Availability of Fresh and Slightly Saline Ground Water in the Basins of Westernmost Texas

U.S. GEOLOGICAL SURVEY

Open-File Report 78-663

Prepared in cooperation with the Texas Department of Water Resources

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By Joseph S. Gates, Donald E. White, W. D. Stanley, and Hans D. Ackermann

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AVAILABILITY OF FRESH AND SLIGHTLY SALINE GROUND WATER IN THE BASINS OF WESTERNMOST TEXAS

By

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ABSTRACT

A study of the availability of fresh and slightly saline ground water in the basins of westernmost Texas was conducted in three phases: (1) The collection of hydrologic data; (2) a series of geophysical surveys; and (3) a program of test-hole drilling. The first phase included an inventory of wells and springs, measurements of water levels in wells, and chemical analyses of water samples.

The second phase consisted of the compilation of available gravity data and conducting earth-resistivity, airborne-electromagnetic, seismic-refraction, and aeromagnetic surveys. Earth resistivity was the principal geophysical technique employed, and these data were used in estimating the thickness and lithology of the basin fill and the quality of the ground water. Airborne-electromagnetic data were used in estimating the lithology of the fill and the quality of water at shallow depths. Seismic, aeromagnetic, and gravity data were used to supplement other data in estimating the thickness of the fill.

The third phase included the drilling of four test holes to depths of 1,100 to 2,000 feet (335 to 610 meters). The test holes were logged by borehole-geophysical methods and water samples were collected at selected depths.

Significant quantities of fresh ground water occur in the basin fill of the northern Hueco bolson and lower Mesilla Valley and in the Wildhorse Flat, Michigan Flat, Lobo Flat, and Ryan Flat areas of the Salt Basin; and may occur in Red Light Draw, Presidio bolson, and Green River Valley. The areas in which freshwater occurs are usually the areas in which the fill is coarse grained and near the zones of recharge. More than 20 million acre-feet (25 cubic kilometers) of freshwater is estimated to be in storage in the basin fill of westernmost Texas; more than half of which, or about 12 million acre-feet (15 cubic kilometers), is in El Paso County in the Hueco bolson and Mesilla Valley.

In addition, the basins contain about 7 million acre-feet (8.6 cubic kilometers) of slightly saline water in the basin fill, in the Rio Grande alluvium in the Hueco bolson and lower Mesilla Valley, and in the Capitan Limestone in the northern Salt Basin. Additional amounts of slightly to moderately saline and poorer quality water occur in the fine-grained basin fill and in the Rio Grande alluvium.

Ground-water pumping for municipal supply and industrial use in the El Paso area caused water-level declines of as much as 95 feet (29 meters) during 1903-76, and pumping for irrigation in the Salt Basin caused a maximum decline of 150 feet (46 meters) at Lobo Flat during 1949-73. Additional development of ground water in westernmost Texas will be accompanied by further declines in water levels, and will probably induce local migration of slightly saline or poorer quality water into freshwater areas. Land-surface subsidence could occur in local areas where water-level declines are large and the basin fill contains large amounts of compressible clay.

INTRODUCTION

Purpose and Scope of the Investigation

From September 1971 through 1975, the U.S. Geological Survey conducted a study to delineate the ground-water reserves in the basins of westernmost Texas, west of the drainage area of the Pecos River and northwest of the Big Bend country. The areas included in this investigation are shown on figure 1.

This study was made in cooperation with the Texas Department of Water Resources (formerly Texas Water Development Board) and was designed to provide the department with data for its continuing assessment of water availability within the State. The study was part of the Rio Grande Regional Environmental Project (RGREP), which was designed to evaluate the water, land, and economic resources of westernmost Texas and south-central New Mexico. The U.S. Bureau of Reclamation is the coordinator of RGREP, but the activities involve other federal agencies, State and local agencies, and the Universities of Texas and New Mexico. The Geological Survey was concerned mainly with the reserves of fresh and slightly saline ground water stored in the alluvial fill of the basins. Water stored in consolidated rocks or in alluvial fill of low permeability was not studied in detail, and the occurrence of moderately saline or poorer quality water was not investigated.

The basins included in the study were, from east to west: (1) The United States part of the Presidio bolson; (2) the Salt Basin south of the Texas-New Mexico State line; (3) the Green River Valley (designated as Glenn Creek on some older maps); (4) Eagle Flat; (5) Red Light Draw (designated as Quitman Arroyo on older maps); (6) the Texas part of the Hueco bolson (which includes the city of El Paso); and (7) the Mesilla Valley south of the Texas-New Mexico State line (the lower Mesilla Valley). Comprehensive field investigations were conducted in the first five basins; the northern Hueco bolson was evaluated by using previous reports, and the southeastern Hueco bolson and lower Mesilla Valley were evaluated by using previous reports and geophysical surveys.

Methods of Investigation

Collection of Hydrologic Data

In all basins except the Hueco bolson and the lower Mesilla Valley, major irrigation, municipal, and industrial wells; selected stock and rural-domestic wells; and springs were inventoried. Water samples were collected from representative wells and springs for chemical analyses, and pumpage was estimated for the major irrigated areas. These data were compiled by White and others (1977). Hydrologic data in progress reports prepared by the U.S. Geological Survey in cooperation with El Paso Water Utilities and the Texas Department of Water Resources such as the most recent by Meyer and Gordon (1972) were used in the study of the northern Hueco bolson. Data compiled by Alvarez and Buckner (1974) were used in the southeastern Hueco bolson, and data compiled by Leggat, Lowry, and Hood (1962) were used in the lower Mesilla Valley.

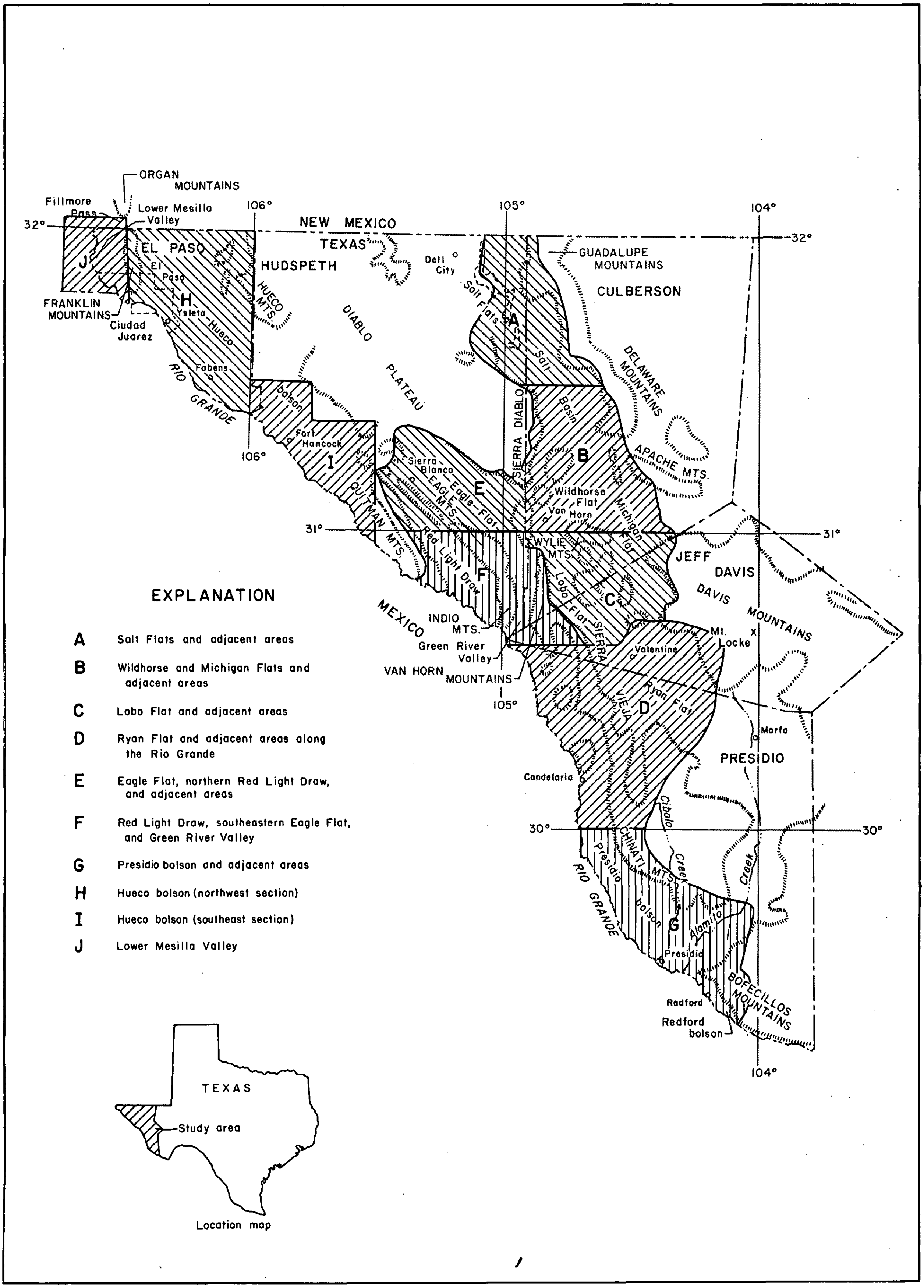

FIGURE 1.-Westernmost Texas and the areas covered by larger-scale maps in this report

Geophysical Surveys

Geophysical surveys were used to estimate the thickness of the basin fill and to obtain information on lithology and the quality of water in the fill. The principal methods used were electrical, including both earth-resistivity and airborne-electromagnetic techniques. Seismic-refraction and aeromagnetic surveys, together with gravity and seismic-reflection data obtained from several oil companies, were also used in estimating the thickness of the basin fill.

The ease with which earth material transmits an electrical current is a function of its resistivity, and resistivity in turn can be related to hydrogeologic properties, including lithology, porosity, permeability, water salinity, and water temperature. Vertical electrical soundings were made at 175 locations in the Salt Basin, Presidio bolson, Eagle Flat, Green River Valley, and Red Light Draw; at 65 locations in the lower Mesilla Valley; and at 67 locations in the southeastern Hueco bolson. Interpretations of the soundings in the Salt Basin and adjacent areas and limited interpretations of the soundings in the lower Mesilla Valley are included in this report; interpretations of soundings in the southeastern Hueco bolson are included in Gates and Stanley (1976).

The Schlumberger electrode array (Zohdy, Eaton, and Mabey, 1974, p. 11), which consists of a four-electrode array to measure voltage distribution for a known input current, was used for the soundings. A sounding consists of (1) applying a voltage to a pair of electrodes (current electrodes), which induces direct-current flow and an electrical field in the earth; and (2) measuring the resulting voltage at a second pair of electrodes (potential electrodes). A succession of measurements are made with the current-electrode spacing increased for each measurement, from a minimum of about 20 feet (6 m) to as much as 24,000 feet (7,300 m). Resistivities for each spacing are computed from formulas derived for the electrode geometry.

Earth resistivities as a function of depth are derived from the sounding curve with the aid of digital-computer programs (Zohdy, 1975). Maximum electrode half-spacings for these surveys commonly ranged from 4,000 to 8,000 feet (1,200 to 2,400 m), with a few ranging up to 12,000 feet (3,700 m). The depth of investigation was from about 1,500 to more than 5,000 feet (450 to more than 1,500 m). The 175 soundings in the Salt Basin and adjacent areas were along 19 profiles and at 20 off-profile locations. Cross sections have been prepared to show the interpreted resistivities for each of the sounding profiles and the individual sounding locations are shown on the appropriate illustrations.

The airborne-electromagnetic surveys were made in the southeastern Hueco bolson (Gates and Stanley, 1976) and in the Salt Basin. The survey in the Salt Basin consisted of 24 flight lines, generally east-west and spaced about 2 miles (3 km) apart, between a point about 4 miles (6 km) north of Van Horn and U.S. Highway 62-180 (fig. 4). The surveys were made using the Barringer INPUT (Induced Pulse Transient) system,[1] which consists of a vertical-axis transmitting coil encircling the aircraft and a horizontal-axis receiving coil towed by the aircraft. A repeated, transient, primary magnetic field created by the transmitting coil induces currents in the earth whose magnitudes are a function of earth resistivities. The receiver coil measures the secondary magnetic field resulting from the earth currents and the results are recorded. The INPUT data primarily reflect resistivities to maximum depths of 300 to 400 feet (90 to 120 m).

To aid in estimating the thickness of the alluvial fill, seismic-refraction surveys were made along four resistivity profiles. Ammonium nitrate-dynamite shots, placed in holes augered to depths of 20 to 70 feet (6 to 21 m), provided energy for the surveys. Four spreads were shot along two lines near resistivity profile A-A' east of the Salt Flats; three spreads were shot along resistivity profile C-C' north of Wildhorse Flat; four spreads were shot along resistivity profile F-F' across Ryan Flat; and three spreads were shot along resistivity profile M-M' across Red Light Draw. The velocity profiles and interpretations of these surveys and the individual shotpoints are shown on the appropriate illustrations.

Aeromagnetic surveys were made over the Salt Basin and adjacent areas, the southeastern Hueco bolson, and the lower Mesilla Valley. The data were used to construct maps of magnetic intensity, which aided in estimating the thickness of alluvial fill. Several oil companies contributed gravity data that were compiled into a generalized gravity map of the Salt Basin and adjacent areas. This map also aided in estimating the thickness of the fill.

Test Drilling

The final phase of the investigation was a test-drilling program to determine the thickness of the alluvial fill and the quality of water at various depths in selected areas and to aid in the interpretation of geophysical data. The drilling sites were selected in areas (1) where geophysical and available ground-water data indicated significant thicknesses of fill saturated with freshwater, (2) where ground-water data were sparse, and (3) where future development of ground water is likely to occur.

On the basis of these criteria, test holes were drilled at four sites with the highest priority--Leopold Guerra No. 1 in Red Light Draw, 20 miles (32 km) southeast of Sierra Blanca; Clay Evans No. 1 on Ryan Flat, 5 miles (8 km) south of Valentine; Culberson County Airport No. 1 on Wildhorse Flat, 4 miles (6 km) northeast of Van Horn; and J. C. Davis No. 1 on Eagle Flat, 10 miles (16 km) southwest of Van Horn. At each test hole, samples of drill cuttings were collected, borehole geophysical logs were made, and water samples were collected from specific zones. Gates and White (1976) summarized the test-drilling program and presented an analysis of the data.

[1] The use of brand names in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

Previous and Related Investigations

Several reports have been prepared as a part of this investigation. White and others (1977) compiled the hydrologic data, and Gates and White (1976) summarized results of the test-drilling program. Gates and Stanley (1976) interpreted the geophysical data in the southeastern Hueco bolson in terms of the hydrology. Zohdy, Bisdorf, and Gates (1976) compiled the earth-resistivity data collected in the lower Mesilla Valley.

Several reports have been prepared on other investigations of ground water in westernmost Texas, mostly by the Geological Survey in cooperation with the Texas Department of Water Resources and its predecessor agencies. Hood and Scalapino (1951) summarized ground-water conditions at Lobo Flat, and Scalapino (1950) discussed ground water in the consolidated rocks in the Dell City area, west of the Salt Flats. Davis and Gordon (1970) prepared the most recent of a series of compilations of ground-water data for the Salt Basin and adjacent areas.

Meyer and Gordon (1972) prepared the most recent of a series of progress reports for the northern Hueco bolson, which contains compilations of data and discusses development of ground water in the El Paso area. Meyer (1976) prepared the most recent of a number of reports that interpret the hydrology of the El Paso area, and Alvarez and Buckner (1974) compiled ground-water data and discussed the water resources of the southeastern Hueco bolson. Leggat, Lowry, and Hood (1962) compiled ground-water data and summarized the hydrology of the lower Mesilla Valley. Davis and Leggat (1965) discussed the general ground-water hydrology of the upper Rio Grande basin, Texas. The study described in this report included the Salt Basin and adjacent areas along the Rio Grande, the Hueco bolson, and the lower Mesilla Valley.

Geography

Topography

The topography of westernmost Texas and adjacent areas in New Mexico and Mexico is characterized by broad structural depressions, locally called "bolsons," "flats," or "basins," filled with alluvium and roughly delineated by isolated fault-block mountain ranges or broad plateaus. The major features along the eastern boundary of the area of investigation include the Guadalupe, Delaware, Apache, Davis, Chinati, and Bofecillos Mountains. The Mexican border along the Rio Grande bounds the study area to the southwest, and the New Mexico State line bounds it to the north. The Diablo Plateau, in the north-central part of the area, was not included in the investigation because it is underlain at shallow depths by consolidated rocks that are not known to contain significant quantities of freshwater.

The major mountain ranges and uplands within the area of investigation include the Sierra Vieja; the Van Horn, Eagle, and Quitman Mountains; the Diablo Plateau, bordered by the Sierra Diablo on the southeast and the Hueco Mountains on the northwest; and the Franklin Mountains. The Salt Basin, which is the major topographic depression on the east side of the area, includes Wildhorse, Lobo, and Ryan Flats, and drains internally into the salt flats in the northern and north-central parts of the basin. Southeastern Eagle Flat drains into the Salt Basin, but the Presidio bolson, Green River Valley, Red Light Draw, and northwestern Eagle Flat all drain to the Rio Grande.

The Hueco bolson drains to the Rio Grande, but for all practical purposes much of the bolson is undrained, and only the incised valley of the Rio Grande (the El Paso Valley) and adjacent areas drain to the river. West of the Franklin Mountains, the Mesilla bolson also drains to the Rio Grande, but only the incised valley of the river (the Mesilla Valley) and adjacent areas actually drain to the river.

Climate

The climate of westernmost Texas is arid to semiarid, with hot summers and mild winters. The average annual precipitation west of the Pecos River drainage area for 1941-70 was 11.57 inches or 294 mm (U.S. Department of Commerce, 1973). In and near the area of investigation, the average annual precipitation at National Weather Service stations ranges from 7.20 inches (183 mm) at Ysleta, now incorporated into southeast El Paso, to 18.74 inches (476 mm) at Mount Locke in the Davis Mountains. In general, precipitation is greater at higher altitudes, and is generally higher in the southeastern part of the area (the Presidio bolson and Ryan Flat) than in the northern Salt Basin and Hueco bolson. Precipitation in the valley areas is about one-tenth of the potential evaporation rate, and agriculture is completely dependent upon irrigation.

Population and Economic Development

El Paso, which is the major commercial center of the area, had an estimated population of about 377,000 in January 1976; and El Paso County had an estimated population of 420,000 (El Paso Department of Planning, Research, and Development, 1976). In 1976, Ciudad Juarez, Mexico, supplied water to about 548,000 persons, and the total population of the city was about 650,000 (as reported in the newspaper El Fronterizo on July 1, 1976, and May 23, 1976).

