Geology and Hydrology of Valle Grande and Valle Toledo, Sandoval County, New Mexico

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By C. S. CONOVER, C. V. THEIS, and R. L. GRIGGS

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

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ABSTRACT

A large caldera in the Jemez Mountains of north-central New Mexico was studied for its potential as a source of water supply for the town of Los Alamos, N. Mex. This caldera is roughly 12 miles in diameter. The floor of the depression is divided into a network of valleys by numerous domes of rhyolite. Two valleys in the eastern half of the depression, the Valle Grande and the Valle Toledo, compose the area investigated for this report. The eastern margin of the study area is about 5 miles west of Los Alamos.

Altitudes in the area range from slightly less than 8,500 feet on the valley floor to about 11,250 feet at the top of the highest rhyolite dome. The crest of the rim ranges from 9,500 to 10,500 feet.

The Jemez Mountains consist of a volcanic pile whose interior has collapsed. Rhyolite domes were extruded in the caldera area and the lowland area remaining between rhyolite domes and a caldera rim was, for a time, a lake. The lake gradually filled with debris derived largely from the rhyolite domes and, in part, from rocks of a caldera rim.

The rocks that crop out in the area are volcanic and sedimentary. An older sequence of flow rocks (Chicoma volcanic formation of Smith, 1938) is of probable Pliocene and Pleistocene ages, a younger series of extrusive domes and tuff (Bandelier rhyolite tuff of Smith, 1938) is of probable Pleistocene age. The sedimentary rocks are lacustrine deposits of Pleistocene age and surface alluvium consisting of terrace, fan, and channel deposits, all younger than the volcanic rocks.

The Chicoma volcanic formation of Smith (1938) and the Bandelier rhyolite tuff of Smith (1938) do not contain important aquifers in the area. The same is true of the rhyolite domes, but the blocky crust and the porous rhyolite of the domes make them important as areas of recharge for the sedimentary rocks of the caldera fill. Probably little if any water flows off the domes; it infilters downward through the porous rhyolite and into the porous strata in the lakebeds and perhaps the alluvial fan material on the edges of the valleys.

Several clayey members interfinger with the pumiceous sand and gravel of the caldera fill. Test drilling indicated that individual clay members are as much as 20 feet thick in the Valle Toledo; however, at places in that valley, the clayey members unite to form a clayey zone as much as 80 feet thick. In

the Valle Grande, a thick zone of clay overlies a thicker zone of pumiceous sand and gravel. The maximum known thickness of the upper clay and underlying sand and gravel are 295 feet and 880 feet, respectively. The pumiceous sand and gravel of the lake sediments form the principal aquifers in the Valley Toledo and the Valley Grande, and ground water in these aquifers is confined under pressure by clay zones.

A pumping test in the Valle Toledo indicated that the coefficient of transmissibility of the aquifer in that valley is about 50,000 gpd (gallons per day) per ft, and its coefficient of storage is about 0.005 The specific capacity of the pumped well used in the test was about 50 gpm (gallons per minute) per ft of decline in pressure.

A pumping test in the Valle Grande indicated that the coefficient of transmissibility for the aquifer in that valley is at least 25,000 gpd per ft; the coefficient of storage was not determined. The specific capacity of the discharging well was about 10 gpm per ft of drawdown.

Properly constructed wells developing water from the lake deposits might be expected to yield more than 1,000 gpm each. Large-discharge wells should be spaced far enough apart to avoid undue interference among the wells.

Considerable water could be pumped from storage but the amount of water perennially available to wells in each valley would be the amount of water issuing from springs in their respective valley—about 2,200 acre-feet in the Valle Grande and about 1,600 acre-feet in the Valle Toledo. Pumping from wells would deplete the flow of the springs and thereby interfere with surface-water rights downstream.

Water from the lake deposits is high in silica content but low in total dissolved solids. The water is soft. Water in the Valle Toledo is relatively high in fluoride content and would have to be mixed with low fluoride water before using in a municipal system.

INTRODUCTION

The town of Los Alamos, N. Mex., was established in 1943 as a research center for the Atomic Energy Commission. A water supply for the town was obtained from springs and surface flows in canyons west of town on the eastern slope of the Jemez Mountains. In time, these sources of water were fully developed, but the quantity of water available from them was insufficient to meet the increasing water requirements of the town. Several sites for the development of a water supply from underground sources were considered. In 1949, the Atomic Energy Commission requested the U.S. Geological Survey to study the ground-water potential of a volcanic depression at the top of an extinct volcano several miles west of Los Alamos. The investigation was limited to two valleys, the Valle Toledo and the Valle Grande, in the eastern half of the depression. Fieldwork for the report was completed in 1949.

This report explains the nature of the water-bearing materials in the two valleys, based on geologic observations and test drilling data, the yield of water to wells, and the relation of ground water to the surface-water discharge from the valleys.

LOCATION AND SETTING

The volcanic depression studied is in the northeastern part of Sandoval County, N. Mex., in the north-central part of the State. The eastern boundary is about 30 airline miles northwest of Santa Fe and about 5 miles west of Los Alamos. (See fig. 1.) The project

Base from U.S. Geological Survey
topographic map, State of New
Mexico, 1955

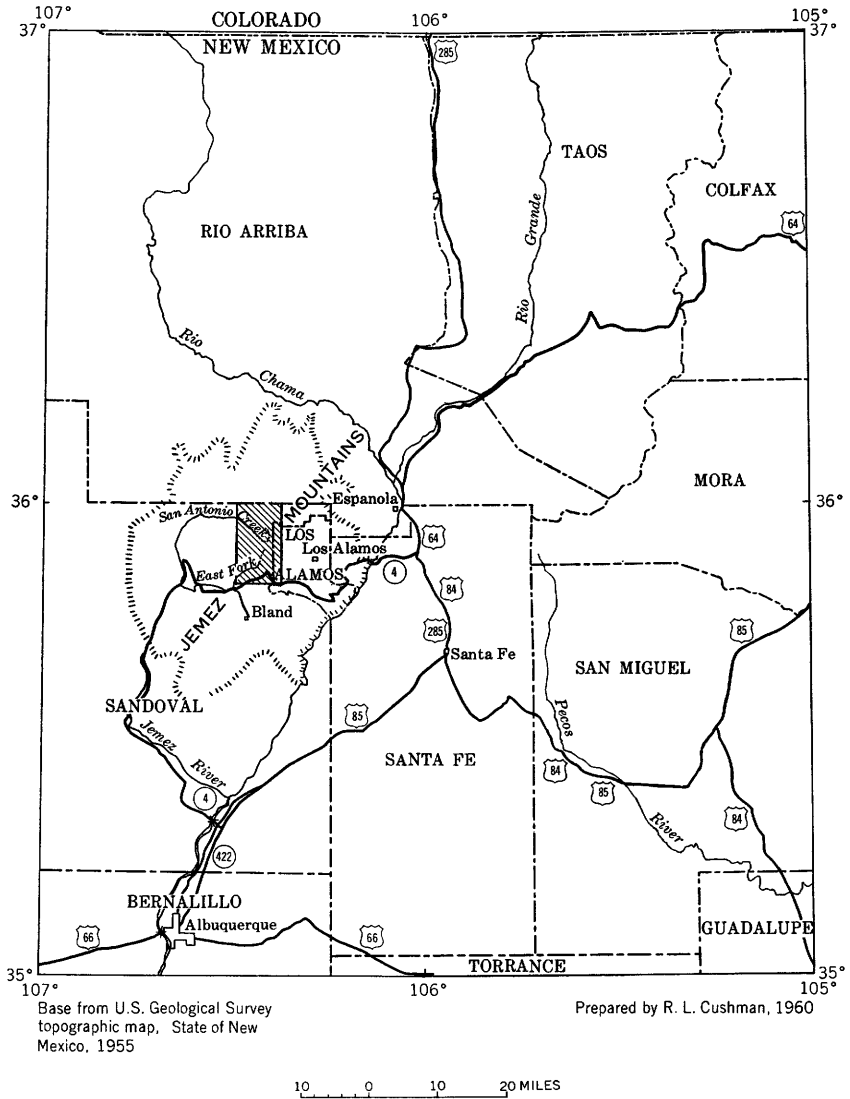Prepared by R. L. Cushman, 1960

10   0   10   20 MILES

FIGURE 1.—Map of north-central New Mexico showing the location of the Valle Grande and the Valle Toledo area (diagonal lines) in Sandoval and Los Alamos Counties, N. Mex.

area or eastern half of the depression is bounded approximately by the meridians 106°23′ and 106°30′ W., and the parallels 35°50′ and 36°00′ N. This rectangular area is about 13 miles from north to south and 8 miles from east to west.

The Valle Grande and the Valle Toledo area covers the eastern part of the depression. The caldera contains subround to irregularly shaped rhyolite domes protruding above a relatively flat floor. The roughly circular boundary of the depression is approximately 12 miles in diameter. This boundary is formed by a steeply sloping, inward-facing escarpment whose upper limit is a serrate arrangement of peaks and saddles; the crest of the escarpment stands about 500 to more than 1,000 feet above the floor of the depression. The numerous steep-sided rhyolite domes divide the circular depression into a network of valleys. In much of the depression the rhyolite domes are closely spaced and the valleys are narrow; but in the eastern part of the depression the domes are more widely spaced and the valleys, such as the Valle Grande, are as much as 3 miles wide. (See pl. 1.)

The depression is drained by two streams. The East Fork of Jemez River drains the southern part of the area. It heads at a group of springs in the Valle Grande. From there it follows an arcuate course to a breach in the southwest rim of the depression, 8 miles west of the mapped area. The Valle Grande is a large unwooded valley or mountain park in the southeastern part of the depression. San Antonio Creek drains the northern part of the area and heads in the northeastern part of the depression. It follows a semicircular course and joins the East Fork to form the main stem of the Jemez River (fig. 1). Rhyolite domes pinch the San Antonio Creek drainage at several points to form a series of valleys through which the creek flows. The uppermost of these valleys is the Valle de los Posos; the second, in which most of the exploration for water in the San Antonio Creek drainage was done, is the Valle Toledo; the next, largely beyond the west edge of plate 1 is the Valle Santa Rosa.

In the eastern part, the floor of the depression rises from southwest to northeast. The lowest altitude in this area is in the Valle Grande and is about 8,475 feet above sea level where the East Fork of Jemez River leaves the western boundary of the area on plate 1. The low divide separating the drainages of the East Fork and the San Antonio Creeks is about 9,050 feet above mean sea level. The lowest altitude on San Antonio Creek in the area shown in figure 1 is about 8,490 feet above sea level. Altitudes on top of the rim of the depression in the Valle Grande area range from 9,500 feet

at the Quemazon and the Valle saddles to about 10,500 feet at Pajarito Peak. The interior hills or domes extend to various altitudes; the highest, Redondo Mountain, rises to 11,252 feet a short distance west of the area shown on plate 1.

The southern part of the project area is accessible by State Highway 4. Access to most of the area is by private ranch roads.

PREVIOUS INVESTIGATIONS

C. S. Ross, U.S. Geological Survey, made a brief study of the geology of the Jemez Mountains in the 1920's, but his work was postponed because base maps were inadequate for further geologic work.

