent). | |
| (b) Total storage: 4,128 acre ft. | | (b) Storage (per sq. mi.), 128,000+ acre-ft. | |
| **4. Data needed for supply inventory** | | | |
| (a) In storage: Record of reservoir level for each reservoir. | | (a) In storage: (1) Sufficient water level data to contour top of saturated zone. (2) Test holes to determine thickness and extent of reservoir. (3) Aquifer tests to determine transmissibility and storage coefficients, and boundaries. | |
| (b) Future inflow predictable by analysis of data on streamflow, ground-water levels, soil moisture, and water content of snowpack. Usable inflow can be increased only by additional storage or increased use. | | (b) Future inflow a parameter of surface flow in part. Additional inflow from adjacent aquifers is largely from storage therein. Excess surface flow can be utilized for artificial recharge and storage in the cone of depression in the well field. | |

basin and 7,000 acre-feet in the area between Santa Fe and the Rio Grande) if wells are located and operated so as to divert all natural discharge.

### EFFECTS OF GROUND-WATER DEVELOPMENT

The long-term average annual runoff of the upper Santa Fe River drainage basin is greater than the annual use could reasonably be expected to become in the immediate future, but a supplementary ground-water supply is needed in dry years. At present several large-capacity wells in Santa Fe obtain their water from the Tesuque formation above Cieneguita. Of these wells, 5 are public-supply wells which currently are intended to be pumped only during droughts when surface flow and storage reserve are insufficient. These 5 wells (figs. 41–46) were pumped continuously for various periods of 3–12 months during the drought of 1950–52. Eventually, however, pumping of one or more of the public-supply wells may be necessary to supplement the surface supply in all but the wettest years. In addition to the 5 public-supply wells, 3 wells were used for irrigation during 1950–52, and 1 of them had been used in previous summers. Use of these and possible additional irrigation wells would cause additional depletion of storage in the ground-water reservoir.

Pumping rates and water levels of Public Service Co. wells in 1950 and 1951 are shown in figure 42. The water levels were measured by the Public Service Co. to the nearest foot with a steel tape, and weekly mean pumping rates were computed from total pumpage of individual wells for 7-day periods. Many individual measurements of water levels and pumping rates do not correlate, possibly because of irregularities in the pumping times used to compute the mean pumping rates. However, the general influence of pumping on water levels is shown by the graphs to be a continuing slow decline of water levels after an initial period of large drawdown. The marked recoveries of water levels in the Alto and Ferguson wells are the result of declining production due to pump difficulties and to extended shutdowns.

The Tesuque formation above Cieneguita is a hydrologic unit within which a complete cycle of rainfall, surface runoff, surface inflow, ground-water recharge and movement, and ground-water discharge across a partial barrier takes place. The natural ground-water discharge from this unit is in equilibrium with the recharge to the unit. Long-continued pumping in Santa Fe will lower water levels in the Tesuque formation above Cieneguita and eventually decrease outflow across the partial barrier. Records of pumpage and water levels during the 1950–51 drought are inadequate for long-term quantitative predictions of the effects of future pumping. The general trend of water levels, as reported by the Public Service Co. of New Mexico and indicated by a few measured water levels and pumping tests by the U.S. Geological Survey, indicate qualitatively that all the wells above Cieneguita are hydrologically

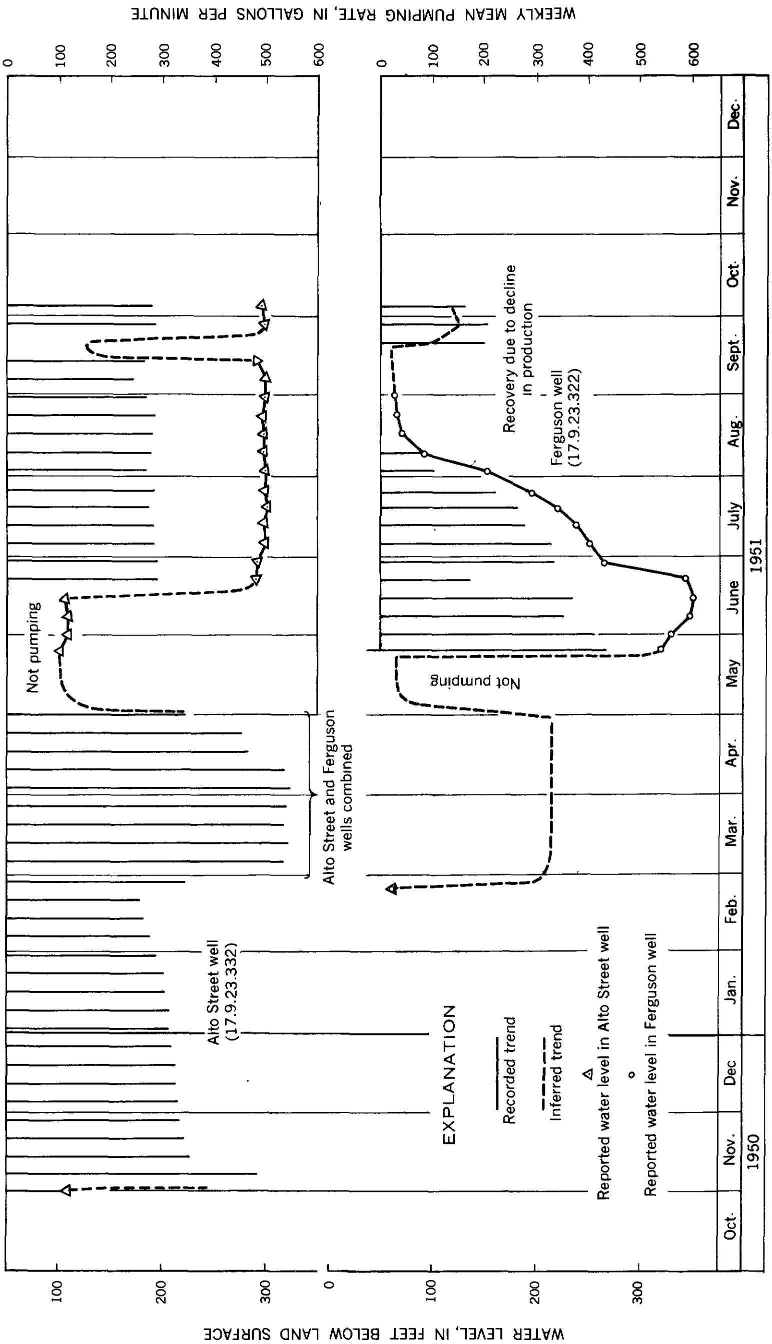


FIGURE 41.—Water levels and discharge of public-supply wells, Santa Fe, N. Mex.

connected and are sufficiently close to have measurable effects upon each other. Mutual interference of the wells is not excessive at present, however, except in the Alto, Ferguson, and Hickox wells. Continuing records of pumpage and water levels are needed to provide data for determining fully the characteristics of the ground-water reservoir.

Future increased use of ground water above Cieneguita will partly deplete that ground-water basin despite the relatively large recharge afforded by the Santa Fe River and irrigation return. Artificial means may be required to accomplish the recharge of the salvageable part of the excess water in a wet year. The several methods of artificially increasing recharge in the Cieneguita area are described in another section.

### PERFORMANCE OF THE ALTO STREET WELL

Figure 43 shows the water levels and pumping rates in the 1947 pumping test and in the 1950–51 production period, superposed on one semilogarithmic graph. Water levels during the pumping test and in a previous test were highly variable because of large fluctuations in discharge, and the data are too erratic to allow accurate evaluation of transmissibility and storage coefficients or to predict future effects. (See discussion at end of this section for evaluation of decline of yield at constant drawdown.) Although discharge in the latter part of the 1947 pumping test decreased significantly on the third day, water levels continued downward as a result of dewatering of lenses of the aquifer, of the presence of aquifer boundaries, or of both.

Water levels in an observation well 655 feet west of the Alto Street well were measured daily during the pumping test of February 1947. The nonpumping level was not measured at the start of the test but had been measured to be 67.75 feet below the measuring point on January 28, 1947, before a period of pumping that preceded the formal pumping test. This level is assumed to be the static water level at the start of the test, but because of the precedent pumping the actual water level at the start of the formal test may have been lower. Water levels in the observation well are plotted on figure 44, according to the method described by Wenzel (1942, p. 87–89) and Ferris (1949, p. 231–240). The first water level measured apparently was abnormally low, possibly because of residual effects of trial pumping prior to February 3, 1947; it is not plotted on figure 44 and is disregarded here. Water levels on the last 3 days of the test are probably somewhat high because the yield of one pump decreased during this time. Water levels adjusted for constant discharge are also plotted on figure 44 in an attempt to compensate for this decrease in yield. Transmissibility

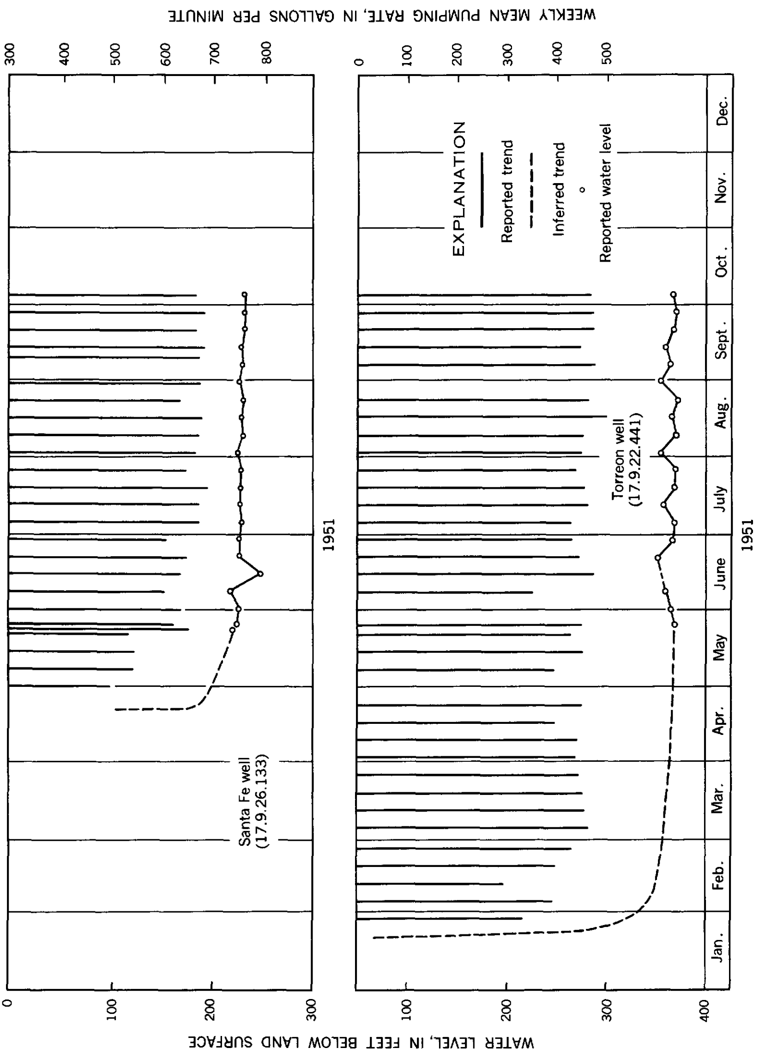


FIGURE 42.—Water levels and discharge of public-supply wells, Santa Fe, N. Mex.

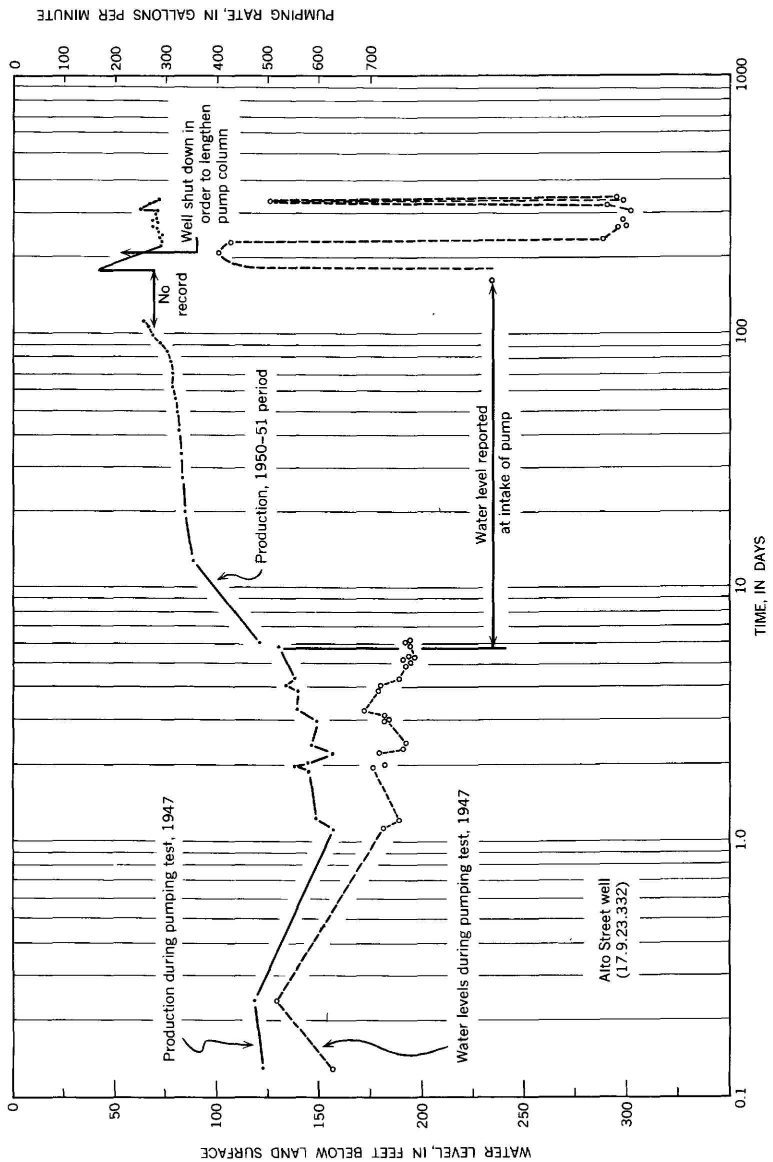


FIGURE 43.—Water levels and discharge, Alto Street well, Santa Fe, N. Mex.

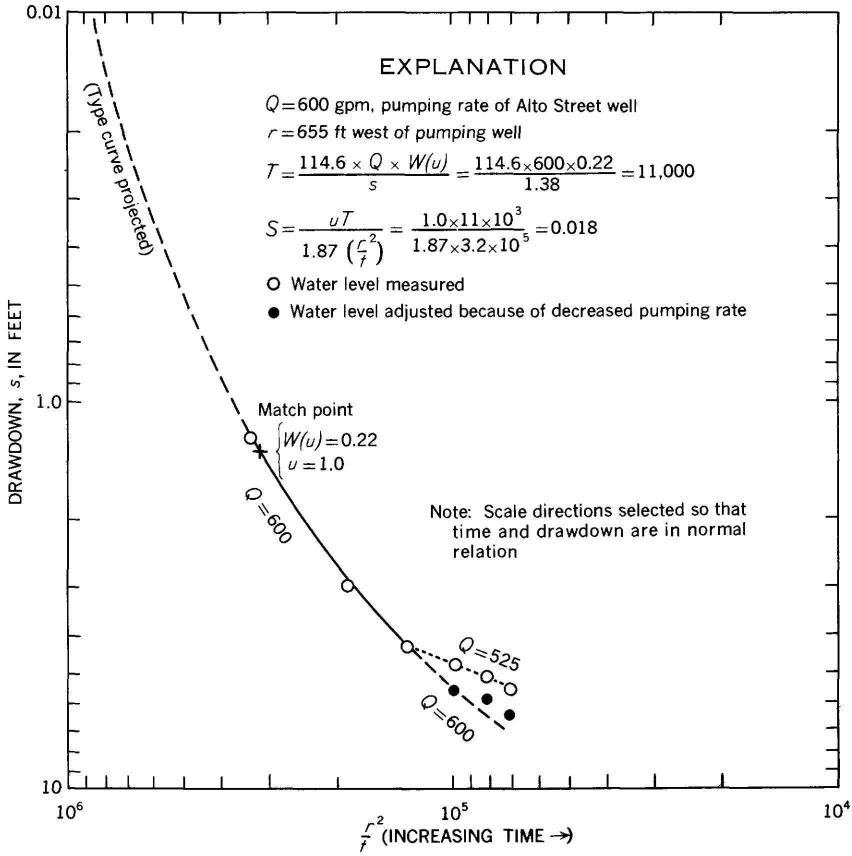


**FIGURE 44.—Drawdown in an observation well west of pumped Alto Street well, Santa Fe, N. Mex.**

and storage coefficients were determined to be about 11,000 gpd per foot and 0.018, respectively, from the coordinates $W(u)$, $u$, $s$, and $r^2/t$ of the match point indicated on the figure.

The recovery data for the Alto Street well (17.9.23.332) were tabulated and plotted by a modification of the Theis (1935) recovery method (fig. 45, curves A and B) that enables graphical comparison of recovery from pumping at different rates. The flattening of the curves with increasing time (decreasing $t/t'$), giving an apparent increase in transmissibility, is probably due to slow recovery of drained upper beds, which are under water-table conditions during part of the pumping and recovery periods, and to the decrease in thickness of saturation caused by the large drawdowns in these wells.

Water levels were not measured for the first 160 days of the production period of the Alto Street well (17.9.23.332), although weekly mean pumping rates are reported (figs. 42, 43), because the water level was reported to be at the pump intake in this

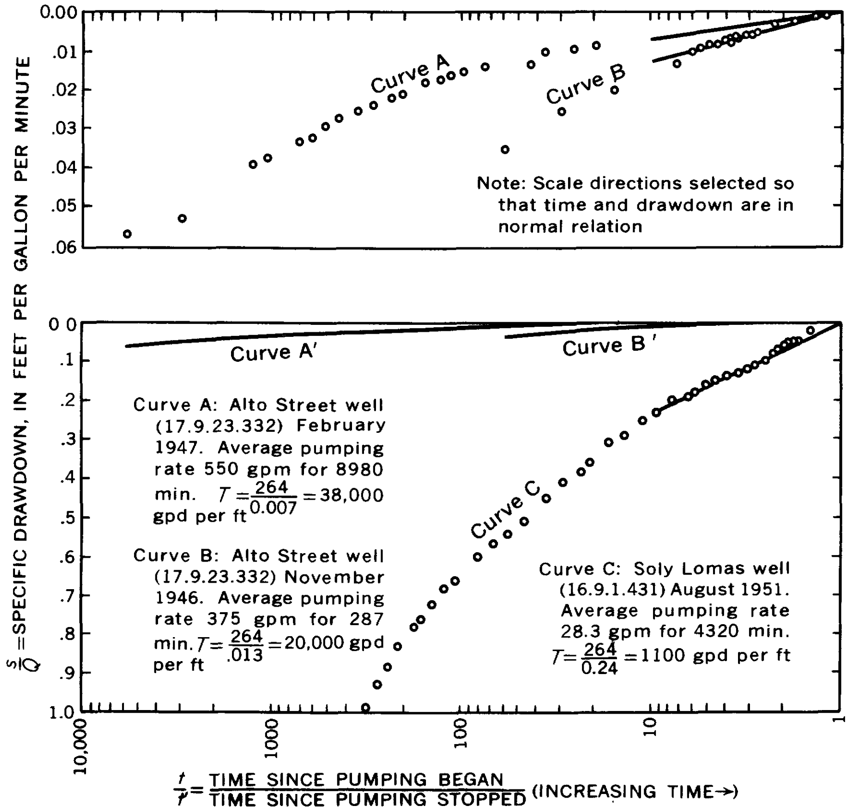


FIGURE 45.—Recovery data for wells at Santa Fe, N. Mex.

period (reported measurement, 234 feet on April 9, 1951). A plot of the reciprocal of the discharge against the logarithm of time (curve B, fig. 46), according to the procedure outlined by Jacob and Lohman (1952, p. 566) for interpreting decline in yield at constant drawdown, shows a large increase in slope, as does curve A. The break in curve B occurred about January 22, 1951, about the time of the start of pumping of the Torreon well (17.9.22.441), 0.7 mile to the northwest. The decrease in yield (45 gpm by Feb. 19, 1951) is so large, however, as to require that boundary effects must be present in addition to direct lowering resulting from pumping of the Torreon well; but the weekly discharge computations are too infrequent to enable determination of the distance to the boundary or to differentiate clearly the effects of pumping the Torreon well.

**Performance of the Hickox Street well**

Water levels in the Hickox Street well (17.9.26.222) were drawn down to the pump intake in the first week of pumping. The

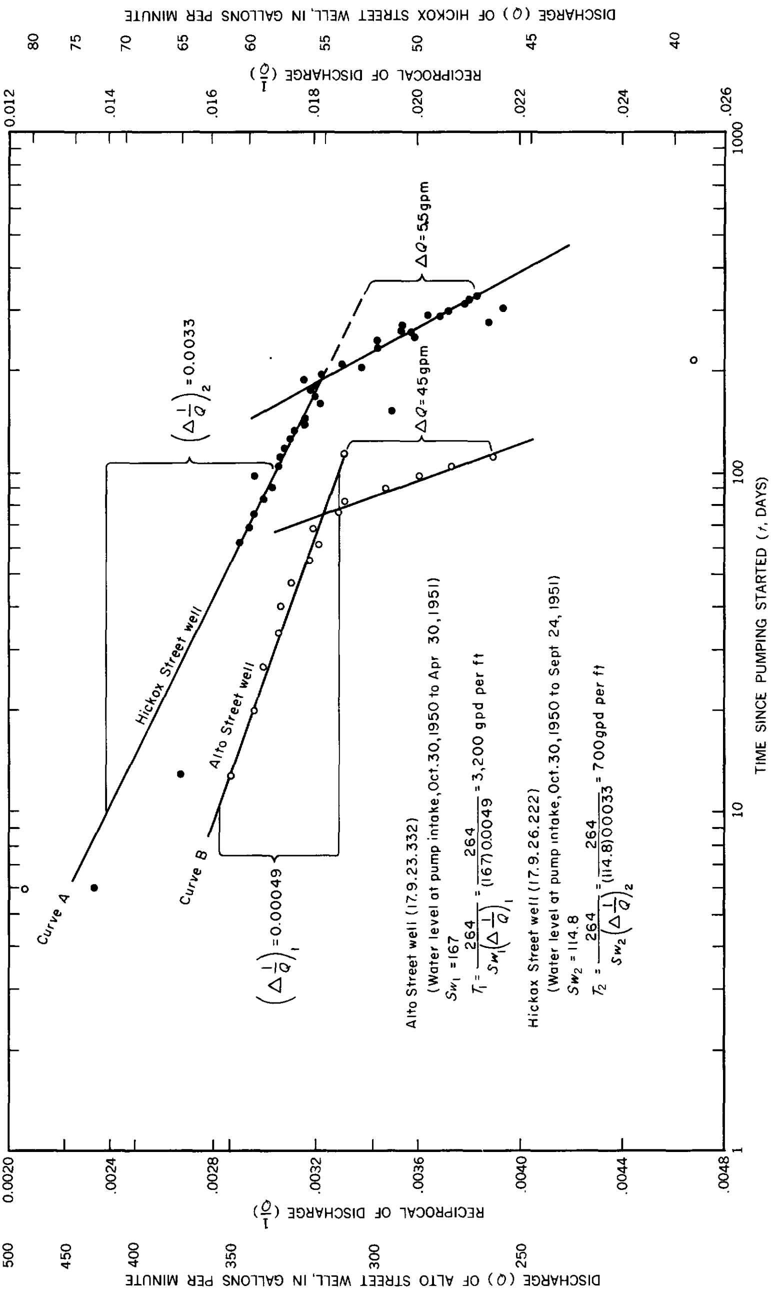


**FIGURE 46.—Decline in yield at constant drawdown.**

water level is reported to have remained at this level throughout the period of record, but the yield of the well declined.