The economy of El Paso is based on defense establishments (Fort Bliss at El Paso and the White Sands Missile Range nearby in New Mexico), light manufacturing, international and local trade, oil refining, smelting, and irrigated agriculture.

Much of the rest of the area of investigation consists of ranchland, with irrigated farmland along the Rio Grande in the Mesilla, Hueco, and Presidio bolsons, and in the Dell City area, Wildhorse and Michigan Flats, and Lobo Flat. Most of the towns in the area are centers for ranch and farm supplies or are located along and serve users of major highways or railroads. Outside of El Paso County, the area is sparsely populated, with the 1976-77 Texas Almanac and State Industrial Guide (A. H. Belo

Corp., 1975) reporting an estimated population in 1973 of 2,600 for Hudspeth County, 3,500 for Culberson County, 1,400 for Jeff Davis County, and 4,900 for Presidio County.

Terminology for Water-Quality and Resistivity Data

In general, freshwater is defined as water containing less than 1,000 milligram per liter (mg/L) dissolved solids. Slightly saline water contains 1,000 to 3,000 mg/L dissolved solids; moderately saline water contains 3,000 to 10,000 mg/L dissolved solids; very saline water contains 10,000 to 35,000 mg/L dissolved solids; and brine contains more than 35,000 mg/L dissolved solids.

The term "salty" is used in this report in a general or relative sense to describe the chemical quality of water in which the degree of salinity varies or is not known.

In this report, low resistivity is defined as less than 15 ohmmeters; moderate resistivity as 15-60 ohmmeters; and high resistivity as more than 60 ohmmeters. These definitions are applied to data obtained from the earth-resistivity surveys. The terms high and low as applied to the resistivity obtained from airborne-electromagnetic data are relative and do not imply a specific numerical range.

In general, high resistivities indicate consolidated sedimentary or volcanic rock or dry coarse alluvium; moderate resistivities indicate alluvium containing freshwater or indicate volcanic clastics; and low resistivities commonly indicate volcanic tuff or indicate clay, sand, or gravel saturated with slightly saline or poorer quality water.

Metric Conversions

For readers interested in using the metric system, the metric equivalents of U.S. customary units of measurements are given in parentheses. The U.S. customary units used in this report may be converted to metric units by the following factors:

From		Multiply by	To obtain	
Unit	Abbreviation		Unit	Abbreviation
acre	--	0.004047	square kilometer	km^2
acre-foot	--	1,233	cubic meter	m^3
		1.233^{-6}	cubic kilometer	km^3
acre-foot per acre	--	.3048	cubic meter per square meter	m^3/m^2
foot	--	.3048	meter	m
foot per mile	ft/mi	.189	meter per kilometer	m/km
foot per second	ft/s	.3048	meter per second	m/s
gallon per minute	gal/min	.06309	liter per second	L/s
gallon per minute per foot	(gal/min)/ft	.207	liter per second per meter	(L/s)/m
inch	--	25.4	millimeter	mm
mile	--	1.609	kilometer	km
square mile	--	2.590	square kilometer	km^2
square foot per day	ft^2/d	.0929	square meter per day	m^2/d

Acknowledgments

The authors gratefully acknowledge the assistance of the many landowners and leaseholders in El Paso, Hudspeth, Culberson, Jeff Davis, and Presidio Counties who allowed access to their properties to obtain well and spring data, to collect water samples, to conduct earth-resistivity and seismic surveys, and who provided information on wells and ground water.

Several corporations, public agencies, and communities also allowed access to their land and information files, including the Texas Pacific Land Trust, Six-Bar Cattle Co., Faith Cattle Co., King Ranch Co., Two-Bar Land and Cattle Co., Dunham Land, Inc., Longfellow Corp., Atlantic-Richfield Co., Amarex Inc., the General Land Office of the State of Texas, the Texas

State Department of Highways and Public Transportation, the U.S. Bureau of Reclamation, and the towns of Van Horn, Valentine, Presidio, and Sierra Blanca.

The Texas Department of Water Resources and El Paso Water Utilities generously supplied information from their files, and Ed L. Reed and Associates, consulting hydrologists in Midland, Texas, supplied geologic and hydrologic information on the Beacon Hill and Sierra Blanca areas. J. T. Smith of the International Boundary and Water Commission, formerly of the U.S. Geological Survey, collected much of the basic hydrologic data for this study in Red Light Draw, Eagle Flat, Green River Valley, and the Presidio bolson.

GENERAL GEOLOGY

The basins of westernmost Texas are in the southeastern part of the Basin and Range Province, a physiographic and structural unit that extends from western Texas across southern New Mexico and southern Arizona, through Nevada to southeastern Oregon, southern Idaho, and western Utah. In this province, normal faulting of Tertiary and Quaternary age formed alternating structurally high mountain blocks and structurally low basins. The relatively depressed basins, or valley areas, commonly are filled with large thicknesses of unconsolidated alluvial and lacustrine clay, silt, sand, and gravel eroded from the mountain blocks. These deposits are the major sources of ground water in the Basin and Range Province, and in many basins are the only significant sources of water.

The rocks exposed in westernmost Texas, mostly in the mountains and upland areas, range in age from Precambrian to Holocene. Rocks of almost all geologic systems are present, but the rocks of a few systems dominate the stratigraphic sequences at the outcrops and in the shallow subsurface.

Unconsolidated deposits of late Tertiary and Quaternary age fill the basins; and volcanic, volcanic-clastic, and intrusive rocks of Tertiary age crop out over much of the southeastern part of the area, including parts of the Quitman, Eagle, and Van Horn Mountains, and compose most of the Sierra Vieja, the highlands south of the Wylie Mountains, and the Davis, Chinati, and Bofecillos Mountains.

Rocks of Cretaceous age, mostly limestone and sandstone, crop out on the southern Diablo Plateau, between the Davis and Apache Mountains, and in the Van Horn Mountains. Thick sections of these Cretaceous rocks crop out in the Quitman and Indio Mountains and in the mountain ranges in Mexico that form the southwestern border of the Hueco bolson. Rocks of Permian age, mostly limestone, crop out in the Wylie, Apache, Delaware, and Guadalupe Mountains, and on the Diablo Plateau.

The Texas lineament, a prominent structural feature that crosses the area along the northern side of Eagle Flat (Muehlberger and Wiley, 1970), is considered by some geologists as part of a transcontinental fracture zone. At Eagle Flat, the Texas lineament coincides with the boundary between the Diablo Plateau and the Chihuahua Trough, a structurally low area underlain by thick deposits of mostly Cretaceous age.

Volcanic rocks, which may be related to the Texas lineament and which affect the ground-water quality, are common south of Eagle and Wildhorse Flats, while to the north they are rare. Therefore, much of the fill in the basins in the southern part of the area--Lobo and Ryan Flats, Presidio bolson, Red Light Draw, and Green River Valley--is composed of relatively insoluble volcanic rocks. In contrast, the alluvial fill of the Salt Basin north of Van Horn and much of the Hueco bolson includes a greater percentage of limestones and sandstones, which generally contain more soluble minerals. The water-bearing characteristics of the geologic units that yield significant amounts of ground water are summarized in table 1.

GENERAL GROUND-WATER HYDROLOGY

The source of the ground water in westernmost Texas is local precipitation, and to some extent, infiltration from the Rio Grande. Because the annual recharge, other than local recharge from the Rio Grande, is very small, the amount of ground water in storage has accumulated over a long period of time. In the northern Hueco bolson, including areas in New Mexico, Texas, and the Ciudad Juarez area, Mexico, for example, about 20 million acre-feet (25 km^3) of freshwater is stored in the bolson deposits (Meyer, 1976, p. 8, 14). The annual recharge in this area is only about 6,000 acre-feet (7.4 million m^3) or 0.03 percent of the freshwater in storage (Meyer, 1976, p. 18).

Ground-water recharge in the basins of westernmost Texas occurs along the foothills of the mountains and plateaus where the sediments are coarse grained and permeable, and possibly locally along the channels of ephemeral streams in the basins. Recharge probably does not occur unless precipitation is sufficient to cause surface flow through the foothill areas and in the ephemeral streams. Most precipitation in the area is either quickly evaporated or infiltrated to very shallow depths where it is lost by evapotranspiration.

Recharge cannot be estimated accurately over most of westernmost Texas because few data are available on the location of recharge areas and on the amounts of precipitation and streamflow on or above the recharge areas. However, some rough relations between drainage area, precipitation, and recharge can be used to obtain order-of-magnitude estimates. In the northern Hueco bolson, about 1 percent of an assumed annual average precipitation of 10 inches (254 mm) over the 1,200 square miles (3,100 km^2) of drainage area in the United States is about 6,000 acre-feet (7.4 million m^3), which is comparable to Meyer's (1976) estimate.

The drainage area of the Salt Flats at the northern end of the Salt Basin, which includes most of the Diablo Plateau in Texas, the extension of the plateau in New Mexico to the foothills of the Sacramento Mountains,

Table 1.--Water-bearing characteristics of geologic units that are significant sources of ground water

Erathem	System	Unit	Physical and lithologic characteristics	Water-bearing characteristics (Yields to wells are defined as small when less than 50 gal/min, moderate when between 50 and 500 gal/min, and large when greater than 500 gal/min)
CENOZOIC	Quaternary	Rio Grande alluvium and alluvium of tributary streams	Gravel, sand, silt, and clay deposited by the Rio Grande and its tributaries; may be as much 200 feet thick at some locations.	Supplies moderate to large quantities of fresh to moderately saline water in the Rio Grande Valley in the Mesilla, Hueco, and Presidio bolsons, at the lower ends of Red Light Draw and Green River Valley, and between Green River Valley and the Presidio bolson; alluvium of tributary streams is commonly unsaturated in many basins but supplies small amounts of freshwater for domestic and stock use in the Presidio bolson and near the Rio Grande in other basins.
	Quaternary and Tertiary	Bolson deposits	Clay, silt, sand, and gravel deposited by the ancestral Rio Grande or streams local to individual basins; commonly 1,000 to as much as 9,000 feet thick (in the Hueco bolson).	Principal freshwater aquifer in westernmost Texas; supplies moderate to large quantities of fresh to slightly saline water in basin areas; contains moderately saline or poorer quality water at depth in the Hueco bolson and in parts of the Hueco, Mesilla, and Presidio bolsons and the Salt Basin, mostly in fine-grained lacustrine and alluvial deposits.
	Tertiary	Volcanic-clastic and volcanic deposits	Reworked tuffs and alluvial deposits consisting almost exclusively of volcanic debris (volcanic clastics) interbedded with ash-fall tuffs and volcanic flows or ash-flow tuffs; up to 6,000 feet thick at Ryan Flat.	Supplies small to large quantities of freshwater in Ryan and Lobo Flats; probably occurs at depth in Red Light Draw, Green River Valley and southeastern Presidio bolson; permeable zones probably most common in the uppermost 1,000 feet and may include well-reworked tuff, well-sorted volcanic clastics, weathered zones above and below volcanic flows, and possibly fractured volcanic-flow rocks.
MESOZOIC	Cretaceous	Limestones, undifferentiated, but including the Campagrande Formation, Bluff Mesa Limestone, and Yucca Formation; and the Cox Sandstone	Limestone units include beds of marl, sandstone, conglomerate, siltstone, and shale, and locally aggregate more than 5,000 feet in thickness; Cox Sandstone is mostly quartz sandstone with some pebble conglomerate and siltstone, shale and limestone; very fine- to medium-grained; commonly less than 200 feet thick, but can be as thick as 700 feet.	Limestones supply small to moderate quantities of fresh to moderately saline water in the Sierra Blanca area; Cox Sandstone supplies small to moderate quantities of fresh to moderately saline water in the southeastern Hueco bolson, the Sierra Blanca area, and eastern Wildhorse Flat.
PALEOZOIC	Permian	Limestones, including the Capitan Limestone, the Goat Seep Limestone, and the Bone Spring and Victorio Peak Limestones, undifferentiated; and sandstones, including the Delaware Mountain Group	Capitan and Goat Seep Limestones are massive, thick-bedded reef limestone and dolomite; Capitan is 1,000-2,000 feet in the Guadalupe Mountains and Beacon Hill area and up to 900 feet thick in Apache Mountains area; the Goat Seep is up to 1,200 feet thick in the Guadalupe Mountains area; the Bone Spring and Victorio Peak Limestones are limestone and dolomite with sandstone and siltstone, aggregate thickness 1,800 to more than 3,000 feet; the Delaware Mountain Group is sandstone and limestone with some siltstone, aggregate thickness is on the order of 3,000 feet.	Capitan and Goat Seep Limestones supply moderate to large quantities of fresh to slightly saline water in the Beacon Hill area and the Capitan supplies moderate to large quantities of fresh and slightly saline water in the Apache Mountains area; the Bone Spring and Victorio Peak Limestones supply small to large quantities of slightly to moderately saline water in the Dell City area and the northeastern Diablo Plateau; the sandstones and limestones of the Delaware Mountain Group supply small quantities of slightly to moderately saline water along the eastern side of the northern Salt Basin and the foothills of the Delaware Mountains.
PRECAMBRIAN	--	Carrizo Mountain Formation and possibly Allamoore Formation	Carrizo Mountain Formation is metaigneous rocks; Allamoore is limestone, conglomerate and metamorphic, volcanic, and igneous rocks.	Supplies small quantities of freshwater in the Allamoore area, permeable zones probably are weathered or fractured rock.

and the northern end of the Salt Basin in Texas, totals about 5,000 square miles (13,000 km^2). Ground-water discharge in the Salt Flats is about 40,000 acre-feet (49.3 million m^3) per year (Davis and Leggat, 1965, p. U67), which probably approximates the average annual recharge. One percent of an assumed average annual precipitation of 11.57 inches (294 mm) within the drainage area is about 31,000 acre-feet (38.2 million m^3). If this rough relation is sufficient to yield an order-of-magnitude estimate, recharge to the rest of the Salt Basin, with a drainage area of 2,760 square miles (7,150 km^2) is about 17,000 acre-feet (21 million m^3) per year.

Recharge to the 1,100-square-mile (2,850-km^2) area of the Presidio and Redford bolsons in the United States (not including the tributary Cibolo and Alamito Creek drainages outside the Presidio bolson) may be about 7,000 acre-feet (8.6 million m^3) per year. Recharge in the 160-square-mile (410-km^2) area of the Green River Valley may be about 1,000 acre-feet (1.2 million m^3) per year and about 2,000 acre-feet (2.5 million m^3) per year in the 370-square-mile (960-km^2) area of Red Light Draw.

Part of Eagle Flat is tributary to the Salt Basin and part to Red Light Draw, but water-level contours do not indicate that ground water flows to these basins from Eagle Flat. Eagle Flat, which has an area of 560 square miles (1,450 km^2), may receive about 3,000 acre-feet (3.7 million m^3) per year of recharge. If the 1,560-square-mile (4,040-km^2) drainage area of the United States part of the southeastern Hueco bolson receives an average of about 10 inches (254 mm) of precipitation per year, this part of the bolson may receive about 8,000 acre-feet (9.9 million m^3) per year of recharge, for a total of 14,000 acre-feet (17.3 million m^3) in the entire United States part of the bolson. Leggat, Lowry, and Hood (1962, p. 18) estimated recharge and ground-water inflow to the lower Mesilla Valley to be 18,000 acre-feet (22 million m^3) per year.

Ground water moves from the recharge areas around the margins of the basins and the ephemeral-stream channels to areas of discharge in the lower parts of the basins. The Salt Basin is a topographically closed basin, and ground water from the northern part of the drainage area moves toward and discharges at the Salt Flats. Ground water in the southern part of the Salt Basin moves generally north in the direction of surface drainage. Part of the water discharges at the small salt flat east of the Sierra Diablo; part of the water may discharge from the basin in the subsurface through the limestone bedrock, possibly to the Pecos River drainage area to the east; and some of the water discharges through volcanic rocks to the Rio Grande drainage area to the west.

Ground water in the Presidio and Redford bolsons, Green River Valley, Red Light Draw, the Hueco bolson, and the lower Mesilla Valley discharges to the Rio Grande. Ground water in Eagle Flat may discharge from the basin to the Rio Grande drainage area to the south through the subsurface. In addition to natural discharge, large amounts of ground water are pumped for irrigation in the Dell City, Wildhorse and Michigan Flats, and Lobo Flat areas, and for municipal and industrial use in the Hueco bolson and lower Mesilla Valley. Ground water is also pumped for irrigation along the Rio Grande Valley from the Hueco bolson to the Presidio bolson, especially when surface water is in short supply. Some of this pumping probably intercepts ground water moving to points of natural discharge and reduces the natural discharge.

SALT FLATS AND ADJACENT AREAS

The Salt Flats in the northern part of the Salt Basin extend from the New Mexico State line to the northern end of the Sierra Diablo (fig. 2). The Guadalupe Mountains and Delaware Mountains, which are composed of Permian limestones and sandstones, are on the eastern boundary; and the eastern edge of the Diablo Plateau, underlain by Permian limestone, forms the western boundary.

Ground-Water Hydrology

The basin fill underlying the Salt Flats is predominantly lacustrine clay and sand saturated with saline water. The maximum thickness of the fill ranges from about 800 feet (244 m) north of U.S. Highway 62-180 to about 2,000 feet (610 m) southwest of Bitter Well Mountain (fig. 2). Figure 3a-u shows interpretations of earth-resistivity and seismic data collected in the Salt Basin, Presidio bolson, Green River Valley, Eagle Flat, and Red Light Draw. Figures 3a and 3b show the general lithology and thickness of the fill in the Salt Flats area as determined from earth-resistivity data. The available data do not indicate the occurrence of any significant volumes of basin fill that are saturated with fresh or slightly saline water. Most of the fill, which has low permeability, is not a good aquifer.

Figure 4 shows the location of the 24 flight lines for the collection of airborne-electromagnetic data over the northern Salt Basin and the response curves for each flight line. These curves indicate conductivity, and therefore vary inversely with resistivity. The INPUT data reflect resistivities to maximum depths of about 300 to 400 feet (90 to 120 m), and indicate the location where significant thicknesses of low-resistivity (high conductivity), fine-grained basin fill are bounded by high-resistivity consolidated rock. The data also indicate the local areas where coarse, resistive, alluvial-fan deposits grade into fine-grained fill and where consolidated rock, probably limestone, occurs at shallow depths in the eastern part of Wildhorse Flat. The INPUT data were used, in conjunction with other data, to construct the maps showing the thickness of the fill in the Salt Flats and Wildhorse Flat areas.