Between 1932 and 1935, Smith (1938) studied and mapped the geology of the Abiquiu quadrangle, whose southern boundary is a few miles north of the volcanic depression.

From 1946 to the start of the investigation for this report in 1949, C. S. Ross and R. L. Smith, U.S. Geological Survey, were engaged in a detailed study of the volcanic series in the Jemez Mountains. The results of their studies were not published prior to 1949, but their discussions with Griggs assisted in the interpretation of the geology of the eastern part of the volcanic depression.

In 1948, H. T. Stearns, consulting geologist from Hope, Idaho, supervised the drilling of seven test holes in the Valle Grande and the Valle Toledo. Information obtained from these test holes indicated that the beds of pumiceous sand and gravel of the fill in the volcanic depression would yield water readily to wells.

Selected references listed at the end of this report catalog publications pertaining to the geology and hydrology of north-central and northwestern New Mexico.

ACKNOWLEDGMENTS

The area described in the report is owned by Frank Bond and Son, Inc., a cattle company. The company granted permission to work in the area and to drill test holes and wells necessary for the investigation.

Officials of the Atomic Energy Commission, Black and Veatch consulting engineers of Kansas City, Mo., and the Zia Co. of Los Alamos extended the facilities of their organizations to expedite the investigation.

GEOLOGY

The chief geological features of the region consist of a complex volcano whose interior has collapsed, and discontinuous aprons of pumice and tuff that overlap the volcano. In places tuff extends

high on its flanks, and in places it occurs in the caldera area. The diameter of the volcanic mass, including the encircling pyroclastic rocks, is nearly 40 miles.

The original volcano, comprising the Chicoma volcanic formation of Smith (1938), interfingers with an is equivalent in age to the upper part of the extensive deposit of silt, sand, and gravel of the Santa Fe group of middle(?) Miocene to Pleistocene(?) age that fills the Rio Grande Valley through most of New Mexico. The volcano consists chiefly of flows of latite and quartz latite, which in this area is a bluish- to purplish-gray rock with conspicuous whitish crystals (phenocrysts) of feldspar.

After the deposition of the Santa Fe group and after deep radial valleys had been cut on the flanks of the volcano, tuffaceous eruptions occurred and the central part of the volcano collapsed into the magma chamber, to form a large basin or caldera area in its interior. The tremendous explosions showered the region in and around the volcano with pumice and ash. These materials consolidated and formed the encircling apronlike plateaus, which surround the volcano. Toward the end of the explosive activity, after the dissolved gases in the melt beneath the volcano were largely dissipated, quiet eruptions of pasty lava took place within the caldera area forming the rhyolite domes. The pumice and tuff deposits of this phase of activity are referred to herein as the Bandelier rhyolite tuff of Smith (1938), and the domes of the collapsed area are referred to as the rhyolite domes.

After the final collapse of the volcano, the lowland area between the interior rhyolite domes and the caldera rim was, for a time, a lake. This lake gradually filled with debris derived largely from the rhyolite domes but in part derived from rocks of the caldera rim.

STRATIGRAPHY

The rocks that crop out in the area are volcanic and sedimentary rocks of late Tertiary and Quaternary ages. The volcanic rocks, in ascending order, consist of the Chicoma volcanic formation of Smith (1938) of middle(?) Pliocene to Pleistocene(?) ages and the Pleistocene Bandelier rhyolite tuff of Smith (1938). The sedimentary rocks, which are younger than the volcanic rocks, consist of lake deposits, terrace deposits, fan deposits, and channel deposits.

VOLCANIC ROCKS

CHICOMA VOLCANIC FORMATION OF SMITH (1938)

The oldest rocks of the area are the thick sequence of flows, the Chicoma volcanic formation of Smith (1938), that form the complex

cone of the original volcano. These are the chief rocks of the eastern rim of the caldera and are well exposed on the higher flanks of the volcano. These flows are conspicuously porphyritic rocks containing blocky crystals, or phenocrysts, of white feldspar that are as much as 1 inch in greatest dimension. In some of the flows subrounded phenocrysts of quartz also occur. The groundmass surrounding the phenocrysts is gray, commonly with a bluish or purplish cast. The rocks apparently range from latite to quartz latite in composition.

It probably is not possible for ground water to move along or occur within intergranular pore spaces in these rocks, because they are composed of tightly interlocking mineral grains with tight crystal boundaries. The ground water in these rocks moves along secondary open fractures that cut the rocks or possibly in broken zones at the boundaries of individual flows. However, the secondary fractures, though locally conspicuous, do not appear to be sufficiently open or continuous to transmit large quantities of water, and broken zones at the boundaries of flows are not conspicuous.

BANDELIER RHYOLITE TUFF OF SMITH (1938)

The Bandelier rhyolite tuff of Smith (1938), exposed chiefly on the lower flanks of the volcano, locally extends up to the rim of the caldera, as at the Quemazon saddle. There it fills an old valley that had been cut out in the Chicoma volcano prior to the time when the Bandelier rhyolite tuff of Smith (1938) was laid down.

This tuff is light buff to gray within the area, and for the most part highly welded. Most specimens show numerous crystals of iridescent sanidine. Doubly terminated crystals of quartz with a very indistinct prism zone also are prominent in the tuff.

This tuff is not an important water-bearing unit, although it apparently yields some water to streams on the eastern slope of the volcano. In general, much of the tuff is fine grained and sufficiently welded so that it probably can transmit no more than small quantities, or at most moderate quantities, of water.

RHYOLITE DOMES

The rhyolite domes typically stand as wooded hills. They occur both as simple and composite masses, and on the north rim of the depression they form a complex group extending from the Rito de los Indios to the Quemazon saddle (pl. 1).

The simple domes are subrounded in plan view and subconical in section. The composite masses are larger than the simple domes and are irregular in plan and cross section. The visible parts of the domes in the caldera represent only their upper parts. Many of the domes may grade into a single mass in depth, but their bases are covered

by later sediments. Some small domes may be completely buried by sediments.

In general, the interiors of the domes are composed of light-gray to pinkish rhyolite which contains small phenocrysts of glassy or iridescent sanidine and, in smaller amount, quartz. Tiny hornblende phenocrysts were noted in a few specimens. This type of rock grades outward into spherulitic rhyolite and obsidian, and in turn this grades into an outer shell of pumice which has been removed by erosion over large areas. In many places the surface material is a jumble of blocks of pumiceous rhyolite, presumably representing a solidified crust, broken and rearranged by movement of a still plastic mass below.

The rhyolite domes were extruded as a viscous melt through the fractured, collapsed floor of rocks of the Chicoma volcanic formation. Most of them were probably extruded immediately after the phase of intense explosive activity that produced the youngest Bandelier rhyolite tuff, after most of the volatile constituents in the melt in the magma chamber had been dissipated. However, between the Quemazon saddle and the Rito de los Indios, some domes are older than the latest Bandelier rhyolite tuff. It appears, therefore, that collapse of the interior of the volcano occurred in two stages.

The blocky rhyolite crusts and the frothy rhyolite crusts of the domes are capable of transmitting relatively large quantities of water, but the dense rhyolite of the interior of the domes is relatively impermeable. Springs flowing nearly 1,000 gpm (gallons per minute) emerge from blocky and pumiceous rhyolite at the west end of the Valle Toledo, where a prong from the Cerros del Abrigo dome extends into the valley. The water levels in wells in the valley indicate that ground water moves westward through the valley fill and rises through the blocky rhyolite past the clay layer that confines the water elsewhere in the valley. The apparently impervious cores of the two domes just west of the springs and west of the Rito de los Indios, that close the Valle Toledo at its lower end, act as a dam preventing the further movement of the ground water to the west.

Springs flowing nearly 1,000 gpm emerge also from highly fractured rhyolite at the southern end of Cerro del Medio, north of the Valle Grande. In this area rhyolite transmits water through two types of openings—secondary open fractures where they are well developed and interconnected; and primary interstices, which are probably erratic though apparently connected. The primary openings occur at the boundary of glass that imperfectly fills the voids between finely crystalline spherulites.

The blocky crusts and the porous rhyolite on the hills serve as important recharge areas for the valley. Probably little if any water or snowmelt flows off the blocky parts. The infiltering water moves downward through the porous parts of the rhyolite until it comes in contact with porous strata in the lakebeds and perhaps the alluvial fan material at the edges of the valleys.

SEDIMENTARY ROCKS

LACUSTRINE DEPOSITS

The lacustrine deposits consist of the unconsolidated fill that accumulated in a lake that occupied the caldera during Quaternary time. This fill covers the bedrock floor of the caldera and the lower parts of the rhyolite domes and is younger than the Bandelier tuff. It is overlain by a veneer of surface deposits.

The character of the lake sediments is known in part from samples taken from test holes and in part from pebbles washed from the holes by flowing water. In the Valle Toledo and the Valle Grande they consist of clay and pumiceous sand and gravel. Along the eastern margin of the caldera they consist of pumiceous sand and gravel and probably pyroclastic debris.

Surface exposures of the lakebeds are poor because they are almost completely covered by recent alluvium, alluvial fans and other surficial sediments (pl. 1) Clay beds crop out in places on the slope below benches on both sides of the Valle Toledo and along the Rito de los Indios. The best exposures are a few hundred feet south of test hole 4 where about 10 feet of clay can be seen. The clay is olive buff, weathering light gray, and the bedding ranges from massive to laminated. One bed contains numerous cylindrical diatoms. In an exposure a few hundred feet southeast of test hole 1, the clay is sandy and contains pebbles as much as 1 inch in diameter. The top of the clay beds are clearly marked on the south side of the valley from the vicinity of test hole 4 to within a short distance of hole 6 by a break in slope at the top of the clay. This horizon is accentuated by several seeps.