When the reciprocal of the discharge is plotted against the logarithm of time (curve A, fig. 46) for the Hickox Street well, a sharp increase in rate of the decline in yield is apparent about May 20, 1951, when the Santa Fe well (17.9.26.133) started pumping, and the Ferguson well (17.9.23.322) resumed pumping. It is likely that the increased rate of decline in yield is due to interference by these wells. The decline in yield due to pumping the Hickox well alone after May 14, 1951, would be 5.5 gpm less than the measured decline in yield, as determined by extending the initial drawdown curve. Trial computations of drawdown caused by the Santa Fe and Ferguson wells in this period, using the method outlined by Theis (1935), indicate drawdowns of the order required to give the actual measured decrease in yield. Data for the early part of the pumping period are insufficient or too erratic to permit determination of effects of aquifer boundaries, which also probably influence the rate of water-level lowering.

#### Santa Fe and Torreon wells

Both these wells penetrate a greater thickness of permeable sand beds and have greater specific capacities than the previously mentioned wells. Pumping drawdowns in these wells are thus relatively small when considered in relation to yield and depth of the wells. The water-level curves for these wells (fig. 42) do not indicate any boundary effects or significant interference. However, the data available do not permit detailed analysis of the relations of these wells to each other or to other wells. Logs of these and nearby wells and examination of the few nearby outcrops of the aquifer suggest that water-table conditions (characterized by slow transmission of pumping effects) are probably prevalent, at least in the upper parts of the sediments pentrated by the wells. The deeper beds penetrated are probably equivalent to the strata penetrated by the other public-supply wells, and artesian conditions (characterized by rapid transmission of pumping effects) are probably present.

#### Conclusions

Data for the Alto, Hickox, and Ferguson wells indicate that pumping rates used in the pumping tests and in the 1950–51 production period were excessive. The pumping levels were initially so near the bottoms of the wells that water levels or yields continued to decline and reached undesirably low levels in relatively short times.

The pumping of a well at a lower rate increases greatly the total amount of water that can be pumped before excessive local depletion occurs. For example, if the drawdown in an isolated well in a large aquifer is 150 feet after 1 year of production at 1,000 gpm and 200 feet after 10 years of production at this rate, pumping the well at a rate of 500 gpm initially would produce a drawdown of 75 feet in the first year and only 100 feet at the end of 10 years. Many years would elapse before the drawdown would reach 200 feet, and thus many times as much water could be produced from the well at the smaller discharge rate before a given level was reached.

#### ARTIFICIAL RECHARGE

Artificial recharge is a means of increasing the amount of water recharged to an aquifer. The practice is ideally suited to areas where surface flow exceeds surface storage capacity at certain seasons or in wet years. As the natural recharge to the groundwater reservoir underlying Santa Fe occurs largely by infiltration of surface runoff into channel gravels of the Santa Fe River, the simplest method of artificial recharge would be to limit spill from the reservoirs to no more than the amount that could be completely absorbed above Cieneguita. In wet years when the surface runoff of the Santa Fe River greatly exceeds the available storage, unsalvageable natural spill would occur in large quantities for a relatively short period, generally in May or June. Smaller discharges could be made intentionally from the reservoirs before spillway level was reached, in order to keep the spill to a minimum value for a longer period in the early spring of years when heavy snowpacks assure excessive runoff.

The use of spreading canals or fields (Thomas, 1949b), is an effective means of increasing the rate of infiltration. The terraces along the Santa Fe River and the existing ditch system would be convenient aids to this type of artificial recharge, if sufficient surplus water became available.

A third means of artificial recharge is by direct injection of surplus surface water down wells, using either special recharge wells or the supply wells themselves. This practice has been successful in several localities (Thomas, 1951). Filtration and chlorination of the recharge water are apparently necessary to prevent clogging by sediment or by growth of certain bacteria in the well.

Records of the rates of recharge, the water levels in recharge wells and nearby wells, and the quality of water recharged or pumped out should be kept to determine the efficiency of any of these methods.

### ARROYO HONDO

A gaging station with a staff gage was established in February 1913 on Arroyo Hondo, 5½ miles southeast of Santa Fe. In the original publication of the records for this station it was stated that the drainage area above the station was 13½ square miles, but on a later, more accurate map the drainage area was measured at 6.7 square miles. The drainage area lies in the lower ridges and foothills of the Sangre de Cristo Range, the highest part of the area being at an altitude of about 9,000 feet. This station was operated until September 1922, and the record obtained represents natural flow. Because of the unstable stage-discharge relation and because of insufficient discharge measurements to define the many changes, the quality of several of the monthly discharges is questionable. However, the average of the annual discharges, as used in this report, is believed to be relatively accurate.

The recorded average yield of this basin is low (535 acre-feet) compared to the yield of the Little Tesuque Creek basin, although it is nearly as large. The basin of Arroyo Hondo is farther from the crest of the Sangre de Cristo Mountains and contains no high areas of heavy winter snowpack. In dry years the runoff from melting snow is negligible, whereas in wet winters the runoff may be very large. The peak runoff occurs in April, a month earlier than in the Santa Fe River and Rio Tesuque basins, which drain higher areas.

Most of the runoff of Arroyo Hondo probably recharges the ground-water reservoir of the middle ground-water unit. As in the Santa Fe River, the runoff below the former gaging station, although occasionally large in instantaneous flow, is small in comparison to that from the higher areas. No records of flow are available for these areas of low altitude.

### CIENEGUILLA AND CIENEGA

Ground water in both the Cienega and Cieneguilla areas discharges through springs and seeps, generally in arroyo bottoms. (See fig. 47.) In some places springs and seeps emerge on hillsides at the contact of the Ancha formation with underlying rocks. Some of these springs are used individually for domestic supplies, but the major use is represented by diversion of the aggregate flow for irrigation. The dry-weather winter flow in the Cienega and Cieneguilla areas is considered to be representative of the average discharge of the Cienega ground-water unit (fig. 31). As no measurements had been made of the discharge of these spring areas prior to this study, a program of measurement was set up at the outset of this investigation. The location of the gaging points is shown on figure 30. Approximate areas of consumptive use by evapotranspiration were planimetered from aerial photographs.

FIGURE 47.—View southward from Cerro de la Cruz toward the Cerrillos. Ortiz Mountains on middle skyline, Sandia Mountains on right skyline. The valley of Alamo Creek in foreground is damp and grassy owing to ground-water discharge.

### CIENEGUILLA

About 30 acres on a terrace on the northwest side of the Santa Fe River at Cieneguilla is irrigated by diversion of the flow of springs (S. 16.8.20.312) which emerge from the broad, sandy channel of the creek. The total area of consumptive use of water is about 38 acres. The flow of the springs was reported by Max Romero, a lifelong resident of the area, to have been nearly constant for the past 60 years.

As no suitable location was found at which the full spring discharge could be measured above diversions, a site below all diversions, use, and irrigation return was selected. This site is in the narrow canyon about 0.1 mile below the irrigated areas. Measurements of the discharge were made monthly from July 1951 to June 1952 with a pygmy current meter. As these measurements were made below points of diversion and use, only the winter discharge approaches the amount of the true ground-water discharge. The flow measurements at this station are presented in the upper part of figure 48.

Monthly measurements for only one year are not usually sufficient to estimate surface-water flow; however, as the Cienega and Cieneguilla measurements represent principally the discharge of ground water from an extensive aquifer, the annual variations are probably not large. The area of the portion of the aquifer that dis-

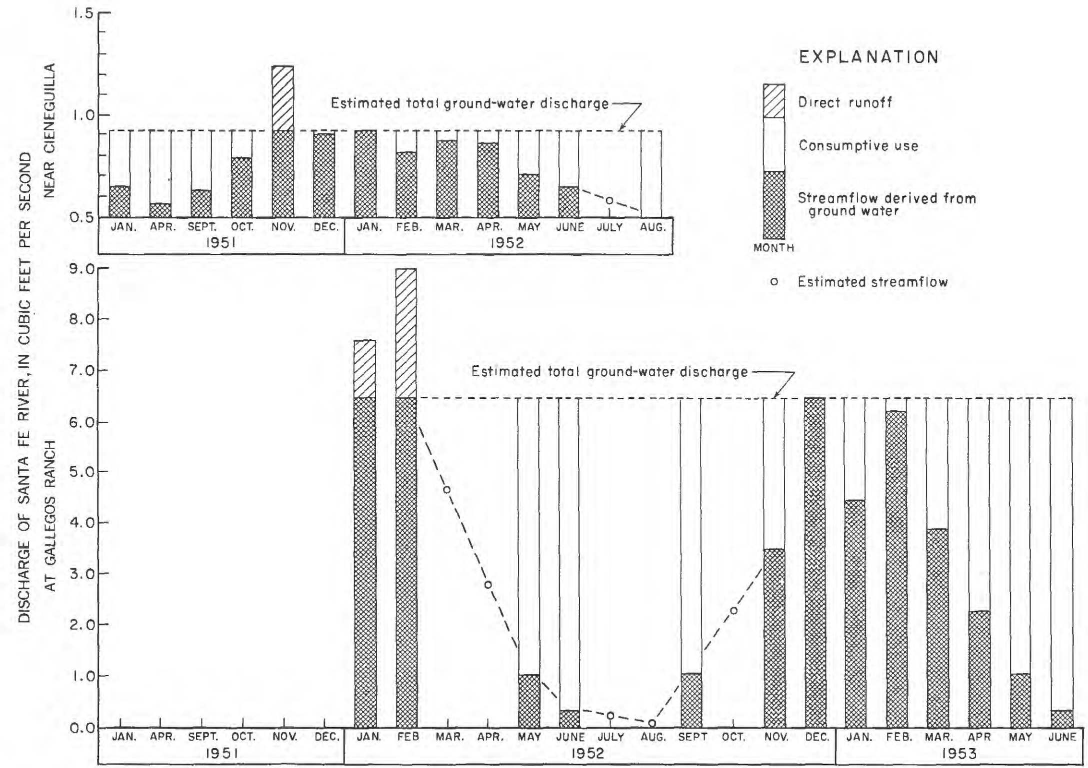


**FIGURE 48.**—Discharge of Santa Fe River near Cieneguilla and at Gallegos ranch. Monthly measurements on representative days are inferred to be average discharges for the month, except in months when surface discharge was included in the monthly measurement. Consumptive use is inferred to be the difference between assumed total discharge (based on winter discharge) and the measured flow.

charges at Cieneguilla alone cannot be determined accurately from present water-level data, but the area contributing ground water to the entire Cieneguilla-Cienega area can be estimated with reasonable accuracy. However, the measurements of flow at Cieneguilla are useful in making an estimate of consumptive use in the discharge area. If the December and January measurements are assumed to be representative of the annual average flow (evaporation rates are at a minimum in these two months), the difference between the January flow and flow in other months represents the consumptive use by vegetation and evaporation in 38 acres. Assuming that the flow measured each month was the average flow for the month, and the January flow of 0.92 cfs was the true discharge, the consumptive use was 109 acre-feet, and the use per acre was 2.9 feet, or 34 inches. The total ground-water discharge at Cieneguilla was therefore about 700 acre-feet in that year of measurement.

### CIENEGA

Several measurements of the flow of Cienega Creek, and of the Santa Fe River downstream from all major tributaries, were made in 1952 to determine the total flow and consumptive use along this part of the stream. The data collected are not conclusive, and continuing measurements are needed to obtain an accurate estimate of the ground-water discharge.

The lower part of figure 48 is a plot of the measurements of the flow of the Santa Fe River near Gallegos ranch. This flow represents the total outflow of ground water from the Ancha and Tesuque formations in the Cienega ground-water unit (fig. 31). If the December 1952 flow is representative of the annual flow, the total ground-water discharge from the middle ground-water unit was about 4,700 acre-feet per year. Of this amount about 2,500 acre-feet was used consumptively above the gaging station. As the area of natural consumptive use plus the irrigated area is about 812 acres, the consumptive use of water averaged 3.1 feet in that area. However, a length of about 4.5 river miles of channel alluvium is saturated in the Cienega area, the total area being perhaps 100 acres. If the total evapotranspiration is averaged for the entire area of 812 plus 100 acres, then the mean annual unit consumption for the entire Cienega area is 2.7 feet.

As the average annual ground-water discharge is equivalent to the annual average recharge, the recharge per unit area of the basin can be estimated from the total discharge (4,700 acre-feet). The area of the ground-water basin contributing to the Cienega-Cieneguilla area is about 131 square miles (83,800 acres). Thus, the unit recharge is about 0.06 foot, or about 0.7 inch, annually.

The average annual water yield of Arroyo Hondo above the former gaging station (drainage area, 6.7 square miles) is about 535 acre-feet, or 1.5 inches (table 11). If the remainder of the area of Precambrian rocks (17.1 square miles) south of Arroyo Hondo and tributary to the middle ground-water unit has an average yield of 1.2 inches (1,095 acre-feet), the total water yield of the foothills would be about 1,600 acre-feet. If it is assumed that all this yield recharges the aquifers in the middle ground-water unit, then the recharge originating from precipitation directly on the Ancha formation on the plains is the balance, or 3,100 acre-feet (see table 11). The computed recharge directly on the plains alone is thus 0.5 inch annually. This figure is probably somewhat high, inasmuch as a large area north of the ground-water basin discharges occasional flood flows into the Cienega ground-water basin, and the small recharge from such flows is included in the computed direct recharge.

## RIO TESUQUE

### STREAM MEASUREMENTS

From May 7 to October 31, 1919, a temporary gaging station was operated on Tesuque Creek, about 6 miles above Tesuque Pueblo and 175 feet downstream from the present site (18.10.32.400). Although the station was above all diversions, and although the record obtained May 7–September 3 and October 8–31 represents natural flow (see table 19), the record is too short to be of value.

As part of a general program to obtain information on use of water by irrigation ditches diverting water from the Rio Grande and its tributaries, gaging stations were established in 1936 on Tesuque Creek above diversions; Rio Tesuque in Tesuque; Little Tesuque Creek; and the following points of diversion from the Rio Tesuque: Cajon Grande and De la Cruz ditches, Acequia Madre at head and at waste, Acequia Medio at head and at waste, and Mitchell, Post, Qwiyo, and Corral ditches. The Hubbard ditch station was established in 1938. All these stations were discontinued after a few years, except for the station at Tesuque Creek above diversions, which was operated until January 1952.

In March 1936 a station was established on the Rio Tesuque at the bridge on U.S. Highway 285, below the head of Acequia Medio and 1½ miles below the mouth of Little Tesuque Creek. Discharge records for this station are available for March 28, 1936, to October 25, 1938, when the station was discontinued because of increasingly adverse channel conditions. It was replaced by a station having a concrete control, established in October 1938, 3,100 feet upstream from the Tesuque bridge, 2,000 feet upstream from the head of Acequia Medio, and about 1 mile downstream from the mouth of Little Tesuque Creek. Discharge records were collected at this site from October 26, 1938, to September 30, 1941, when the station was discontinued. The records for this station (table 19) are not equivalent to those at the station at Tesuque bridge, except for flood flows.

#### UPPER DRAINAGE AREAS

As the geology, topography, vegetation, and climate of the Rio Tesuque and Santa Fe River valleys are similar, the natural hydrologic cycles also are similar. The mountain drainage basin of Rio Tesuque is smaller and has a smaller proportion of high area; therefore, the average precipitation and unit runoff from the entire basin are lower, and the base flow is relatively somewhat lower.

As in the upper Santa Fe River basin, the dry-weather flow of Tesuque Creek is sustained by ground-water discharge from numerous springs that emerge from fractured or weathered zones in the Precambrian rocks of the mountain drainage basin and the valley alluvium and glacial deposits, and by surface-water runoff of melt water from winter snows. The usual pattern of runoff, shown graphically in figure 49, is a slowly declining base flow sustained by ground-water discharge through the fall and winter months, only slightly modified by precipitation, freezing, and melting. The spring snowmelt runoff of Tesuque Creek usually is largest in May. However, the runoff of Little Tesuque Creek is usually largest in April, as its basin is at a lower altitude than the basin of Tesuque Creek. Melting of accumulated winter snows begins in March, but it is large only in April and May, usually declining in June, by which time practically all the snow has melted. The spring precipitations and snowmelt usually contribute a major part of the annual runoff, and afford most of the recharge of ground water.

The total runoff for little Tesuque Creek above diversions was one-half to one-fourth that of Tesuque Creek in the wet years, but was less than one-tenth the runoff of Tesuque Creek in the water year 1938, a dry year, although the drainage areas do not differ greatly—8.6 and 12.2 square miles, respectively (table 11). The relatively low runoff and even lower base flow of Little Tesuque Creek are probably due to the lesser areas at high altitudes and the absence of glacial deposits in its drainage basin. Comparison of the water yields of various drainage basins and the relation to altitude are shown in figure 50. Both the Santa Fe River and the Tesuque Creek drainage basins have large headwater areas above an altitude of 10,000 feet, where there is appreciable glacial material and winter snowpack. Thus these streams have a relatively larger base flow than streams in the lower drainage basins. The large increase in precipitation, accompanied by only a small increase in evapotrans-

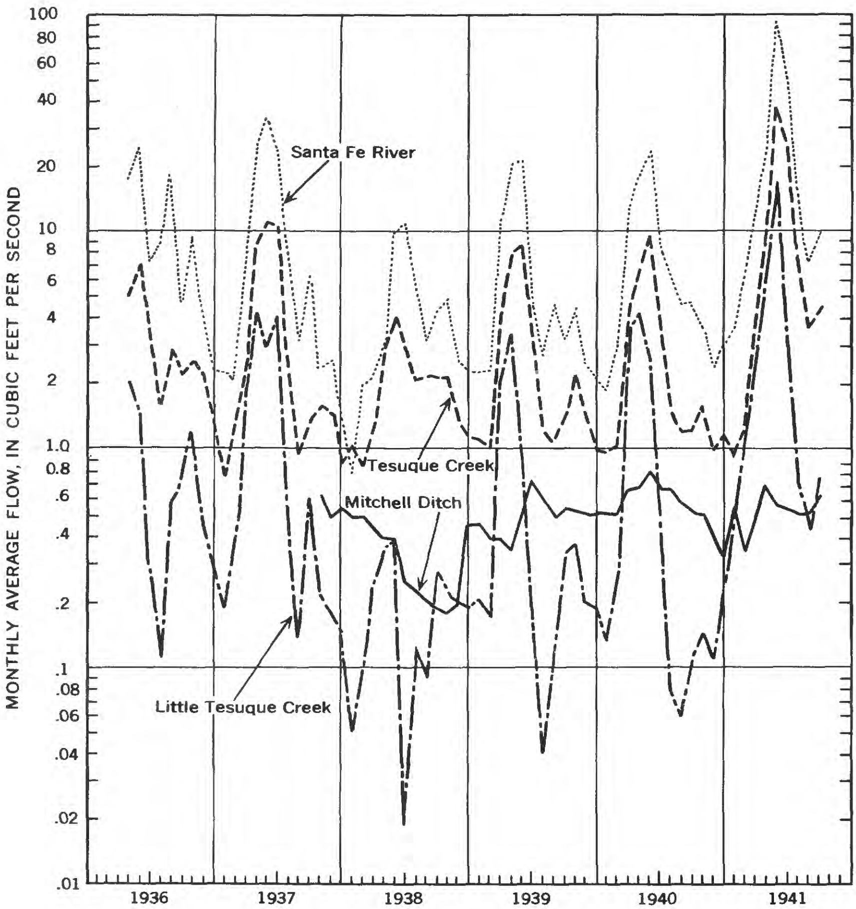


FIGURE 49.—Streamflow near Santa Fe, N. Mex., calendar years 1936–41.

piration with altitude, are important factors contributing to the large increase of water yield at high altitudes. It can be seen from table 11 that the evapotranspiration losses in drainage basins near Santa Fe have a small range, from about 13 inches to about 19 inches. Although potential evaporation rates decline with increasing altitude (decreasing temperature), the increased precipitation and vegetation allow greater actual consumptive use (evapotranspiration) at higher altitudes. However, water yields are much larger in drainage basins where the precipitation appreciably exceeds the actual annual consumptive use than in areas where precipitation is only slightly greater than consumptive use.

### TESUQUE VALLEY

The streamflow pattern of the Rio Tesuque differs from that in the lower stretch of the Santa Fe River because the artificial de-

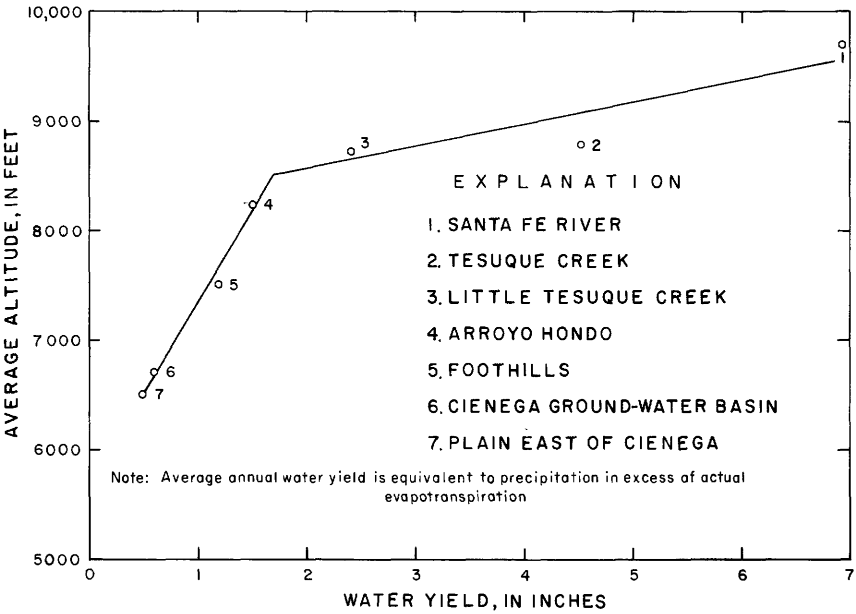


**Figure 50.—Annual water yield and altitude of drainage basins near Santa Fe, N. Mex. (See table 11.)**

velopment and use of water in the Tesuque valley are markedly different from the present development and use in the Santa Fe River valley. The mountain drainage basin of the Rio Tesuque is probably more modified by man than the upper basin of the Santa Fe River, but the lower basin is much less modified. Tesuque Pueblo Indians have used the flow of the Rio Tesuque near the Pueblo for centuries, and settlers in the Tesuque valley have diverted it for irrigation since 1740. Such irrigation diversions use consumptively some of the surface flow, but a large part undoubtedly is returned to ground water or surface flow by infiltration and ditch waste. Tesuque Pueblo also uses ground water derived from an infiltration gallery in the Recent channel fill of the Rio Tesuque, in sec. 25, T. 18 N., R. 9 E. No surface storage is available on the Rio Tesuque, except for 18 acre-feet of storage below the outlet of the Tesuque infiltration system (Mitchell ditch).