Figure 4 also indicates that the basin fill in Wildhorse Flat is coarser and that the ground-water quality is better than to the north, where the low resistivities of the response curves indicate that the fill consists of lacustrine clays or sands and clays containing poor-quality water.

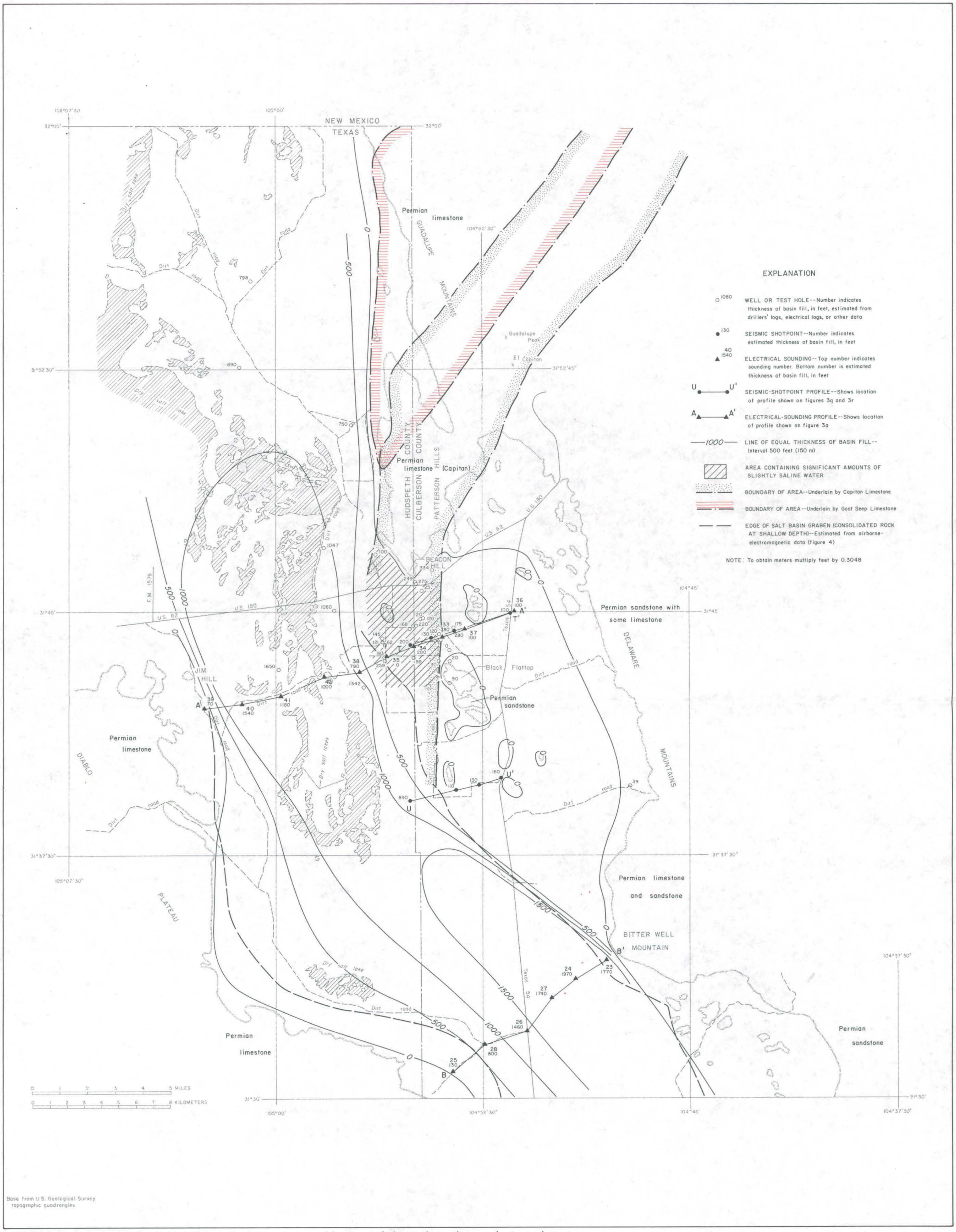

FIGURE 2.-Hydrologic data for the Salt Flats and adjacent areas and locations of electrical soundings and seismic shotpoints

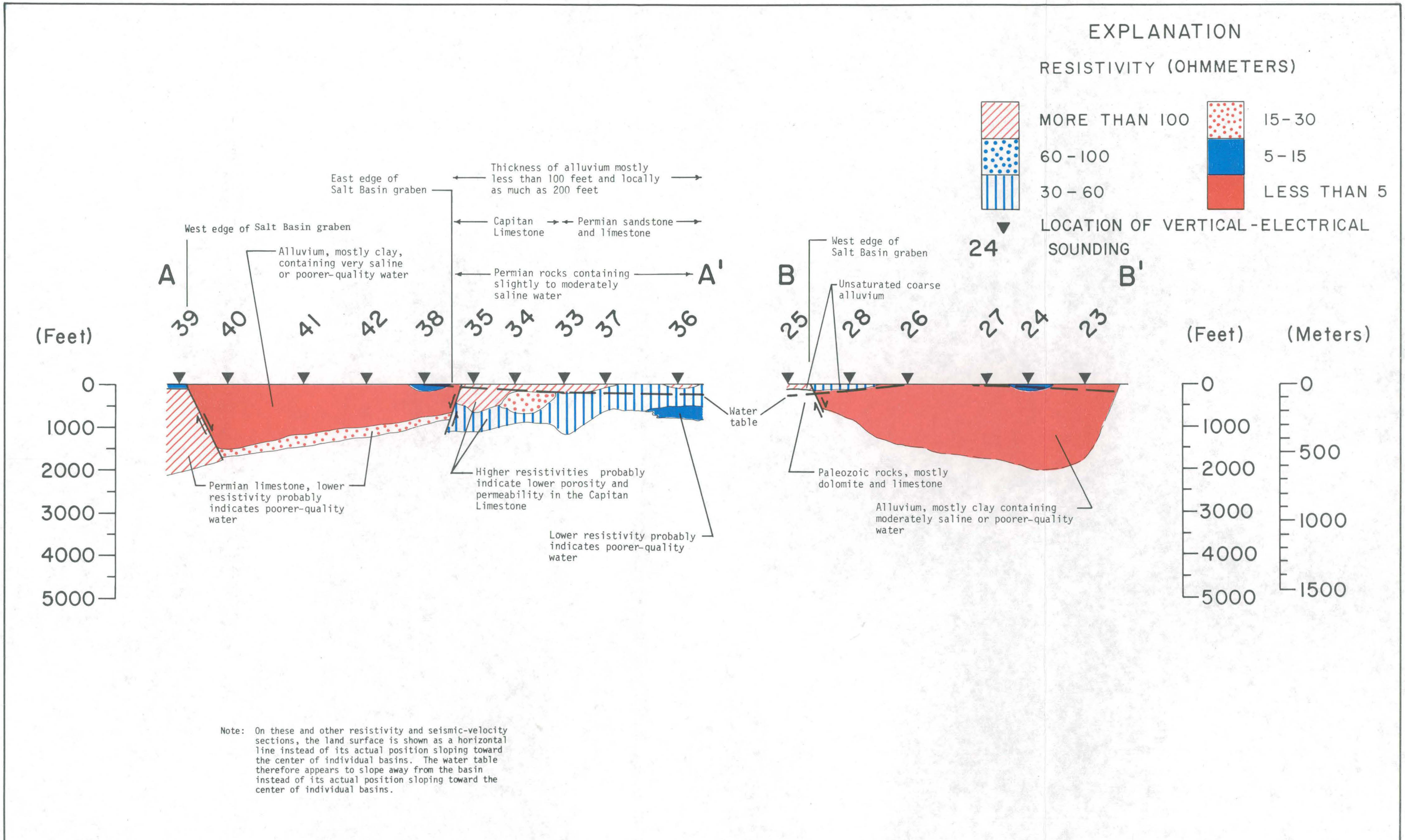

FIGURE 3a.-Cross sections A-A' and B-B' of electrial resistivity along electrical-sounding profiles in the Salt Flats area

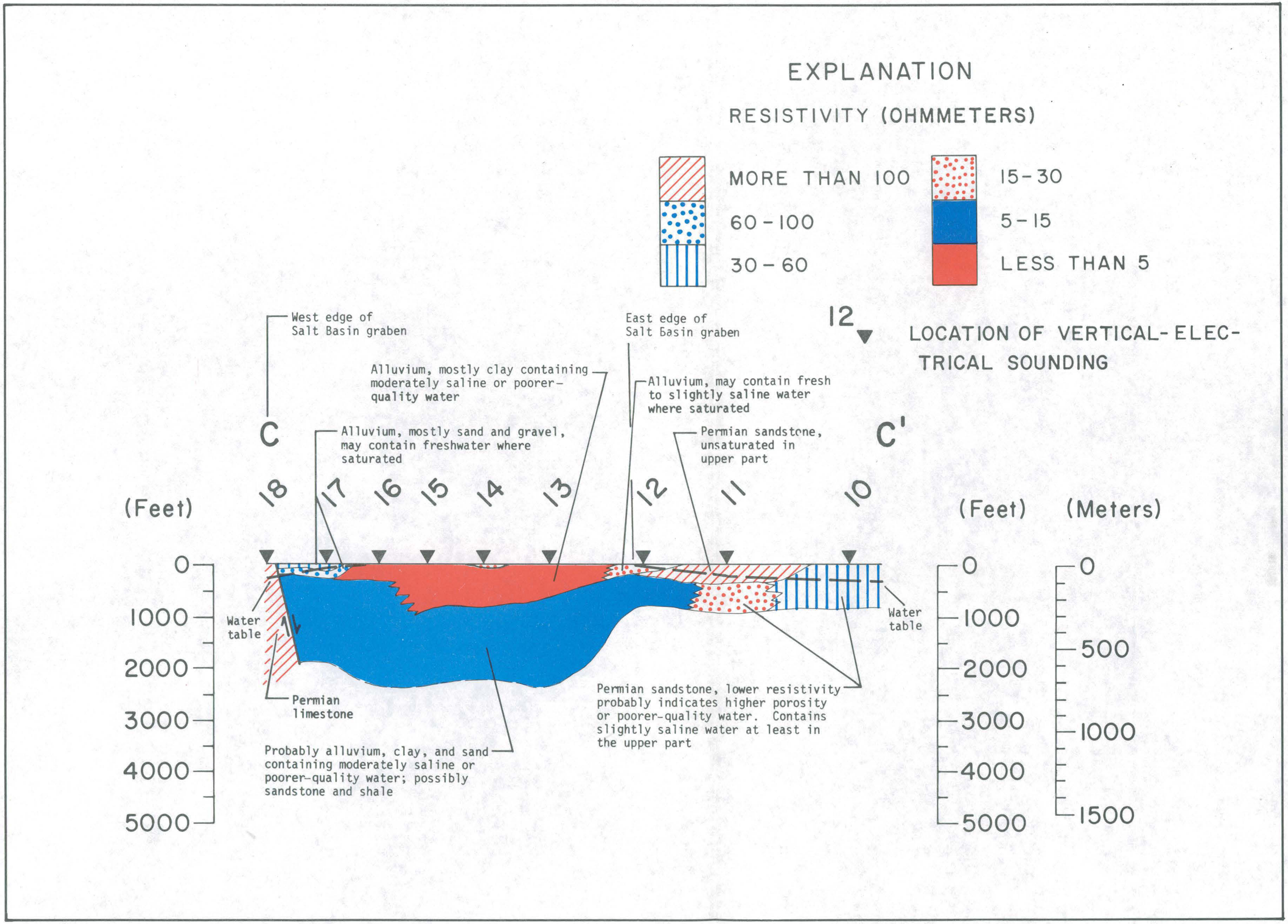

FIGURE 3b.-Cross section C-C' of electrical resistivity along an electrical-sounding profile in the Wildhorse and Michigan Flats area

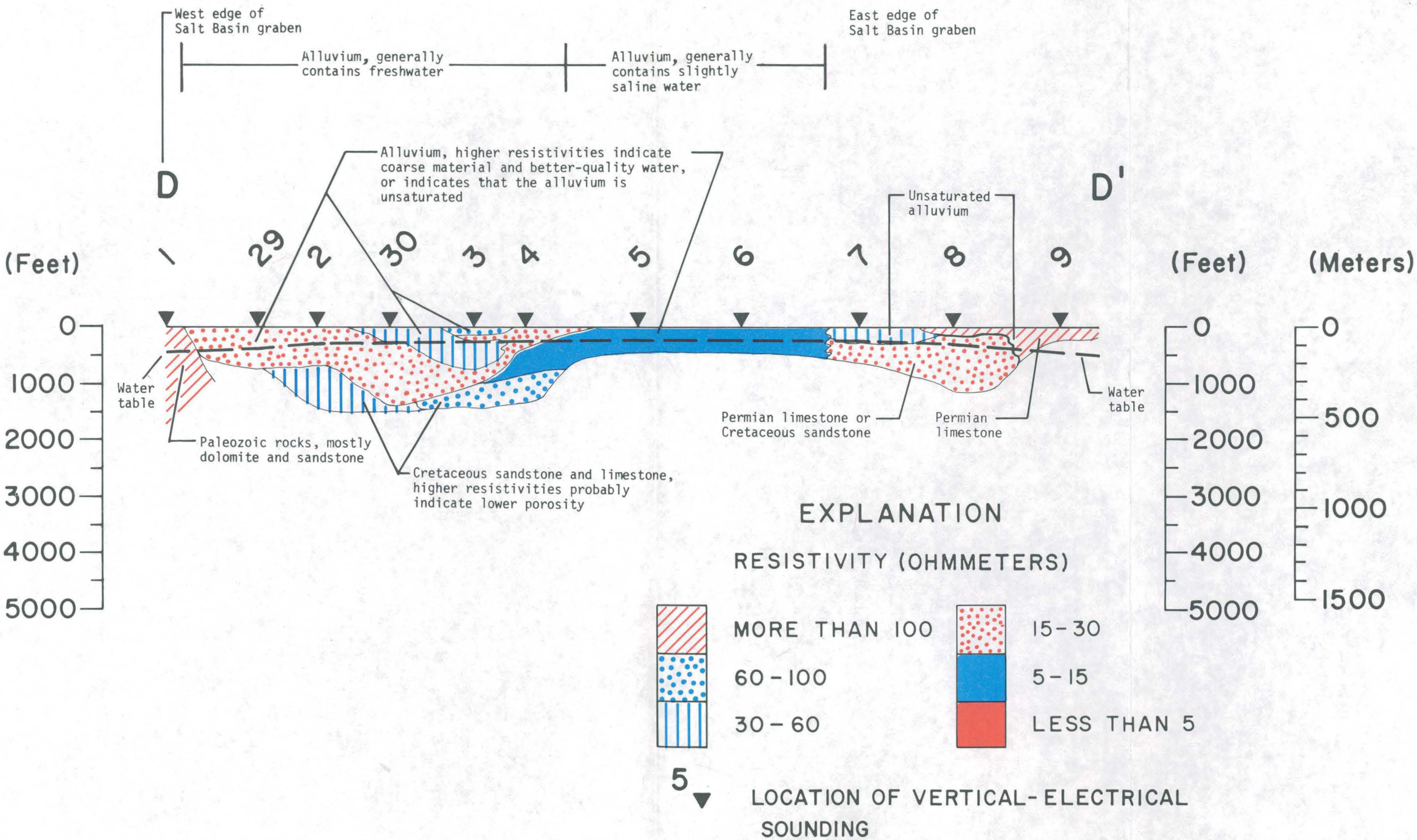

FIGURE 3c.-Cross section D-D' of electrical resistivity along an electrical-sounding profile in Wildhorse Flat

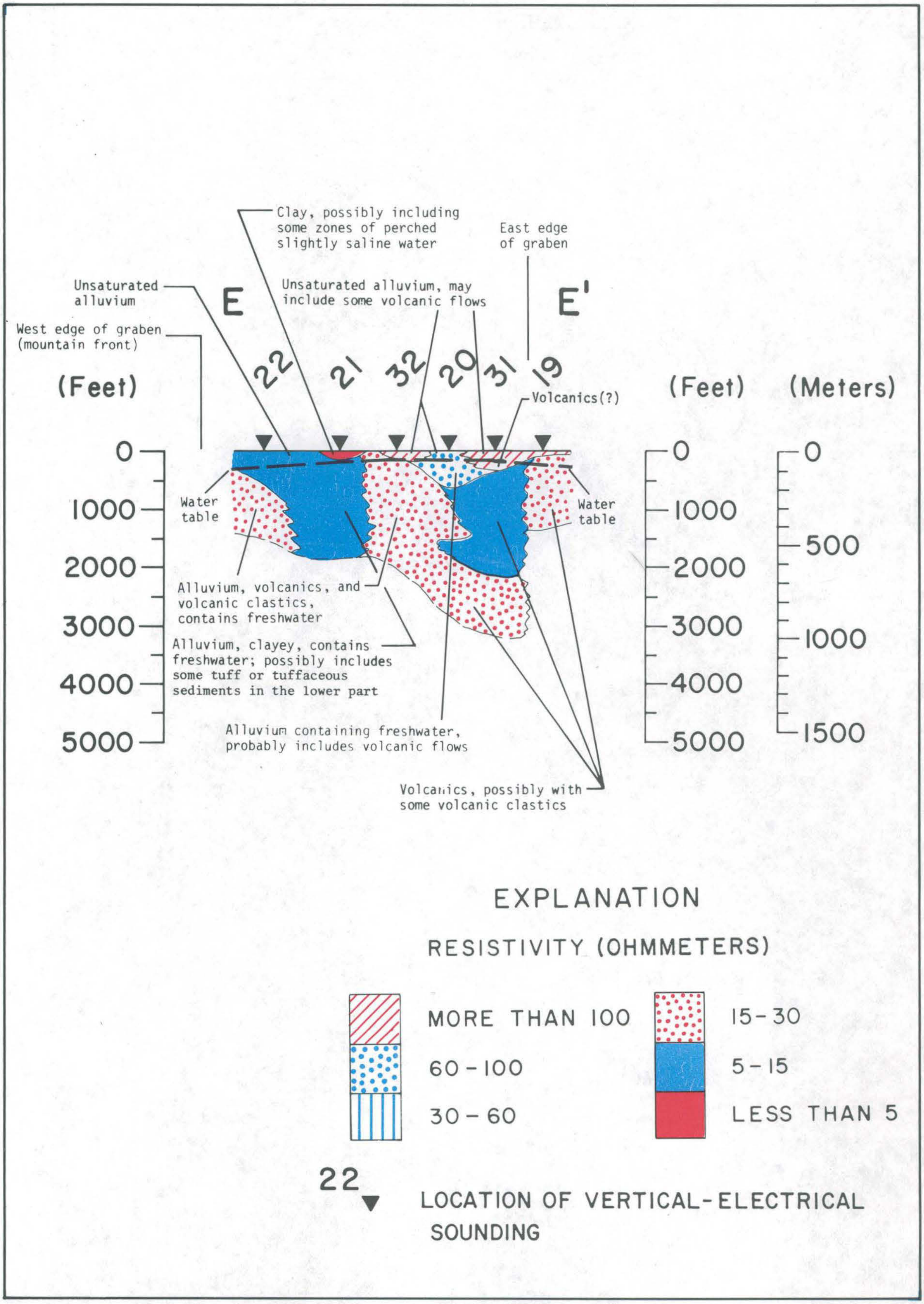

FIGURE 3d.-Cross section E-E' of electrical resistivity along an electrical-sounding profile in Lobo Flat