Several sets of clayey beds interfinger with the pumiceous sand and gravel in the lake sediments in the Valle Toledo. Test drilling indicated that these clayey beds are thickest at the western end of the Valle Toledo and thin and pinch out to the east. In hole 6 only one set of clayey beds were noted in the subsurface, and the set is only 10 feet thick. Farther west, in hole 1, the same set is 20 feet thick, and 5 other zones are developed. At hole 4 at the west end of the valley, 5 sets of clayey beds have united to form 1 set, 80 feet thick (fig. 2). Few data are available as to the lateral extent of the clayey
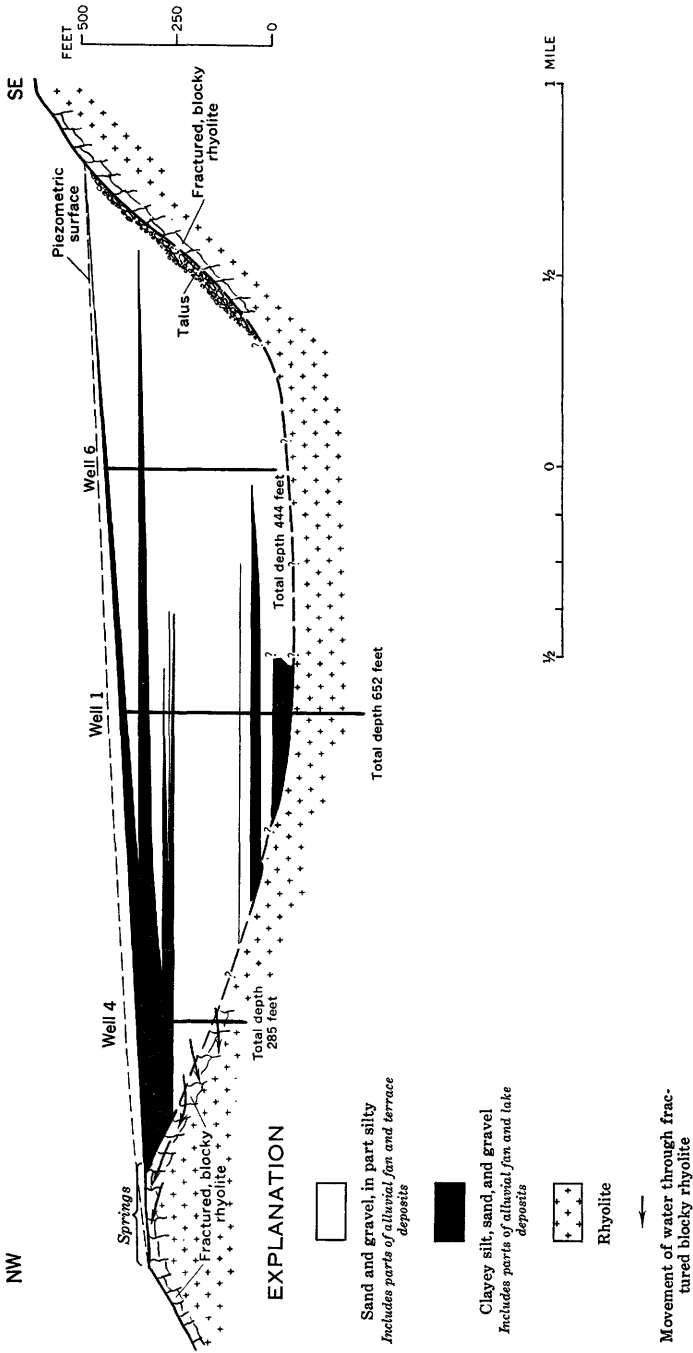
FIGURE 2.—Generalized section of the Valle Toledo along the axis of San Antonio Creek, Sandoval County, N. Mex.

beds, but 3 or 4 sets were identified in drill cuttings from hole 5, indicating that the beds may extend for a considerable distance toward the sides of the valley. Presumably, as indicated by figure 3, they
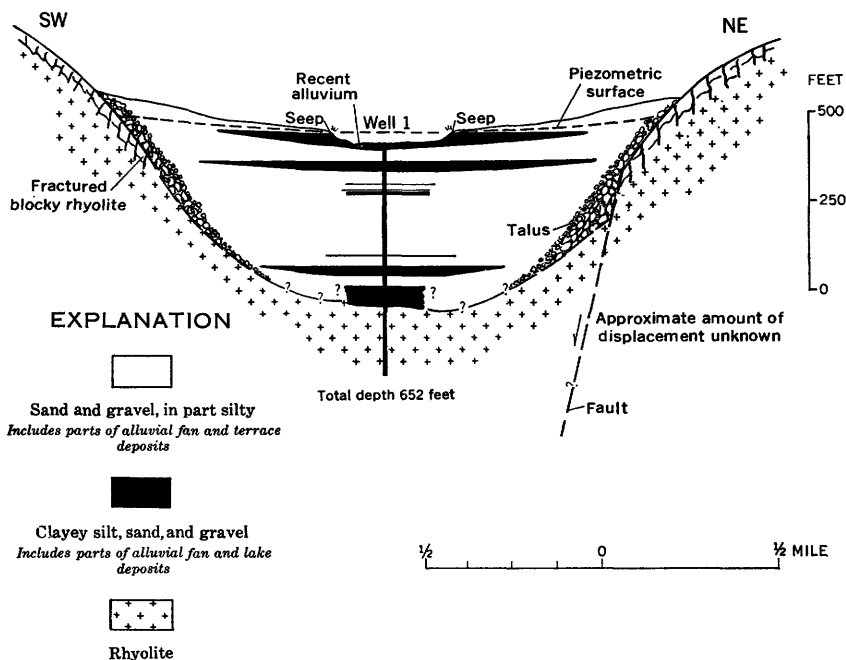
FIGURE 3.—Generalized section of the Valle Toledo along a northeast-southwest line across San Antonio Creek, Sandoval County, N. Mex.

pinch out against old talus materials before they reach the valley walls. In the well cuttings, the clayey material ranges from olive buff to dark brownish olive. Most of these clayey beds contain some silt, sand, and gravel.

The pumiceous sand and gravel, in which the clayey beds are interbedded, are composed of fragments of pumice, obsidian, stony rhyolite, and grains of sanidine and quartz. Pumice is the predominant constituent, and some beds are mainly all pumice. Most of the particles are subangular, showing but little wear, but much of the pumice is subrounded, and some is fairly rounded. The pumiceous sand is predominantly coarse. Some unbroken pieces of well-rounded pumiceous gravel washed up by flowing water from test hole 1 were more than 1 inch in diameter. Presumably, the material coarsens toward the sides of the valley where it probably grades into fanlike or deltaic deposits that must have built up under the lake surface in the immediate vicinity of the rhyolite domes. Immediately adjacent to the domes and the caldera rim, there is proba-

bly a zone of talus composed of boulders and smaller debris that collected at the bases of the steep slopes immediately following the formation of the caldera.

Only two surface exposures of the lake sediments have been noted in the Valle Grande. Both exposures are poor and were not mapped. One is about a quarter of a mile southwest of test hole 7 where a small area of olive-buff clay crops out in the bottom of a shallow arroyo that cuts through recent alluvium adjacent to the East Fork of Jemez River. The other exposure is in the Valle Jaramillo, where Redondo Mountain and Cerro del Medio are closest together. Here a small area of olive-buff clay crops out through the alluvial fan on the flank of Redondo Mountain.

Test-hole data in the Valle Grande indicate a thick lens of clay overlying pumiceous sand and gravel. Clay was penetrated in test holes 7 to 12, which, with the exposure in the Valle Jaramillo, indicates that it underlies a rather extensive area. The clay wedges out abruptly, however, between holes 12 and 15 and is absent along the eastern side of the caldera. Presumably, it also wedges out toward the edges of the valley. The clay is virtually identical in lithology with that of the Valle Toledo. It ranges from olive to dark brownish olive and contains notable amounts of gravel, some of which may be ash-fall pumice. The maximum known thickness of the upper clay, 295 feet, was in holes 7, 8, and 9. It is 200 feet thick in hole 10, 235 feet thick in hole 11, and about 250 feet thick in hole 12. Data indicate that in north-south section, at least, the base of the clay lens is convex downward, and the log of hole 11 indicates that it interfingers with pumiceous sand and gravel toward the edges of the valley as shown in figure 3.

The pumiceous sand and gravel beneath the clay lens, and interfingering with the clay near its margins, are composed of fragments of pumice, obsidian, stony rhyolite, and grains of sanidine and quartz. The pumice is predominant. The sand ranges from fine to coarse, and unbroken pieces of gravel larger than 2 inches in diameter were obtained from hole 10. Larger sizes were probably broken by the drilling bit. As in the Valle Toledo, it is assumed that the gravel progressively coarsens toward the sides of the valley where fanlike deposits probably extend outward from the rhyolite domes and caldera rim. Immediately adjacent to the solid-rock boundaries of the valley there is probably a zone of coarse talus that collected on and at the base of the steep slope soon after the caldera was formed. In hole 7 it is believed that near the bottom of the hole pyroclastic pumice was found.

No data are available as to the maximum thickness of the sand and gravel member in the Valle Grande. Test hole 7, which bottomed at a depth of 1,185 feet, penetrated 880 feet of the member without reaching bedrock at the bottom of the caldera. (See fig. 4.)

The coarse materials of the lake sediments form the aquifers in both valleys, and the water is artesian in these aquifers. These materials are quite permeable, as shown by the discharge tests made on the wells. The uppermost clay members form the confining beds for the artesian aquifers in both valleys and the lower clay members appear to impede the movement from one set of beds to the others; test drilling showed that the water in the lowest beds was under greater pressure than that in the upper beds. The clay members in the part of the lakebeds above creek level inhibit the downward movement of water. Comparatively small bodies of ground water are perched above these clay beds and appear to feed the high-level springs.

SURFACE ALLUVIUM

Lying on top of the lake sediments is a cover of coarse alluvium consisting of pediment gravel, alluvial-fan material, and stream-channel alluvium.

In the Valle Toledo there are conspicuous pediments or pediment-like benches on both sides of the valley. The surfaces of these benches slope toward the axis of the valley at a rate of about 100 feet per mile, and they appear to slope about 25 feet per mile downstreamward. In the vicinity of test hole 1, the benches are about 45 feet above the streambed of San Antonio Creek. The benches commonly are cut on lake sediments but near the west end of the valley they are cut on rhyolite. The material capping these benches is a poorly sorted mixture about 25 feet thick consisting of gravel, sand, and clay, and a few boulders as large as 2 feet in diameter. The material just under the surface consists of a few feet of black clay and silt containing isolated pebbles and cobbles. Presumably this material formed during severe frost action, possibly near the end of Pleistocene time.

In the Valle Grande the benches are not so conspicuous as those of the Valle Toledo, but remnants of them cover a large area. They are on both sides of the East Fork of Jemez Creek and Jaramillo Creek, as indicated on plate 1. The surfaces of the benches slope toward the present drainage about 100 to 125 feet per mile and their projections intersect the drainage lines about 25 to 30 feet above the beds of the streams. Most of the remnants are cut on lake sediments but a few are cut on rhyolite. The bench remnants are capped by 10–20 feet of poorly sorted material similar to that of the Valle Toledo
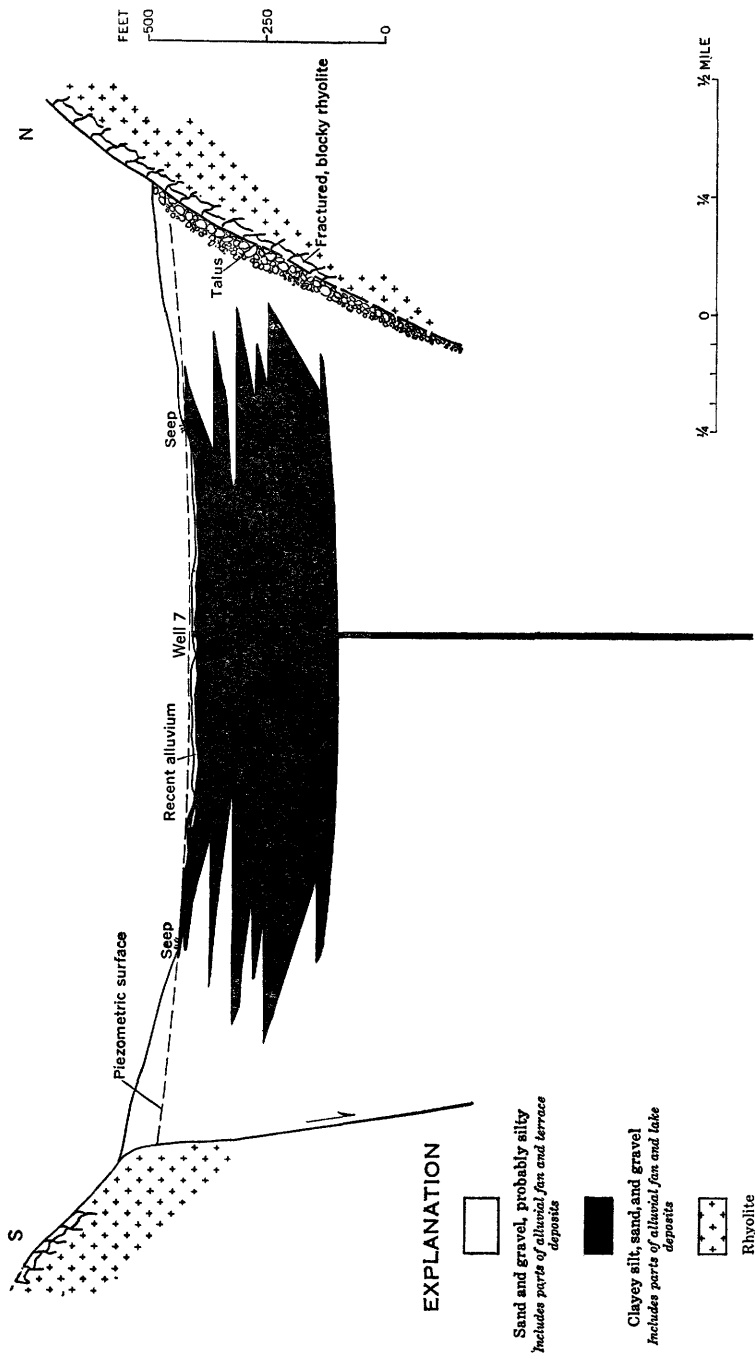
FIGURE 4.—Generalized section of the Valle Grande along a north-south line, Sandoval County, N. Mex.