As the surface water has been fully appropriated and used for many years, surface flow and ground-water conditions in the Rio Tesuque valley can be assumed to be essentially in equilibrium with the present climate and irrigation system, although many local variations of ground-water levels, discharge rates, and infiltration rates are superimposed on the overall equilibrium.

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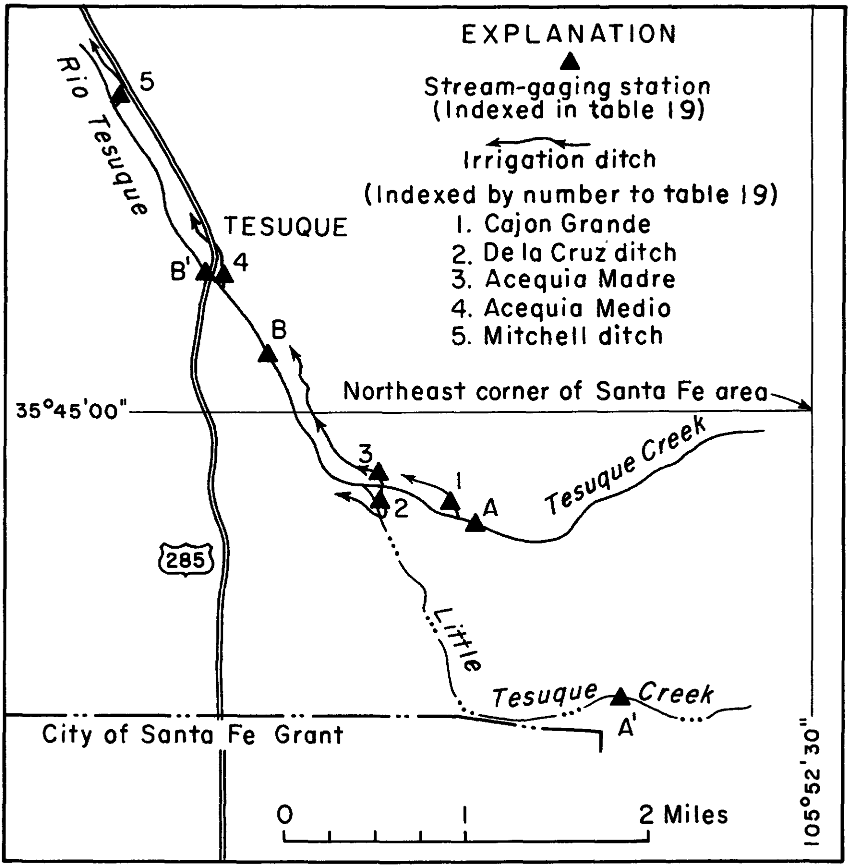


FIGURE 51.—Major diversions from, and losses of, Rio Tesuque, Santa Fe County, N. Mex.

Records of the flow of the Rio Tesuque at Tesuque are available for only a few years (table 19). Stream losses were computed for the period for which records are available for the important main stream and diversion points, by subtracting the sum of the flows of the Rio Tesuque past the Tesuque gaging station, De la Cruz ditch, and Acequia Madre (and Acequia Medio in water years 1937 and 1938, when the gaging station was below that diversion) from the sum of the flow past the former gaging stations on Tesuque and Little Tesuque Creeks. The location of these ditches and stations is shown in figure 51. Diversions to Cajon Grande ditch and minor diversions are included in the loss figures, which therefore include the amount of consumptive use below these diversions. It is apparent from these records that an appreciable amount of water is consistently lost between the upper gaging stations and the Tesuque station.

Between the previously mentioned upper and lower groups of gaging stations, the Tesuque River and Little Tesuque Creek flow in incised channels cut into relatively broad valley floors flanked by thick terrace gravels. In the part of the valley downstream from the edge of the pre-Tertiary rocks, the Tesuque formation underlies terrace gravels and Recent alluvium at depths ranging from a few feet to as much as 50 feet. The terrace gravels and channel alluvium are sufficiently permeable to absorb, retain, and transmit underground large quantities of the surface flow. Water-spreading and ditch losses incident to the diversion of streamflow for irrigation greatly aid recharge. The consumptive use by irrigated and natural vegetation is only a part of the loss that was computed from the streamflow records. However, the loss computed from these records is merely an apparent loss, which is less than the true loss because runoff from the 2.8 square miles tributary to the Rio Tesuque between the gaging stations is not measured. Although this area contains more than 10 percent of the total area above the Tesuque gage, the average runoff contributed directly is probably less than 5 percent, or less than the error of measurement. As there are some periods when no water is contributed in this stretch of the Rio Tesuque, the true channel loss and relation of loss to streamflow can be inferred (fig. 52) by plotting the difference of daily or monthly flow between the upper and lower stations against the flow at the upper stations. All points to the right of the curve represent apparent losses smaller than the total loss. Departures from the curve are due principally to inflow entering below the upper stations but measured at the lower stations. The curve is therefore an "envelope" of all the plotted points and approximates the true loss at any monthly average flow. Large increases of flow above 4 cfs do not cause appreciably larger losses. An average monthly flow of 2 cfs at the upper stations is apparently the maximum that is completely absorbed above the Tesuque gaging station, and optimum conditions for recharge exist at this rate of flow. The rate of infiltration loss might drop somewhat with long-continued flow in excess of 2 cfs, as ground-water levels and storage would approach a new equilibrium with the higher flow rates.

The mound on the water table in the northeastern part of the Santa Fe area (pls. 6, 7) further substantiates the belief that the Tesuque formation is being recharged by the Rio Tesuque in that area. As in the Santa Fe River valley, the zone of saturation in the alluvium of the Rio Tesuque valley probably allows more recharge to the less permeable underlying Tesuque formation than could be obtained directly from surface flow in a stream channel cut into the Tesuque.

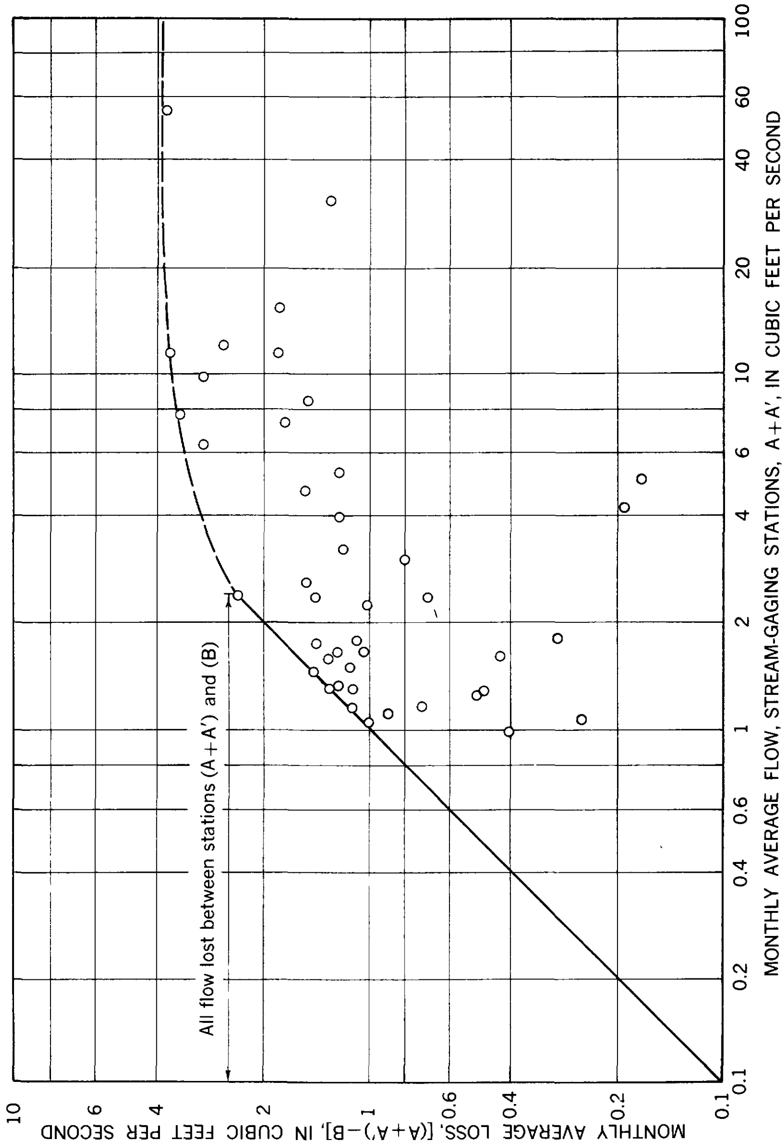


FIGURE 52.—Losses of Rio Tesuque, Santa Fe County, N. Mex. See figure 51 for location of stations.

#### FLOW OF MITCHELL DITCH

Mitchell ditch conducts the discharge of an infiltration gallery in sec. 25, T. 19 N., R. 10 E., just outside the Santa Fe area. The gallery was constructed by burying an intake pipe 6–8 feet below the surface of the Recent channel gravels of the Rio Tesuque and below the low water level of the saturated zone in the alluvium.

The general pattern of the hydrograph (fig. 49) suggests that the discharge of Mitchell ditch is related to the flow of Tesuque and Little Tesuque Creeks, in that peak flows occur in the spring, with secondary peaks in some wet summers, when the Rio Tesuque also has a nearly continuous flow. Part of the flow of Mitchell ditch is due to direct infiltration of surface water from the Rio Tesuque in times of short-term high flow past the gallery. However, as the flow of a drain (infiltration gallery) is proportional to the height of the water table in the adjacent strata, the major causes of fluctuations in flow of the ditch are probably the fluctuations in water level of the zone of saturation feeding the infiltration gallery, which in turn are caused by fluctuations in surface flow. Peaks in the hydrograph of Mitchell ditch after 1938 usually occur a month later than in the Rio Tesuque. The fluctuations do not appear to correlate well with diversions to ditches serving irrigated lands east of the Rio Tesuque and the infiltration gallery, although field observations indicate that return of water by irrigation and ditch losses are the principal sources of recharge and flow to Mitchell ditch.

A marked increase in flow usually occurs in October, even when there is no increase in precipitation or flow of the Rio Tesuque upstream. The pumping of many domestic wells and a few small irrigation wells in Tesuque depletes the flow in summer months to some extent, and part of the increase in flow in October may be due to shutting down these wells. The water table in the vicinity of the infiltration gallery and for several miles upstream is not far below the land surface, and a large number of cottonwoods, sustained by the shallow ground water, grow in the valley. The increase in flow therefore probably results in part also from a rise in the water table resulting from reduction of evapotranspiration. Any corresponding decrease in flow in the spring is masked by the high direct flows of the spring runoff.

### RIO GRANDE BETWEEN OTOWI BRIDGE AND COCHITI

#### STREAM MEASUREMENTS

The reach of the Rio Grande receiving most of the runoff from the Santa Fe area is gaged at Otowi bridge (sec. 18, T. 19 N., R. 9 E.) and at the bridge between Cochiti and Pena Blanca (sec. 17, T. 16 N., R. 6 E.). The accuracy of gaging records at the Otowi bridge station is considered good (error less than 10 percent).

It is one of the oldest and most reliable stations on the Rio Grande, and records from this station are used as a basis for division of water between New Mexico and Texas. The station is at the head of White Rock Canyon, and all waste water from diversions upstream is returned above the station. Records from this station represent the full flow of the Rio Grande.

No water is diverted in White Rock Canyon and the canyon bottom is relatively narrow. Some water is consumed by vegetation on the banks of the river, but the amount is extremely small in comparison to the amounts consumed by vegetation upstream and downstream from the canyon. The flood plain of the reach of the river from the mouth of White Rock Canyon to the Cochiti gaging station is wider and contains some phreatophytes. It is reported that, prior to the construction of the Cochiti diversion dam in 1931, water for irrigation of 2,200 acres was diverted above the gaging stations, but the diversions were not measured. The records for the Cochiti station from 1925 to 1931 are not consistent in their relations to the Otowi station and cannot be used directly to determine water yield in this stretch of the river, but records for later years were used in preparing the discussion below.

Although the crests of the mountains west of the Rio Grande are lower than those east of the river, the forest cover, average altitude, and average precipitation to the west are greater. The rocks and soils of the forested mesas west of the Rio Grande are permeable, and a relatively large proportion of the precipitation is probably recharged to zones of saturation, discharge from which composes the base flow of streams draining the area. For the most part the waters of these streams percolate into deep, thick, and permeable strata underlying their lower courses, and much of their flow is transmitted to the Rio Grande as ground-water increment. Each of these perennial streams resembles the Santa Fe River in that each has long, narrow ground- and surface-water basins from which most of the ground water recharged in wet periods can drain to the stream within a few months. Abnormally high precipitation increases flow temporarily, and some surface water may reach the Rio Grande directly, but the discharges drop back to normal low flows (ground water) within an average of 3 months.

If the months in which large total increments resulting from heavy precipitation are excluded, the average ground-water increment from both east and west is computed to be approximately 25 cfs in this reach of the Rio Grande.

### INCREMENTS IN FLOW

Most of the surface water from the Santa Fe area and the adjacent mountains discharges to the Rio Grande either north or south of the reach of the river between these gaging stations (fig. 30). The direct distance between the gages is about 20 miles, and the river distance is 26 miles (Herron, 1916, pl. 1). The surface drainage areas tributary to the Rio Grande between the Otowi and Cochiti gaging stations are 137 square miles on the east and 252 square miles on the west. Present information suggests that the surface-water and ground-water basins on the west side of the river practically coincide. However, the ground-water basin east of the Rio Grande that is tributary to this reach of the river has limits which are considerably different from the surface drainage basin. It consists of 338 square miles of ground-water reservoir tributary to the Rio Grande between Otowi bridge and the Cochiti gaging station (fig. 31).

The gain of the Rio Grande in this reach of the river was determined by computing the daily differences in flow in the nonirrigation season (November–February), and a monthly average gain for days in which a gain was apparent. It was assumed that apparent losses of flow in this stretch of the Rio Grande represent diversions or errors in measurements, although the possible errors in measurement are of the same order of magnitude as the apparent losses or gains. For a 19-year period of record, periods having a large computed gain correspond with periods of greater precipitation. During the irrigation season unmeasured diversions are considerably larger than the probable gain and this method cannot be used.

East of the south half of White Rock Canyon, blocks of nearly impermeable rocks are faulted relatively upward and impede the movement of water underground from the lower Santa Fe River surface-water drainage basin (Cienega area) to the Rio Grande. Northward to Canada Ancha, dikes and feeders to the Cerros del Rio volcanoes impede ground-water movement westward. At the north end of the Cerros del Rio (sec. 12, T. 18 N., R. 7 E.) a spring emerges from the Tesuque formation, where Canada Ancha cuts through a basalt dike. Surface drainage from the area east of White Rock Canyon is blocked by the Cerros del Rio mass, except for drainage from their own precipitous western slopes. Canada Ancha has no perennial flow and drains a small area of low precipitation.

Although there is no perennial surface discharge from the Santa Fe area to the Rio Grande in this stretch of the river, there is some perennial discharge of ground water. Many springs and moist areas, well above river level, line the banks of the Rio Grande. The spring near the mouth of Canada Ancha and one artesian well in the vicinity discharge small quantities of water from beds in the Santa Fe group, giving visible evidence that ground water discharges to the river from the east. Water-table contours (pl. 7) also indicate ground-water discharge to the Rio Grande from the vicinity of Santa Fe. This discharge is a part of the increment to the Rio Grande which was computed from flow past the Otowi and Cochiti gaging stations.

The Tesuque formation dips to the northwest and includes some strata that are only slightly permeable. Water in the interbedded permeable beds is confined, but it does move across the less permeable beds to discharge into the Rio Grande. The ground-water gradients range from about 50 to 100 feet per mile, and the amount of water in storage in the northern ground-water unit is large. Therefore, changes in water level of a few feet due to seasonal and annual precipitation cycles should have no appreciable seasonal effect on the rate of ground-water discharge from the Tesuque formation. The water level in perched or semiperched saturated zones in the post-Tesuque rocks adjacent to the Rio Grande may fluctuate appreciably with precipitation, but the saturated lenses probably do not extend far back from the river. The total discharge from these shallow aquifers is likely to be small, so that these fluctuations probably are insignificant compared to the total increment to the flow of the Rio Grande. The records of flow of the Rio Grande at Cochiti since 1931 are rated generally as fair (error less than 15 percent). Diversions have not been measured except in parts of 1936–39. (See table 19.) Records in this period are also inconsistent in their indications of gain or loss, partly owing to lack of records of some diversions, the poor locations of the gaging stations for this purpose, and some consumptive use in and below White Rock Canyon.

Nearly all the increment exceeding about 25 cfs (the average ground-water increment) probably represents direct runoff from the area west of the Rio Grande. Although it is difficult to estimate what proportion of the dry-weather increment comes from the east, probably about one-half, or about 12 cfs, comes from east of the Rio Grande. This quantity represents essentially the average annual ground-water discharge of the northern ground-water unit (338 sq mi), and would represent an average annual recharge of about 0.34 inch over the area. The difference between this figure and the value of 0.5 inch in the last line of table 11 represents (a) the consumptive use of ground-water discharge from springs along the Santa Fe and Rio Tesuque, and (b) any error in the estimates.

Previous measurements of inflow into White Rock Canyon were made by the State Engineer of New Mexico (French, 1913, 1924). The first estimate was made in October 1913 by subtracting the measured discharge of the Rio Grande at Otowi from the sum of the discharges of the Rio Grande at Pena Blanca and a diversion at Pena Blanca. No surface inflow was reported. The indicated gain of 47.7 cfs in the 26.5-mile stretch of the river is about twice the quantity computed above, but is of the same order of magnitude. A later measurement (January 1924) indicated a gain of 131 cfs in 23 river miles. However, this gain is abnormally high because of snow-melt runoff during that month.

## METHODS OF CONSTRUCTING AND TESTING WELLS

Nearly all the wells in the vicinity of Santa Fe were dug by hand or drilled by cable-tool rigs. Two city wells were drilled by rotary rigs. Excellent descriptions of well-drilling methods are given by Bennison (1947) and Bowman (1911), in Technical Manual 5–297 of the War Department (1943) and in trade journals; detailed description of such methods is not given in this report.

Cable-tool drilling is probably most satisfactory where the strata to be penetrated are not subject to caving, or where high artesian pressures will not be encountered. In general, cable-tool holes give to nontechnical observers more satisfactory information on the type of strata encountered and permeability of the water-bearing zones. However, in aquifers like those of the Santa Fe area the deep, large-diameter wells required for large municipal, industrial, or irrigation requirements probably are more satisfactorily completed by the hydraulic-rotary method, despite the possibility of sealing some water-bearing zones off with drilling mud. The ease of setting large-diameter casing to great depths and the ease of setting screens or perforated sections in their proper place are some of the advantages of rotary drilling. It is also easier in rotary-drilled wells to install gravel envelopes to prevent excessive sand from entering the well. The reverse hydraulic method combines the advantages of good drilling information with these advantages. However, it may be preferable in some areas to drill cable-tool holes for purely testing purposes, and use rotary methods if necessary for adequate production wells. Reliable information can be obtained by rotary methods if the driller is experienced, if proper sampling techniques are used, and preferably if the entire drilling process is observed by a geologist experienced in rotary-drilling procedures.

Entrance of excessive sand into wells is a common problem in the Santa Fe area. Entrance is commonly prevented by means of a gravel envelope or screen which retains the larger grains but allows the finer grains to enter the well and be removed during development of the well. The most effective size of gravel and screen opening depends on the materials penetrated in individual wells, and a correct decision on these points is extremely important to the efficiency of the well. More detailed information on the construction and development of wells to prevent entrance of sand is limited largely to publications by various drilling and screen companies, by the American Water Works Association, and by the petroleum industry.

Records of the construction details and the performance of wells are essential. Data on the size of casing used, position of perforations of screens, and the initial water level in the well should be kept in written form, along with a log of the strata penetrated and a record of the water levels observed during the drilling, for this information is frequently found useful in later reconditioning of wells or for determination of the reasons for decrease in yield with time. Such information, when collected and studied, also forms the basis for overall determinations of the possibilities of development and conservation of water resources, and as a guide to the conditions to be encountered in future drilling.

The basic principle in the testing of well yield is that the drawdown caused in a well by pumping for equal times is approximately proportional to the pumping rate, if the "entrance losses" (frictional losses in head that occur as the water enters the well) are moderate. A drawdown test is which the well is pumped at a constant, measured rate for an adequate period of time, generally at least 8 hours and preferably 24 or more, with periodic measurement of water levels before, during, and after pumping, is an excellent way to determine accurately the potential capacity of a well. Wenzel (1942) described methods for testing wells and interpreting pumping-test data. Ferris (1949), Jacob (1950), and Jacob and Lohman (1952) discuss additional methods of interpreting pumping tests. Additional references are given in their papers, and examples of interpretations of pumping tests are given in parts of this report.

An important point is that ground water is withdrawn almost entirely from storage until the cone of depression has become large enough to divert ground water from other .outlets in an amount equal to the withdrawal of water. Therefore, water levels in wells decline with pumping until the diversion has occurred and equilibrium is reached. Reaching equilibrium may take a long time, and water levels may approach the bottom of the well before equilibrium is reached. The direct effect of droughts on water levels in the Santa Fe area is generally small, except in aquifers that are thin and of small lateral extent. The required depth of penetration of the well into the aquifer to assure an adequate water supply for the future is thus dependent on the hydrology of the aquifer encountered, the rate at which the well will be pumped, and the effects of pumping other wells in the area. It is not possible to give a definite rule as to the penetration required, but probably it should be at least 2 or 3 times the drawdown in a 24-hour test at the required pumping rate—or, to put it somewhat differently, the drawdown should not exceed one-third to one-half the depth of penetration. If water-level lowering as a result of pumping other wells is expected, even greater penetration would be required. It is usually much cheaper to drill a few extra feet initially than to deepen a well at a later date. In some cases the desired pumping rate may be so high as to deplete the ground water near the well before the cone of depression has spread very far. (For an excellent discussion of this and similar ground-water problems see Thomas, 1951.) In such cases, additional, dispersed wells would be necessary to secure the desired supply, or a lower pumping rate, perhaps with extended pumping time.