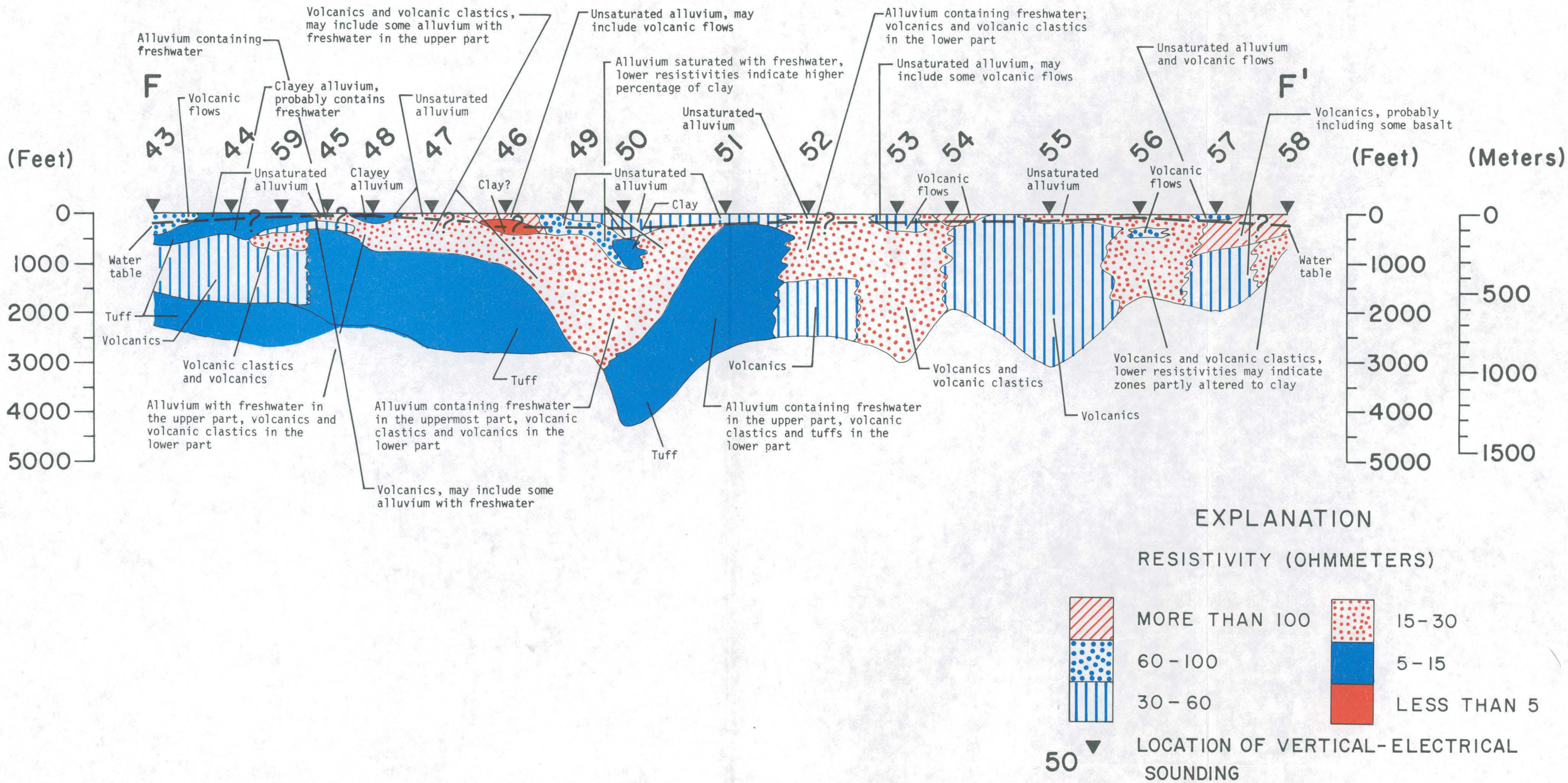

FIGURE 3e.-Cross section F-F' of electrical resistivity along an electrical-sounding profile in Ryan Flat

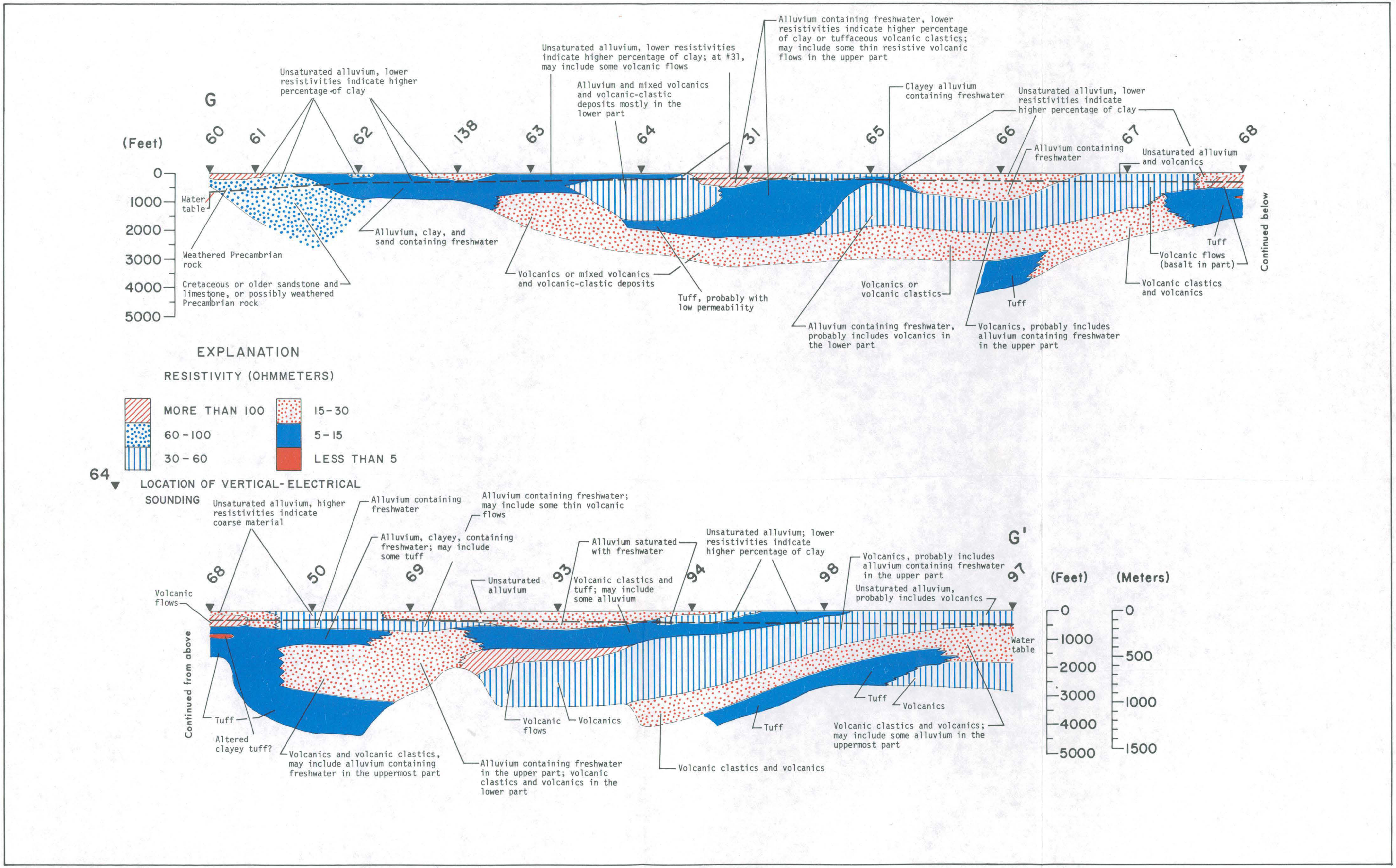

FIGURE 3f.-Cross section G-G' of electrical resistivity along an electrical-sounding profile in the Wildhorse, Lobo, and Ryan Flat areas

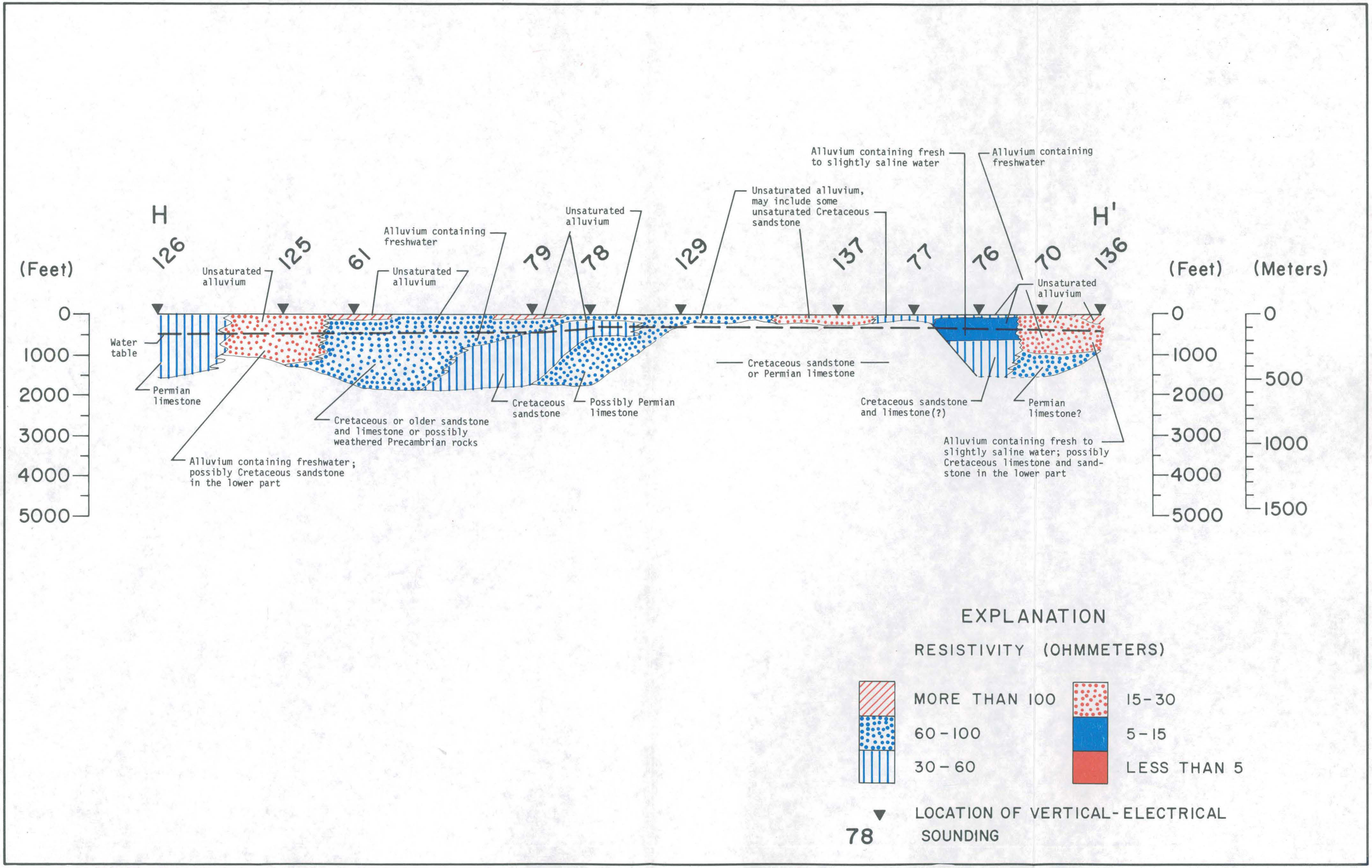

FIGURE 3g.-Cross section H-H' of electrical resistivity along an electrical-sounding profile mostly in the Wildhorse and Michigan Flat areas

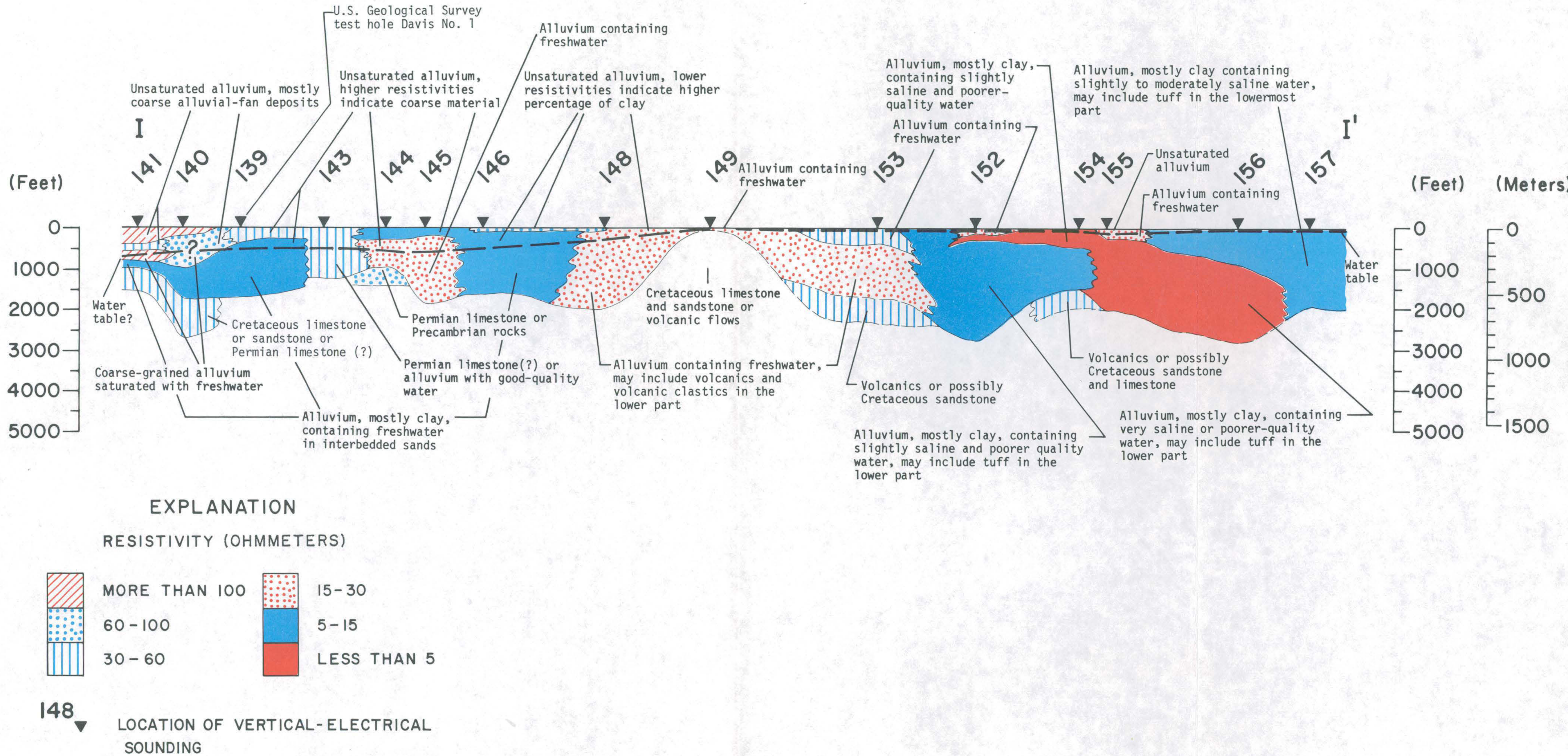

FIGURE 3h.-Cross section I-I' of electrical resistivity along an electrical-sounding profile in the southeastern Eagle Flat and Green River Valley areas

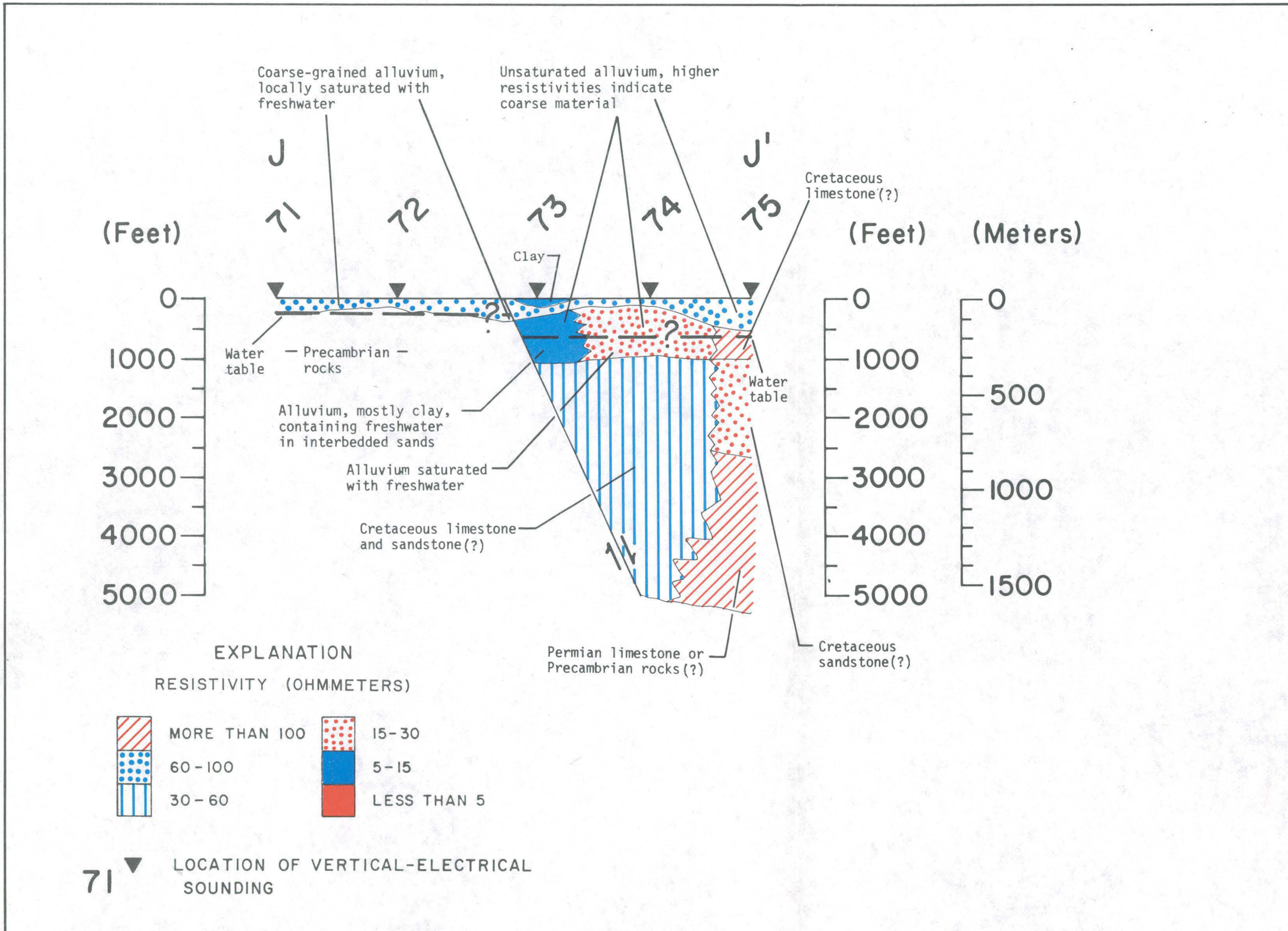

FIGURE 3i.-Cross section J-J' of electrical resistivity along an electrical-sounding profile in southeastern Eagle Flat