although no boulders have been noted in the material in the Valle Grande.

Alluvial fans occupy a belt between the gravel-covered benches and the bedrock boundaries of the Valle Toledo and a large part of the Valle Grande. In the upper part of the Valle Grande and in the headwaters of San Antonio Creek they form a continuous cover across the valley floors. These fans extend outward from the rhyolite domes and the caldera rim and their surfaces slope toward the axes of the valleys. In places these slopes are as great at 20°. The fans are composed of coarse alluvium derived from the domes and caldera rim, and they have their greatest thickness adjacent to these bedrock features. The fans overlap or interfinger with the bench gravels, and locally, they form a veneer over rhyolite or lake sediments.

Stream-channel alluvium is the youngest material in the caldera. It underlies the valley flats adjacent to the main drainage and in places is about 20 feet thick. As it has been derived largely from the pedimentlike benches, it is composed of clay, sand, and gravel.

The various types of alluvium are hydrologically important because of their influence on recharge. The silty, clayey material forming the caps of the benches allows some recharge, but it probably has a low infiltration rate, and probably hinders downward moving water during the spring thaw. The fan material probably is fairly permeable and is most advantageously located for recharge, but its lithologic characteristics are not well known. The stream-channel alluvium is too thin and too insignificant in area to be an important recharge area. Actually this alluvium is an area of discharge because of artesian water rising from the underlying sediments. This rising water is not stored in the alluvium but is discharged to the adjacent streams though in part it is lost to the atmosphere by evaporation.

HYDROLOGY

An important element in an appraisal of the ground-water potential in the Valle Grande and the Valle Toledo was the determination of the hydraulic characteristic of aquifers in the caldera fill. The principal characteristics studied were transmissibility and storage.

The capability of an aquifer to transmit water is called transmissibility; the degree of transmissibility is expressed as the coefficient of transmissibility, which, in this report, is defined as the gallons of water per day that will move through a full section of the aquifer 1 mile wide under a hydraulic gradient of 1 foot per mile.

The coefficient of storage is defined as the ratio of the volume of water released from or taken into storage per unit surface area per

unit change in pressure. The coefficient of storage is dimensionless because it expresses a ratio.

These coefficients may be obtained from laboratory analyses of materials collected from an aquifer or by discharge tests of wells under field conditions. The discharging-well method was used in this investigation.

PUMPING TEST IN THE VALLE TOLEDO
DESCRIPTION OF TEST SITE

In order to test the hydraulic characteristic of the formations, one large-diameter test well and five small-diameter outlying observation wells were drilled in the Valle Toledo. The locations of these are shown on plate 1 and in detail in figure 5. The large-diameter well,
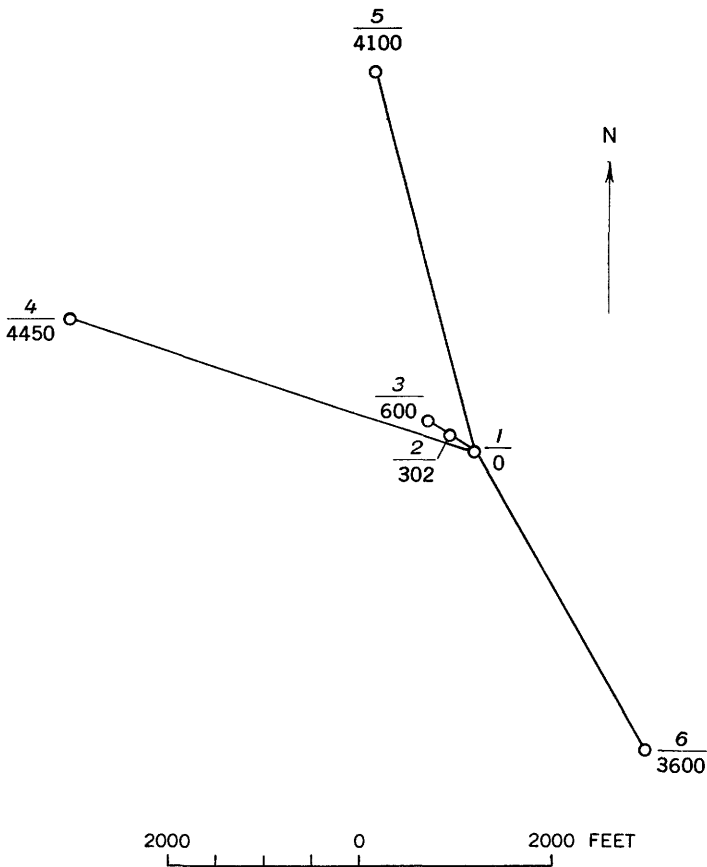

FIGURE 5.—Sketch showing the location of observation wells 2–6 with respect to well 1 in the Valle Toledo, Sandoval County, N. Mex.

well 1, from which water was discharged for the test, was drilled near the site of a 97-foot well drilled during H. T. Stearns' study in 1948. The latter well had indicated the probability of obtaining water at that place. Because of difficulties which will be described below, 3 holes were drilled at this site and the last one completed is shown as well 1. Observation wells 2 and 3 were placed in a line 302 and 600 feet respectively northwest of well 1 in order to measure the effects of discharge from well 1 on nearby water levels. The sites for wells 4 and 6 were chosen in order to investigate the effects of discharge from well 1 on water levels upstream and downstream from well 1 and to determine the character of the aquifer along the axis of the valley. Well 5 was located to test the continuity of the aquifer toward the side of the valley. A gaging station was installed by the Surface Water Branch of the Geological Survey about 3,400 feet downstream from well 4 and below the large springs emerging near the west end of the Valle Toledo. (See pl. 1.)

CONSTRUCTION OF WELLS

The site of well 1 was the first drilled in the Valle Toledo in the program. Artesian conditions were expected, but the character of the sediments, the quantity and pressure of the artesian water, and the zones where it would be found were not known below a depth of 97 feet.

Three holes were drilled at the site of well 1 by rotary drilling methods before one hole was completed successfully as a well. The first hole was begun on June 22, 1949, and had reached a depth of 478 feet when the well began to flow, and the flow increased rapidly to about 1,200 gpm. Several attempts were made to shut off the flow but they were unsuccessful, and the well finally was plugged and abandoned. Drilling started on the second hole on July 1 and had reached a depth of 652 feet when it began to flow at about the same rate as the first hole. Casing was run in the hole and the flow reduced to about 425 gpm. This flow was decreased to about 100 gpm by pumping mud into the hole, though it was necessary finally to plug and abandon the hole. The well was plugged and abandoned on August 12. Drilling of the third hole was started on August 20 and this hole was completed as a well on September 27. This third hole was drilled 70 feet, well into the confining bed overlying the aquifer, and a string of 16-inch surface pipe was set and cemented at this depth. The hole then was drilled to a final depth of 450 feet. Twelve-inch diameter blank pipe and spiral brass screen were welded together and set in the hole to form a column of blank pipe from about 450 to 427 feet, brass screen from 427 to 383 feet, and blank pipe from 383 feet to the land surface.

A flange was welded from the 16-inch to the 12-inch pipe in order to confine the discharge to the 12-inch string.

The well started to flow about 80 gpm after the drilling mud was cleaned from the well. A pump was set on the well and the well was surged with the pump to develop the well. The maximum rate of pumping was about 300 gpm with a drawdown to approximately 300 feet below land surface. This rate was too small for a test to determine the water transmission and yield characteristics of the aquifer. The pump was pulled from the well, and the blank casing was perforated with a Mills knife from 125 to 150 feet, 265 to 300 feet, and from 329 to 340 feet. These intervals were selected because the log of the well showed relatively clean sand and gravel at these depths. The pump was reinstalled, and the well surged again. The discharge was greater than previously but still insufficient to determine the hydraulic characteristics of the aquifer. The pump was removed again and the casing perforated from 80 to 120 feet and from 170 to 240 feet. Because the natural flow showed little change during or after perforating the casing and because test perforations left doubt as to the functioning of the Mills knife, adjustments were made on the knife and the casing reperforated from 80 to 120 feet and from 170 to 240 feet. The artesian flow increased from about 80 to 350 gpm. The well was developed by churning with an 8-inch bailer. When churned at a depth of between 270 and 300 feet a noticeable increase in flow occurred, and final development of the well by the bailer resulted in removal from the well of large quantities of pumice sand and gravel by the flowing water. During the final period of development, the natural flow from the well increased to about 3,000 gpm.

The well drew water from practically all horizons in the aquifer, but not in equal amounts from all horizons, as concluded from the temperatures of the water discharged during different stages of development. The temperature of the water after final completion of the well was 61°F, whereas water from the bottom of the hole, before the casing was perforated and when all water was coming into the well through the screen, had a temperature of 64°F. Water from the 97-foot well nearby, which had been flowing since it was drilled in June 1948, had a temperature of only 50°F. Therefore it appears that most of the water entering well 1 came from the lower part of the aquifer.

The observation wells 2, 3, 5, and 6 consisted of 6-inch casing sunk to a depth of 60–100 feet into the clay confining bed overlying the main aquifer and cemented in place. The holes were deepened to an altitude near that of the bottom of well 1 and casing of 2-inch internal diameter with a well point on the end was run from the surface to the bottom of each hole. Both casings were capped and fitted with

valves so that the pressures or water levels in both 6-inch and 2-inch casings could be measured. The 2-inch casings were back flushed, thus forcing water and mud up through the 6-inch casing to the surface. As a consequence of this construction the zones of the aquifer with which each casing was in hydraulic contact were rather indefinite, although in general the pressures in the 6-inch casing represented that in the upper part of the aquifer and those in the 2-inch casing that in the lower part of the aquifer. In wells 2, 3, and 6 the artesian pressures in the 2-inch casings were uniformly higher than those in the 6-inch casings. The water level in the 6-inch casing in well 5 was not measured regularly because measuring was difficult owing to mud adhering to the casing, but the level was approximately that in the 2-inch casing.