In summary, the pumping rate of a well and the depth of a well required for the desired pumping rate are dependent on the hydrology of the aquifer and can be determined only by a pumping test on the well in question. Even for small-capacity wells, it is worth while to be certain that the depth of the well is adequate to support future pumping.

# PART 4—GEOPHYSICS

By H. A. Winkler

## INTRODUCTION

Geophysical exploration of the Santa Fe area was directed toward determining the geologic conditions beneath the Ancha formation, which forms a blanket 100–300 feet thick over two-thirds of the area and thus obscures the relations between the underlying geologic units. Resolution of the boundaries of the following geologic units was attempted: basement rocks (the Precambrian complex of igneous and metamorphic rocks); consolidated sedimentary rocks (the sedimentary and extrusive rocks of Pennsylvanian through Miocene age); Tertiary intrusive rocks; and unconsolidated sediments (the Tesuque formation, largely sandstone, and the Ancha formation, mainly sand and gravel).

The results of the geophysical exploration, coordinated with geologic, topographic, and hydrologic information, are summarized on plate 5. Table 13 summarizes the geophysical characteristics of the geologic units.

Each of the four geophysical methods used has been important in determining certain of the boundaries between the several geologic units (table 14). The shape of the surface of the basement rocks is a regional feature; it was determined by measurements of gravity. The smaller features, which are superimposed on the regional structure, were studied by seismic, resistivity, and magnetometer methods. Refraction seismology determined the depth to the interface between the unconsolidated sediments and the consolidated sedimentary rocks. Seismic study also supplied information locally on the distribution of masses of Tertiary igneous rocks, the depth to the water table, and the interface between the Ancha and Tesuque formations. Resistivity studies were most suited to determining the depth to the base of the Ancha formation and were most effective where the Ancha formation is underlain by dipping beds of the Tesuque formation. Except in one small part of the area there was no recognizable resistivity contrast at the water table. Magnetometer measurements supplied information locally concerning Tertiary intrusive bodies. Geophysical control was not adequate to determine the subdivisions of the consolidated sedimentary rocks.

TABLE 13.—*Geophysical properties of rocks in the Santa Fe area, New Mexico*

| Geologic units and types of rocks tested | | | Laboratory measurements | | | | Field data | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Number of samples | Bulk density (gm/cm³) | Volume susceptibility ($10^6$ c.g.s.) | Magnetization (ratio of remanent to induced) | Resistivity (ohm feet) [1] | | Seismic wave velocity (feet/sec) | |
| | | | | | | | Dry | Wet | Dry | Wet |
| Basalt | Basalt | | 3 | 2.81 | 6,100 | 5.3 | [2] 6,000± | | | |
| | | | | 2.62 | 9,600 | 14.2 | | | | |
| | | | | 2.54 | 2,100 | 3.3 | | | | |
| | | Average | | 2.66 | | | | | | |
| Unconsolidated rocks | Alluvium and Ancha formation | Alluvium | 1 | [3] 1.57 | 0 | | 100–2,000 | 30–500 | 600–2,000 | 6,000 |
| | | | | [4] 2.1 | | | | | | |
| | | Ancha fm | 1 | [5] 1.4 | 0 | | 100–2,000 | 30–500 | 600–3,600 | 5,100–8,500 |
| | | Average | | [6] 1.7 | 0 | | | | 2,500 | 6,000 |
| | Tesuque formation | | | [6] 2.1 | 0 | | 30–600 | 10–500 | | 7,000–8,500 |
| Consolidated sedimentary and volcanic rocks (except basalt) | Pre-Santa Fe Tertiary rocks | Limburgite | 2 | 3.08 | 4,950 | 1.35 | 7,500 | | 11,500 | |
| | | Flow latite | 1 | 2.69 | 6,000 | .17 | | | | |
| | | Brecciated latite | 1 | 2.18 | | | | | | |
| | | Andesite dike | 1 | 2.47 | 4,200 | .73 | | | | |
| | | Monzonite | 1 | 2.50 | 25 | | | | | |
| | | Trachyte | 2 | 2.54 | 1,900 | 0.4–5.7 | | | | |
| | | Sandstone of Galisteo fm | 3 | 2.40 | 0–140 | 0–0.65 | | | | |
| | | | 3 | 2.45 | | | | | | |
| | | Average | | 2.54 | | | 400–1,000 | | [7] 8,900–12,000 | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mesozoic sedimentary rocks | Mancos shale | 8 | 2. 59 | | | | | |
| | | Hornstone | 1 | 2. 38 | 0 | | | | |
| | | Wingate and Entrada sandstones | 1 | 2. 64 | | | | | |
| | | Average | | 2. 55 | | | | 50–1, 000 | |
| Basement Rocks | Precambrian rocks | Granite | 2 | 2. 65 | | | | | |
| | | Granulite | 1 | 2. 64 | | | | | |
| | | Amphibolite | 1 | 2. 99 | | | | | |
| | | Granite | 1 | 2. 49 | 810 | 0. 47 | | | |
| | | Average | | 2. 69 | | | [2] 1, 000± | | 13, 700–16, 000 |

[1] 1 ohm-foot=30.48 ohm-cms=0.3048 ohm-meters.
[2] Data from other areas.
[3] Dry bulk density of surface samples.
[4] Wet bulk density at 23-percent porosity.
[5] Bulk density by Nettleton's method.
[6] Estimated bulk densities.
[7] 5,500 ft/sec for weathered rocks.

TABLE 14.—*Geologic contacts resolvable by geophysical methods, Santa Fe area, New Mexico*

[×, Resolution usually possible in Santa Fe area; 0, Resolution occasionally possible in Santa Fe area]

| Contact / Geophysical method | Ancha formation and Tesuque formation | Water table in unconsolidated sedimentary rocks | Unconsolidated sedimentary and consolidated sedimentary rocks | Unconsolidated sedimentary rocks underlain by flow rocks | Unconsolidated sedimentary rocks and intrusive rocks | Unconsolidated sedimentary rocks and basement rocks | Consolidated sedimentary rocks and intrusive rocks | Consolidated sedimentary rocks and basement rocks |
|---|---|---|---|---|---|---|---|---|
| Seismic | --------- | × | × | × | × | × | × | 0 |
| Magnetic | --------- | --------- | --------- | 0 | 0 | × | 0 | × |
| Gravimetric [1] | --------- | --------- | 0 | × | × | × | --------- | × |
| Resistivity | 0 | --------- | --------- | × | 0 | × | --------- | 0 |

[1] When supplemented by information from other geophysical methods, or from geologic or well data.

Faults or fault zones were delineated by seismic, resistivity, and gravity studies.

In May 1952, subsequent to completion of the geologic and hydrologic fieldwork, geophysical exploration of the Santa Fe area was discussed by Winkler, Baldwin, Kottlowski, and Spiegel. Several geologic problems were outlined and the expected geophysical contrasts were discussed. A tentative geophysical program was agreed upon to establish the degree of usefulness of the various geophysical methods in areas of good geological control. At the same time, those areas were designated where geophysical solutions to some existing geologic and hydrologic problems were likely to be obtained.

The geophysical laboratory of the New Mexico Institute of Mining and Technology, with the aid of an appropriation by the State of New Mexico for ground-water research and emergency exploration, carried on the geophysical fieldwork between late June and September 1952. The writer supervised the project. Preliminary analysis and interpretation of the data, prior to the completion of fieldwork, permitted close control and effective direction of the work by the staff. The progress of geophysical exploration guided the intensiveness with which each area was explored. The boundaries between the several principal geologic units were investigated by the most suitable geophysical methods, but time was not available for complete areal coverage.

The Santa Fe area is on the east border of the Rio Grande trough. Structurally the Santa Fe area is, therefore, a part of a much larger area, most of whose boundaries are outside the mapped area. This survey concerns itself largely with the areas designated the middle and southernmost ground-water units, because the need for large amounts of water is greatest there.

## METHODS AND TECHNIQUES

Geophysical methods fall into two major categories: natural-field methods and artificial- or induced-field methods. Natural-field methods utilize the natural fields of the earth. They measure disturbances of the field that are due to the presence of bodies of rock whose properties are different from those of adjacent rocks. Artificial- or induced-field methods utilize a temporary or transient field that is artificially created when needed. Such a field may be of very limited dimensions. Its usefulness, like that of the natural field, requires a measurable effect caused by a contrast in physical properties between adjacent bodies of rock. The geologic contacts found resolvable in the present investigation are listed in table 14. The locations of geophysical sections constructed from data obtained in this study are shown in plate 5.

### GRAVIMETRY

In the study of the Santa Fe area a Worden gravimeter (model W–111) was used. In order to standardize and reduce the labor of measurement and computation, gravity measurements were made at points selected on a network to give information on the regional structure (pl. 5). Additional measurements, made at fixed intervals along straight traverses, were included as points in the major network. These traverse measurements served to define the local structure and also to establish an arbitrary datum for all gravimetric data. All measurements were corrected for meter drift, tidal variation, latitude, and topographic effects. Altitudes were corrected to 6,100 feet above mean sea level using an elevation factor of 0.76 gravity unit per foot, corresponding to a density of 1.4 g per cu. cm. Terrain corrections were calculated by the methods and tables of Hammer (1939). Those corrections for terrain immediately surrounding each station out to 5,000 feet were calculated separately for each station, but those for terrain beyond 5,000 feet were calculated for a limited number of points on a grid network and these values were contoured (pl. 5).

In order to assist in the interpretation of the field measurements, it was convenient to measure in the laboratory the densities of rock samples representative of the geologic units. Also, geologic and seismic studies gave information on the position of the contact between the consolidated and unconsolidated sedimentary rocks.

### MAGNETOMETRY

Magnetic measurements were made with a Ruska Scout Magnetometer No. 3279. Magnetometer stations were chosen to permit a study of the buried extension of igneous rocks.

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## ELECTRICAL RESISTIVITY

The apparatus used in the electrical-resistivity surveys was of the Gish-Rooney type (Gish and Rooney, 1925). The Lee partitioning electrode system (Lee, 1929), a Wenner expanding-electrode system (Wenner, 1916) with center stake, was employed. Interpretation is based on a curve-matching procedure outlined by Roman (1931, 1934, 1941), Wetzel and McMurry (1939), and Perret (1949) and systematized by Holmes.[16] Profiling with a constant electrode spread (Jakosky, 1950) was tried and found unsuitable in this area. In this investigation the limit of useful information on the depth of interfaces was found to be about 500 feet.

In the present study the resistivities of the upper layers, those above the second layer of the set considered, have been systematically reduced to an equivalent resistivity corresponding to a fictitious layer of thickness equal to that of the combined upper layers. This, of course, assumes a constant resistivity of the individual layers. The reduction is accomplished by means of Hummel's principle, which states that, for sufficiently large electrode spacings, the upper layers behave as though they were a single layer of equivalent resistivity $\rho'_1$ (Hummel, 1932). Thus the upper layers are considered as parallel conductors, and their equivalent resistivity is given by $\frac{h_1+h_2}{\rho_1'}=\frac{h_1}{\rho_1}+\frac{h_2}{\rho_2}$ where $h$ indicates the bed thickness, $\rho$ indicates the bed resistivity, the subscripts indicate the bed position in the set as measured from the surface downward, and the prime indicates the equivalent bed.

## REFRACTION SEISMOLOGY

The apparatus used in the seismic survey was a P–11 portable SIE 12-trace seismograph. Refraction shooting was employed exclusively in this survey. Seismometers and shotholes were kept in line, and the seismometers were usually spaced 90 feet apart, although for near-surface detail the seismometer spacing was commonly 20 feet. For deeper work the seismometer spread was moved 600 feet from the shot point. Time-distance curves were analyzed individually without assuming lateral uniformity in the velocity of near-surface formations. Shots were made with dynamite (40-percent gelatin), usually at depths of 1–3 feet below the ground surface.

General discussions of seismic surveying are given by Heiland (1946) and Jakosky (1950), among others.

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[16] Holmes, C. R., 1952, A method for systematic analysis of resistivity—depth curves: New Mexico Bur. Mines and Mineral Resources [unpub. ms.].

## LABORATORY METHODS

The field data on the properties of the rock units were supplemented by laboratory measurements on hand specimens collected in the Santa Fe area (table 13). Average bulk densities of the unconsolidated sediments were obtained by the method of Nettleton (1939). This is essentially a field procedure similar to other gravity-measuring techniques. For this purpose, the data were analyzed statistically after a method suggested by Siegert (1942). Magnetic volume-susceptibility values are the result of laboratory measurements of hand specimens by the method of Hyslop (1941).

## LOCATION OF GEOPHYSICAL SURVEY SITES

The location of geophysical stations is shown on plate 5. The visible or inferred geology was responsible for the selection of many test locations. The remaining sites were selected on the strength of geophysical reconnaissance work and preliminary examination of all geophysical data. Topographic and cultural features made minor location adjustment desirable in many cases.

Contrasts between various types of unconsolidated sediments were most commonly indicated by observed discontinuities of electrical resistivity. The resistivity method was particularly successful in measuring the thickness of the Ancha formation in those localities where it is underlain by dipping beds of the Tesuque formation. In such localities, two successive resistivity depth stations, set 500 feet apart on a line normal to the strike of the Tesuque, were ordinarily located over different layers of the Tesuque formation, as the layers are generally not thicker than 300 feet. The resistivities of the beds of the Tesuque formation are, therefore, inconsistent from one station to the next. Where probes are made along such a line, the deepest consistent layer is interpreted as the lowest unit of the Ancha formation, which is essentially flat lying, and the line between the zone of consistent resistivities and that of inconsistent resistivities is interpreted as the Ancha-Tesuque interface.

In addition to determinations of the thickness of the Ancha formation, resistivity measurements have given some data on other geologic units. The water table is not generally determinable by this method in most of the Santa Fe area. However, the data showed a diagnostic contrast between Precambrian and consolidated or unconsolidated sedimentary rocks in several places. Contrasts between extrusive and other rock units were not investigated. In summary, reliable resistivity values were obtained for the terrace gravels and the Ancha formation, and less valid values were determined for the Tesuque formation and shallow pre-Tesuque rocks. The accuracy of determination was still less for the resistivities of the deeper rocks.

Seismic-velocity discontinuities are diagnostic of the water table in the unconsolidated sediments, of the zone of weathering if it differs from the water table, of horizontal or inclined beds of different elasticities, and of intrusive bodies. The Ancha-Tesuque contact may be resolvable where no other interface (such as the water table) is nearby, and the contrast surface between unconsolidated and consolidated sedimentary rocks is clearly distinguishable. The refraction method is a useful tool in areas of this type, but caution is necessary to avoid local areas of velocity inversion—for instance, at the base of a lava flow—or of large vertical refraction surfaces whose locations are not known. At some locations, propagation velocity in the surface formation increases with depth, but because the topmost layer (Ancha formation) is relatively thin (100–200 ft) and velocities at the surface are very low (a few hundred feet per second), the functional relation cannot be determined accurately.

Density contrasts of appreciable magnitude were found between the Precambrian complex and younger rock units except for the intrusives along the west rim of the basin which have densities comparable to those of the Precambrian. Another usable density contrast exists between consolidated and unconsolidated sedimentary rocks. The water table in the unconsolidated sediments also creates a density contrast. Doubtless, there are minor contrasts within the consolidated sedimentary rocks, and perhaps also within the Precambrian complex, but their effects cannot be calculated without more detailed and precise control.

Magnetic-susceptibility contrasts exist between sedimentary and basement rocks, and between these two and intrusive rocks.

## GEOPHYSICAL RESULTS

The profiles shown in figures 54–56 are the composite results of interpretations based on several geophysical methods. Only those interfaces are shown by solid lines that were clearly evidenced. Interfaces located by less definitive methods are indicated by dashed lines. The geophysical profiles give information on several kinds of geologic boundaries and are discussed in the succeeding pages.

### EVIDENCE FOR THE EXISTENCE OF A BASIN

The gravity data are consistent with the interpretation of the major general structure as a basin that trends north-northwest. Toward the north the basin widens somewhat and the block forming its west rim diminishes in magnitude. The gravity minimum shown in plate 5 indicates that the basin is deep and contains a sedimentary section that may be as much as 2 miles thick, though probably less. The steep gravity gradients on the east side of the anomaly suggest the existence of a major zone of faulting. The similar zone of steep gradients on the west side suggests that there may be faulting on the west side of the basin, which, though important, is not as prominent as that on the east side.

### RELATION OF TERTIARY IGNEOUS COMPLEX TO INTRUDED SEDIMENTARY ROCKS

A ground-water high in the NW¼ sec. 17, T. 15 N., R. 9 E., was investigated by all four geophysical methods (pl. 5, figs. 53, 54).

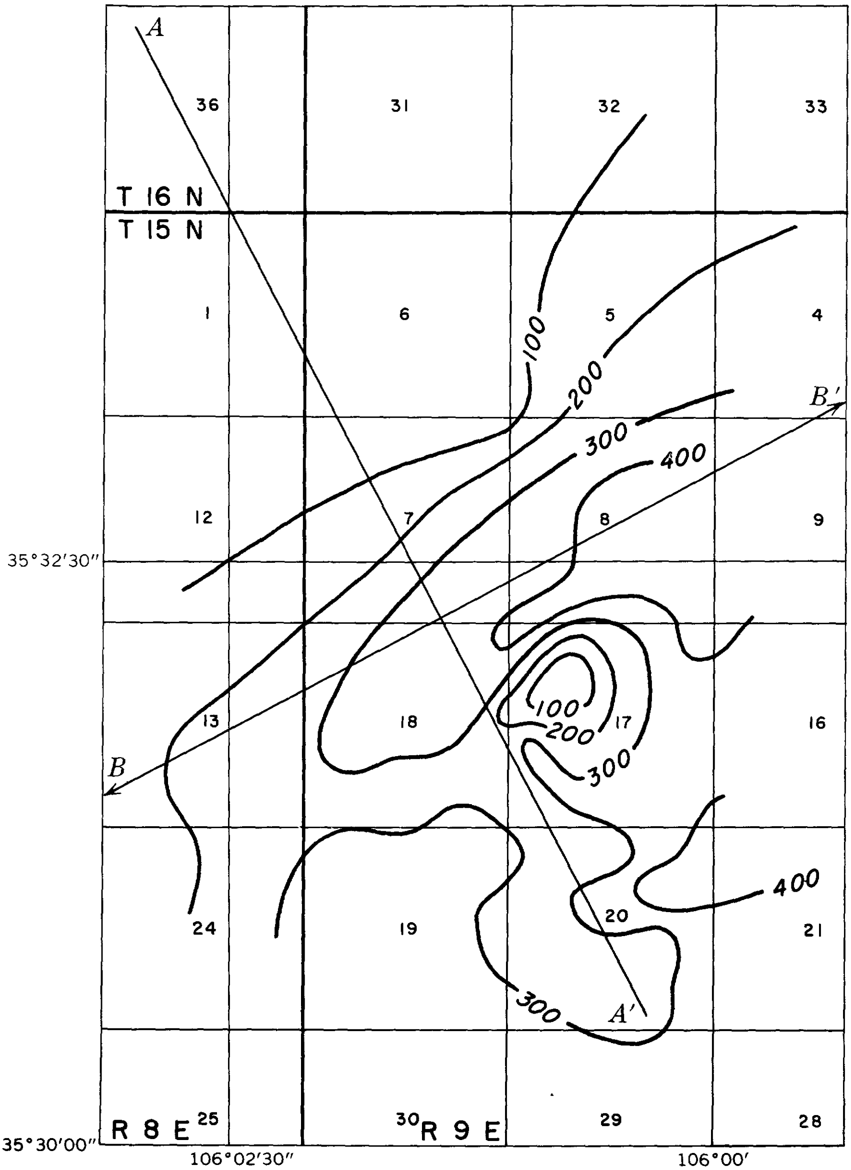


FIGURE 53.—Magnetic anomalies in T. 15 N., R. 9 E., Santa Fe area, New Mexico.

There is both a magnetic and a gravity low here. The interpretation most consistent with all the geophysical data is a slightly arched or domed sheetlike mass of igneous rocks, from which a thin magnetic section has been eroded.

## DISTRIBUTION OF THE TESUQUE FORMATION

The base of the unconsolidated sediments (upper surface of the pre-Tesuque rocks) is easily recognized from seismic data along line *B–B′* (fig. 54). East of line *A–A′* this interface is nearly coincident with a depth at which a resistivity contrast occurs. The water table, although very close to the resistivity interface, is not recognizable from seismic data, because the velocity contrast at the water table is concealed by the proximity of the water table to the interface between unconsolidated and consolidated sedimentary rocks. The unconsolidated sedimentary rocks are interpreted as the Ancha formation because the near-surface electrical properties are similar to those of that formation farther north. In general, the Tesuque formation is absent along line *B–B′*, unless it is present as a thin, unrecognized layer. However, a propagation velocity of 8,000 feet per second between seismic stations 13 and 15 is interpreted as showing the presence of an infaulted block of the Tesuque formation. The Tesuque-Ancha contact is discussed below.

Seismic velocities in the consolidated sedimentary rocks are approximately 10,500 feet per second. The minor faulting in the sedimentary series near the east border is probably an expression of the major border faults in the basement rocks.

Figure 54 also shows a seismic section along line *A–A′* northward from *B–B′*. This section illustrates the dip of the pre-Tesuque sediments and the Ancha-Tesuque contact.

## STRUCTURE OF AND PERMEABLE ZONES IN THE TESUQUE FORMATION

The three structural sections of figure 55 (*C–C′*, *D–D′* and *E–E′*), exhibit the resistivity layering of the exposed Ancha formation and the inconsistent resistivities of the Tesuque formation below it. The Ancha layers generally conform to the regional topographic slope, whereas the Tesuque layers dip consistently toward the basin axis. This arrangement makes it possible to distinguish between otherwise electrically similar formations.