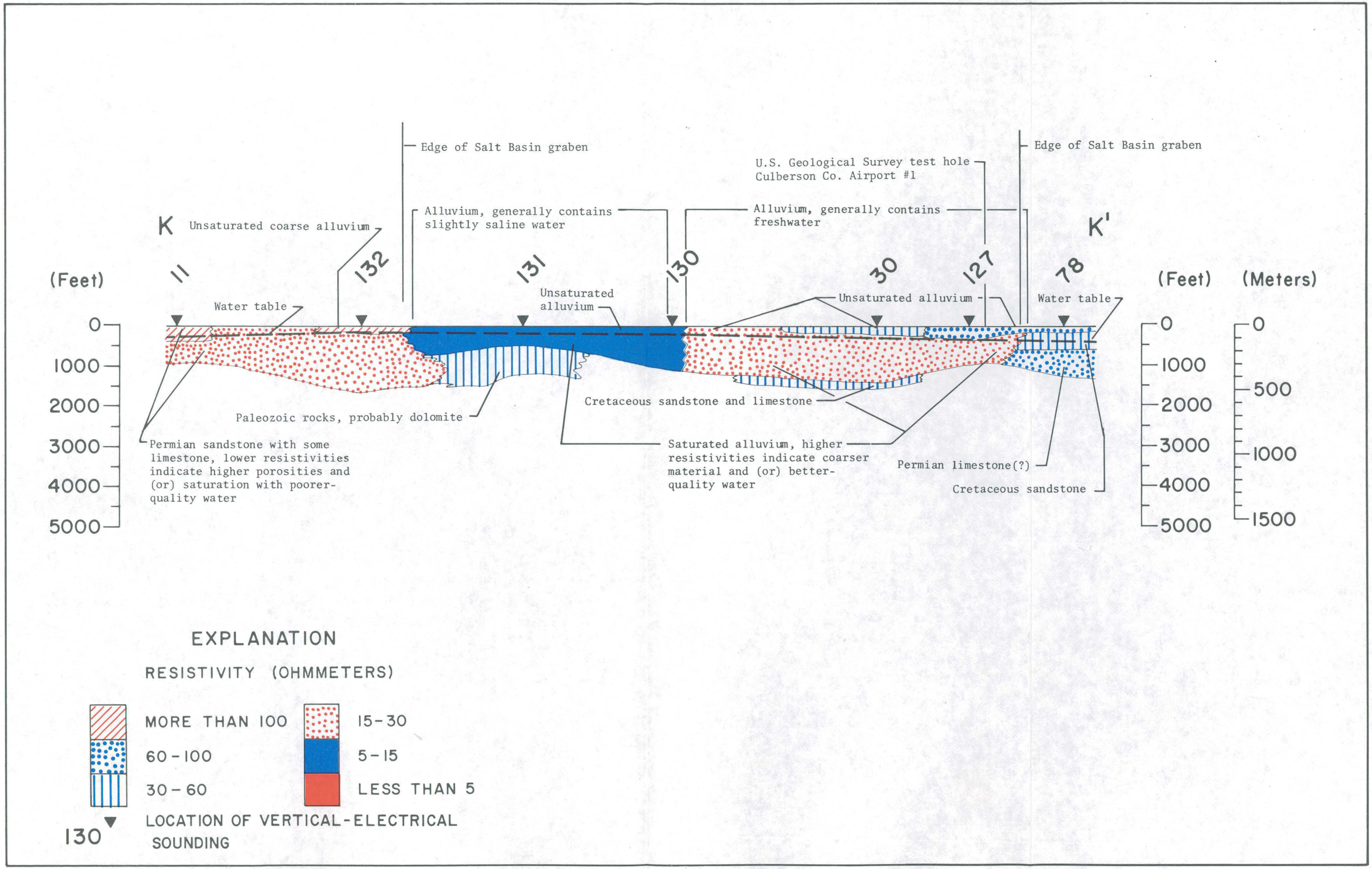

FIGURE 3j.-Cross section K-K' of electrical resistivity along an electrical-sounding profile in the Wildhorse Flat area

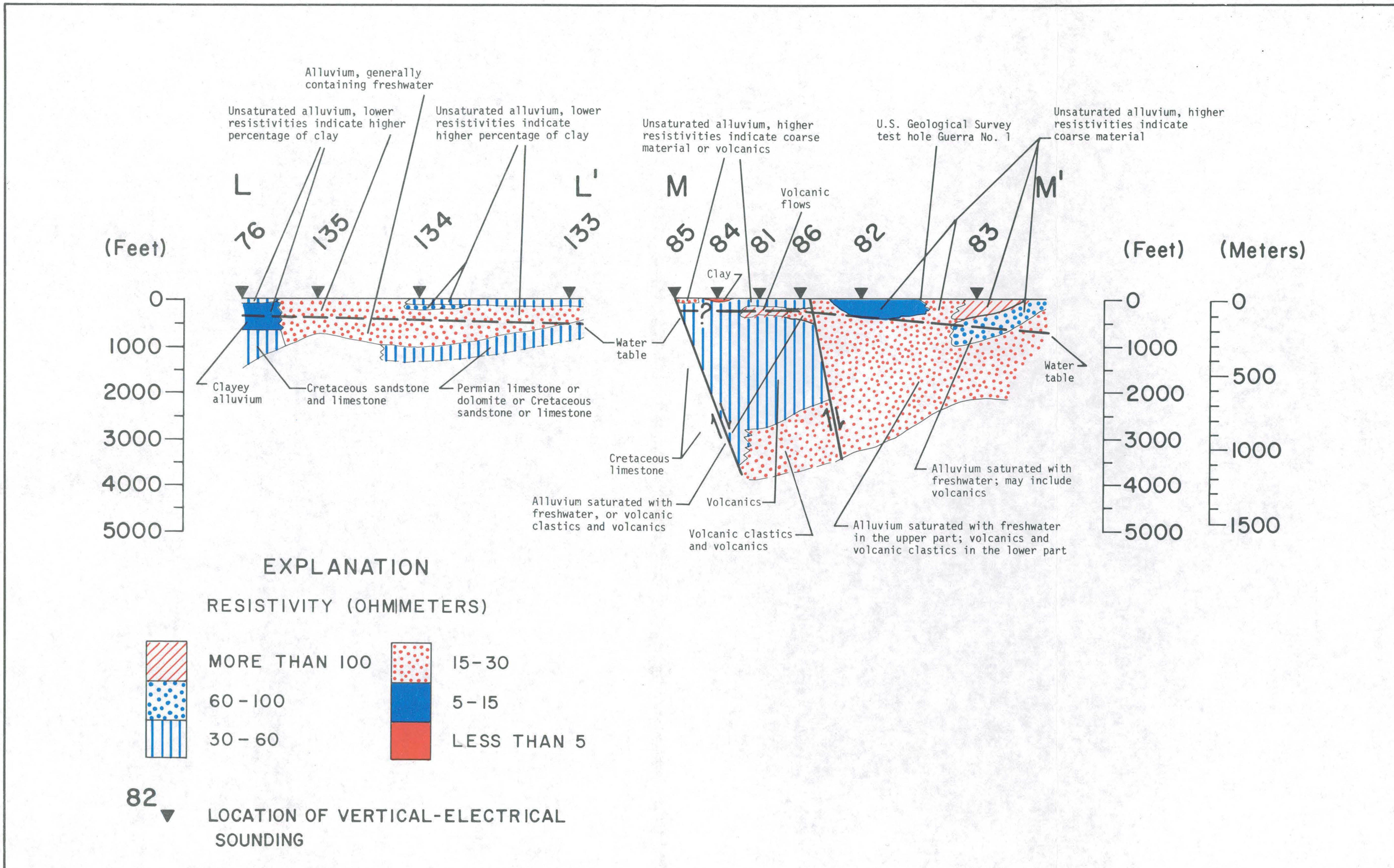

FIGURE 3k.-Cross sections L-L' and M-M' of electrical resistivity along electrical-sounding profiles in the Michigan Flat and Red Light Draw areas

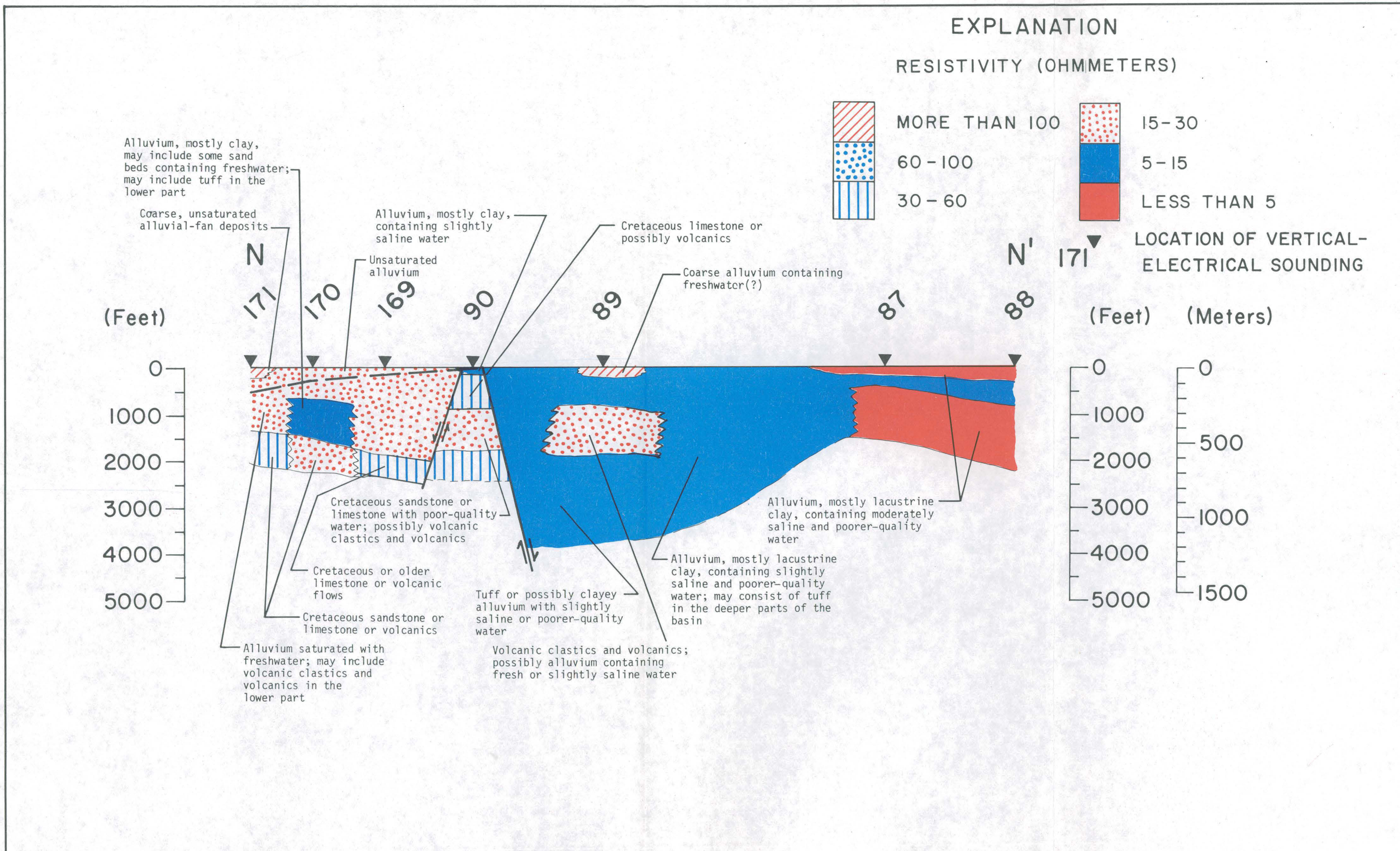

FIGURE 31.-Cross section N-N' of electrical resistivity along an electrical-sounding profile in Red Light Draw

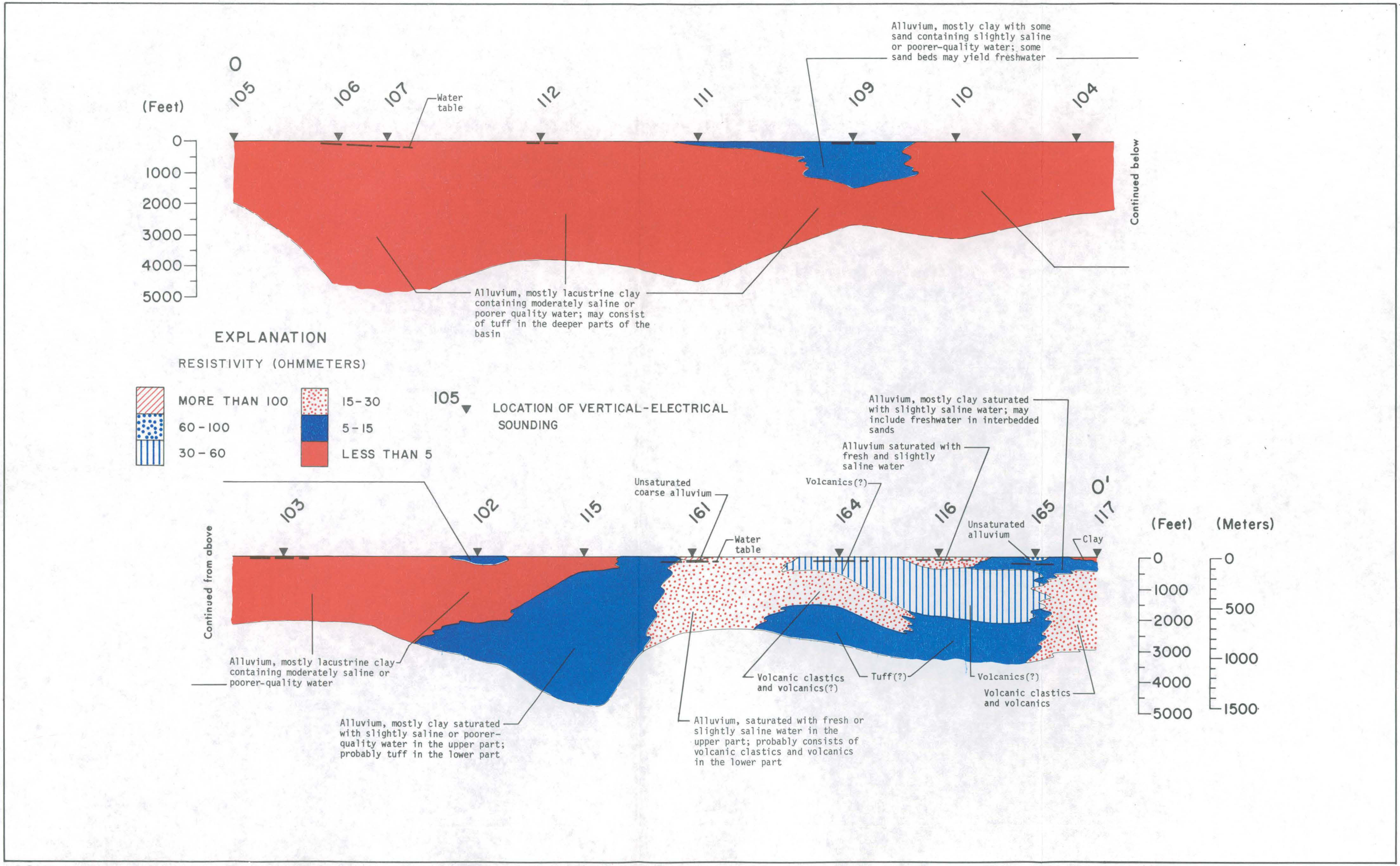

FIGURE 3m.-Cross section O-O' of electrical resistivity along an electrical-sounding profile in the Presidio bolson