Because of certain difficulties in drilling well 4, it was necessary to construct it in a way unlike the other wells. The 6-inch casing was set in the capping bed at 50 feet and cemented as in the other wells. However, in order to shut off an artesian flow that broke in when the well was 120 feet deep and to case off a zone at 212 feet where circulation was lost, a 4-inch pipe was run to a depth of 220 feet. The 2-inch casing was set with the well point at a depth of 240 feet although the hole was carried to a depth of 285 feet. From a depth of about 212 feet to the bottom the hole was in porous rhyolite. The water level in the 6-inch casing in well 4 would rise to more than 30 feet above the ground surface when the casing was extended that high, whereas the water levels in the 2-inch and 4-inch casings were about 10 feet below ground surface. The flow from the 6-inch casing was connected from September 17 to 25 to the 4-inch casing through an external hose. When this was done water would flow to the surface through the 2-inch casing when the valve on the 2-inch was open and flowed in an unknown amount, into the aquifer when the valve on the 2-inch was closed. In well 4 the pressure in the 6-inch casing represents the pressure in the same aquifer as that tapped by the other wells, whereas the water level in the 2-inch casing represents that in the porous rhyolite which presumably is hydraulically continuous with the springs issuing from rhyolite at the lower end of the valley.

WELL DISCHARGE PRIOR TO TEST

Because of the uncontrolled discharge at various times from the unsuccessful first and second holes at the site of well 1, from the nearby 97-foot well drilled in 1948, and during the final development of well 1, the water levels in the vicinity of well 1 were never in a state of equilibrium during the period of observation including the 3-day period of complete shut-in prior to beginning the test. The lack of an equilibrium condition introduced some disturbing factors into the

interpretation of the pumping test, although none of these seem to be of a critical nature. Inasmuch as all discharge from the wells passed the gaging station at the lower end of the valley, the stream-flow at that point was augmented by the irregular flow from the wells. Hence the streamflow record does not represent a natural condition, and any effect of the well discharge upon the springs at the lower end of the valley is obscured by the lack of a previous equilibrium record of discharge at the gage.

Well 1 discharged both by natural flow and pumping at greatly varying rates from September 15 to September 27 as shown on plate 2. The pressure changes in the aquifer caused by this discharge probably affected the pumping test more than other prepumping test discharge. The discharge from the two unsuccessful wells drilled prior to completion of well 1 probably had little effect on the pumping test. The 35 gpm flow from the 97-foot well drilled in 1948 at the site of well 1 was stopped on September 20, 1949, by plugging the well. Residual pressure disturbances in the aquifer caused by the long term discharge from this well probably had only minor effects on the pumping test.

METHOD OF CONDUCTING TEST

Well 1 was shut in completely at 12:03 p. m., October 7, 1949. From 10:32 a. m., on October 10 until 10:35 a. m., October 13, the well was allowed to discharge by artesian flow. The flow was maintained at a constant rate of 1,000 gpm by adjustments of the valve controlling the flow. Only minor adjustments of the valve were necessary to maintain this flow and even at the conclusion of the test the well would have flowed at a larger rate had it been desired. The flow was measured by means of the pressure read in a water manometer tapped into the 8-inch discharge pipe 4 feet upstream from a 6-inch orifice plate installed at the end of the discharge pipe. The pressure in the well was measured by a Bourdon-type pressure gage tapped into the 12-inch casing below the discharge pipe. The change in pressure, indicated on plate 2 for well 1, is greater than the actual reduction in pressure in the well by the small amount of friction head loss caused by the water flowing from various depths to the surface in the 12-inch casing. This loss could not have exceeded 1 foot of head.

The pressures in both the 6-inch and 2-inch casings in wells 2, 3, and 6, and in the 6-inch casing in well 4, were read by means of mercury manometers, graduated to read in feet of water. Due to freezing temperatures every night during the test and also during the day on October 11, a few gallons of water per hour were allowed

to trickle from the wells during these times. It is improbable that this caused a loss of head exceeding the limit of error in measuring the mercury column. The water levels in the 2-inch casing of well 4, and for a time that in the 2-inch casing of well 5, were read by means of a steel tape. During most of the test a recording gage, consisting of a sensitive diaphragm-type gage capable of recording pressure changes with an accuracy equivalent to 0.01 foot of water, was in operation on the 2-inch casing of well 5. The gage was connected to a copper tube, one end of which was connected to a cylinder of carbon dioxide, and the other end of the tube was about 1 foot below water level in the well. A constant movement of carbon dioxide was maintained through the apparatus causing a gas bubble to emerge from the submerged end of the tube at a rate of about 1 bubble per second.

Measurements were made frequently at all wells from the time well 1 was closed in on October 7, preliminary to the test on October 16, to about 3 days after the completion of the flow period of the test. These measurements are given on plate 2.

A gaging station was operated on San Antonio Creek at a site below the springs and downstream from well 1. Records of changes in stage of the streamflow obtained by a water-stage recorder at the gaging station were used to compute a record of flow in the creek before and during the test. Streamflow past the gaging station was from springs that are the natural source of the stream and occasionally from wells. The record of streamflow obtained during the summer of 1949 probably would have been representative of flow before the equilibrium between recharge and discharge if the streamflow had not been disturbed by well discharge and obstructions caused by road construction in that period. The record during the summer was complicated by variations in the discharge from wells during their construction and development. In addition, work being done on road culverts just above the gaging station during the summer resulted in changing the course of the stream and partially damming it for irregular periods.

TEST RESULTS

CHANGES IN GROUND-WATER LEVEL AND STREAMFLOW

The controlled discharge of well 1 at the rate of 1,000 gpm during the 72-hour period of flow produced the following effects:

1. The head in well 1 lowered about 20 feet from its static level, indicating a specific capacity of about 50 gpm per foot of drawdown.

2. The head declined 7.7 feet in the 2-inch casing and 7.5 feet in the 6-inch casing of well 2, which is 302 feet northwest of well 1. The small difference in decline probably indicates a good connection either between the aquifers tapped by the two casings or between the casings.
3. The head declined 8.2 feet in the 2-inch casing and 4.5 feet in the 6-inch casing of well 3, which is 600 feet northwest of well 1. The head reduction in the 2-inch casing of well 3 was greater than that in the 2-inch casing of well 2, which appears anomalous. The water level in the 2-inch casing of well 2 probably does not reflect the true pressure in the aquifer it taps.
4. The head declined 1.1 feet in the 2-inch casing and 1.7 feet in the 6-inch casing of well 6, which is 3,600 feet south of well 1.
5. In the 2-inch casing of well 5, which is 4,100 feet north of well 1, the water level rose slightly after well 1 began to flow on October 7, and was only down 0.03 foot after well 1 had been discharging for 24 hours. It had lowered 0.25 by the time well 1 was closed in and continued to lower to a total of about 0.45 foot, 2 days after well 1 was closed, after which it began to rise.
6. The effects on well 4, which is 4,450 feet downstream from well 1, are not obvious. Neither in the 6-inch casing with water level 30 feet above ground nor in the 2-inch casing with water level about 10 feet below ground was there a significant fall in water level. Frequent water-level measurements in the 2-inch casing during the period of the test and records of water level taken thereafter by the recording gage indicate erratic fluctuations of water level from some unexplained but apparently natural cause.
7. The streamflow during the period October 10–13 as observed from the recording gage and corrected for the discharge from well 1 was 2.3 cfs (cubic feet per second). The flow was also 2.3 cfs for the 2 days following the end of the pumping period after which the streamflow increased to 2.5 cfs and higher. There is some evidence therefore that the natural discharge of the springs of the valley and subsequently the stream probably would have been about 2.6 cfs during the period of the test and that the discharge of the well caused a decrease in the natural flow of the stream of about 0.3 cfs during this period; however, the evidence is inconclusive.

INTERPRETATION OF DISCHARGE TEST

The theory of ground-water movement indicates that the drawdown of the water level or pressure in wells caused by the uniform discharge from a nearby well, plotted against the logarithm of time since discharge began, will form approximately a straight line after

a period of time, depending on the distance the observation well is from the pumped well. Such a straight line plot would result only if the aquifer is continuous and unvarying in character between the wells and for a considerable distance beyond the wells. Further, the plot of the drawdown for all wells should fall on the same straight line if the time factor is modified by dividing the time by the square of the distance between the observation well and the discharging well. The rate of recovery of water levels or pressures follows the same rule. From such plots the aquifer characteristics (transmissibility and storage coefficients) can be computed. Also, to the extent departures from ideal aquifer conditions exist, some inferences concerning these differing conditions can be deduced from the plotted curves.

Plate 3 shows plots of the drawdowns during the period of the 72-hour discharge and of the recovery thereafter for wells 2, 3, 5, and 6. The changes in water pressures in the 2-inch and 6-inch casings of well 2 and 6-inch casing of well 3 follow each other closely. The water pressure in the 2-inch casing of well 3 decreased more in comparable periods of time than did the pressures in the other wells and casings. The water levels in wells close to the discharging well measured at successive intervals after the lapse of a few hours lie upon straight lines, indicating that the lowering of water levels was proceeding at a logarithmic rate as would be expected in an ideal aquifer in which the cone of depression caused by the discharge has not yet spread to the boundaries of the aquifer. The pressures in both the 2-inch and 6-inch casings at well 6 appeared to be following the same pattern of lowering as shown by those in wells 2 and 3. The action of the water in the two casings at well 6 is better shown on the plot of recovery (pl. 3) which ideally should duplicate the curves of drawdown on plate 3, after both curves are corrected for water-level trends prior to the beginning of the discharge period and following the cessation of discharge. During the time of discharge, the water level in neither casing at well 6 had begun to follow a straight line on the figures, indicating that the cone of depression had not extended far beyond well 6.

The plot of water levels in well 5 on plate 3 is short because of the large distance between wells 1 and 5 and does not indicate whether or not the drawdown in well 5 would follow the same pattern as those of wells closer to well 1. The water in well 5 presumably is not artesian and the water level would lower at a slower rate than the pressures in the artesian wells.

The slopes of the drawdown and recovery curves on plate 3 is governed by the rate at which water flows through the parts of the aquifer

with which the wells are in contact. The 2-inch casings in the observation wells were open to the aquifer only by means of a well point near the bottom of the aquifer; the 6-inch casings ended just above the top of the aquifer. As a consequence the water pressures in the 2-inch casings presumably measured the pressures near the bottom of the aquifer and those in the 6-inch casing presumably measured the pressures in the upper part of the aquifer. In well 3, the two parts of the aquifer were apparently separated, but in well 2 the temperature, chemical character, and pressures in the two casings indicated that the hole was connected in general with the entire aquifer. Hence, well 2 apparently indicates approximately a mean pressure in the aquifer, whereas well 3 shows the pressures toward the top of the aquifer in its 6-inch casing and the pressures toward the bottom of the aquifer in its 2-inch casing.