Depth stations 1,500 feet apart were used to measure the resistivities of successive layers in the Tesuque. The resistivities vary principally because the layers differ in lithology, porosity, and permeability. Clayey and silty layers normally have a lower resistivity than sandy or gravelly beds. Hence, the high-resistivity layers should have greater permeability than the low-resistivity beds, inas-

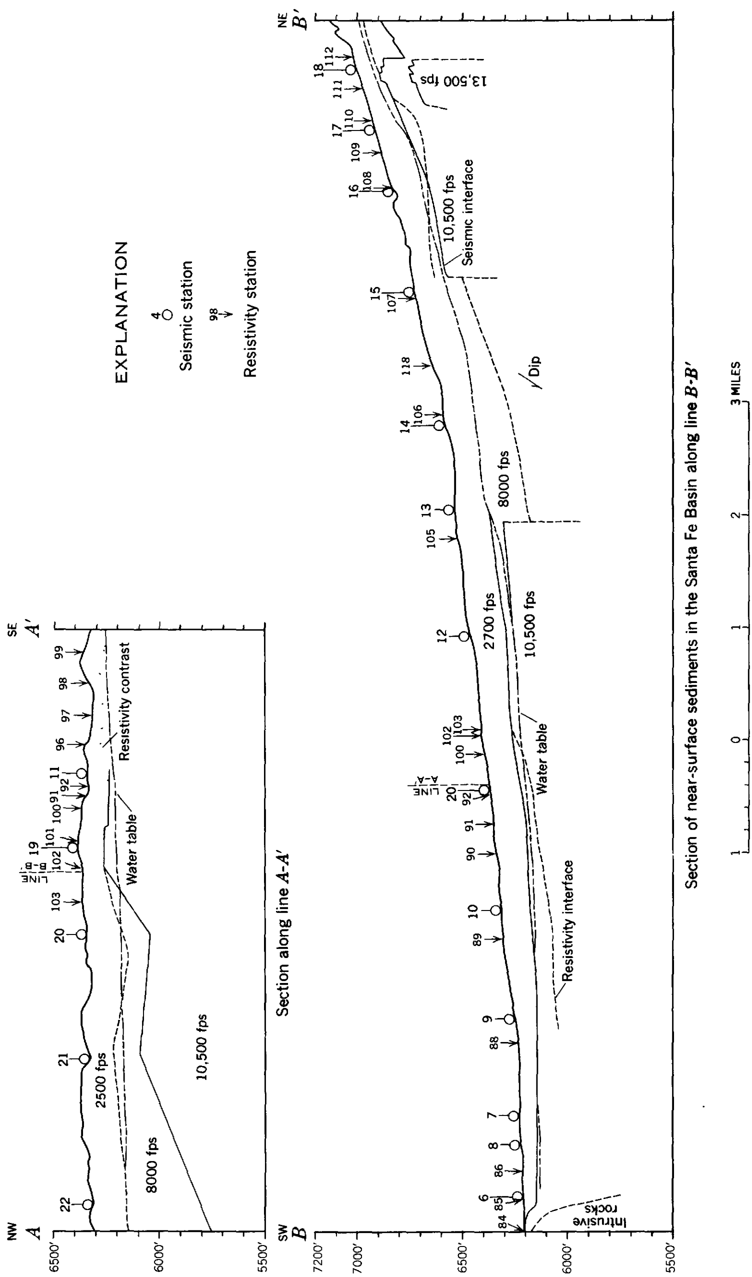


FIGURE 54.—Geophysical sections *A–A′* and *B–B′* (see pl. 5 for location of sections).

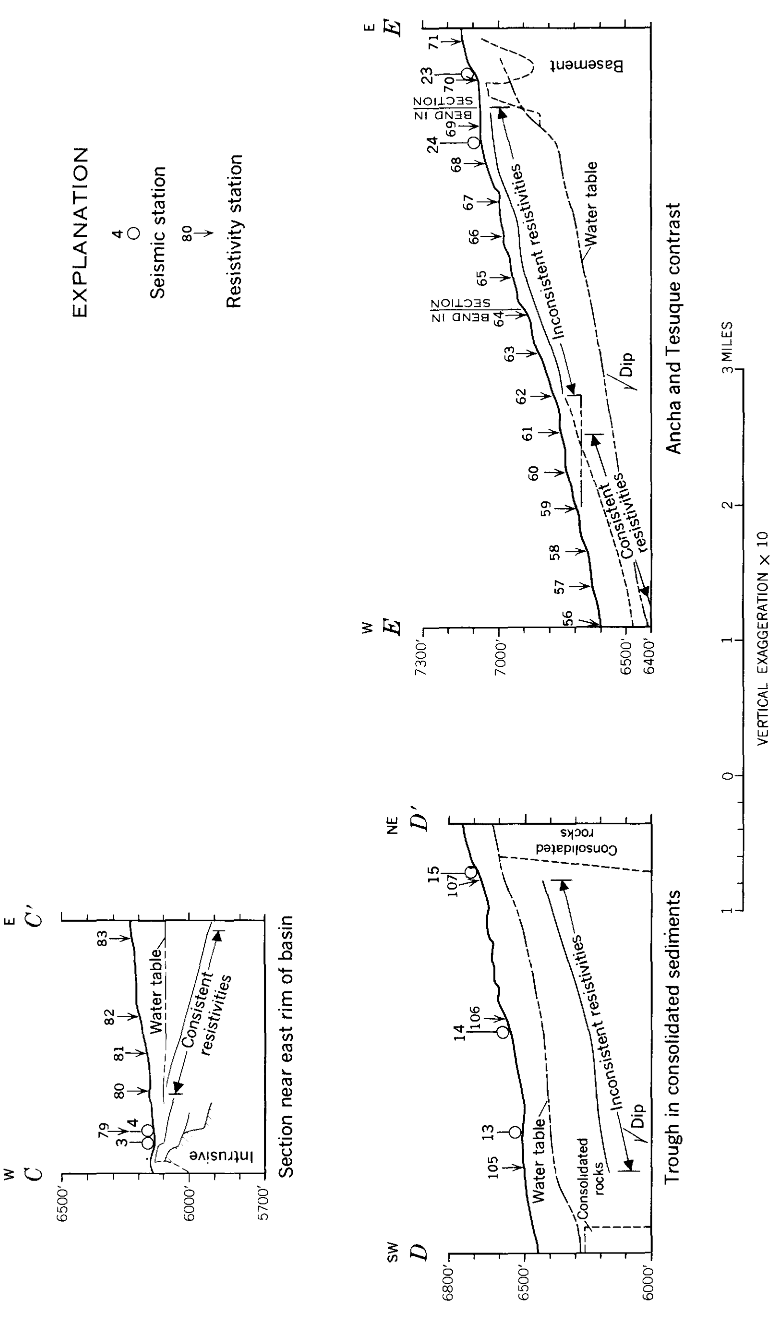


**FIGURE 55.**—Geophysical sections *C–C′*, *D–D′*, and *E–E′*.

much as the quality of ground water is good in the Santa Fe area and its resistivity therefore high. However, resistivities in the Santa Fe area cannot be related quantitatively to formation permeability with present data.

The direction of dip indicated by the resistivity data and shown on the sections is indicated by most individual probe data and correlates with surface observations where the Tesuque formation is exposed.

### THICKNESS OF ANCHA FORMATION AND QUATERNARY ALLUVIUM

Contours on the base of the Ancha formation, as compiled from resistivity and seismic data and from surface geology, are shown on plate 5.

The three sections of figure 56 illustrate the resistivity structure under the Santa Fe River. Section *G–G′* is a transverse profile and *F–F′* and *F′–F″* are consecutive longitudinal profiles along the stream channel from Cieneguilla to Santa Fe. The buried channel of the pre-Ancha Santa Fe River (*G–G′*) is too deep to permit recognition of the bottom interface, and so the deepest consistent-resistivity layer can be used only to give a minimum channel depth of 200 feet. Vertical discontinuities in the contrasts between stations 6 and 7 and between 12 and 13 are interpreted as north-trending faults. A major fault zone is evident at Cieneguita between stations 34 and 35; this fault affects ground-water movement greatly (see pls. 5 and 6).

### WATER-TABLE CONTRAST

Geophysical contrast at the water table could be found only by seismic methods. Propagation velocities above the zone of saturation range from 2,700 to 4,000 feet per second; below the water table the velocity increases to above 5,000 feet per second in this area, as is illustrated by the section along line *A–A′* (fig. 54). Every seismic depth to the saturated zone was checked against the water-level contour map, and several seismic depths to water were used in areas of scant well control to supplement hydrologic data (pl. 6). The near coincidence of the water table and a resistivity interface along line *B–B′* east of the basin axis (fig. 54) is thought to be due to the coincidental proximity of the water table to the base of the Ancha formation. The stations in all other parts of the area showed no consistent resistivity contrasts near the water table.

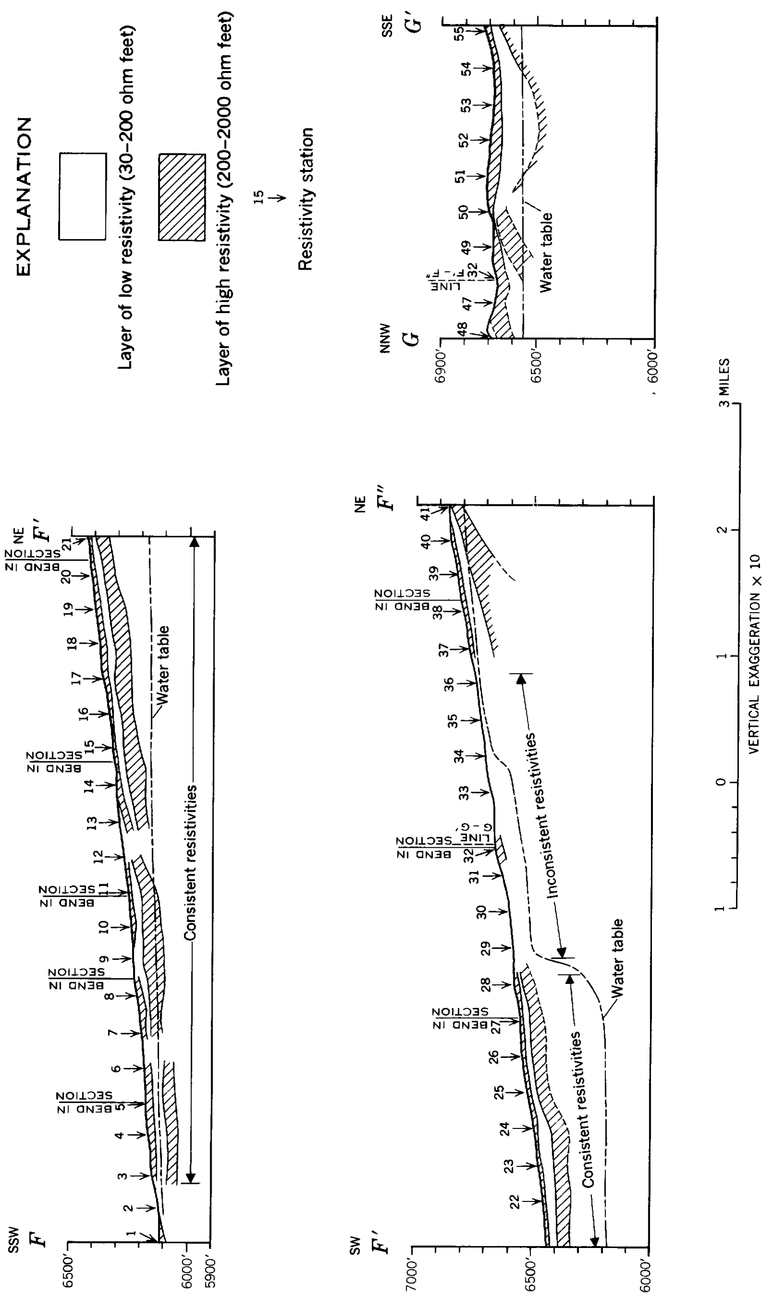


**FIGURE 56.—Resistivity sections *F–F'*, *F'–F''*, and *G–G'*, near Santa Fe River, N. Mex.**

# PART 5—REFERENCES AND APPENDIX

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## HAYDEN'S DESCRIPTION OF THE SANTA FE MARLS [17]

From Santa Fe to the banks of the Gallisteo Creek, eighteen miles, we pass over the recent marls and sands which seem to occupy the greater portion of the valley of the Rio Grande, above and below Santa Fe, which I have called Santa Fe marls. These are mostly of a light cream color, sometimes rusty yellow, and sometimes yellowish white, with layers of sandstones, varying in texture from a very fine aggregate of quartz to a moderately coarse puddingstone. These marls and sands weather into unique forms north of Santa Fe, like the "bad lands" or "Mauvais Terres" of Dakota * * *.

"* * * The Cerrillos are merely a dike, or a series of dikes, forming a small independent range of mountains composed entirely of eruptive rocks. On the south and west side, the Cretaceous beds flank them closely, while on the east and northeast side the Santa Fe marls jut up against them. Occasionally, on the east side, a little stream will cut through the marls, revealing the sandstones of the Gallisteo group.

"On the western flank of the Santa Fe Mountains, near Santa Fe, I found the foot-hills, which are exposed by the wearing away of the marls, to be composed of carboniferous beds. These beds of limestone rest directly on the granite, and are associated with gray and reddish shales and some beds of sandstone, the whole dipping west at an angle of thirty-five to forty-five degrees. The limestones were charged with fossils, as many and as well preserved as I have seen them at any locality east or west. In many places these beds of limestone are carried high up on the granite hills; sometimes dipping toward the mountains as if a portion of an anticlinal. The metamorphic rocks are gneissoid at first on the flanks, but gradually become massive granites toward the main axis of the range. In a small creek, which leads down from the mountains, I saw immense masses of granite breccia, mostly angular fragments of gneiss or red feldspar, with some rounded masses cemented with a granite paste. The limestones about Santa Fe are converted into excellent lime. The foundations of the jail and court-house are made of it. The fossils are very numerous, both in individuals and species. Dr. Newberry has given a list of them. I found several species of *Productus*, *Spirifera subtilita*, and many others. These limestones do not seem to extend far along the sides of the mountains. From Santa Fe to Embudo Creek, and mostly even to Taos, the Santa Fe marls cover the country. On the east side of the Rio Grande I did not observe a single dike, from the Cerrillos to the mouth of the Chama Creek. North of that the melted material has been poured over the marl so as to form broad mesas. On the west side there are numerous outbursts of igneous matter. These Santa Fe marls reach a great thickness north of Santa Fe, in the Rio Grande Valley, from one thousand two hundred to one thousand five hundred feet, and have a tendency to weather into similar monumental and castellated forms, as in the Bad Lands. The upper portions are yellow and cream colored sandstones, sands, and marls. Lower down are some gray coarse sand beds with layers

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[17] Excerpts of the Third Annual Report of the U.S. Geological Survey of the Territories for the year 1869, by F. V. Hayden, p. 166–170.

of sandstone. All these marls dip from the range westward three to five degrees. The Rio Grande wears its way through these marls with a bottom about two miles wide. On the west side are distinct terraces with the summits planed off smoothly like mesas. The first one is eighty feet above the river; the second one, two hundred feet. These marls extend all the way between the margins of the Santa Fe Mountains on the east side and the Jemez Range on the west * * *."

## PETROGRAPHIC DESCRIPTIONS OF METAMORPHIC AND IGNEOUS ROCKS

By F. E. Kottlowski

### PRECAMBRIAN ROCKS

#### SCHISTS AND GNEISSES

The fine-grained quartz-feldspar-biotite-magnetite schist consists of pinkish folia, 0.2–1.8 mm thick, that alternate with discontinuous grayish-brown or nearly black micaceous folia. Darker specimens contain proportionally more magnetite and biotite, whereas the gray-brown samples contain some muscovite and large amounts of orthoclase, quartz, and microcline. In places thick lenses of quartz and feldspars give the schist a gneissic texture. The rock corresponds to the quartz-microcline-albite-biotite-muscovite member of the chloritoid-almandine subfacies of the albite-epidote-amphibolite facies as defined by Turner and Verhoogen (1951, p. 463), which is derived from psammitic and semipelitic rocks under regional metamorphism. The percentages of the principal minerals calculated from thin sections are: quartz 33–38, orthoclase 17–45, microcline 2–16, albite-oligoclase 5–14, biotite 8–13, magnetite 3–5, and muscovite up to 2.

The gray micaceous gneiss varies greatly in appearance and mineral composition. Folia are thick, discontinuous, and in some specimens form contorted folds. Crystals are as much as 5 mm long. Thick quartzofeldspathic folia alternate with thin folia of biotite, muscovite, magnetite, and plagioclase. In many outcrops the folia are thick pods of felsic minerals separated by thin warped folia of mafic minerals.

The percentages of the principal minerals in a thin section of a medium-grained closely-foliated specimen are: quartz 58, microcline 23, muscovite 18, and magnetite 1; there are small amounts of garnet, apatite, and rutile. The percentages of minerals in a more mafic phase are: quartz 25, albite-oligoclase 34, biotite 10, orthoclase 26, and microcline 5; there are minor amounts of apatite, sphene, magnetite, hornblende, and epidote. Intergrowths of quartz and plagioclase were observed.

The quartzite is a gray-laminated, coarse-grained rock composed of 93 percent quartz and minor amounts of muscovite, magnetite, orthoclase, oligoclase(?), and chlorite. The quartz occurs as elongated, strained crystals. Small, scattered strings of muscovite and chlorite laths and magnetite octahedra parallel the foliation and the elongation of the quartz crystals. The minor minerals form the megascopic light-brown, closely spaced streaks that give the quartzite a finely foliated appearance.

The chlorite-muscovite schist is a felty, flaky rock, dark gray with a greenish to bluish tint. Megascopically, the medium- to fine-grained, granulose rock is mottled by blue-black stains in a gray-green felty matrix; a contorted foliation is faintly visible. Outcrops of this schist are isolated bodies, surrounded and intruded by granite, so that the schist may not be of the same age as the other early schists.

The chlorite-muscovite schist is typical of the muscovite-chlorite subfacies of the green schist facies (Turner and Verhoogen, 1951, p. 469). Rocks of this facies are formed at the lowest metamorphic temperatures from pelitic rocks. Microscopically, the schist is composed predominantly of tabular crystals of clinochlore, with minor amounts of muscovite and magnetite. Scattered relict pseudomorphs of augite and biotite are common.

The quartz-mica schists are grayish-brown rocks with pronounced foliation. Granulose, medium-grained lenticular folia of felsic minerals alternate with thin wavy and folded lenses of mica. The schists split easily parallel to foliation, revealing a glistening surface of silvery and brown mica flakes. In some beds, the rock is spotted by rodlike porphyroblasts of black garnet. In thin sections the percentages of minerals in quartz-mica schists average: quartz 31, muscovite 32, biotite 17, orthoclase 10, albite-oligoclase 5, and magnetite 4; and there are minor amounts of garnet, zircon, and sphene. The zircon occurs with pleochroic halos in biotite. The mineral assemblage of this schist is similar to Turner and Verhoogen's classes B3 and E7 of the chloritoid-almandine subfacies of the albite-epidote-amphibolite facies (1951, p. 462), except that orthoclase occurs in place of microcline—an anomalous stability, for orthoclase is supposedly unstable at the temperature of this facies.

The quartz-hornblende schists are black glistening rocks, fine- to medium-grained, finely foliated by films of dark-gray quartz separating folia of equigranular hornblende crystals. A few specimens show irregular laths of green chlorite altered from hornblende.

In the percentages indicated, the quartz-hornblende schists consist mostly of elongated quartz grains (25) and laminae of decussate hornblende crystals (56), but they include significant amounts of magnetite (7), apatite (4), and ilmenite (8). Some relict augite and diamond-shaped sphene crystals occur concentrated in the hornblende laminae.

The biotite-granulite is mineralogically similar to the quartz-mica schist, except that foliation is not as pronounced and the rock has a fine-grained granulose texture and includes scattered flakes and tiny parallel folia of mica. Several beds contain flat, elongate aggregates of intergrown muscovite and quartz, which probably were once pebbles in a feldspathic conglomerate. The average percentages of mineral composition of the biotite granulite from thin sections are: quartz 69, microcline 13, biotite 13, muscovite 4, and oligoclase 1; small amounts of orthoclase(?) and magnetite are present.

The hornblende-andesine schist is black and finely schistose, being composed of folia of hornblende, chlorite, and epidote alternating with folia of dark-gray andesine and gray quartz—all fine-grained. Typically, the rock is gneissic in outcrops because the hornblende-andesine schist is interbedded with light-gray quartzofeldspathic beds.

Microscopically, round crystals of quartz occur in the andesine and hornblende crystals. The ratio hornblende: andesine: quartz: chlorite: epidote may range from 57:38:3:1:1 to 46:25:19:7:3. A roof pendant of this schist that was injected by granite has much epidote with a mineral ratio of 44:16:15:3:22. This mineral assemblage does not fit into any of the metamorphic facies of Turner and Verhoogen (1951, p. 459), although it approaches their class 1A of the almandine-diopside-hornblende subfacies of the amphibolite facies.

### GRAY GRANITE

The gray orthoclase granite is gray, tinted with pale brown and white. The rock is equigranular to vaguely schistose and is characterized by a salt-and-pepper coloration of gray rounded quartz crystals, white orthoclase, and pale-brown microcline. When the rock is broken parallel to the faint foliation, glittering flakes of biotite and muscovite are exposed. Average percentages of mineral composition of a specimen of the gray granite are as follows: quartz 35, orthoclase 35, microcline 21, oligoclase 3, and biotite 4; there are minor amounts of muscovite (up to 4 percent), magnetite, chlorite, and sphene. Other samples appear to contain more biotite, significant amounts of hornblende, and considerable twinned plagioclase feldspar.

### AMPHIBOLITE

The amphibolite is a grayish-green rock speckled with light-gray laths of andesine. In places the amphibolite is schistose, but in most of the outcrops the rock is equigranular and medium- to coarse-grained, the texture ranging from ophitic to diabasic. Chemical composition calculated from modes indicate that the original rock ranged from an iron-rich diorite to a gabbro as shown in table 15.

This intrusive amphibolite has been altered by granitic solutions and by weathering so that as much as 26 percent chlorite and 5 percent epidote is developed, chiefly at the expense of the hornblende. Mineral percentages average as follows: quartz 2, andesine ($Ab_{53}$–$Ab_{63}$) 52, biotite 2, and hornblende 44; there are minor amounts of magnetite (up to 3 percent), apatite, chlorite, ilmenite, epidote, and calcite.

In thin sections the amphibolite is characterized by tiny quartz grains poikiloblastic in green hornblende. Some of the biotite flakes surround cores of green hornblende. In one thin section most of the green hornblende crystals have cores of blue-green chlorite having prominent closely spaced cleavage.

TABLE 15.—*Chemical composition of amphibolite compared with standard rock compositions*

[Weight percent]

| Oxides | Diorite [1] | Amphibolite | Gabbro [2] | Amphibolite [3] |
|---|---|---|---|---|
| $SiO_2$ | 57.2 | 52.6 | 48.6 | 43.8 |
| $Al_2O_3$ | 17.0 | 18.7 | 16.8 | 16.6 |
| CaO | 6.2 | 9.4 | 10.0 | 10.0 |
| $Na_2O$ | 3.4 | 4.3 | 2.8 | 2.0 |
| MgO | 3.5 | 5.9 | 6.8 | 8.9 |
| $K_2O$ | 2.2 | .2 | 1.2 | 1.3 |
| FeO | 4.0 | 5.5 | 6.1 | 10.2 |
| $Fe_2O_3$ | 3.5 | 2.9 | 4.3 | 3.5 |
| $TiO_2$ | | .4 | 1.2 | 1.6 |
| Total | 97.0 | 100.0 | 97.8 | 97.9 |

[1] Wahlstrom (1947, p. 307).
[2] Wahlstrom (1947, p. 311).
[3] Buddington (1939, p. 44).

### RED GRANITE

The muscovite-microcline granite is equigranular, medium grained, pale reddish brown, and speckled with gray quartz grains. Scattered muscovite flakes glitter from the matrix of pink microcline, tan orthoclase, and gray quartz. A few specimens contain small red garnet crystals having almost perfect crystal faces. This microcline granite contains, on the average, the following percentages of minerals: quartz 45, orthoclase 7, microcline 23, albite 19, biotite

1, muscovite 3, and magnetite 1, and minor amounts of hematite, apatite, zircon, garnet, and chlorite. In comparison with the gray orthoclase granite, the microcline granite contains 10 percent more quartz, 28 percent less orthoclase, 2 percent more microcline, 16 percent more albite-oligoclase, 3 percent less biotite, 3 percent more muscovite, and abundant magnetite and hematite. Apatite, zircon, and garnet occur in the microcline granite, whereas these minerals are practically absent from the gray granite.