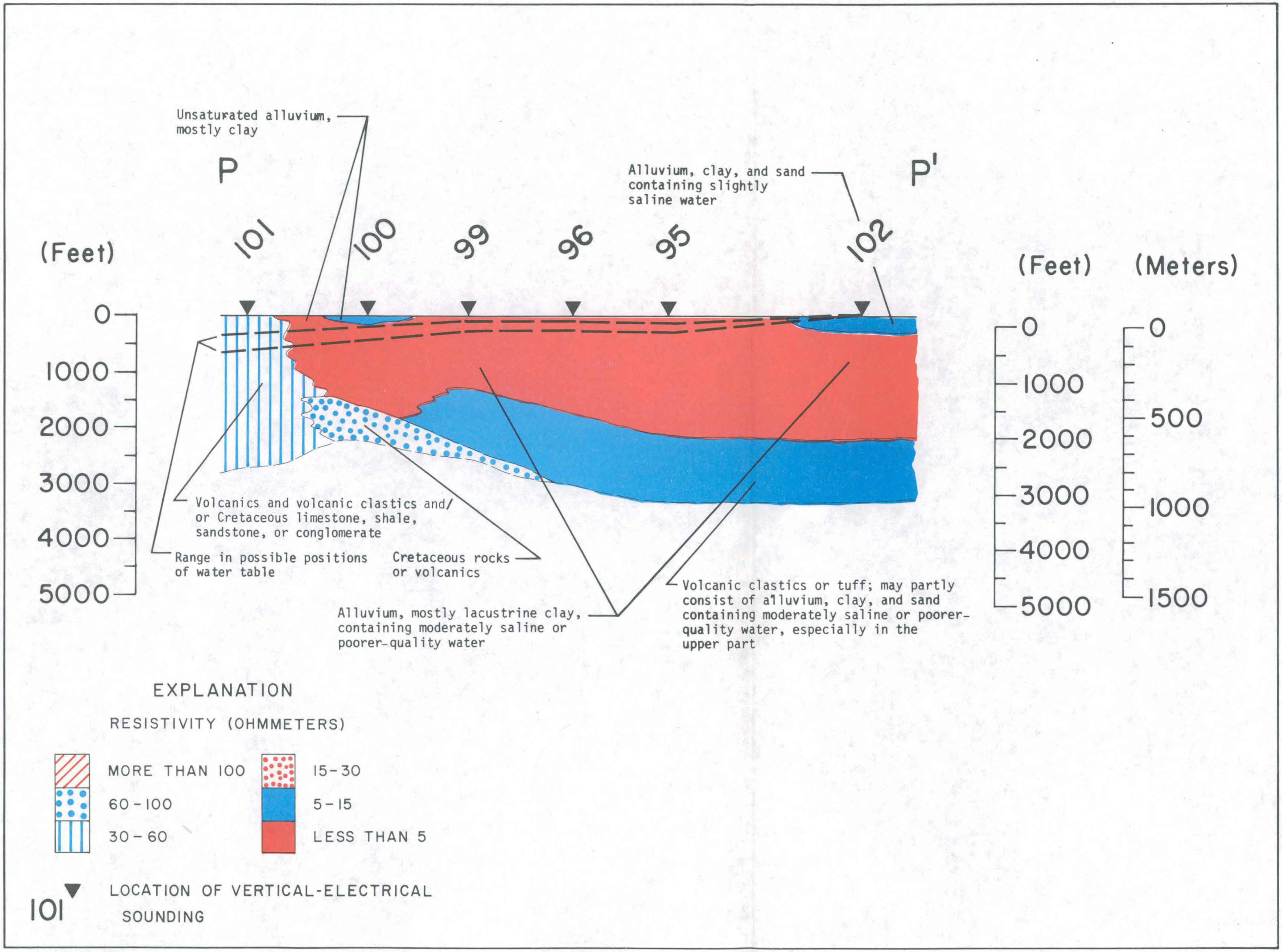

FIGURE 3n.-Cross section P-P' of electrical resistivity along an electrical-sounding profile in the Presidio bolson

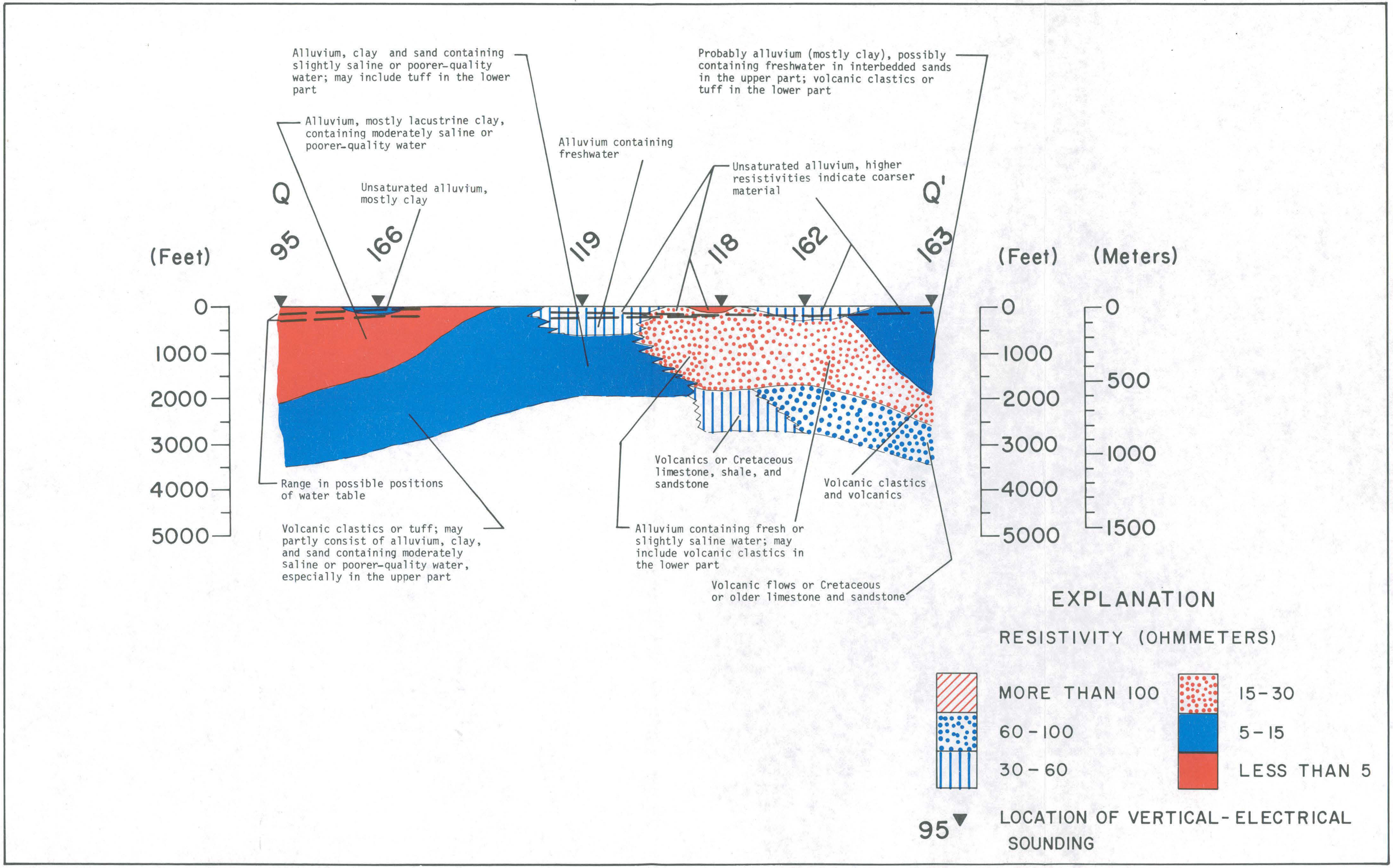

FIGURE 30.-Cross section Q-Q' of electrical resistivity along an electrical-sounding profile in the Presidio bolson

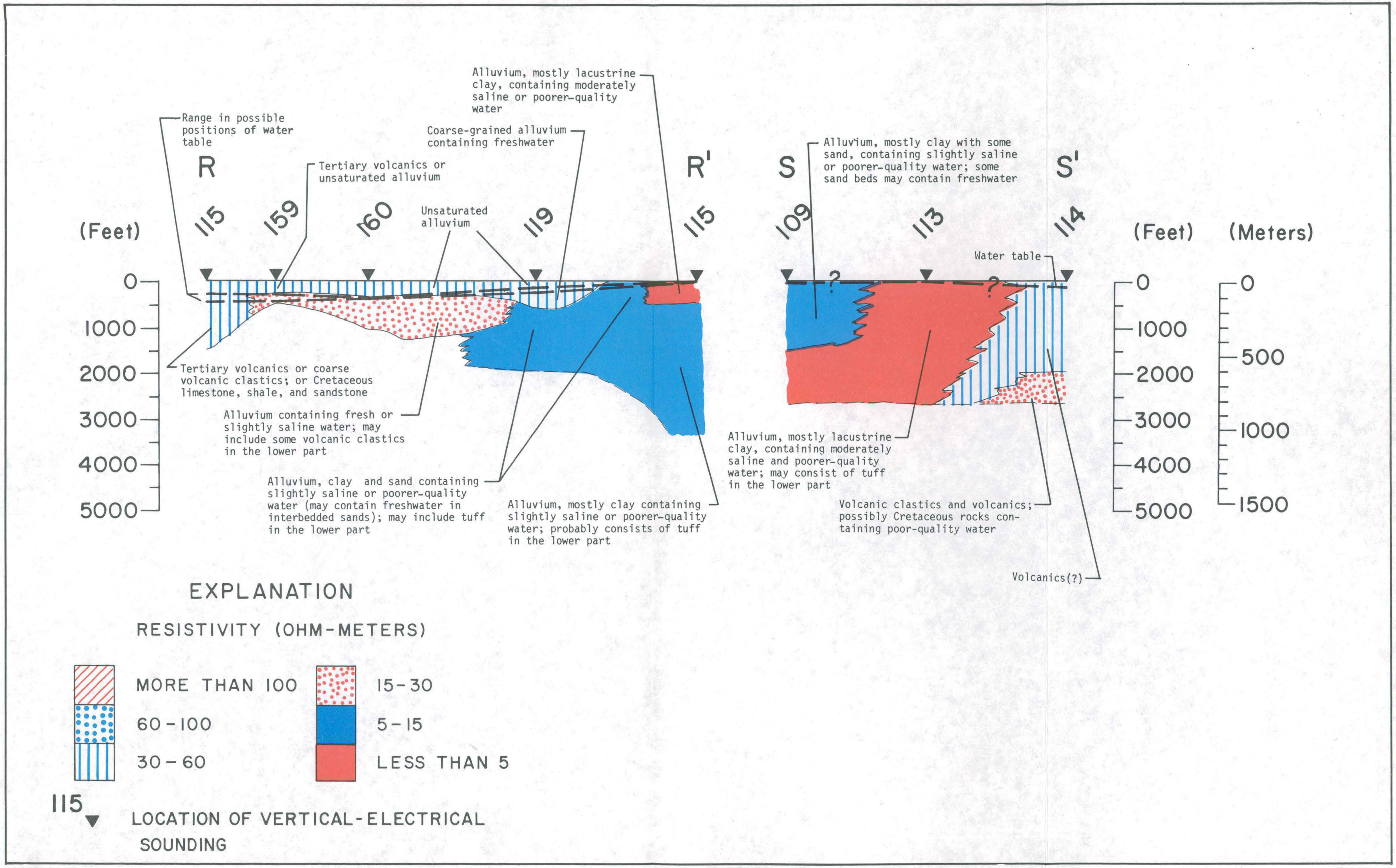

FIGURE 3p.-Cross sections R-R' and S-S' of electrical resistivity along electrical-sounding profiles in the Presidio bolson

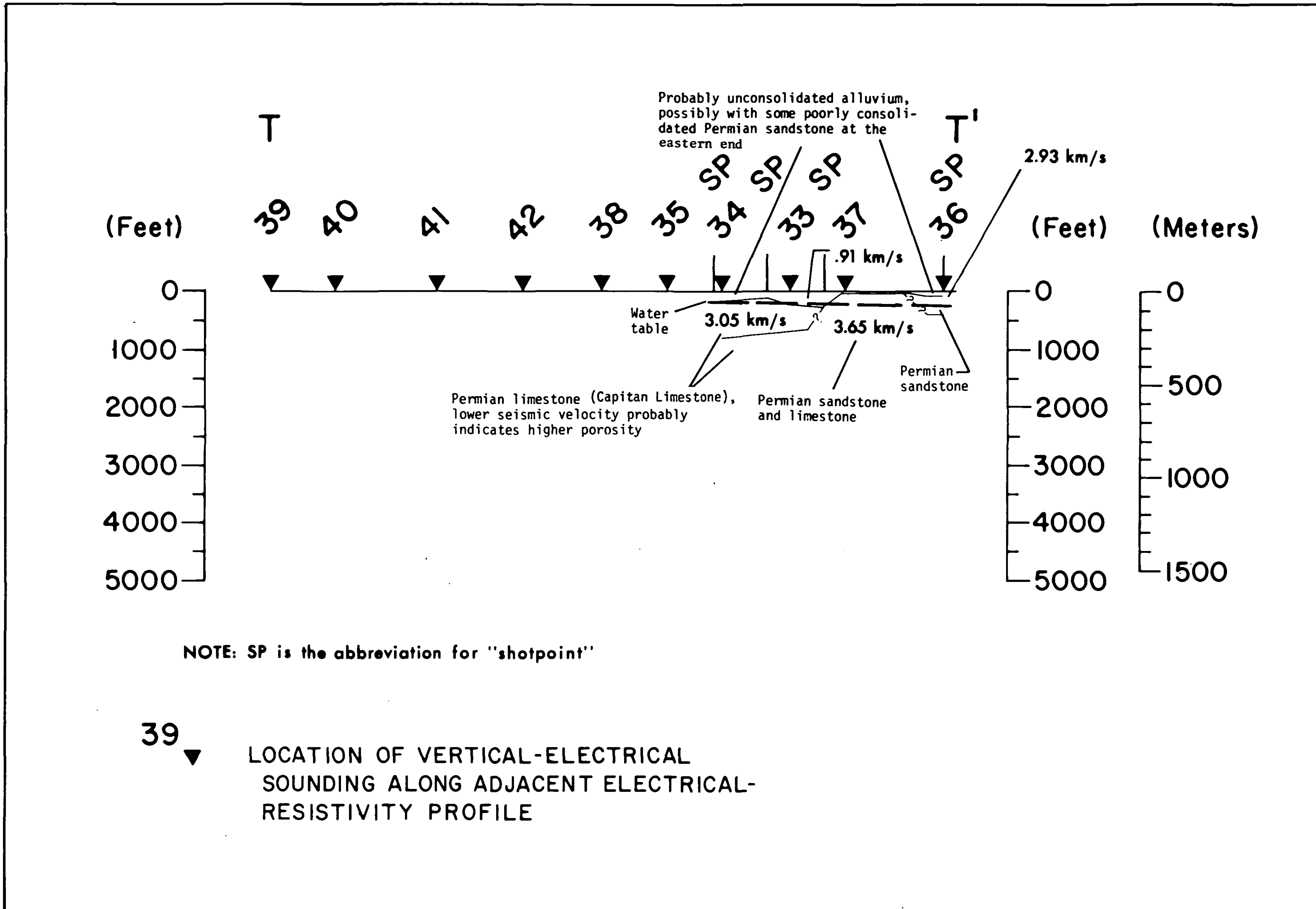

FIGURE 3q.-Cross section T-T' of seismic velocity along a seismic profile in the Salt Flats area

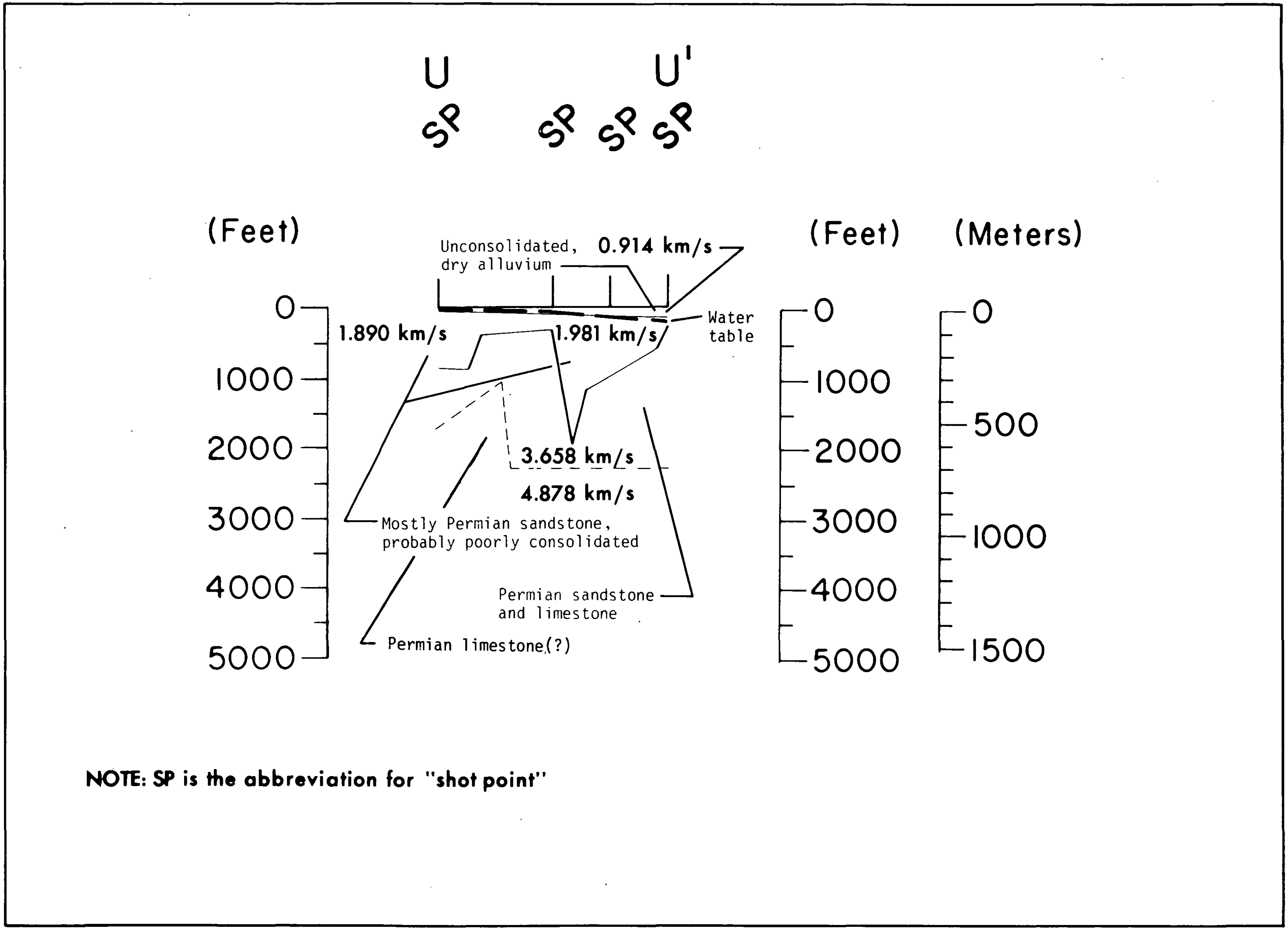

FIGURE 3r.-Cross section U-U' of seismic velocity along a seismic profile in the Salt Flats area