The rate of recovery in well 2 indicated a coefficient of transmissibility for the aquifer as a whole of about 60,000 gpd per ft. The rate of recovery in well 1 (fig. 6) indicated a coefficient of transmissibility of about 50,000 gpd per ft. This well was open through perforations to the full thickness of the aquifer.

The coefficient of transmissibility also can be computed from the drawdowns at the end of the test in pairs of wells involving 1, 2, and 3. The coefficient computed from the drawdown in the 6-inch casings of wells 2 and 3 is about 55,000 gpd per ft; that involving the drawdown in well 1 in combination with the 2-inch in well 2, the 6-inch in well 2, and the 6-inch in well 3, respectively, is in each case about 40,000 gpd per ft; and that involving drawdowns in well 1 and in the 2-inch casing of well 3 is about 45,000 gpd per ft. All methods of computation indicate a figure for transmissibility not far from 50,000 gpd per ft.

The specific capacity of well 1 was about 50 gpm per ft of drawdown. Experience indicates that the specific capacity of a well in many areas is numerically equal to about one-thousandth of the coefficient of transmissibility. Well 1 was constructed and developed to about its optimum point.

The specific capacity and coefficient of transmissibility in the Valle Toledo wells is in apparent agreement with this rule of thumb.

Computations show that with each foot of fall of pressure about 0.005 of a cubic foot of water is released from each vertical column of the aquifer 1 square foot in cross section, or in other words the coefficient of storage of the aquifer is 0.005. Apparently either the pumice of the artesian aquifer is much more compressible than ordinary sand and gravel or there is included in it a good bit of clayey material not recognized in the rotary cuttings.
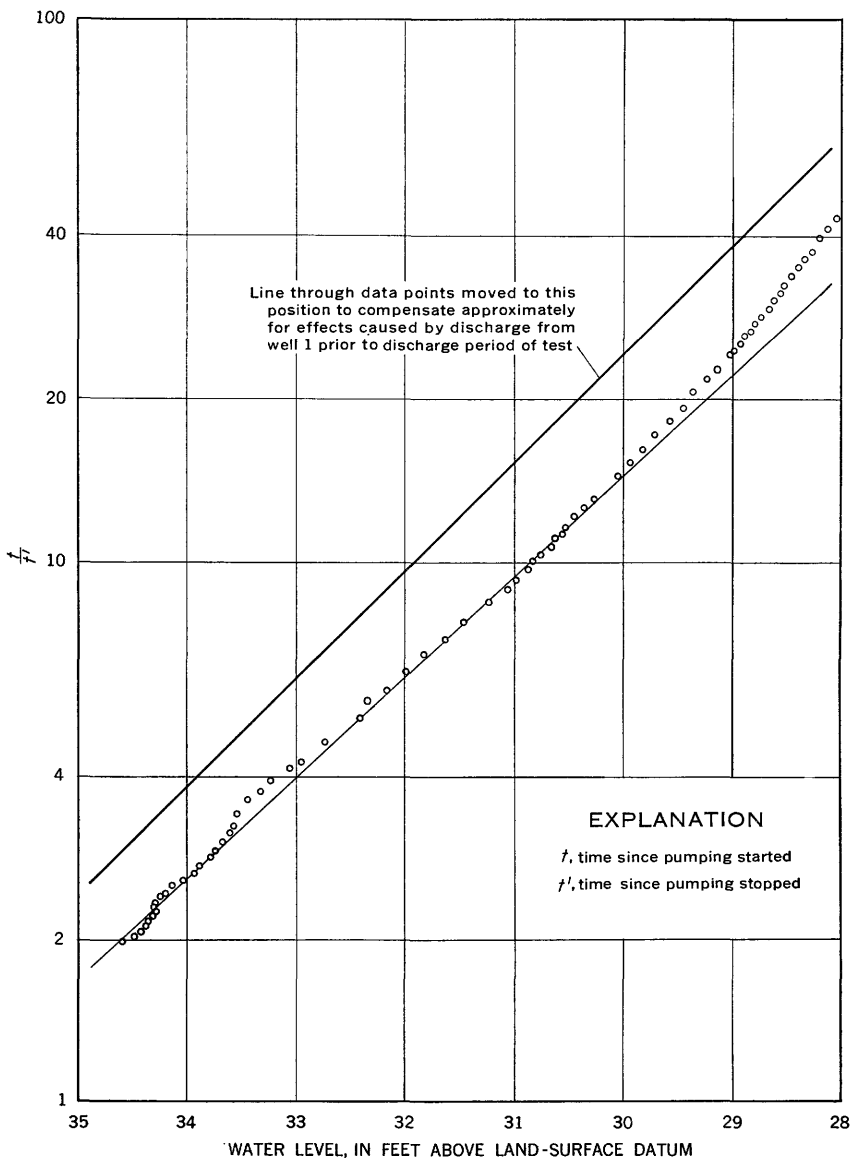
FIGURE 6.—Graphic plot of the water-level recovery in well 1 following the end of a 72-hour discharge period.

PUMPING TEST IN THE VALLE GRANDE

DESCRIPTION OF TEST SITE

Wells 8 and 9 were 300 and 600 feet respectively west of well 7; well 10 was near the junction of Jaramillo Creek and East Fork, about 7,125 feet southwest of well 7; well 11 was on a bench near Jaramillo

Creek, 5,400 feet west of well 7; and well 12 was 3,750 feet east of well 7. Well 18, near the head springs on East Fork, was drilled entirely in rhyolite during Stearns' study in 1948. A Parshall flume with recording gage was installed on East Fork about 1,800 feet north and upstream from well 7, and about 2,000 feet downstream from the springs forming the head of permanent flow of East Fork. The layout of the wells is shown in figure 7.
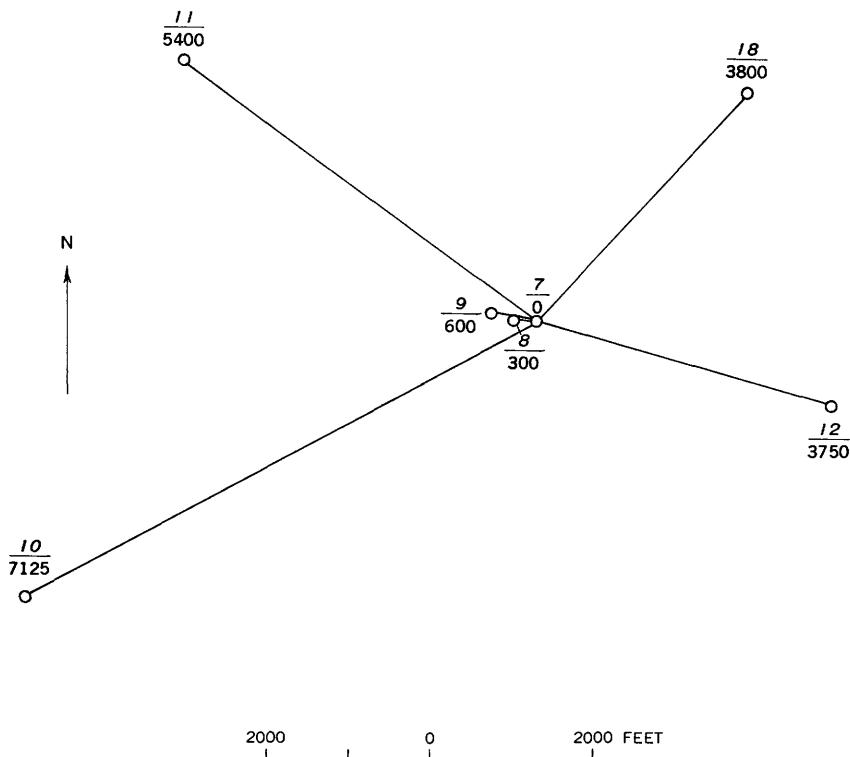
FIGURE 7.—Sketch showing the location of observation wells 8–12 and 18 with respect to well 7 in the Valle Grande, Sandoval County, N. Mex. Figure above line is well number; figure below line is distance, in feet. to well 7.

CONSTRUCTION OF WELLS

The pilot hole at well 7 was drilled to a depth of 1,185 feet without finding solid rock. The production well was drilled by reaming out the pilot hole to a depth of 595 feet. In general, clay was found to a depth of 300 feet and pumiceous sand and gravel occurred below this depth. The water in the sediments was under pressure sufficient to raise it about 10 feet above ground level. A 16-inch casing was cemented from land surface to a depth of 66 feet, and a 12-inch casing was set from 66 feet to 595 feet. The 12-inch casing had five 10-

foot sections of screen set at intervals from 300 feet to the bottom, and the intervening casing was perforated with a torch in slots 4 inches long and about ⅛-inch wide, spaced 4 around the casing at 1-foot intervals along the casing. The well was open to all the water-bearing sediments.

When first cased the well did not flow because of the weight of the drilling mud in the hole. The hole was cleaned and surged with the bailer from October 15 until October 25 and at the end of the period the well flowed about 50 gpm. When the pump was put into the well it produced about 300 gpm with a drawdown of about 300 feet. Attempts were made to clean the screens and perforations by means of a fire-engine pump that forced water into the well and through the screens and perforations into the aquifer. This process increased the production of the well to around 750 gpm with a 300-foot drawdown. However, when the well was pumped for the test it produced 500 gpm with a drawdown of only about 40 feet below the ground or about 50 feet below its static level. This well was not thoroughly developed before the pumping test.

The construction of observation wells in the Valle Grande was about the same in the Valle Toledo. Casing of 6-inch diameter was cemented into clay at depths of 60 to 70 feet and a 2-inch casing with a well point was run into the 6-inch casing to an altitude equal to about that of the bottom of well 7 or to a depth approximately 600 feet, depending on the altitude of the ground surface at the respective holes.

METHOD OF CONDUCTING TEST

Well 7 was shut in at noon, November 3, 1949. Pumping started at the rate of 500 gpm at 10:30 a.m., November 7. The pump broke down at 2:55 a.m., November 9, operated for 12 minutes from 3:30 a.m. until 3:42 a.m., and after repairs, started again at 3:34 p.m. the same day. Pumping stopped at 4:00 p.m., November 11.

During the progress of the pumping test and for 3 days thereafter water levels were measured periodically in both casings of wells 8, 9, and 10 and in the 6-inch casing of well 11. Recording gages measured the water levels in the 2-inch casings of wells 11 and 12. (See pl. 4.) Because water would have frozen at this season if allowed to stand in the exposed parts of the casings of the artesian wells, diesel fuel was pumped into these wells to depress the water level about 10 feet below ground surface. The pressures on these wells were measured with a mercury manometer attached to an air line. Water levels in all wells responded to the pumping of well 7 except that in the 2-inch casing of well 10, to which reference will be made later.

TEST RESULTS
CHANGES IN GROUND-WATER LEVEL AND STREAMFLOW

Plate 4 gives graphically the fluctuations of water level in the wells. The following effects were observed.