The red granite shows two kinds of deformation—foliation and brecciation. The former, where the minerals are merely alined in vague lenticular streaks, is marked by elongated quartz grains, crude alinement of the scattered mica flakes, hematite-rich bands, and albite crystals with faulted and twisted twinning planes. This gneissoid granite and the Precambrian rocks are in turn brecciated along wide zones. The breccia is composed of large, angular rock fragments in a matrix of tiny, crushed rock grains stained by hematite. In the same zones the schists commonly are complexly folded and faulted rather than brecciated.

Associated with the red granite are numerous pegmatites, aplite dikes and sills, quartz veins, a few lamprophyre dikes, and epidote veins.

The pegmatites are thin, ranging from a fraction of an inch to 2 feet in thickness, and only a few are zoned. Quartz, perthite, microcline, albite-oligoclase, muscovite, and garnet, in the order of decreasing abundance, were observed. Plagioclase and muscovite are abundant only in the cores of the thicker dikes. Spessartite garnet is found in pegmatitic stringers and apophyses that metasomatized amphibolitic schists. Books of muscovite reach three-quarters of an inch in diameter but are too scattered to be of commercial value.

Needles of black tourmaline and tiny octahedra of magnetite occur in a few pegmatites. Crystals of felsic minerals are up to 3 inches in length. The thick pegmatites typically have a core of white plagioclase speckled by books of muscovite and scattered crystals of reddish-brown garnet with walls of graphically intergrown light-gray quartz and pale-reddish-brown microcline and laminated perthite.

The dark-reddish-brown aplite bodies are second in areal extent only to the microcline granite. Aplite sills, concordant with the foliation of the various schists, are especially numerous. The aplites are xenomorphic-equigranular, the grains averaging about 0.1 mm in diameter, although in some specimens there are pods in which crystal diameters average 0.4 mm. The average percentages of mineral composition are: quartz 49, microcline 37, orthoclase 4, albite 8, and muscovite 2; there are minor amounts of magnetite, hematite, chlorite, and sphene. The aplites are parallel to the long axes of the intrusive bodies. Dark zones are relatively rich in magnetite, hematite, and feldspars. Muscovite crystals are not alined parallel to the lamination, and the overall texture is a mosaic of interlocking crystals with sutured contacts.

Quartz veins are numerous but they do not form resistant outcrops as do pegmatites. The veins are of massive cloudy quartz, are stained by iron oxides in many places, and contain vugs lined with tiny euhedral quartz crystals. In places much black tourmaline occurs in the quartz veins, and adjoining foliated rocks are silicified and tourmalinized parallel to folia.

Several lamprophyre dikes cut the red granite. The dike rock is thoroughly weathered to an earthy greenish-brown porphyritic, felty mass of cloudy oligoclase, chlorite, calcite, magnetite, hematite, and limonite. Epidote veins are numerous in and near the red granite. Epidote fills fractures as felty masses of elongate yellow-green crystals, the long axes being approximately normal to the walls. Thin laminae of epidote parallel to the foliation project from the solid veins into foliated rocks, in part as fillings and in part as replacements. Mafic minerals of many xenoliths appear to be altered to epidote. Thin pegmatite veins that cut through amphibolitic metamorphic rocks contain scattered wedge-shaped crystals of epidote near the walls.

#### MIGMATITES

The migmatites are gneisses ranging from a coarse-grained pink and gray augen gneiss to a fine-grained micaceous granite gneiss. Large microcline porphyroblasts are typical in the coarser phase. Myrmekite and wormy intergrowths of quartz and muscovite are characteristic. Mineral percentages vary greatly, but usually quartz and microcline-rich folia alternate with others richer in albite, oligoclase, and mica. The finer grained gneisses contain more quartz, less microcline, and more equal portions of biotite and muscovite. Ranges of mineral percentages are as follows, the percentage in finer grained migmatites being listed first: quartz 37–21, orthoclase 0–27, microcline 11–45, albite-oligoclase 26–0, biotite 3–15, muscovite 3–27, magnetite, hematite, apatite, zircon, and sphene 0–2, and augite as much as 6.

#### METAMORPHOSED AMPHIBOLITE

In places the amphibolite appears to have been changed to medium-grained biotite granulite in which quartz is poikiloblastic in biotite. In a few roof pendants of amphibolite in red granite the contact zone contains a greenstone composed of chlorite, epidote, iron oxides, altered feldspar, and calcite. Mineral ratios of quartz, orthoclase, microcline, oligoclase, biotite, and magnetite are as follows for three specimens of the biotite granulite: (a) biotite-rich, 16:5:0:42:34:3; (b) silica-rich, 36:25:12:8:16:1; and (c) intermediate, 32:20:0:24:18:1. Minor amounts of hornblende, augite, epidote, clinozoisite, sphene, and apatite also are present.

## TERTIARY IGNEOUS ROCKS

#### AUGITE-OLIVINE BASALT

Thin sections of the basalt near the base of the Tesuque formation have the following percentages of mineral composition: labradorite ($An_{55}$) 61.9, augite 20.6, olivine 15.5, and magnetite and calcite each 1. About one-fifth of the olivine is altered to iddingsite along cracks and rims of the olivine crystals. The rock has an ophitic texture, with augite grains interspersed among labradorite laths. The augite and labradorite are fresh and most of the calcite seems introduced, perhaps by ground water.

#### AUGITE ANDESITE PORPHYRY AT ARROYO HONDO

The matrix of the augite andesite porphyry is microcryptocrystalline to microcrystalline, and crystals grade in size from phenocrysts to matrix. The groundmass averages 72 percent of the rock and is composed of tiny crystals of andesine, magnetite, hematite, and augite. Phenocrysts range from 0.3 to 3.4 mm in diameter, averaging about 1.1 mm. The phenocrysts are andesine (23 percent) and augite (5 percent). No flow lines were observed. Calcite veinlets cut through the rock and fill cracks in phenocrysts.

#### DIKE ROCKS

Two dikes that cut the Bishops Lodge member of the Tesuque formation crop out along Arroyo San Marcos just south of the map area (E½ sec. 34 and NW¼ sec. 35, T. 15 N., R. 9 E.). The groundmass is microcrystalline and felty, constituting 80–95 percent of the rock and being composed of fine granular augite, altered plagioclase, magnetite, and orthoclase. Phenocrysts are of altered plagioclase, 15 percent; fresh augite, 4 percent; and altered biotite, 1 percent. Biotite is, in part, altered to magnetite and chlorite; oligoglase ($Ab_{72}$) is altered to sericite and clay; magnetite is altered to hematite. This rock is classed as an augite andesite porphyry, but it may approach an augite latite porphyry, according to the amount of cryptocrystalline orthoclase in the groundmass.

### WELDED TUFF

The augite andesite porphyry dikes cut a gray welded tuff that underlies the Bishops Lodge member near Arroyo San Marcos in the NW¼ sec. 35, T. 15 N., R. 9 E. The groundmass, 54 percent of the rock, is mostly glassy but contains tiny andesine microlites. Percentages of phenocrysts are: andesine ($Ab_{59}$) 30; hornblende 13; augite 2; and magnetite 1. Most of the andesine crystals are zoned; some crystals are broken and have some absorbed edges. The hornblende is green and strongly pleochroic; the augite is pale green. Magnetite occurs as small, scattered crystals partly altered to hematite.

## STRATIGRAPHIC SECTION OF THE MAGDALENA GROUP

By F. E. Kottlowski

*Section measured along Little Tesuque Creek 1,000 feet south of Bishops Lodge, Santa Fe County, N. Mex.*

| | Feet |
|---|---|
| Tertiary. | |
| Tesuque formation: | |
| 26. Sandstone and sand, conglomeratic, light-gray to pinkish-gray, in part well cemented with crystalline calcite, cross-bedded; pebbles and boulders of Precambrian igneous and metamorphic rocks and of Pennsylvanian sedimentary rocks up to 5 in. in diameter; lenses of tuffaceous quartz sand present to north but absent to south; boulders most abundant near base. | |
| Thickness of Tesuque formation (incomplete) | 30+ |
| | 30+ |
| Pennsylvanian. | |
| Magdalena group. | |
| Madera limestone. | |
| Lower gray limestone member: | |
| 25. Limestone, gray-brown; weathers to light-brown smooth surface; medium-crystalline, hard, very fossiliferous; beds average 1 ft in thickness; fragments of crinoids, bryozoans, and brachiopods abundant; many lenses of well-cemented coquina | 15. 1 |
| 24. Shale, pinkish-yellow, laminated, soft, lenticular | 2. 4 |
| 23. Limestone, gray-brown; weathers to light-brown smooth surface; finely crystalline, fossiliferous; beds average 8 in. in thickness | 4. 6 |
| 22. Sandstone, gray-brown, chiefly quartz cemented by silica and iron oxides, hard, massive, medium-grained; grains subangular to subrounded | 4. 8 |
| 21. Shale, sandy, gray; weathers to limonitic-stained yellow brown; hard; platy lamination of fine and coarse grains | 3. 3 |
| 20. Limestone, gray-brown; weathers to light brown; hard, aphanitic to finely crystalline, massive, fossiliferous | 16. 0 |

Pennsylvanian—Continued
Magdalena group—Continued
Madera limestone—Continued
Lower gray limestone member—Continued

| | Feet |
|---|---|
| 19. Shale, banded red and green, soft; light and dark laminations; thin bedded | 5.2 |
| 18. Limestone, gray-brown; weathers to light-brown smooth surface; finely crystalline, fossiliferous, hard; beds average 6 in. in thickness; minor amout of hematitic cement | 4.1 |
| 17. Shale, banded red and green, soft, thin-bedded, light and dark laminations; weathers to soft clay; slumps on slopes | 8.2 |
| 16. Limestone, gray-brown; weathers to medium-brown smooth surface; coarsely crystalline with many fossil fragments of crinoid stems, bryozoans, and brachiopods | 1.9 |
| 15. Shale, banded green and red; soft, laminated | 2.6 |
| 14. Limestone, light-brown; weathers to gray-brown smooth surface; coarsely crystalline with many fragments of especially large fossil productid brachiopods, beds average 10 in. in thickness; 1½-ft unit of thin-bedded, platy, argillaceous, pink limestone that is partly rotten leached argillaceous limestone near base | 19.8 |
| Total thickness, lower gray limestone member of Madera limestone (measured) | 88.0 |

Sandia formation.
Upper clastic member:

| | Feet |
|---|---|
| 13. Clay, banded red, black, and green; soft, somewhat shaly, platy, forms slope | 11.2 |
| 12. Limestone, gray-brown; weathers to light-brown relatively smooth surface; fossiliferous, with many well preserved fossil crinoids, bryozoans, brachiopods; beds average 1 ft in thickness; few lenses of hard coquina; upper part conglomeratic with fossil fragments, stained red by hematite cement | 19.8 |
| 11. Shale, pink; soft, unbedded; laminated light and dark; partly covered | 16.0 |
| 10. Shale, black, carbonaceous; platy, hard, blocky; carbonaceous imprints of plants | 6.8 |
| 9. Sandstone, red-brown; weathers red brown with pebbles protruding; hard, massive, silica cement; cross-laminated; coarse-grained, pebbles up to 0.3 in. in diameter, grains are rounded quartz; clay balls; fragments of crinoids and brachiopods; forms prominent resistant unit | 4.4 |
| 8. Sandstone and shale, alternating lenses, stained green and yellow by iron oxides; fine-grained; lenses of sandstone in sandy shale, fine and coarse lamination | 10.4 |
| 7. Shale, black, carbonaceous; soft, thinly laminated light and dark; calcareous nodules | 2.7 |
| 6. Sandstone, shaly, drab-green, weathering to limonite-stained yellow brown; irregular, lenticular, thin-bedded, fine-grained, ferruginous concretions, small green nodules | 7.1 |
| Total thickness, upper clastic member of Sandia formation | 73.0 |

Pennsylvanian—Continued
Magdolena group—Continued
Sandia formation—Continued

| Lower limestone member (Mississippian?): | Feet |
|---|---|
| 5. Limestone, gray; cherty, medium-crystalline; massive beds up to 2½ ft thick; lenses of black chert in lower part; hard, weathers to rough surface, chocolate colored; partly recrystallized; small irregular chert masses in upper part look like silicified fossils | 25. 8 |
| 4. Sandstone and limestone, alternating beds, 0.1 to 2 ft thick; sandstone, yellow-brown, fine-grained, calcareous, well-sorted; limestone, gray, platy to massive, argillaceous, weathers to tan brown | 9. 5 |
| 3. Shale, sandy, yellowish-buff; thin-bedded, lenticular; lamination of fine and coarse grains | 2. 8 |
| 2. Limestone, light-gray; weathers yellowish gray and pinkish gray; argillaceous, thin-bedded, platy, aphanitic, sun cracks | 7. 1 |
| 1. Sandstone, light-gray; weathers yellow brown; calcareous and limonitic, coarse-grained, many quartz pebbles, mildly friable, thick- to thin-bedded | 6. 2 |
| Total thickness of lower limestone member | 51. 4 |
| Total thickness of Sandia formation | 124. 4 |
| Total measured thickness of Pennsylvania strata | 212. 4 |

## PROCEDURE AND RESULTS OF LABORATORY ANALYSIS OF SAMPLES OF THE TESUQUE AND ANCHA FORMATIONS

Laboratory study by W. M. Bundy of 19 samples of the Tesuque formation and 8 of the Ancha formation gives a qualitative check on the nature of the sediments. Four samples of the common lithologic types of each formation are illustrated graphically in figures 11, 12, 16, and 17; the locality from which each sample was collected is listed in table 16. Samples *A*, *B*, and *C* represent single sandstone beds only a few inches thick, whereas samples *D*, *E*, *F*, and *G* represent lenticular channel deposits of gravel 1 to 2 feet thick. The latter method of sampling decreases the apparent degree of sorting of the gravels in comparison to that of the sandstones, but the size range of the gravels is better approximated by a channel samples, whereas the sandstone beds are fairly uniform and can be represented by a thin bed.

About 100 grams of sample was weighed, digested in hydrochloric acid, washed, and dried. The loss in weight is interpreted as the weight of calcium carbonate cement, though it may include up to 3 percent iron oxide. Some of the carbonate may have been present as clastic fragments of limestone; however, few particles of limestone have been observed in the field, and the very low calcium carbonate content in most samples suggests that no limestone fragments were originally present in these samples. The next step was a standard mechanical analysis of the samples by Rotap on screens down to 325-mesh. These data are shown on cumulative frequency curves (figs. 12, 17) and the coefficients of sorting $\sqrt{Q_3/Q_1}$, where $Q_3>Q_1$ and the quartiles ($Q_3$ and $Q_1$) are the size values on the frequency curves at their intersection with the 25- and 75-percent lines (Pettijohn, 1957, p. 37), has been determined for each. Frequency curves (figs. 11, 16) were drawn from the cumulative frequency curves. The percentage of sample in each grade size was similarly determined from the cumulative frequency curves.

The composition of grains was estimated by 50-grain counts of each sieve fraction; for the samples chosen for illustration the data are plotted on a rectangular graph under each frequency curve (figs. 11, 16). In the coarser grade sizes granite, quartzite, and minor other Precambrian rock types are found, although granite predominates; "granite" includes minor other rock types, and quartzite is plotted as "quartz." Quartz is the most abundant mineral (represented by quartzite in the coarser grade sizes), though granite (including minor amounts of hornblende and mica schists) is predominant in the coarser sizes. Feldspar is present in amounts averaging 5–10 percent but ranging from 0 to 25 percent in individual sieve fractions; in sample *D* the feldspar content reaches 73 percent in the sand sizes, but this appears to be abnormally high. There is a suggestion that the feldspar content is proportionately higher in samples of gravel than in those of sandstone, but exceptions are almost as marked as the generalization itself.

Heavy-mineral grains separated by acetylene tetrabromide include magnetite, garnet, amphibole, anhydrite (authigenic), epidote, zircon, and tourmaline, listed in the order of decreasing importance. Only magnetite and garnet are ubiquitous. Garnet, amphibole, and anhydrite each form more than half the volume of heavy minerals in one sample, and in the remaining samples magnetite forms more than two-thirds of the heavy-mineral fraction. The only appreciable difference between samples of the Tesuque formation and those of the Ancha formation is that amphibole is present in moderate amounts in the Ancha but is found in only a few samples of the Tesuque.

The Ancha and Tesuque formations exhibit wide ranges of lithology, and therefore study of hundreds of samples would be required to give a statistical description of the sediments. The few samples illustrated graphically merely indicate lithologic varieties that have been considered to be representative of each formation and do not include all "typical" lithologic types. In this light, the following qualitative conclusions are drawn from the study, but they serve more as an independent check on field observation than as a source of new information.

1. The unsorted gravels of the Ancha formation are not distinguishable from those of the Tesuque formation;
2. The bulk of the Tesuque formation is sandstone containing only minor amounts of silt, although much of the sandstone is fine grained;
3. The percentage of cement is not in itself diagnostic of one formation or the other, although relatively high proportions of cement are more commonly found in the Tesuque formation;
4. The composition of grains is essentially the same in both formations;
5. The distribution of minerals with size grades appears to be normal; quartz and feldspar appear through all the sand sizes, and magnetite is restricted to the smaller sand fractions and to silt.

In summary, the limited laboratory study lends support to certain field observations of the characteristics of the Ancha and Tesuque formations; on the other hand the study has not revealed any new diagnostic features. In view of the changes in climate, source rocks, and drainage lines that must have taken place during the deposition of the Tesuque and Ancha formations, even a detailed and thorough sedimentary analysis of hundreds of samples might prove far less helpful than careful field mapping.

TABLE 16.—*Localities from which samples of the Tesuque and Ancha formations were collected*

Tesuque formation:

- *A*[1] SE¼SE¼ sec. 35, T. 18 N., R. 8 E.
- *B*[1] NW¼SE¼SE¼ sec. 36, T. 18., R. 9 E.
- *C*[1] NE¼NW¼NW¼ sec. 2, T. 17 N., R. 9 E.
- *D* NE¼NW¼NW¼ sec. 2, T. 17 N., R. 9 E.

Ancha formation:

- *E* NE¼ sec. 27, T. 16 N., R. 8 E.
- *F*[1] W side SW¼NW¼ sec. 32, T. 17 N., R. 9 E.
- *G* Sec. 32, T. 18 N., R. 8 E., unsurveyed.
- *H*[1] N side NE¼NW¼ sec. 8, T. 16 N., R. 9 E.

[1] Thin sections.

TABLE 17.—*Records of selected wells near Santa Fe, N. Mex.*

*Explanation*

Location: The location is described by means of location numbers, as explained on pages 100–102.
Asterisk (*) after location number indicates chemical analysis given in table 5, page 111.
Aquifers: Symbols are same as used on geologic map, plate 1.
Depth of well: All depths reported except those marked M (measured). Indefinite depths queried.
Altitude: Altitudes interpolated from topographic maps, contour interval 20 ft; accuracy generally within 3 ft.
M.P.: Top of casing is measuring point unless otherwise noted in Remarks column.
Water level: Measured to nearest hundredth but rounded to nearest tenth, with date of nonpumping water-level measurement.
Reported measurements to nearest foot, with year or month and year of reported level. Indefinite depths queried.
Notes on effects of previous pumping are in Remarks column. E=Static level estimated from recovery curve, to nearest foot.
Diameter of well: Small diameters indicate drilled wells; diameters greater than 24 in. indicate dug wells.

Method of lift:
Lw=Lift pump, windmill operated.
Lg=Lift pump, gasoline operated.
Le=Lift pump, electrically operated.
Lh=Lift pump, hand operated.
Te=Turbine pump, electrically operated.
Tse=Submersible turbine, electrically operated.
Je=Jet pump, electrically operated.
C=Centrifugal pump, electrically operated.
B=Bucket.

Use of Water:
D=Domestic
Di=Domestic and irrigation
P=Public supply
I=Irrigation
Ind=Industrial or commercial
Sch=School
S=Stock
T=Test well
A=Abandoned.