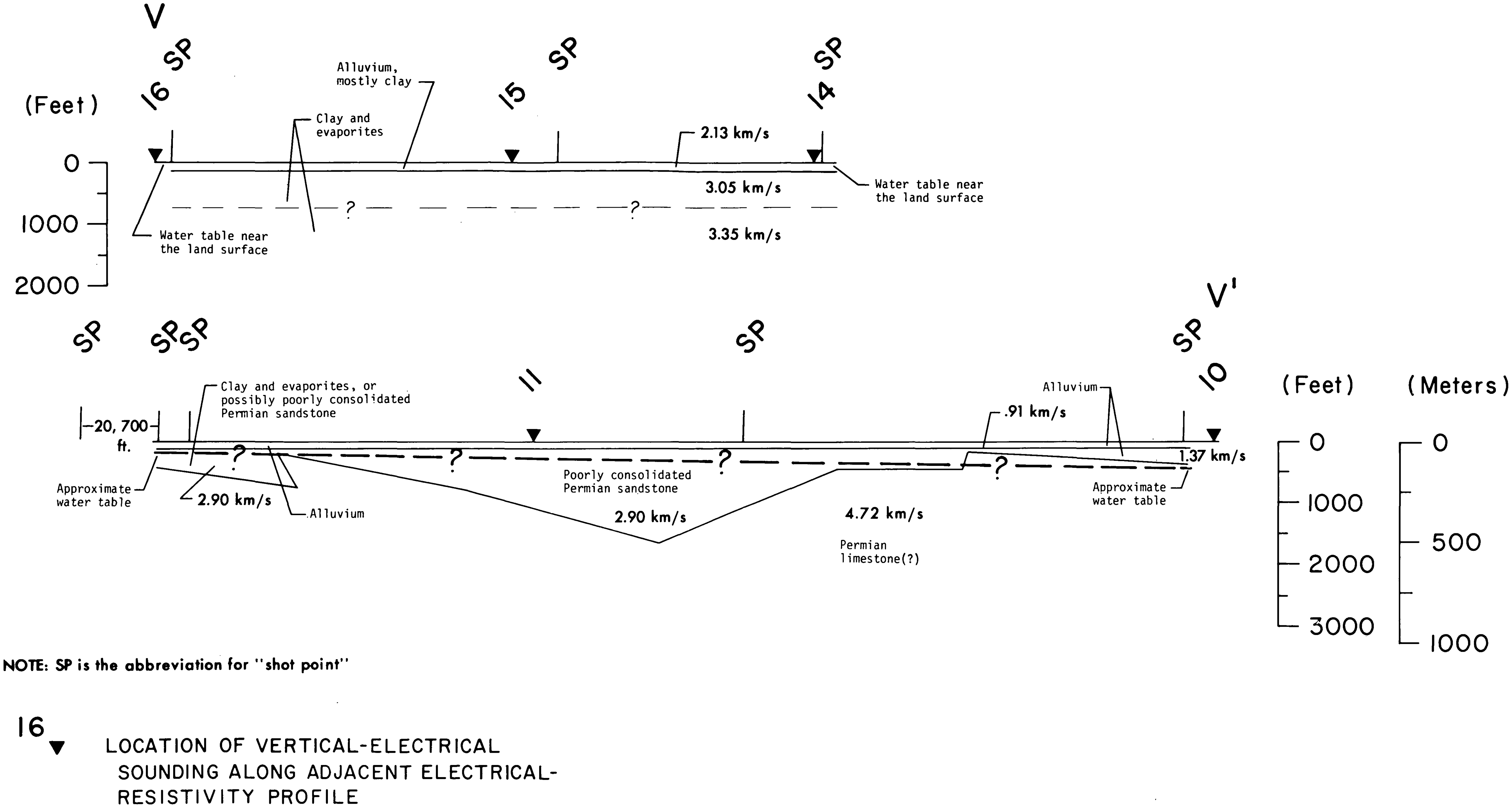

FIGURE 3s.-Cross section V-V' of seismic velocity along a seismic profile in the Wildhorse and Michigan Flats area

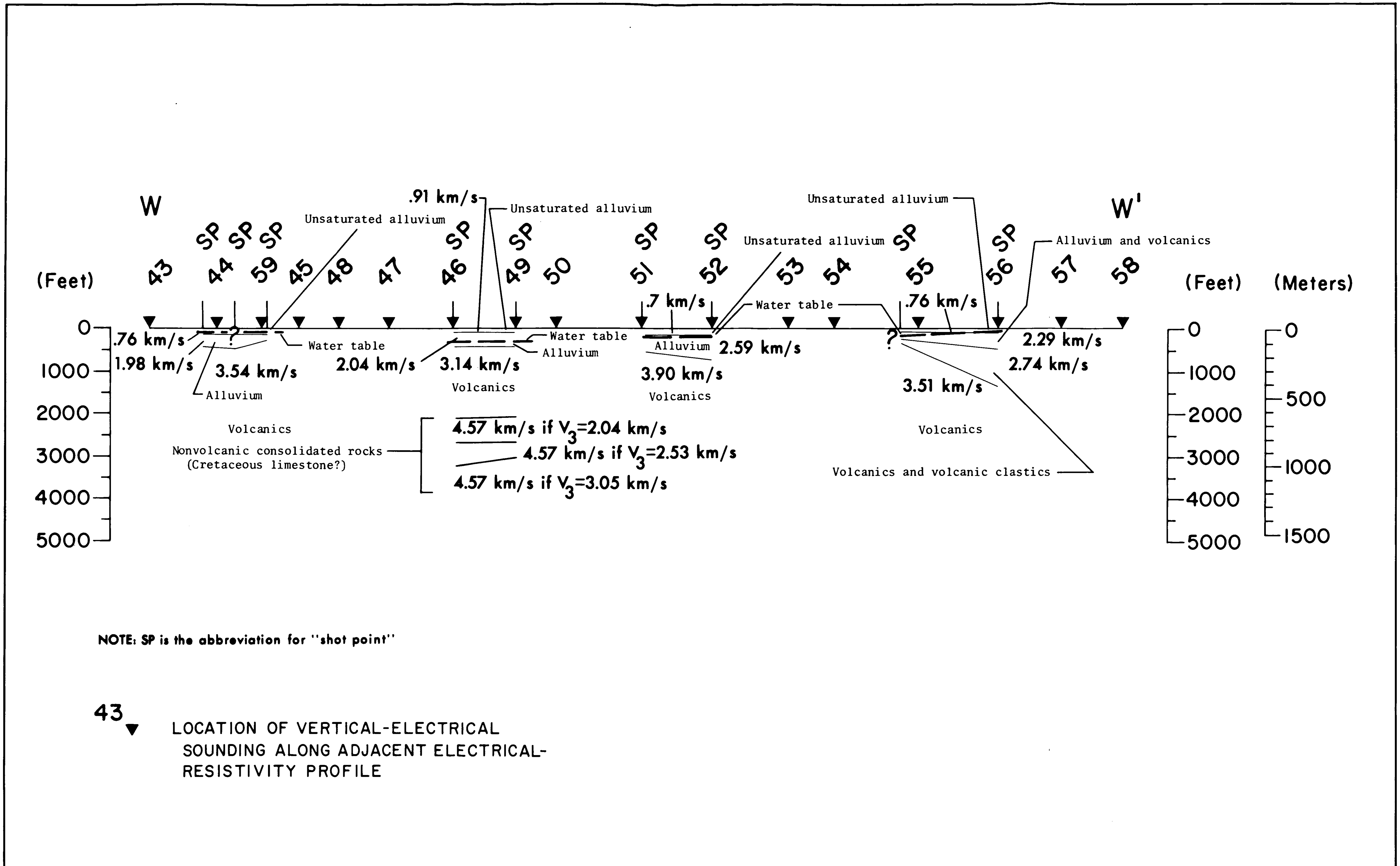

FIGURE 3t.-Cross section W-W' of seismic velocity along a seismic profile in Ryan Flat

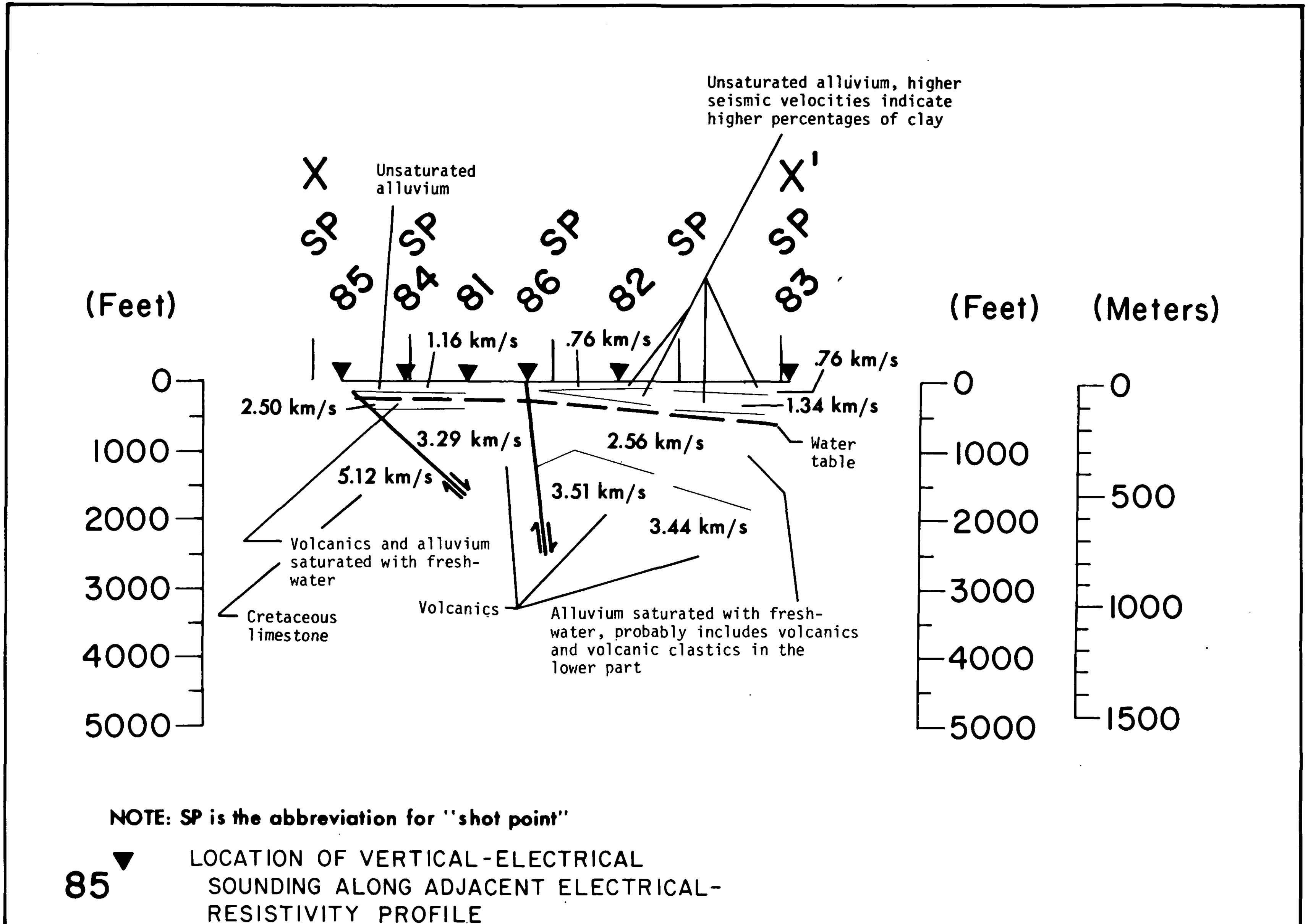

FIGURE 3u.-Cross section X-X' of seismic velocity along a seismic profile in Red Light Draw

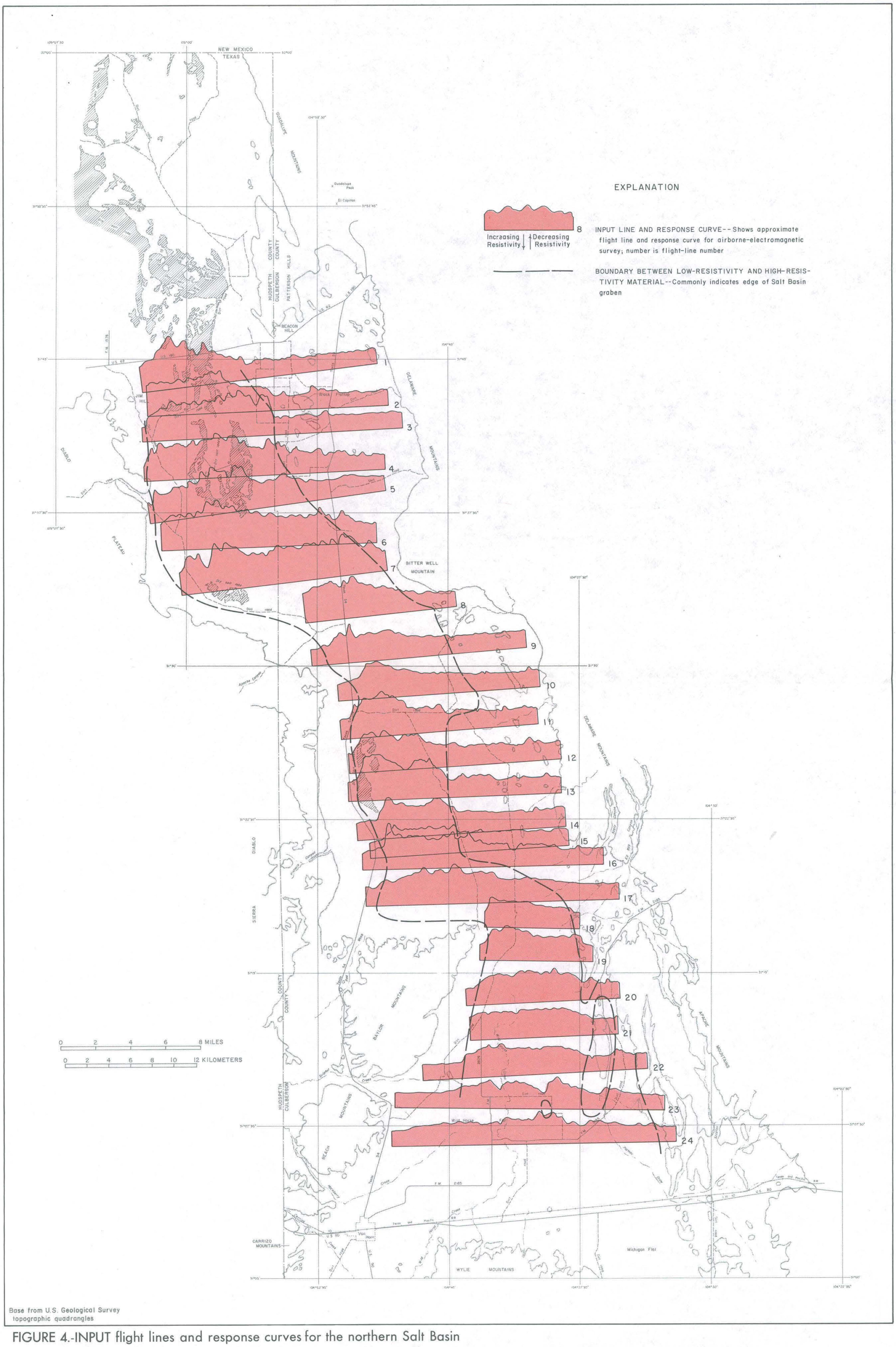

FIGURE 4.-INPUT flight lines and response curves for the northern Salt Basin

The principal aquifers of the Salt Flats area are the Capitan and Goat Seep Limestones of Permian (Guadalupian) age. These massive reef limestones crop out in the Guadalupe Mountains and the Patterson Hills (fig. 2), and the subcrop of the Capitan Limestone is within a few hundred feet (100 m) of the surface in the Beacon Hill irrigation area south of the Patterson Hills. These reefs at least partly encircled the Permian Delaware Basin to the southeast and grade into shelf limestones to the northwest and into sandstones of the Delaware Mountain Group to the southeast.

The Goat Seep Limestone is as much as 1,200 feet (370 m) thick in the Salt Flats area (King, 1948, p. 39), is about 7 miles (11 km) wide (fig. 2), and lies below and shelfward (northwest) of the Capitan Limestone. Irrigation well PD-47-09-207, west of the Patterson Hills, yields large quantities of freshwater and probably taps a downfaulted part of the Goat Seep. No other wells are known to tap this limestone in the Salt Flats area, so the extent of freshwater-bearing Goat Seep in the subsurface west of the Guadalupe Mountains and Patterson Hills is not known.

The Capitan Limestone is 1,000-2,000 feet (300-610 m) thick in the Guadalupe Mountains and is about 4 miles (6 km) wide (King, 1948, p. 61). The Capitan trends southwest in the Guadalupe Mountains and then appears to swing slightly to the south in the Patterson Hills. The Capitan is probably the permeable limestone tapped by irrigation wells that yield moderate to large quantities of slightly saline water in the Beacon Hill area, where is is reportedly (White and others, 1977) first penetrated between depths of 60 to 275 feet (18 to 84 m) and extends to a depth of as much as 1,686 feet (514 m).

On the basis of the locations of wells that penetrate significant thicknesses of the Capitan Limestone, the formation appears to swing to the south across the Beacon Hill area to its southwestern edge, where the Capitan is probably downfaulted into the Salt Basin (fig. 2).

Wells in the Capitan Limestone yield from about 400 to more than 6,000 gal/min (25 to more than 380 L/s); the wells on the western side of the Beacon Hill area tend to have lower yields. Few aquifer tests have been made in the Salt Basin, Eagle Flat, Red Light Draw, and Presidio bolson. For this reason, transmissivity values were estimated by using the specific capacities of wells (Theis, Brown, and Meyer, 1963). The theoretical transmissivity of a typical aquifer in westernmost Texas, in ft^2/d, can be estimated roughly by multiplying the specific capacity of a well by about 200, on the assumption that the aquifer has a storage coefficient of 0.1, the diameter of the well is 12 inches (30 cm), and that specific capacity was measured after 1 day of pumping. This estimate also assumes that the well is 100-percent efficient. A comparison of available aquifer-test and specific-capacity data from individual wells completed in limestone or basin fill suggests that in the Salt Basin, transmissivity is better estimated by multiplying specific capacity by about 330. Specific capacities in the Beacon Hill area range from about 6.5 to 58 (gal/min)/ft [1.3-12 (L/s)/m], and the median value of 16.5 (gal/min)/ft [3.4 (L/s)/m] indicates a transmissivity of about 5,400 ft^2/d (500 m^2/d). One aquifer test (Ed L. Reed, written commun., 1965) yielded a transmissivity of 16,000 ft^2/d (1,500 m^2/d), but the test was conducted in a well that had an above average specific capacity. The specific yield of the Capitan Limestone is probably large in places where the limestone is cavernous, but overall, the specific yield of the formation is probably 5 percent or less. Maclay and Rettman (1973, p. 7) estimated the regional specific yield of the Edwards and associated limestones in the San Antonio, Texas, area to be 2.5 percent.