1. The water level in well 7 drew down while pumping 500 gpm from a level slightly less than 10 feet above land surface to slightly more than 40 feet below land surface. The specific capacity was therefore almost 10 gpm per foot of drawdown.
2. The 2-inch and 6-inch casings in well 8 were evidently in good connection as the heads in both were about equal at all times. The pressure in the 2-inch casing decreased about 8.2 feet and that in the 6-inch casing 8.3 feet during the pumping.
3. The pressure in the 2-inch casing of well 9 decreased 4.6 feet during the pumping and that in the 6-inch casing 5.4 feet.
4. The pressure in the 6-inch casing of well 10 showed no distinguishable change during the pumping. The pressure in the 2-inch casing in this well gave erratic readings. It is not certain whether this well was poorly cleaned or if erratic fluctuations occur in it similar to those in the 2-inch casing of well 4 of the Valle Toledo test. At any rate there were no discernible fluctuations caused by the test pumping.
5. The water levels in the 2-inch casings of wells 11 and 12, and to a less distinct extent in the 6-inch casing of well 11, rose during the period of pumping and fell at its conclusion. This apparently anomalous action is explained by reference to the barometric curve shown on plate 4. Artesian wells act as inverse barometers, rising during periods of falling air pressure and falling during periods of rising air pressure. The barometric curve, replotted from the record of a microbarograph near well 1, shows the fluctuation of air pressure expressed in feet of water and to an inverted scale in order to make the graph of its fluctuation vary in the same direction as the induced fluctuations in the wells. The barometer began to fall rapidly a few hours after the start of pumping, maintained an unusually low pressure throughout the period, and began to rise a few hours after the end of the test. The ratio of the rise of water levels in artesian wells to the fall of a water barometer varies considerably in different aquifers and can be determined only by accurate records of fairly long duration when the aquifer is undisturbed. The record of water levels in the 2-inch casings of wells 11 and 12 indicate either a small drawdown or none at all.

6. The graph of well 18 shows the record of water level in the rhyolite near the springs at the head of East Fork. No significant fluctuations of water level took place in this well.

7. The gage on East Fork was upstream from well 7, and hence, the discharge from the well did not pass the gage. The gage showed clearly a decrease in streamflow while the well was pumping. Upon initially starting the pump the recording gage almost immediately showed that the streamflow began to decrease and continued to do so, until the pump broke down. The breakdown of the pump on November 9, 1949, unfortunate in many respects, helped to verify this indication. During the interval of pumping the stage in the Parshall flume fell 0.04 foot from 0.40 to 0.36 foot. During the approximately 12-hour period while repairs were being made to the pump engine, the stage in the flume rose to 0.38 foot. During the second period of pumping the stage dropped to 0.35 foot. It began to rise immediately on cessation of pumping. The flow of the stream before pumping began was constant at 1.9 cfs but diminished to an average of 1.6 cfs on the day of least flow during the pumping. Three days after the conpletion of the test the flow had increased to 2.0 cfs. Any effect that the change of barometric pressure may have had on the flow of the springs feeding the stream would have been to increase the streamflow during the period of pumping.

INTERPRETATION OF PUMPING TEST

The drawdown and recovery of water levels in the observation wells during the pumping test did not proceed in the expected manner, largely because of the interruption owing to pump failure. Plate 3 represents a graph of recovery of water levels in the wells.

The curves shown on this graph do not display the same regularity as those from data obtained from the Valle Toledo test. The water levels in wells 8 and 9, respectively 300 and 600 feet from the pumping well, were not falling in accord with the theory of a simple extensive aquifer. The graphs do not approach distinct straight lines. The slope of the graphs increases with time, whereas the effect of the increase in spring flow, as shown by records of the gaging station during the period of recovery, was undoubtedly in the opposite direction. Although the interruption in the pumping phase of the test makes interpretation questionable, the increase in slope indicates a boundary in some part of the aquifer that affected the cone of depression. The increase in slope of the graph could indicate one or both of the following boundaries—thinning of the aquifer or a nearby zone of low permeability within the aquifer. Thinning of the

aquifer could be caused either by a thickening of the overlying clay or a decrease in depth to the buried rhyolite domes forming the bedrock. A zone of low permeability could be caused by a greater percentage of fine material, maybe clay, in the pumiceous sand and gravel. Data are insufficient to reach a definite conclusion as to the true nature of the boundary.

If it is assumed that the curves of plate 3 are approaching tangents, the coefficients of transmissibility computed from their slopes are about 30,000 gpd per ft. for the 2-inch casing in well 8; about 27,000 gpd per ft. for the 6-inch casing in well 8; about 45,000 gpd per ft. for the 2-inch casing in well 9; and about 18,000 gpd per ft. for the 6-inch casing in well 9. If the slopes of the graphs for the two casings in well 9 are averaged, under the assumption that the average change in pressure in the aquifer would be represented by this average, the computed coefficient of transmissibility is about 26,000 gpd per ft. From the drawdowns in the 2-inch casings of wells 8 and 9 the computed coefficient is about 23,000 gpd per ft. and from the drawdowns in the 6-inch casings of these wells, about 28,000 gpd per ft.

Figure 8 shows the recovery of water level in well 7. The slope of the line indicates a coefficient of transmissibility of about 70,000 gpd per ft. This higher value is probably related to the greater depth of aquifer opened up by the pilot hole in this well, which extended to 1,185 feet. This higher value, however, should be considered as preliminary only, and probably would have to be revised if the graph could be adjusted to compensate for all factors affecting the changes in water level during the test. Inasmuch as all the implications of the stoppage of the pump during the test and the effects of boundaries in the aquifer have not been worked out, the aberrant character of the recovery curve may be due to the effects of one of these.

The coefficient of transmissibility of the Valle Grande aquifer is conservatively estimated to be at least 25,000 gpd per ft. The specific capacity of well 7 was about 10 gpm per foot of drawdown during the pumping test. Before the test it showed a specific capacity of less than 3 gpm per foot of drawdown, producing about 750 gpm with a drawdown of 300 feet. Well 7 was not developed fully, therefore the rule of thumb that the specific capacity is equal numerically to one-thousandth of the coefficient of transmissibility cannot be applied to this well. Although the transmissibility of the aquifer in the Valle Grande probably is less than that of the Valle Toledo, the aquifer will yield more water to a well per foot of drawdown than that indicated by well 7. Either there were not enough effec-
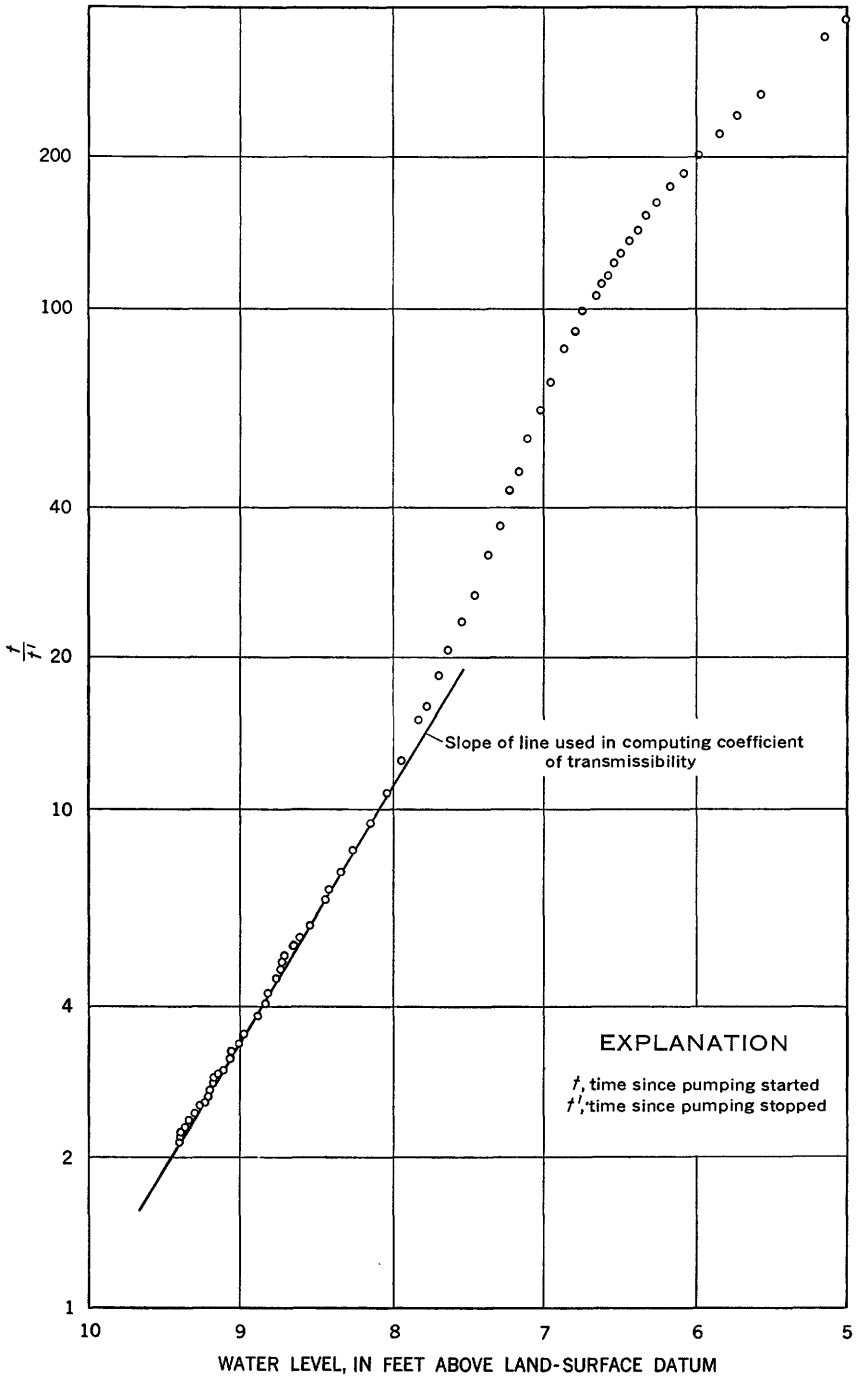
FIGURE 8.—Graphic plot of water-level recovery in well 7 following the end of about 90 hours of pumping.

tive openings in the casing of well 7, or as seems more probable to the writers, the pumice aquifers of this region, which are a rarity among aquifers and about which practically nothing is known, require a type of development to be learned only by experiment. The character of the aquifer may be such that the development method used actually closed some of the openings.

PROBABLE EFFECTS OF DISCHARGE BY WELLS

Any discharge by wells in the Valle Toledo and the Valle Grande is a new discharge superimposed upon a previously approximately stable hydraulic system in which recharge and natural discharge are by and large in balance. Hence, the well discharge must be balanced by an increase in recharge, a decrease in natural discharge, a loss of storage, or a combination of these.

In the Valle Toledo and the Valle Grande, recharge takes place by infiltration of rain and snowmelt on some of the mountain slopes, which are in part blocky and porous, and on the alluvial fans and upper parts of the benches bordering them. Recharge under natural conditions is impossible in the parts of the valleys where flowing wells and artesian springs are present because the water pressure increases with depth, thus the movement of water would be upward from depth. It is doubtful if much water can join the main water body in the areas where thick clays underlie the surface such as were found throughout the area in which drill holes were put down in both the Valle Grande and the Valle Toledo.