Remarks: Sp. cap.=Specific capacity. (See p. 107.)

| Well location | Owner | Aquifers | Depth of well (feet) | Altitude of well (feet) | Ft. M.P. is above (+) or below (−) land surface | Water level: Depth below M.P. (feet) | Water level: Date measured | Year completed | Well diameter (inches) | Method of lift | Use of water | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15.8.1.321 | R. M. Jarrett | QTa | 200? | 6,288 | +0.5 | 128.9 | Jan. 12, 1952 | | 6 | Lw | S | |
| 7.242 | W. C. de Baca | QTa | | 6,035 | +0.5 | 36.4 | Aug. 7, 1951 | | 48 | Lw | D | |
| 8.341 | R. M. Jarrett | Qal, QTa | 90? | 6,045 | 0 | 28E | do | | 6 | Lw | D, S | |
| 10.244 | do | QTa | 55M | 6,195 | 0 | 51.5 | do | | 4 | Lw | S | |
| 13.242 | do | Tt | 190 | 6,322 | +1.2 | 164.8 | Feb. 13, 1952 | 1952 | 6 | Lw | S | Coarse sand and gravel 151 to 190 ft. |
| 15.333 | do | QTa | 31M | 6,157 | | Dry | Aug. 7, 1952 | 1933 | 48 | B | D | Reported 45 to 50 ft deep, 1937. |
| 17.223 | do | Qal? | | 6,055 | +3.5 | 12.1 | Jan. 2, 1952 | | 8 | | S, A | |
| 22.242 | do | QTa | 96 | 6,217 | +1 | 86.0 | Aug. 7, 1952 | | 5 | Lw | S | Drawdown more than 5 ft at 2 gpm. |
| 25.114 | Gene West | QTa | | 6,198 | 0 | 68.2 | Jan. 4, 1952 | | 48 | Lw | S | Yield reported small. |
| 29.234 | R. M. Jarrett | Ti | 202 | 6,265 | +1.0 | 48 | Oct. 1, 1951 | 1951 | 6 | Lw | S | Alluvium 0–35 feet (dry). Sp. cap., 0.1. |
| 15.9.9.222 | do | QTa? | 190 | 6,483 | +1.5 | 114.6 | Jan. 12, 1952 | | 6 | Lw | S | M.P. is top of coupling on pump column. |
| 14.113 | F. Teal | QTa | | 6,527 | +0.5 | 58.0 | Jan. 6, 1952 | | 6 | Lw | S | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 15.9.16.414 | R. M. Jarrett | QTa? | 70?M | 6,417 | +2.0 | 55.9? | Jan. 6, 1952 | | 6 | Lw | S | |
| 17.133 | do | Tg? | 240? | 6,350 | +1.5 | 158.4 | Jan. 12, 1952 | | 6 | Lw | | Water level drawdown by pumping. Yield very small. |
| 17.133a | do | Tg | 164 | 6,355 | 0 | 121.4 | Feb. 8, 1952 | 1952 | 6 | | T | Sand and gravel 0–130 ft. Hard red siltstone 130–164. |
| 19.211 | F. Teal | QTa? | | 6,323 | +2.0 | 126E | Jan. 6, 1952 | 1951 | 6 | Lw | S | |
| 19.332 | R. M. Jarrett | QTa | | 6,258 | | | | 1951 | 6 | Lw | S | |
| 31.113 | do | QTa? | 220M | 6,385 | +1.0 | 196.4 | Jan. 12, 1952 | | 6 | | D,S,A | |
| 15.10.4.314 | do | Qal? | 24 | 7,035 | +0.5 | 14.7 | Jan. 7, 1952 | | 6 | Lw | S | M.P. is top of coupling on pump column. Water level not static. Yield reported small. |
| 4.442 | F. Teal | Qal? | 38M | 7,130 | +1.5 | 29.6 | July 5, 1951 | | 6 | Lw | S | |
| 16.141 | do | QTa? | | 6,961 | −5.0 | 65.1 | Jan. 6, 1952 | | 6 | Lw | S,D | |
| 16.7.33.444 | Soil Cons. Service | QTa? | 795 | 6,175 | | 595 | May 5, 1938 | | | Lw | S | |
| 16.8.1.321* | A. J. Baca | Tt | 210 | 6,445 | +1.0 | 179E | July 24, 1951 | 1948 | 6 | Lw | S | M.P. is drilled hole in casing. Drawdown 2 ft at 2 gpm. |
| 4.132 | do | QTa | 150 | 6,268 | +1.2 | 136.0 | do | 1920 | 6 | Lw | S | Sp. cap., 1. |
| 9.421 | Mr. Gilcrease | QTa? | 160 | 6,263 | +1.5 | 143E | | 1935 | 5 | | S,A | Water reported at 100 ft (perched) when drilled. Dry at 125 ft Aug. 13, 1951. |
| 10.422* | J. C. Roak | QTa? | 248 | 6,365 | | 208 | 1948 | 1936 | 6 | Lw | D | |
| 12.131 | Golf Course | QTa?, Tt? | 400 | 6,420 | 0 | 262.5 | Aug. 13, 1951 | 1939 | 5 | | Di, A | Yield reported 60 gpm. |
| 12.312* | do | QTa?, Tt? | 384 | 6,423 | | 272 | 1939 | 1939 | 6 | Te | P | Yield reported 45 gpm. Water encountered at 305–384. 40 ft of casing perforated. |
| 12.322 | F. Packard | QTa?, Tt? | 317 | 6,450 | | 275 | | 1927 | 4 | Lw | D,S | Water encountered 292–317. |
| 12.324 | do | QTa?, Tt? | 300 | 6,445 | +1.5 | 291.7 | Aug. 13, 1951 | 1927 | 6 | Lw | D | |
| 12.332 | J. Catron | QTa?, Tt? | 340 | 6,417 | −4.0 | 256.8 | Jan. 14, 1952 | 1951 | 6 | Tse | D,S | Encountered water at 272. |
| 13.243 | N. Smith | QTa?, Tt? | | 6,415 | +0.5 | 252.8 | Jan. 15, 1952 | | 5 | Lw | D,A | |
| 13.323 | B. Woods | QTa?, Tt? | | 6,376 | 0 | 212.26 | Aug. 14, 1952 | | 5 | Lg | D,S | |
| 13.444 | H. Nelson | QTa?, Tt? | 299 | 6,408 | | 190 | | 1936 | 6 | Lwe | D,S | |
| 14.444 | Mrs. H. W. Brown | QTa?, Tt? | 201 | 6,325 | +1.0 | 158.6 | Aug. 8, 1952 | | 8 | Lg | D,S | Pumped 2 hrs previous to water-level measurement. |
| 15.143 | Municipal Airport | QTa?, Tt? | 290 | 6,317 | | 150 | Oct. 19, 1946 | 1943 | 5 | Te | P | Sp. cap., 4. |
| 16.8.23.434 | J. J. Mastin | QTa, Tt | 180 | 6,284 | | 145±5 | 1949 | 1932 | 6 | Le | D | |
| 24.144 | D. Chavez | QTa | 201M | 6,366 | | 201+ | | | 4 | | D,A | Dry Jan. 15, 1952. |
| 24.333* | M. Crow | QTa, Tt | 225 | 6,322 | −4.5 | 171.8 | Aug. 1, 1952 | 1951 | 6 | Le | D | |
| 24.421 | HH Chicken Ranch | QTa, Tt | 296 | 6,392 | | 270 | Feb. 1950 | | 6 | Le | D | Cylinder set at 286. |
| 25.424 | M. R. Lugibhil | QTa, Tt | 220 | 6,350 | | 171 | Nov. 1950 | 1921 | 6 | Lw | D,S | Water reached at 178. |
| 35.111 | R. M. Jarrett | QTa, Tt | | 6,216 | +1.0 | 87.4 | July 4, 1951 | | 6 | Lw | S | |
| 16.9.1.132 | P. Robinson | Tt | 157 | 6,925 | | 139 | | | 6 | Le | D,A | Caved 1951. |
| 1.431* | A. Stamm | Tt | 300 | 7,000 | −6.0 | 40 | 1950 | 1950 | 6 | Te | P | Yield 28 gpm; Sp. cap., less than one-half. |
| 1.432 | do | Tt | 189 | 7,036 | | 60 | 1946 | 1946 | 6 | | T,A | Bishops Lodge member. |

See explanation at beginning of table.

TABLE 17.—*Records of selected wells near Santa Fe, N. Mex.*—Continued

| Well location | Owner | Aquifers | Depth of well (feet) | Altitude of well (feet) | Ft. M.P. is above (+) or below (−) land surface | Water level: Depth below M.P. (feet) | Water level: Date measured | Year completed | Well diameter (inches) | Method of lift | Use of water | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 16.9.1.444 | A. Stamm | Tt | 100 | 7,072 | 0 | 23.1 | July 23, 1951 | 1950 | 6 | | T,A | Yield rept. 3 gpm. Water hit 28–30. |
| 2.322 | Rhodes Pumice Co | Tt | 210 | 6,864 | | 180 | June 1951 | 1951 | 5 | Je | D | Perched water at 153. |
| 2.412 | M. L. Clodfelter | Tt | 223 | 6,910 | +0.5 | 192.8 | Aug. 24, 1951 | 1951 | 6 | Te | Ind | Water encountered 207–223. |
| 2.441 | Santa Fe County | Tt | 149 | 6,890 | 0 | 131.6 | Jan. 2, 1952 | 1950 | 6 | | D | |
| 3.121 | B. Rhoda | QTa | 60 | 6,750 | | 22 | 1945 | 1945 | 6 | Le | D | |
| 3.134* | Mrs. F. Lischke | Tt | 230 | 6,742 | | 180 | 1936 | 1936 | 6 | Le | D | |
| 3.213 | C. A. Bishop | QTa | 100 | 6,818 | | 60 | | | 6 | Lw | S,A | |
| 3.312 | J. L. Gassman | Tt | 237 | 6,730 | | 192 | Oct. 1947 | 1947 | 6 | Le | D | Water reached at 220. |
| 3.321* | H. Da Camara | QTa | 110 | 6,740 | | 60 | 1930 | 1930 | 6 | Le | D | Water reached at 60–105. |
| 3.322 | do | QTa | 27 | 6,730 | | 25 | | 1947 | 60 | Lw | Di | |
| 3.421 | P. Ragle | Tt | | 6,783 | −4.0 | 99.7 | Jan. 2, 1952 | 1951 | 6 | Lw | S | |
| 5.224 | Trigon Realty Co | QTa | 160 | 6,661 | +0.2 | 129.63 | July 18, 1951 | 1951 | 8 | | | Water-bearing sand reported 90–160. |
| 5.234 | R. Mee | QTa | 123 | 6,630 | +0.5 | 90.0 | July 23, 1951 | 1947 | 8 | Te | P | Some residual drawdown from previous pumping. Sp. cap. less than 1. |
| 5.331 | F. Packard | Tt | 327 | 6,560 | +1.0 | 223.3 | Nov. 30, 1950 | | 5 | | A | |
| 5.334 | do | Tt | 285 | 6,568 | | 231 | March 1951 | 1923 | 6 | Le | D | |
| 5.411 | Yucca Theatre | QTa | 117 | 6,610 | | 65±5 | 1950 | 1950 | 8 | Te | P | Reported to yield 58 gpm. |
| 5.441 | R. W. Thomen | QTa | 135 | 6,602 | −6.0 | 84.1 | Nov. 13, 1952 | 1951 | 6 | Je | D | |
| 7.112* | Acre Estates | QTa? | 410 | 6,498 | | | | | 8 | Te | P | Used for about 40 families. |
| 8.111 | C. J. Boyd | Tt? | | 6,561 | +3.0 | 202.7 | Aug. 11, 1951 | 1951 | 5 | | | |
| 8.144 | G. Petcheski | QTa | 25 | 6,528 | +0.5 | 18.7 | Jan. 16, 1952 | | 48 | | A | |
| 8.144a | do | Tt | 150 | 6,560 | | 75(P) | 1950 | 1950 | 6 | | T | Dry except for perched zone at 75. |
| 8.212 | C. B. Templeton | QTa | 165 | 6,616 | | 90 | 1941 | 1941 | 6 | Lw | D | |
| 8.213 | O. E. Jones | QTa | 40M | 6,538 | +7.0 | 31.4 | Jan. 16, 1952 | 1951 | 5 | | | |
| 8.214 | do | QTa | 78M | 6,578 | −7.0 | 55.2 | do | 1951 | 6 | Te | | |
| 8.233 | G. Petcheski | QTa | 110 | 6,568 | | 55±5 | 1950 | 1950 | 6 | Te | D,S | |
| 9.221 | E. L. Zobel | Tt | | 6,732 | 0 | 201.4 | July 7, 1951 | | 6 | Lw | D,S,A | |
| 10.242 | | Tt | | 6,830 | −5.8 | 167.5 | Jan. 2, 1952 | 1951 | 6 | Lw | S | |
| 15.223 | C. Marquez | Tt | 200 | 6,820 | 0 | 187.6 | July 6, 1951 | | 6 | Lw | D,S | |
| 15.242 | R. M. Jarrett | QTa | 25 | 6,802 | | 18 | | | 60 | | I,A | Reported used for irrigation. Caved 1952. |
| 16.243 | do | QTa | | 6,648 | +1.0 | 163.7 | Jan. 16, 1952 | | 6 | Lw | S | |
| 19.221 | S. Larson | Tt | 300 | 6,457 | | 250 | | 1943 | 6 | Lw | D,S | |
| 23.211 | E. M. Chapman | Tt | 285 | 6,888 | | | | | 6 | Lw | D,S | |
| 23.311 | R. M. Jarrett | Tt | | 6,790 | +0.5 | 212.6 | July 5, 1951 | | 5 | Lw | S | |
| 24.112 | J. L. Droege | Tt | 315 | 6,960 | 0 | 258.4 | do | 1951 | 6 | | D,S | |
| 28.113 | R. M. Jarrett | Tt | | 6,543 | +2.5 | 182.4 | Aug. 10, 1951 | | 6 | Lw | S,A | |
| 29.241 | do | Tt | | 6,538 | +0.5 | 208.4 | Jan. 12, 1952 | | 6 | Lw | S | |
| 16.10.6.333 | A. Stamm | QTa, Tt | 300 | 7,102 | −6.0 | 33.0 | July 23, 1951 | 1946 | 6 | Te | P,A | |
| 13.422 | M. Hoxsey | Tt | 238 | 7,023 | | 90 | 1950 | 1950 | 6 | Le | D | 60 ft of casing perforated. Sp. cap. less than 0.1. |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 29.434 | F. Thornton | p€ | 108 | 7,280 | +0.5 | 97.8 | July 5, 1951 | 1947 | 5 | Je | D | Water level lowered by previous pumping. Sp. cap. less than 0.1. |
| 29.443 | L. C. Robinson | p€ | 111 | 7,310 | −2.0 | 36E | do | 1931 | 5 | Le | D | Sp. cap. about one-half. |
| 17.7.35.242 | Soil Cons. Service | | 1,194 | 6,700 | | 1,044 | May 1938 | | | Lw | S | |
| 17.8.1.212* | F. Bond | Tt | 1,500 | 6,540 | +1.0 | 395.9 | Nov. 20, 1952 | | 8 | Lw | D,S | Yield reported 7 gpm. |
| 5.323 | Soil Cons. Service | | 735 | 6,484 | | 641 | May 1938 | | | Lw | S | |
| 21.414 | do | | 350 | 6,439 | | 300 | do | | | Lw | S | |
| 25.233 | J. H. Connell | | 380 | 6,540 | | | | | 6 | Lwg | D,S | |
| 34.342 | A. J. Baca | QTa or Tt | 310 | 6,350 | +4.0 | 177.0 | July 24, 1951 | | 6 | Lw | S,A | Sand enters well. |
| 17.9.1.334 | F. Sayer | Tt | 650 | 7,330 | | 600 | July 1951 | 1951 | 6 | | | |
| 12.222 | C. M. Barker | Tt | 533 | 7,340 | | 490 | April 1951 | | | | D | |
| 22.343 | R. Romero | Tt | 200 | 6,870 | +0.5 | 144.9 | July 28, 1951 | 1942 | 6 | Lw | D,A | Sanded in to 150-ft depth. |
| 22.424 | C. Bridgeman | Qal | 30 | 6,840 | | 25 | 1949 | | 48 | Je | Di | Water perched in alluvium. |
| 22.424a | B. Avant | Tt | 61 | 6,836 | | 47 | 1942 | 1942 | 6 | Lw | Di,A | Reported dry since 1945. |
| 22.432 | J. J. Alarid | Tt | 125 | 6,850 | +0.5 | 99.9 | July 29, 1951 | 1937 | 5 | Lw | D | |
| 22.441* | Public Service Co | Tt | 616 | 6,828 | +3.0 | 55.9 | Nov. 29, 1950 | 1950 | 12 | Te | P | Torreon well. |
| 22.444 | Santa Fe Nursery | Tt | 120 | 6,840 | +0.3 | 56.3 | Feb. 2, 1947 | | 8 | Te | I,A | M.P. is end of discharge pipe 16 ft long. |
| 23.133 | F. M. Jones | Tt | 75 | 6,861 | +3.0 | 57.5 | July 28, 1951 | | 48 | B | D,A | Rept. to dry up when irrigation well 150 ft southeast is operated. |
| 23.322* | Public Service Co | Tt | 492 | 6,878 | | 55 | Dec. 1950 | 1950 | 12 | Te | P | Ferguson well. |
| 23.332* | do | Tt | 347 | 6,863 | 0 | 63.8 | Sept. 2, 1946 | 1946 | 12 | Te | P | Alto St. well. |
| 23.333 | J. Hansen | Tt | 96 | 6,840 | | 54 | 1947 | 1930? | 8 | Te | I,A | Formerly used for irrigation by G and G Gardens. |
| 24.114 | W. Kegel | Tt | 75 | 6,986 | +1.0 | 70.6 | July 27, 1951 | | 48 | Lw | Di,A | |
| 24.122* | A. Senutovitch | Tt | 157 | 7,080 | | | | 1951 | 6 | Tse | Di | Reported yield 20 gpm. |
| 24.123* | P. M. Harkins | Tt | 150 | 7,055 | | 70 | July 1951 | 1951 | 5 | Je | Di | Rept. bailed at 20 gpm with large drawdown. |
| 24.124* | C. H. Murphy | Tt | 100 | 7,020 | | 66 | April 1951 | 1951 | 6 | Tse | Di | Perforated 78–100 ft. Sp. cap. less than one-third. |
| 24.124a* | I-Am School | Tt | 180 | 7,020 | +0.5 | 71.4 | Sept. 11, 1951 | 1951 | 6 | | D | Water sample taken at 145 ft depth. |
| 24.324 | Public Service Co | Tt | 255 | 6,980 | | 10 | | 1925 | 6 | | | Plant well. |
| 24.334 | H. de Castro | Qt | 30M | 6,983 | 0 | 25.6 | July 19, 1951 | | 48 | B | D, A | |
| 24.343 | State Capitol | Tt | 180 | 6,995 | | 24 | 1925 | 1925 | 12 | | A | Water level measured in dug well 30 ft deep before additional 150 ft drilled. |
| 24.432 | St. Vincent's Hospital | Tt | 200 | 7,018 | | 20 | 1943 | 1925 | 6 | | D, A | |
| 25.232 | F. C. Rand | Tt | 85 | 7,062 | | 40 | April 1951 | 1951 | 6 | Te | Di | Yield reported 15 gpm. |
| 25.241 | J. M. Ramirez | Tt | 50 | 7,069 | | 44 | July 1951 | 1915 | 48 | Lw | Di | Water level reported 38 ft, in 1915. |
| 25.312 | C. Cerba | Tt | 106 | 7,020 | | 40 | May 1951 | 1951 | 5 | Te | Di | Yield reported 30 gpm. Water reached at 66 ft. |
| 25.324 | | Tt | 280 | 7,070 | +1.6 | 80.4 | July 19, 1951 | 1951 | 6 | Te | Di | Water reached at 98 ft. |
| 25.343 | E. B. Healy | Tt | 325 | 7,065 | | 75 | Jan. 1951 | 1945 | 7 | Te | Di | Sp. cap., ½ |
| 25.421 | Mrs. A. E. White | Tt | 255 | 7,125 | −5.0 | 65.3 | Aug. 24, 1951 | 1951 | 8 | Te | Di | Perforated 90–250 ft. Sp. cap., ½. |
| 26.133 | Public Service Co | Tt | 1,523 | 6,872 | | 97 | April 20, 1951 | 1951 | 12 | Te | P | Santa Fe well. Cased to 725. |
| 26.142 | School for the Deaf | Tt | 311 | 6,909 | +0.8 | 138.12 | Nov. 11, 1952 | 1952 | 8 | Te | I | Bottom 165 ft perforated. |
| 26.222* | Public Service Co | Tt | 255 | 6,958 | −1.2 | 40.28 | Aug. 28, 1946 | 1946 | 8 | Te | P | Hickox Street well. |

**See explanation at beginning of table.**

TABLE 17.—*Records of selected wells near Santa Fe, N. Mex.*—Continued

| Well location | Owner | Aquifers | Depth of well (feet) | Altitude of well (feet) | Ft. M.P. is above (+) or below (−) land surface | Water level: Depth below M.P. (feet) | Water level: Date measured | Year completed | Well diameter (inches) | Method of lift | Use of water | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 17.9.26.232 | School for the Deaf | Tt | 250 | 6,930 | | 90 | Jan. 24, 1951 | 1951 | 6 | Te | I | Water level after 4 hrs bailing, 110. |
| 26.331 | Mr. Townsend | Tt?, QTa? | 128M | 6,888 | | 80 | | | 6 | Lw | D, A | Dry at 128 ft, July 10, 1951, previous water level 80 ft, measured on pulled pump column. |
| 26.333 | W. N. Chambers | QTa | 80 | 6,885 | | 42 | 1951 | 1951 | | | Di | Rept. bailed at 40 gpm when drilled. |
| 27.133 | O. T. Davis | Tt | 38 | 6,770 | −5.0 | 16 | 1947 | 1947 | 6 | Te | D,Di | Pumping level 19.8 (M) July 18, 1951. Sp. cap. 2½. |
| 27.133a | R. Barela | Tt | | 6,761 | 0 | 19.6 | July 28, 1951 | | 48 | Lw | D | |
| 27.143* | F. Ortiz | Tt | 20 | 6,767 | +3.0 | 21.0 | Sept. 11, 1951 | 1950 | 48 | B | D | |
| 27.144 | A. Velarde | Tt | 75 | 6,780 | | 28 | Sept. 1951 | 1951 | 6 | | | |
| 27.211* | G and G Gardens | Tt | 197 | 6,836 | | 58 | 1948 | 1948 | 8 | Te | I | Yield measured 210 gpm July 17, 1951. Nonpumping level 68 ft, July 17, 1951. |
| 27.232 | Public Service Co | Tt | 740 | 6,810 | +2.2 | 49.0 | Sept. 12, 1951 | 1951 | 16 | Te | P | Agua Fria well. M.P. is top of 1-in pipe. |
| 27.241 | Z. A. Tipton | Tt | 115 | 6,840 | | 96 | 1943 | 1943 | 6 | Lw | D | Deepened to 140 ft in 1950. |
| 27.441 | U.S. Indian School | Tt | 989 | 6,848 | | 70 | 1951 | 1905 | 8 | | | Water level 104 ft (M) 1952. |
| 28.321 | H. Bell | Tt | 230 | 6,770 | | 200 | 1942 | 1942 | 6 | Lw | D,S | |
| 28.414 | J. G. Carrillo | Qal | 10 | 6,718 | | 3 | | | 48 | C | I | |
| 28.423* | E. Kaufmann | Tt | 60 | 6,720 | | 3 | 1947 | 1947 | 8 | Te | Ind | Yield rept. 300 gpm. Drawdown 37 ft or less. |
| 28.434 | Boylan Bros | Qal | 140 | 6,700 | | 15 | | | | | T,A | Water perched in alluvium. No water found in Tesuque formation. |
| 28.434a | | Qt | | 6,717 | 0 | 7.7 | Dec. 27, 1951 | | 48 | | | |
| 28.442 | | QTa? | | 6,740 | +1.0 | 17.9 | July 21, 1951 | | 5 | Lw | S | |
| 30.433 | Mr. Mercer | Tt | | 6,575 | +0.5 | 412.6 | Feb. 28, 1951 | | | Le | D,S | |
| 32.111 | R. D. Smith | Tt | 401 | 6,675 | | 390 | 1950 | 1950 | 6 | | | |
| 32.112 | I. Head | Tt? | 191 | 6,683 | | 160 | 1950 | 1950 | 6 | Le | D | |
| 32.132 | Mr. Felix | | 324 | 6,662 | | | 1950 | 1950 | 6 | | T,A | Reported dry at 324. |
| 33.211 | Mrs. A. M. Harrison | QTa | 50 | 6,720 | +1.0 | 44 | 1945 | | 48 | Lw | D | |
| 33.211 | | | | | | 48.8 | Sept. 11, 1951 | | | | | |
| 33.211a | J. C. Pacheco | Tt | 186 | 6,702 | | 150 | July 1951 | 1951 | | | D | |
| 33.211b | T. Boylan | Tt | 190 | 6,717 | | 170 | 1949 | 1949 | 6 | | D | |
| 33.241 | S. Martinez | QTa | 39M | 6,738 | +2.0 | 33.4 | Dec. 27, 1951 | | 6 | Lh | | |
| 33.241a | A. Valencia | Tt | 216 | 6,729 | | 180 | 1947 | 1947 | | Le | D | Rept. to yield 6 gpm. Cylinder set 205. |
| 33.421 | Mrs. B. Montoya | Tt | 216 | 6,740 | | 180 | 1943 | 1943 | 6 | Le | D | |
| 33.432 | E. Kauffman | Tt | 210 | 6,727 | +0.7 | 175.3 | July 18, 1946 | 1946 | 8 | Le | D | Water reached at 180–208. |
| 34.114 | P. Peck | QTa | 67 | 6,782 | 0 | 47 | 1951 | 1951 | 6 | Te | Di | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 34.311 | F. Zych | QTa | 66 | 6,765 | | | | | | Le | I,A | |
| 35.432 | F. Herrera | Tt | 230 | 6,943 | −3.0 | 195.9 | Jan. 2, 1952 | 1943 | 6 | Le | D,S | |
| 36.234 | T. E. James | Tt | 180 | 7,115 | +1.0 | 102.0 | July 19, 1951 | 1937 | 5½ | | A | 30 ft perforated. Rept. bailed 20 gpm. |
| 36.243 | W. W. Mason | Tt | 115? | 7,120 | 0 | 97.4 | do. | | 6 | Lw | D | |
| 36.343 | Dr. Freidman | Tt | 300 | 7,005 | −4.0 | 90 | July 1951 | 1951 | 8 | Te | D,Di | Drawdown rept. 190 ft at 30 gpm. |
| 36.422 | W. W. Mason | Tt | 145 | 7,122 | 0 | 94 | do. | | 5 | Lw | Di,S | Drawdown rept. 45 ft at 5 gpm. |
| 17.10.5.112 | R. P. Fullerton | Tt | 340 | 7,163 | +0.5 | 104.8 | Oct. 3, 1951 | 1946 | 6 | | T, A | Well cuttings mostly gray latite fragments and weathered material. |
| 5.123 | E. S. Bauer | Pm | 340 | 7,135 | +1.0 | Flows | Oct. 3, 1951 | 1950 | 6 | | T, A | Flow very small. |
| 5.124 | do | Tt? | 300 | 7,230 | | 90 | 1931 | 1931 | | Le | D | Yield reported 3 gpm. |
| 6.242 | O. F. Hopkins | Tt | 60 | 7,048 | −2.0 | 33.5 | Nov. 13, 1952 | 1951 | 4 | Je | D | |
| 7.224 | M. McAdams | Tt | 333 | 7,390 | | 263 | 1948 | 1948 | | Le | D | Yield reported less than 2 gpm. |
| 8.114 | M. Hare | Pm | 388 | 7,440 | +0.5 | 251E | July 13, 1951 | | | | | Originally bottomed in limestone at 133, bailed 15 gpm. Later went dry; deepened to 388. Gas at 380 was cemented off. Yield 3 gpm, large drawdown. |
| 9.312 | A. L. Zinn | Pm | 164 | 7,780 | 0 | 134 | 1948 | | | Le | D, Di | Water level reported 154½ ft, July 1951. Yield reported 1 gpm. |
| 17.333 | A. W. Egenhofer | | 290 | 7,370 | 0 | 75 | 1947 | 1947 | 8 | Te | D, Di | Yield reported 50 gpm. |
| 18.333 | Trigon Realty Co | Tt | 212 | 7,090 | +1.5 | 152.1 | July 18, 1951 | 1951 | 8 | | T, A | Bishop's Lodge member reached at 180. |
| 19.331 | T. Cox | Tt | 124 | 7,042 | 0 | 17 | July 1951 | 1951 | 6 | | Di | Boulders to 30 ft, hard gray sandstone to bottom. Bottom 10 ft perforated; reported bailed at 50 gpm. |
| 20.344 | J. Breese | Qal, p€ | 32 | 7,215 | 0 | 4 | | | | Te | D, Di | Yield reported 5 gpm. |
| 29.131 | L. Rodriguez | Tt | 21 | 7,260 | 0 | 20.9 | July 17, 1951 | | 48 | | A | Water reported to have bad taste. Bishop's Lodge member. |
| 29.134 | do | Qal | | 7,280 | +1.0 | 10.5 | do | | 48 | B | D, S | M.P. is rock sill on north side of well. Yield inadequate. |
| 29.313 | J. Lindsay | Tt | 45 | 7,300 | 0 | 40.6 | July 16, 1951 | 1951 | 48 | B | D | Bishop's Lodge member. Yield inadequate. |
| 30.123 | T. A. Ortiz | Tt? | 35 | 7,108 | +2.4 | 22.6 | July 19, 1951 | | 48 | B | D | |
| 30.131 | J. Flynn | Qt | | 7,095 | +1.0 | 20.5 | July 19, 1951 | | 48 | Lw | D | M.P. is bottom of pump flange. |
| 30.133 | M. Alire | Tt | | 7,135 | +1.0 | 63.0 | July 17, 1951 | | 5 | Lw | Di | |
| 30.413 | K. Gay | pC | 238 | 7,310 | 0 | 208.8 | do | 1931 | 6 | | D, A | |
| 30.433 | St. Mary's Convent | | | 7,265 | −4.0 | 70E | July 16, 1951 | | 6 | Le | Di | |
| 18.7.36.422 | Soil Cons. Service | QTa | 1,080 | 6,700 | 0 | 980 | May 1938 | | | Lw | S | |
| 18.8.33.143 | F. Bond | Tt | 400 | 6,175 | +0.4 | 339.0 | Nov. 20, 1952 | | 6 | Lw | S | Reported yield 7 gpm. |
| 18.10.31.413* | G. W. Armijo | Tt | 400 | 6,980 | 0 | 75.8 | Sept. 12, 1951 | | 6 | Le | D | Drawdown 50 ft at 2 gpm. |
| 31.414 | Mr. Trujillo | Tt | 140 | 6,955 | +1.0 | 32.2 | Oct. 3, 1951 | 1951 | 6 | | D | Drawdown 90 ft at 6 gpm. |
| 19.7.36.314* | | Tt | | 5,650 | | | | | | | | Buckman well. |

See explanation at beginning of table.

TABLE 18.—*Records of springs in the Santa Fe area, New Mexico.*

*Explanation*

Location number: See p. 101–102—for explanation. Asterisk following location number indicates water analysis is given in table 5.
Aquifer: Symbols used are the same as on the geologic map, plate 1.
Yield (gallons per minute): Yields estimated, except where noted.
Use of water: D, domestic; I, irrigation; P, public supply; S, stock; A, abandoned.

| Location | Owner or name | Altitude (feet) | Aquifer | Estimated yield (gpm) | Use of water | Remarks |
|---|---|---|---|---|---|---|
| 15.8.5.114* | Cienega School | 6,030 | QTa | ½–1 | P | Emerges at contact of Ancha formation on Galisteo formation. |
| 9.343 | R. M. Jarrett | 6,095 | QTa | | S, I | Total yield downstream is more than 0.2 cfs (estimated). |
| 16.8.20.312* | Cieneguilla Spring | 6,120 | QTa | 300–500 | I, D, S | Emerges near contact of Ancha formation on Espinaso formation. |
| 28.241* | Cienega Spring | 6,118 | QTa | 50 | I, D, S | Emerges near contact of Ancha formation on Cieneguilla limburgite (of Stearns, 1953b). |
| 28.323 | | 6,110 | QTa | 2–5 | D, S | Emerges above contact of Ancha formation on Cieneguilla limburgite. |
| 33.111 | | 6,095 | QTa | 5–10 | S | |
| 16.9.3.114 | Siringo Spring | 6,720 | QTa | Seep | | Nearly dry Aug. 4, 1951. |
| 13.224 | J. Whittaker | 6,990 | pЄ | 25–30 | | Emerges from jointed granite below base of Tertiary sediments. |
| 17.9.23.300 | F. M. Jones | 6,900 | Qal | | I | Infiltration gallery, ceased flowing about 1945. |
| 28.422 | Cieneguita Spring | 6,723 | Tt | 15–20 | I, A | No flow in July 1951. Former yield reported about 1 cfs. |
| 17.10.20.431 | J. Breese | 7,276 | Pm | ½ | I | Discharges into adjacent irrigation ditch. |
| 28.314 | National Forest | 7,758 | pЄ | 5–10 | S | |
| 29.232 | | 7,370 | pЄ | 2–5 | S | Rocks in vicinity of spring are closely jointed. |
| 18.7.12.244 | Canoncito Spring | 5,700 | Tt | 10 | S | Emerges above basalt dike crossing canyon. |
| 18.9.24.344 | Tesuque Pueblo | | Qal | | I | Infiltration gallery. |
| 18.10.32.211 | E. S. Bauer | 7,180 | pЄ | 10–20 | I, D | Emerges from jointed rocks below contact of Tesuque formation. |

TABLE 19.—*Availability of records of streamflow near Santa Fe, N. Mex., through 1951*

| | Station | Location | Years of record | Type of record | Publication |
|---|---|---|---|---|---|
| | *Santa Fe River:* | | | | |
| | Above storage | Monument Rock 9 miles east of Santa Fe (17.11.19) [2]. | Mar.–Nov. 1911 | Misc. gage height and discharge | SE [1] 1911–12. |
| | | | Sept.–Dec. 1910 | do | SE 1888–1925. |
| (C) [3] | Above diversions | About 0.4 mile downstream from McClure dam (17.10.23.420). | Oct. 1930–1951 (Prior to Oct. 1947 at site 0.3 mile upstream). | Daily and monthly discharge | WSP [4]. |
| | | About 1½ miles downstream from present site. | 1926–31 | do | SE. |
| | | 1½ miles above Santa Fe Water and Light Co.'s reservoir. | Jan. 1913–Dec. 1925 | Monthly discharge | SE 1888–1925. |
| | | | Apr. 1913–Dec. 1914 | do | WSP. |
| | | Three miles downstream from present site. | May–June 1910 | do | WSP. |
| | At Santa Fe | Don Gaspar Ave | June 1907–July 1910 | do | SE 1888–1925. |
| | | | Mar.–Nov. 1911 | Misc. gage height and discharge | SE 1911–12. |
| | *Arroyo Hondo:* | | | | |
| (D) | Above diversions | 2,000 feet above crossing of Santa Fe Trail (16.10.17.200). | 1913–1922 | Monthly discharge | SE 1888–1925. |
| | | | 1913–1917 | Partial daily discharge | SE. |
| | *Rio Tesuque [5] and Tesuque Creek:* [5] | | | | |
| (A) | Above diversions | (18.10.32.400) | Mar. 1936–1951 | Daily and monthly discharge | WSP. |
| | | 175 feet downstream from present site | May–Oct. 1919 | do | SE. |
| (B) | At Tesuque | | Oct. 1938–Sept. 1941 | do | WSP. |
| (B') | Tesuque Bridge | Hwy. 285 bridge | Mar. 1936–Oct. 1938 | do | WSP. |
| | *Little Tesuque Creek:* [6] | | | | |
| (A') | Above diversions | Above Bishops Lodge (17.10.4) | Mar. 1936–Sept. 1941 | do | WSP. |
| | *Diversions from Rio Tesuque and Tesuque Creek:* [5] | | | | |
| (1) | Cajon Grande ditch | 450 feet downstream from head of ditch (18.10.32.400). | 1940–41 | Monthly diversions | WSP. |
| | | | Mar. 1936–1939 | Daily and monthly diversions | WSP. |
| (2) | de la Cruz | 250 feet downstream from head of ditch (18.10.32.300). | 1940–41 | Monthly diversions | WSP. |
| | | | June 1936–1939 | Daily and monthly diversions | WSP. |
| (3) | Acequia Madre | 350 feet downstream from head of ditch (18.10.31.400). | 1940–41 | Monthly diversions | WSP. |
| | | | Apr. 1936–1939 | Daily and monthly diversions | WSP. |
| (4) | Acequia Medio (head) | 350 feet downstream from head of ditch (18.9.25). | Oct. 1946–Mar. 1947 | Monthly diversions | WSP. |
| | | | 1942–46 | do | WSP. |
| | | | 1940–41 | do | WSP. |
| | | | Mar. 1936–1939 | Daily and monthly diversions | WSP. |
| | Acequia Medio (at waste) | At end of ditch (18.9.24 center) | July 1936–June 1938 | do | WSP. |
| (5) | Mitchell ditch | Outlet of infiltration gallery in Rio Tesuque bed (18.9.25. N¼ corner). | 1947–51 (Irr. season only) | Monthly discharge | WSP. |
| | | | 1942–46 (Irr. season plus some winter meas.). | do | WSP. |
| | | | 1940–41 | do | WSP. |
| | | | June 1936–1939 | Daily and monthly discharge | WSP. |

See footnotes at end of table.

TABLE 19.—*Availability of records of streamflow near Santa Fe, N. Mex., through 1951*—Continued

| | Station | Location | Years of record | Type of record | Publication |
|---|---|---|---|---|---|
| | *Rio Grande:* | | | | |
| (E) | Otowi Bridge | 250 feet downstream from highway bridge. | 1930–51 | Daily and monthly discharge | WSP. |
| | | | June 1909–Dec. 1931 | | SE. |
| | | | June 1909–Dec. 1914 | | WSP. |
| | | | Feb. 1895–Dec. 1905 | | WSP and SE. |
| (F) | Cochiti | Highway bridge, below Cochiti and Sili main canals. | 1930–51 | Daily and monthly discharge | WSP. |
| | | | Jan. 1925–Dec. 1931 | | SE. |
| | *Diversions from Rio Grande between Otowi and Cochiti gages:* | | | | |
| | Sili main canal at head (diverts from right bank of Rio Grande). | 0.9 mile downstream from Cochiti Diversion Dam (16.6.16). Gage located 1,000 feet downstream (at highway bridge) prior to March 22, 1939. | May 1937–Nov. 1939 | Daily and monthly discharge | WSP. |
| | Sili main canal at Cochiti | 1.9 miles downstream from Cochiti Diversion Dam. Records equivalent to above if Cochiti west side Acequia is added. | Oct. 1936–May 1937 | do | WSP. |
| | Cochiti west side Acequia | 50 feet below heading from Sili main canal. | Apr. 1936–May 1937 | do | WSP. |
| | Cochiti main canal at head (diverts from left bank of Rio Grande). | 8,400 feet downstream from Cochiti Diversion Dam (16.6.16). Gage 1,000 feet downstream prior to Mar. 6, 1939. | May 1937–Nov. 1939 | do | WSP. |
| | Cochiti main canal at Cochiti. | 1.9 miles downstream from Cochiti Diversion Dam. Records equivalent to above if Cochiti east side Acequia is added. | Apr. 1936–May 1937 | do | WSP. |
| | Cochiti east side Acequia | 200 feet below head from Cochiti main canal. | Apr. 1936–May 1937 | do | WSP. |

[1] State Engineer of New Mexico biennial reports on the Surface-Water Supply of New Mexico, for years listed.
[2] See pages 101–102 for explanation of location references.
[3] See figs. 30 and 51 for location of lettered or numbered stations.
[4] U.S. Geological Survey Water-Supply Papers for water years listed (see table 20), unless specified.
[5] Rio Tesuque (below junction of Little Tesuque Creek) and Tesuque Creek (above junction of Little Tesuque Creek) both called Rio Tesuque in surface water records of U.S. Geological Survey.
[6] Called Rito Tesuque in surface water records of U.S. Geological Survey.

TABLE 20.—*U.S. Geological Survey water-supply papers containing data on streamflow near Santa Fe, N. Mex.*[1]

| *Water year (ending Sept. 30)* | *Water-Supply Paper* | *Water year (ending Sept. 30)* | *Water-Supply Paper* |
|---|---|---|---|
| 1951 | 1212 | 1940 | 898 |
| 1950 | 1178 | 1939 | 878 |
| 1949 | 1148 | 1938 | 858 |
| 1948 | 1118 | 1937 | 828 |
| 1947 | 1088 | 1936 | 808 |
| 1946 | 1058 | 1935 | 788 |
| 1945 | 1038 | 1934 | 763 |
| 1944 | 1008 | 1933 | 748 |
| 1943 | 978 | 1932 | 733 |
| 1942 | 958 | 1931 | 718 |
| 1941 | 928 | 1930 | 703 |

[1] U.S. Geological Survey water-supply papers, Surface water supply of the United States 1958, Part 8, Western Gulf of Mexico Basins.

TABLE 21.—*Computed discharge of the Santa Fe River below McClure dam, Santa Fe, N. Mex., 1914–51 (acre-feet) (Drainage area 18.2 square miles)*

[Discharge based upon records of flow for Santa Fe River near Santa Fe as published in Water-Supply Paper 1312. For period from April 1926 to date, discharge is corrected for evaporation from McClure Reservoir; for October 1931 to date, discharge is adjusted also for change in contents of McClure Reservoir. See pages 95 to 97 for history of reservoir changes]

| Year | October | November | December | January | February | March | April | May | June | July | August | September | Annual: |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1914 | 327 | 246 | 301 | 180 | 205 | 516 | 1,090 | 1,830 | 1,000 | 1,590 | 1,030 | 362 | 8,680 |
| 1915 | 425 | 349 | 221 | 172 | 231 | 749 | 4,080 | 2,600 | 2,150 | 1,200 | 645 | 227 | 13,050 |
| 1916 | 183 | 126 | 136 | 353 | 816 | 1,840 | 2,430 | 3,400 | 1,820 | 774 | 476 | 260 | 12,610 |
| 1917 | 598 | 270 | 170 | 215 | 186 | 149 | 201 | 559 | 589 | 224 | 147 | 109 | 3,420 |
| 1918 | 75 | 72 | 52 | 60 | 126 | 482 | 596 | 1,210 | 980 | 464 | 391 | 227 | 44,740 |
| 1919 | 144 | 122 | 119 | 126 | 133 | 615 | 3,620 | 5,170 | 3,090 | 3,450 | 1,680 | 719 | 18,990 |
| 1920 | 683 | 321 | 329 | 175 | 333 | 352 | 939 | 2,760 | 1,340 | 339 | 214 | 120 | 7,900 |
| 1921 | 57 | 186 | 174 | 158 | 246 | 282 | 494 | 1,860 | 4,470 | 3,110 | 4,550 | 1,030 | 16,620 |
| 1922 | 183 | 155 | 123 | 134 | 109 | 255 | 875 | 999 | 465 | 164 | 70 | 61 | 3,590 |
| 1923 | 46 | 57 | 87 | 103 | 148 | 273 | 741 | 1,720 | 870 | 207 | 308 | 233 | 4,790 |
| 1924 | 158 | 232 | 182 | 143 | 133 | 504 | 2,080 | 2,520 | 1,240 | 336 | 215 | 99 | 7,840 |
| 1925 | 113 | 60 | 75 | 94 | 113 | 215 | 339 | 177 | 63 | 128 | 244 | 161 | 1,780 |
| 1926 | 168 | 149 | 110 | 62 | 107 | 279 | 1,090 | 4,020 | 2,290 | 452 | 241 | 174 | 9,140 |
| 1927 | 98 | 112 | 229 | 72 | 22 | 320 | 716 | 1,570 | 434 | 238 | 293 | 345 | 4,450 |
| 1928 | 471 | | | 93 | 106 | 132 | 89 | 1,770 | 642 | 180 | 576 | 325 | 4,700 |
| 1929 | 309 | 224 | 124 | 229 | 163 | 217 | 323 | 1,900 | 1,130 | 365 | 1,360 | 2,150 | 8,490 |
| 1930 | 609 | 263 | 191 | 185 | 152 | 345 | 1,010 | 844 | 521 | 712 | 1,030 | 354 | 6,220 |
| 1931 | 221 | 122 | 124 | 185 | 169 | 250 | 699 | 2,170 | 967 | 347 | 183 | 1,760 | 7,200 |
| 1932 | 814 | 231 | 168 | 140 | 209 | 657 | 1,470 | 2,000 | 744 | 336 | 470 | 422 | 7,660 |
| 1933 | 191 | 126 | 91 | 78 | 81 | 133 | 188 | 489 | 828 | 400 | 173 | 108 | 2,890 |
| 1934 | 112 | 76 | 91 | 53 | 110 | 103 | 215 | 312 | 140 | 139 | 224 | 355 | 1,930 |
| 1935 | 195 | 110 | 86 | 88 | 101 | 162 | 370 | 1,740 | 1,560 | 312 | 820 | 676 | 6,220 |
| 1936 | 310 | 200 | 145 | 118 | 177 | 392 | 1,090 | 1,510 | 432 | 574 | 1,100 | 336 | 6,380 |
| 1937 | 591 | 262 | 139 | 140 | 114 | 395 | 1,460 | 2,100 | 1,420 | 469 | 197 | 391 | 7,680 |
| 1938 | 144 | 156 | 105 | 50 | 108 | 133 | 182 | 609 | 654 | 396 | 196 | 265 | 3,000 |
| 1939 | 301 | 151 | 142 | 141 | 130 | 662 | 1,210 | 1,340 | 289 | 172 | 311 | 191 | 5,040 |
| 1940 | 269 | 150 | 121 | 117 | 180 | 801 | 1,080 | 1,450 | 532 | 144 | 287 | 284 | 5,420 |
| 1941 | 225 | 146 | 188 | 221 | 340 | 780 | 1,550 | 5,720 | 2,980 | 923 | 458 | 588 | 14,120 |
| 1942 | 1,400 | 790 | 287 | 197 | 192 | 378 | 3,450 | 3,060 | 1,520 | 228 | 211 | 524 | 12,240 |
| 1943 | 174 | 112 | 102 | 126 | 178 | 396 | 1,080 | 993 | 288 | 172 | 181 | 154 | 3,960 |
| 1944 | 120 | 92 | 75 | 81 | 66 | 207 | 574 | 1,780 | 1,020 | 678 | 427 | 166 | 5,290 |
| 1945 | 210 | 193 | 214 | 79 | 255 | 510 | 1,380 | 2,390 | 865 | 203 | 183 | 246 | 6,730 |
| 1946 | 133 | 108 | 73 | 69 | 67 | 224 | 499 | 440 | 143 | 260 | 647 | 262 | 2,920 |
| 1947 | 234 | 233 | 178 | 110 | 88 | 180 | 320 | 1,100 | 471 | 188 | 143 | 274 | 3,520 |
| 1948 | 103 | 73 | 84 | 92 | 134 | 405 | 1,350 | 1,750 | 832 | 254 | 151 | 73 | 5,300 |
| 1949 | 103 | 59 | 59 | 49 | 120 | 295 | 1,270 | 1,890 | 1,430 | 641 | 747 | 516 | 7,180 |
| 1950 | 256 | 152 | 69 | 60 | 68 | 85 | 196 | 222 | 100 | 130 | 113 | 78 | 1,530 |
| 1951 | 57 | 40 | 45 | 31 | 33 | 56 | 96 | 322 | 141 | 49 | 526 | 205 | 1,600 |
| Median | 193 | 150 | 124 | 118 | 134 | 308 | 907 | 1,745 | 848 | 324 | 290 | 264 | 5,820 |
| Mean | 284 | 176 | 141 | 127 | 164 | 388 | 1,064 | 1,797 | 1,064 | 551 | 558 | 390 | 6,706 |
| Mean runoff (inches) | 0.28 | 0.18 | 0.15 | 0.13 | 0.17 | 0.40 | 1.10 | 1.85 | 1.10 | 0.58 | 0.58 | 0.40 | 6.91 |

# AUTHORS CITED

# INDEX

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