In well 11 in the Valle Grande, the water level is about 8 feet below the land surface in the 6-inch casing and about 16 feet below the surface in the 2-inch casing (fig. 7). Here it would be possible for water to percolate with difficulty from the upper water body to the lower, and it might be possible to increase the rate of percolation by lowering the water pressure in the lower part of the aquifer by pumping in the valley. If this occurred it might be possible that more recharge would be received into the additional storage space caused by lowering the water table. However, inasmuch as the water level in the 2-inch casing of well 10 is only about 4 feet lower than in the 2-inch casing of well 9 although the surface altitude is about 15 feet lower than that in the 2-inch casing of well 9 and as the artesian pressure surface is almost flat westward from well 7, it appears that the clay cap is quite impervious and that very little more movement could be induced through it by increasing the difference in pressure above and below it.

In well 5 in the Valle Toledo the water level is 70 feet below the surface. The space above the water table is doubtless more than

sufficient to receive the available recharge at times of snowmelt or heavy rainfall and a lowering of the water table would not cause an increased amount of recharge. It appears, therefore, that a lowering of the water table would not cause an increased amount of recharge. It appears, therefore, that a lowering of the water table would induce little or no additional recharge in either valley.

It appears that the amount of recharge is dependent upon the amount of precipitation and upon the rate at which water can percolate from the surface into the ground before it runs off. More opportunity for study is needed than has been available as yet but it also appears that in view of the extremely low temperatures of the area the ground probably freezes to such a depth that the snow in large part melts and runs off before the ground thaws sufficiently to take a great deal of infiltration. Perhaps artificial works can increase the amount of infiltration, but in the light of knowledge of the area gained in this study, it does not appear that any lowering of the water table will induce greater recharge.

Natural discharge takes place obviously through the springs at the lower end of the Valle Toledo and at the upper end of the Valle Grande and by seepage into the streams, as shown especially by the pickup of San Antonio Creek above the big springs at the lower end of the Valle Toledo. Aside from these discharges there are also some high level seeps and springs. A prominent seep zone, marked by greener grass, runs almost the full length of the Valle Toledo and is above a clay layer in the escarpment of the bench about 30 feet above the creek. The zone of greener grass is about 10 feet wide, and in view of the relatively high rainfall of the area probably represents a discharge of not more than 4 or 5 acre-feet a year—about a day's flow of the creek. Small springs are found probably as much as 100 feet above San Antonio Creek and East Fork. Marshy zones are found at all elevations. These are especially numerous in the early summer. It is not known whether these high-level seeps and springs represent discharge from the main water body or the discharge from minor water bodies perched above clay zones. If from perched bodies, they would not be affected by well discharge. If they are discharged from the main water body, presumably pumping would dry them up, but they do not seem to represent any large amount of water to help balance the discharge from a well.

Apparently, therefore, the amount of water available perennially to wells in the valleys is the amount of water issuing from the springs. This amounted rather constantly during the period June to November 1949 to about 2.3 cfs at the lower end of the Valle Toledo and to 1.9 cfs at the gaging station on the East Fork in the Valle Grande. Probably a somewhat larger flow occurs at the lower end of the Valle

Grande as the East Fork was gaged at 3.2 cfs, on June 28, 1948, just below the mouth of Jaramillo Creek. It appears, therefore, a perennial supply of about 750 million gallons, about 2,200 acre-feet, a year is available in the Valle Grande and about 540 million gallons a year or about 1,600 acre-feet in the Valle Toledo. These estimates are subject to some change when longer records of flow of the creeks are available.

The amount of water in storage is large, although the available data are not sufficient to make more than a rough estimate. To make a better estimate would require a knowledge of the porosity of the materials in the fans and benches into which only 2 or 3 holes have been drilled, which being rotary holes produced no samples from which the porosity could be figured. It also would require a knowledge of the shape of the bedrock floor on which the water-bearing materials have been laid down, which is probably very irregular because of the presence of domes and flows of lava. Conservatively the specific yield of the valley materials can be taken as 10 percent. The area of the Valle Toledo underlain by talus, fans, and lake sediments is about 3 square miles. A general lowering of the water level in this valley of 100 feet should therefore provide nearly 20,000 acre-feet of water from storage alone. The area of the Valle Grande is about double that of the Valle Toledo, but the thick clay bed near the surface over much of the valley reduces the effective volume of the upper part of the aquifer so that the specific yield might on the average be about 5 percent. The amount of water available by drawing the water level down 100 feet probably then would be about the same as that in the Valle Toledo.

Assuming that the average perennial use of water from the Valle Grande and the Valle Toledo does not exceed in either valley the average natural discharge from that valley the effects of the pumping would be approximately as follows: At the beginning of use of water the creeks would be flowing at about their usual rate. Water levels in the producing wells would lower with continued pumping and considerable water would be taken from storage. Concomitantly the flow of the creek would begin to diminish, probably becoming perceptible only after a lag of some time in the Valle Toledo, (probably in a week or two) and practically immediately in the Valle Grande; assuming the wells were approximately in the positions of the producing test wells. The decrease in the streamflow would proceed at a diminishing rate as more and more water was withdrawn from storage. It is probable that the springs in the Valle Toledo would not completely dry up for a decade if the producing wells were in about the location of well 1 and produced on the average no more water than the present flow of the springs, although factors that

cannot be known until more exploration and probably more pumping are done might cause a more rapid decrease in spring flow. In the Valle Grande the flow from the springs at the head of East Fork probably would decrease much more rapidly, but the seeps feeding Jaramillo Creek probably would not be dried up for a decade or longer by wells near well 7.

Still assuming that the pumpage from neither valley exceeded the present spring flow from that valley, the new hydraulic system would approach approximate equilibrium after the probable lapse of some years. When this equilibrium is reached, the yearly high water levels would be lowered permanently about 40 to 50 feet below the prepumping level in the Valle Toledo. During the heavy summer pumping season, the chief springs would be expected to be completely dry and remain so for months at least after the pumping rate had been reduced. If precipatation is above normal during the year the springs might or might not begin to flow weakly in the spring of the year.

If the withdrawals exceeded the natural flow of the springs in either valley the water levels would lower progressively and without limit. The effect upon the annual discharge of the streams would be limited to that contributed as the natural flow of the springs, and would not deplete that contributed as runoff. Additional water pumped would be withdrawn from storage.

QUALITY OF WATER

The waters from both the Valle Toledo and the Valle Grande are low in total dissolved solids although high in silica content (table 1). The calcium and magnesium content is quite low and the water is soft.

One drawback to the use of any of the waters of the Valle Toledo as a source of municipal supply is the relatively high fluoride content. A maximum allowable concentration of fluoride of 1.5 ppm (parts per million) in drinking water on common carriers used in interstate traffic was set by the U.S. Public Health Service (1946). The water would require treatment to reduce the fluoride content to this limit. The fluoride content increases with depth. It was 0.6 ppm in the 97-foot well drilled in 1948 at the site of well 1 and 3.6 ppm in well 1 when it was discharging only from near the bottom of the aquifer. The samples from the observation wells probably were not as dependable as those from the previously mentioned wells, inasmuch as the observation wells were not allowed to flow for extended periods, but fluoride concentrations in these waters ranged from 3.6 ppm in the 2-inch casings of wells 2 and 3 to 1.6 ppm in the 6-inch casing of well 6. The average flouride content of the waters of the Valle Toledo prob-

ably is somewhere between that found in the water discharged from well 1, after the well had been perforated and opened to all water-bearing beds in the aquifer, and that found in the water discharged naturally at the lower end of the valley. The fluoride content of the discharge from well 1 after perforation was 2.4 ppm; that from one of the springs at the lower end of the valley ranged from 1.8 to 2.4 ppm, and that of the creek water at the gaging station, largely spring discharge, was 1.8 ppm on August 23.

TABLE 1.—*Partial analyses of water from the Valle Toledo and the Valle Grande*

[Analytical results in parts per million]

Sampling point	Date of collection	Silica (SiO$_2$)	Fluoride (F)	Dissolved solids	Hardness as CaCO$_3$
Valle Toledo:	*1949*				
Well drilled in 1948 at site of well 1, depth 97 ft__	July 6	62	0.6	105	18
Well 1, before casing was perforated and while drawing water only through screens between 383 and 427 ft_____	Sept. 20	57	3.6	111	26
Well 1, after casing perforated at practically all horizons_____	Oct. 6	57	2.4	108	26
Well 1, after discharge test_____	Oct. 16	52	2.4	104	24
Spring discharging through rhyolite at lower end of Valle Toledo_____	{July 6	55	2.4	98	18
	{Oct. 16	57	1.8	105	27
San Antonio Creek at gaging station in Valle Toledo_____	Aug. 23	57	1.8	101	23
Valle Grande:					
Well 7, during pumping test_____	Nov. 11	72	.4	125	19
Well 8, 2-in. casing_____	Oct. 26	70	.4	142	36
Well 9, 2-in. casing_____	Oct. 26	66	.4	136	26
Well 9, 6-in. casing_____	Oct. 26	74	.6	142	24
Well 10, 2-in. casing_____	Oct. 26	44	.8	154	96
Well 10, 6-in. casing_____	Oct. 26	75	.2	165	42
East Fork at gaging station near well 7_____	{July 21	54	.8	104	26
	{Aug. 23	59	.7	104	20

The water from the Valle Grande is low in fluoride content, ranging from 0.2 to 0.8 ppm in available samples from wells. The fluoride content was 0.4 ppm in a sample taken from well 7 during the pumping test. Results of the chemical analyses of water collected at the gaging station near well 7 from the natural discharge springs for the Valle Grande was 0.7–0.8 ppm.

CONCLUSIONS

The consolidated rocks of the caldera area including the Valle Grande and the Valle Toledo are igneous and are middle(?) Miocene and younger in age. Except the blocky and frothy crust of the rhyolite domes in the caldera, the igneous rocks are considered to be non-waterbearing.

The unconsolidated rocks of the area are clay and pumiceous sand and gravel that compose the caldera fill. The maximum thickness of the caldera fill is unknown, but a test hole in the Valle Grande penetrated 1,185 feet without reaching bedrock.

The principal aquifer in the area is the pumiceous sand and gravel in which water is confined under pressure. The overlying confining bed is a clay zone as much as 295 feet thick in the Valle Grande and about 80 feet thick in the Valle Toledo.

The coefficient of transmissibility of the caldera fill aquifer is at least 25,000 gpd per ft in the Valle Grande and about 50,000 gpd per ft in the Valle Toledo. Wells yielding 1,000 gpm can be developed in the caldera fill; the specific capacity of such wells can be expected to be about 25 and 50 gpm per ft of drawdown in the Valle Grande and the Valle Toledo respectively.

The amount of water that would be available perennially to wells in the Valle Grande and the Valle Toledo without continuous draft from storage would be equivalent to the amount issuing from springs in these valleys. This would amount to about 2,200 acre-feet a year from the Valle Grande and about 1,600 acre-feet a year from the Valle Toledo.

Pumping of wells and transporting the water to Los Alamos would deplete the flow of San Antonio Creek and East Fork and would interfere with surface-water rights on those streams.

The waters from both the Valle Grande and the Valle Toledo are low in total dissolved solids but high in silica content. The water is soft. Water in the Valle Toledo is relatively high in fluoride content, and for municipal use it should be mixed with water of low fluoride content to obtain 1.5 ppm or less concentration of fluoride.

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