Figure 3a shows earth-resistivity measurements across the Beacon Hill area, and indicates that the lowest resistivity in near-surface, saturated Permian rocks occurs between soundings 33 and 34. The wells with the highest yields are in this same zone, which suggests that lower resistivities correlate with higher porosities. Between soundings 34 and 35, the high resistivity probably indicates lower porosities rather than better-quality water because the quality of water is poorer west of sounding 34. Resistivity data indicate that the edge of the Salt Basin graben is located between soundings 35 and 38, where highly resistive consolidated rocks are downfaulted at least 800 feet (240 m).

Figure 3q shows seismic-refraction data across the Beacon Hill area, and indicates lower velocity, probably due to higher porosity, west of sounding 37. Figure 3r shows velocities at the sound end of the Beacon Hill area, where the bedrock is most likely sandstone of the Delaware Mountain Group.

Recharge to the Capitan and Goat Seep Limestones and the sandstones of the Delaware Mountain Group occurs in the outcrop areas in the Guadalupe Mountains, Patterson Hills, and Delaware Mountains and locally from ephemeral streamflow in and east of the Beacon Hill area. Ground water moves generally westward through the Beacon Hill area in the consolidated rocks and then into the basin fill, where it discharges by evapotranspiration at the Salt Flats. The water-level map of the Salt Flats area (fig. 5) indicates this general movement of ground water toward the flats, although a slight cone of depression caused by pumping in the Beacon Hill area distorts the contours.

Quality of Ground Water

Figure 6 shows that the quality of ground water in the basin fill of the Salt Flats area ranges from slightly saline around the edge of the basin, to moderately saline along the axis of the basin, to probably very saline or brine beneath the Salt Flats. Ground-water discharge along the basin axis, and especially at the Salt Flats, has concentrated salts in the shallow ground water. In addition, much of the basin fill in the northern Salt Basin, which was probably deposited in saline lakes, contains salts that are dissolved by circulating ground water.

FIGURE 5.-Water levels in 1972 and water-level declines during 1960-72 in the Salt Flats area

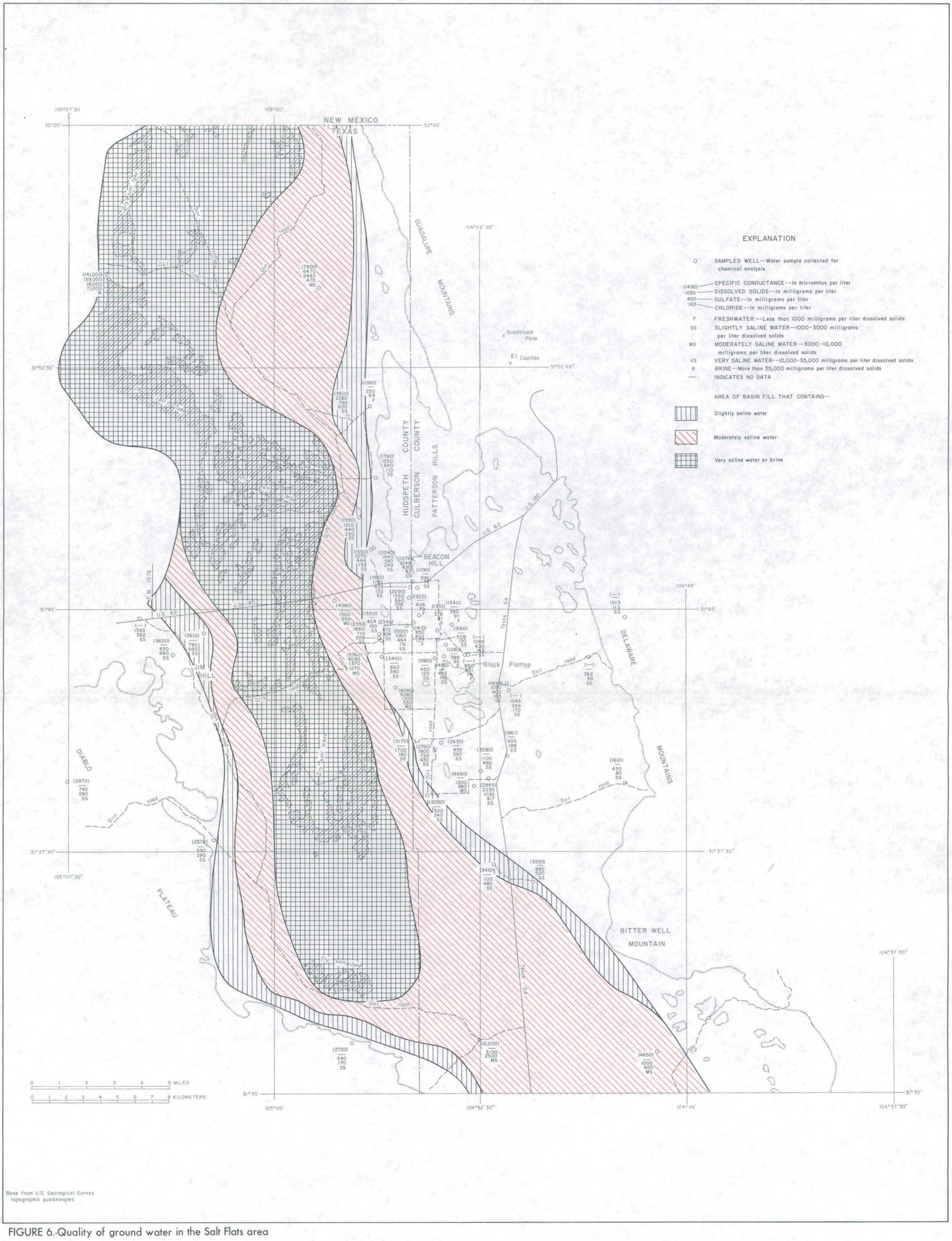

FIGURE 6.-Quality of ground water in the Salt Flats area

Figure 6 also shows chemical analyses of water samples in the areas of consolidated rocks around the Salt Flats. Ground water from the Permian limestones underlying the eastern edge of the Diablo Plateau is mostly slightly saline. In the northeastern part of the Beacon Hill area, ground water in and just east of the Capitan Limestone is fresh to slightly saline; further west, ground water is slightly and moderately saline. Ground water in the Delaware Mountain Group is slightly to moderately saline.

Development of Ground Water, Volumes of Slightly Saline Water in Storage, and Problems of Future Development

The only part of the Salt Flats area where significant amounts of ground water have been developed is in the northern part of the Beacon Hill irrigation area, south of the Patterson Hills. Pumping for irrigation began in about 1951 along the western side of the area and was expanded to the north and east during the 1950's. In the 1960's, ground water in the north-central and southern parts of the Beacon Hill area was developed, but pumping from the Delaware Mountain Group at the southern end of the area was short-lived, probably because of low yields, large drawdowns, and the poor quality of the water.

Although records of pumpage are not available, it is estimated that a maximum of 3,500 acres (14.2 km^3) were irrigated with about 10,000 acre-feet (12 million m^3) per year. During 1972-74, about 1,000 acres (4.0 km^2) were irrigated with about 3,000 acre-feet (3.7 million m^3) per year. The average amount of ground-water withdrawals during 1951-72 was probably 5,000 acre-feet (6.2 million m^3) per year or less.

Figure 5 shows that water levels in the northern Beacon Hill area declined as much as 10-14 feet (3-4 m) during 1960-72. The few measurements available suggest that the maximum decline since the early 1950's is about 15 feet (4.6 m). Measurements from well HL-47-17-903, in the southern end of the area (White and others, 1977), indicate that water levels declined more than 30 feet (9 m) from May 1965 to January 1968, probably because withdrawals were from the sediments of low permeability in the Delaware Mountain Group. Water levels have slowly recovered, however, since pumping ceased in about 1967. Because water levels declined over most of the Beacon Hill area in response to an average withdrawal of 5,000 acre-feet (6.2 million m^3) or less per year, recharge in the area is less than the withdrawals. This conclusion is based on the assumption that water levels have declined below a depth where flow toward the general cone of depression would be in equilibrium with pumpage and that the cone of depression intercepts most of the local recharge.

The amount of water (mostly slightly saline) in the Beacon Hill area, primarily in the Capitan Limestone, is about 0.5 million acre-feet (620 million m^3). This estimate assumes a saturated thickness of 1,500 feet (460 m) of Capitan Limestone with a specific yield of 5 percent in an area of about 10 square miles (26 km^2) in the northern Beacon Hill area (fig. 2).

More than 1,600 feet (490 m) of limestone was reported in a well on the west side of the area, and the water table in the Beacon Hill area is in most places approximately at the top of the Capitan Limestone.

The problems associated with developing the slightly saline water in the Beacon Hill area include encroachment of poorer-quality water from the west, low yields, and water-level declines. The average decline has been about 1 foot (0.3 m) per year for an average annual pumpage of 5,000 acre-feet (6.2 million m^3) or less. If withdrawals were increased, for example to 30,000 acre-feet (37 million m^3) per year, annual declines would also increase to on the order of 6 feet (1.8 m) or more.

Ground Water in the Dell City Irrigation Area

Ground water is pumped for irrigation from the Bone Spring and Victorio Peak Limestones of Permian (Leonardian) age in the Dell City irrigation area, west of the Salt Flats (fig. 1). The Dell City area was not included in the detailed investigation because most of the water in the Bone Spring and Victorio Peak Limestones is moderately saline; slightly saline water occurs on the western and eastern edges of the area.

Pumping for irrigation began in the Dell City area in 1947, and by 1949 about 6,000 acres (24 km^2) were being irrigated (Scalapino, 1950, p. 1). The Dell City area continues north into New Mexico, where the name is changed to the Crow Flats irrigation area. Pumping for irrigation at Crow Flats began in 1949, and in 1956 about 3,000 acres (12 km^2) were being irrigated (Bjorkland, 1957, p. 15). In 1960, about 100,000 acre-feet (120 million m^3) of water was pumped to irrigate about 25,000 acres (100 km^2) in Texas (Davis and Leggat, 1965, p. U67); and in 1967, about 105,000 acre-feet (130 million m^3) was pumped in Texas (Davis and Gordon, 1970, p. 2).

Ground-water withdrawals in 1972 in the Dell City irrigation area were estimated to be about 100,000 acre-feet (120 million m^3) by using spot checks of pumping in relation to power or fuel consumption for 13 wells, data from the more detailed survey in 1967, and valley-wide power and fuel-consumption data. In 1974-74, about 40,000-42,000 acres (160-170 km^2) in Texas and 5,500-6,000 acres (22-24 km^2) in New Mexico were irrigated. Of this amount, irrigation of about 4,500 acres (18 km^2) on the western side of the area in Texas began after 1972 (L. C. Luersen, U.S. Soil Conservation Service, oral commun., 1976). Water levels in the Dell City area declined about 30 to 40 feet (9 to 12 m) during the 24-year period between 1948 and 1972.

In 1948-49, ground water in the Dell City area had a dissolved-solids concentration of 1,100 to 1,800 mg/L; but by 1968, the dissolved-solids concentration in most of the water ranged from 3,000 to 5,000 mg/L, with one well yielding water that contained 6,300 mg/L (Davis and Gordon, 1970, table 2). Water from several wells had a three-fold increase in dissolved solids between 1948-49 and 1968. This deterioration in water quality probably occurred because part of the water applied for irrigation percolated back to the aquifer with an increased salt content due to concentration by evapotranspiration, and partly because additional salts were leached from the shallow alluvial deposits.

In 1972-73, the specific conductance, which is an indicator of the dissolved-solids concentration, was measured in 26 water samples from wells in the Dell City area. The changes in specific conductance from 1966-68 to 1972-73 ranged from a 2-percent decrease to a 35-percent increase. Water from most wells had increases of 5 to 22 percent and the average was a 12.5-percent increase; therefore the average dissolved-solids concentration also increased about 12.5 percent from 1966-68 to 1972-73.

WILDHORSE AND MICHIGAN FLATS AND ADJACENT AREAS

Wildhorse and Michigan Flats and adjacent areas in the northern Salt Basin extend from the northern end of the Sierra Diablo to just south of Interstate Highway 10 (fig. 7), although Michigan Flat continues farther to the south and is shown on figure 11. The area is bounded on the west by the Sierra Diablo, underlain by Permian limestones; the Baylor Mountains, composed of Permian limestone and older rocks, mostly dolomite of Paleozoic age; the Beach Mountains, composed mostly of Paleozoic dolomite and sandstone; and the Carrizo Mountains, composed of Precambrian rocks. The eastern side of the area is bounded by the Delaware Mountains, composed of Permian sandstones; and the Apache Mountains, composed of Permian limestones, including the Capitan Limestone. The southeastern boundary consists of low hills underlain by limestones and sandstones of Cretaceous age. The northern end of the Wylie Mountains, composed mostly of Permian limestones, separates the southern part of Wildhorse Flat from Michigan Flat.

Ground-Water Hydrology

North of Wildhorse Flat, between the Sierra Diablo and Delaware Mountains, is a small salt flat in which the basin fill is predominantly fine-grained, partly lacustrine clay that is saturated with water of varying salinity. The resistivity soundings across this part of the Salt Basin (fig. 3b) indicate that the maximum thickness of the fill is about 2,400 feet (730 m). The resistivity section shows that the edge of the Salt Basin graben is approximately at sounding 12, east of which is Permian sandstone. Figure 3s (line V-V'), which is a seismic velocity profile along the resistivity profile of figure 3b (profile C-C'), indicates the occurrence of high-velocity material at shallow depths completely across this part of the graben. On the east side of the profile, the high-velocity material is probably Permian sandstone and limestone; on the west side, it may be basin fill composed of clay with large amounts of evaporites.

The basin fill at Wildhorse Flat contains more sand and gravel than the Salt Basin to the north, as shown by the resistivity sections on figures 3c, 3g, and 3j. The western side of Wildhorse Flat contains the thickest section of fill and has the highest proportion of coarse-grained,

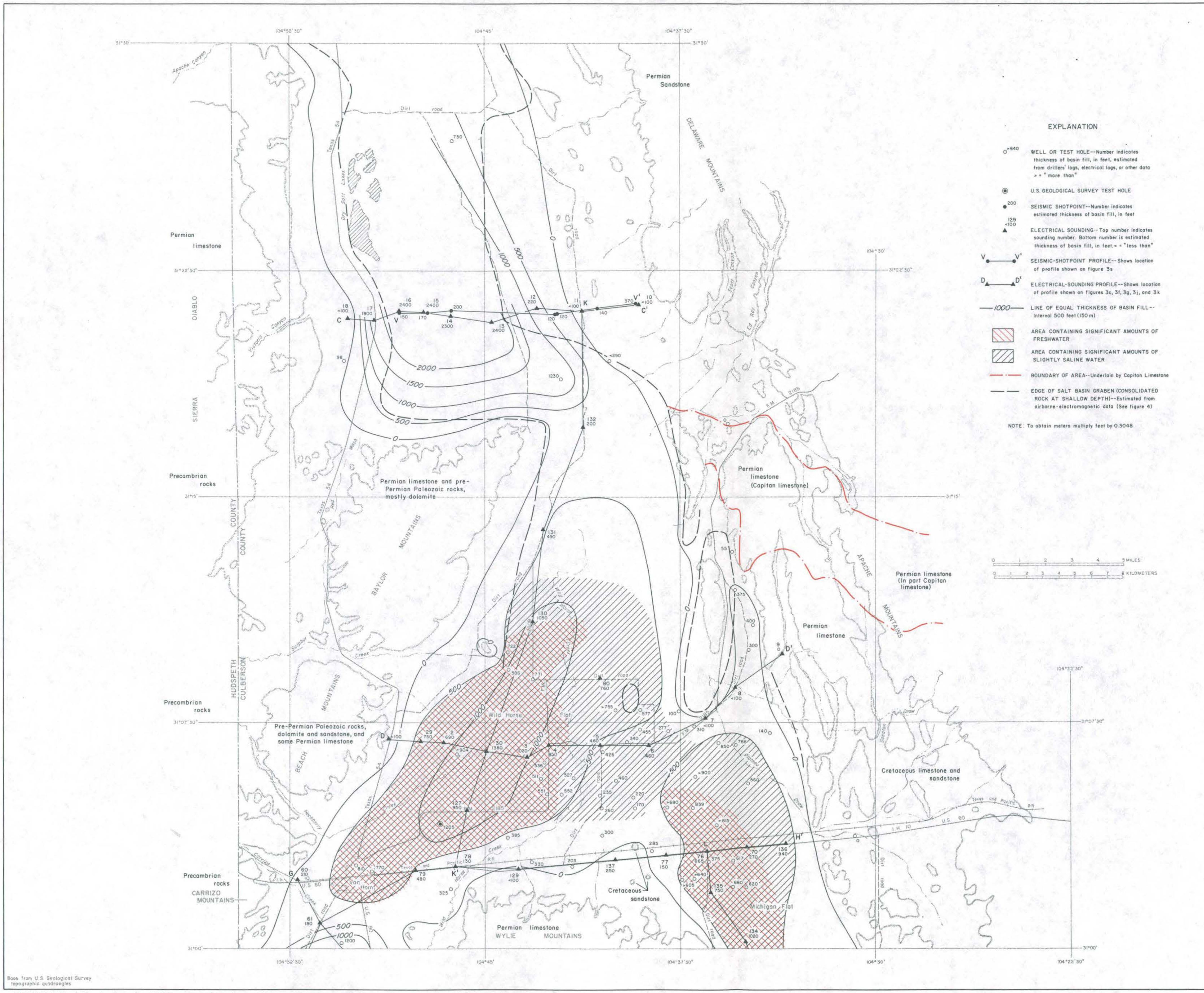

FIGURE 7.-Hydrologic data for Wildhorse and Michigan Flats and locations of electrical soundings and seismic shotpoints

resistive material. The maximum thickness of the fill ranges from 1,000 to 1,200 feet (300 to 370 m) on the west side of the flat to 400-500 feet (120-150 m) on the east side (figs. 7 and 3c). The Geological Survey test hole at the Culberson County Airport, 4 miles (6 km) northeast of Van Horn (fig. 7), penetrated 1,205 feet (367 m) of fill; but the material was partly to well cemented and less permeable below about 1,000 feet or 300 m (Gates and White, 1976, p. 59).

The basin fill at Michigan Flat is between 500 and 1,000 feet (150 and 300 m) thick, and much of the material is coarse grained and resistive (fig. 3k, section L-L').

Two consolidated-rock units, the Capitan Limestone and the Cox Sandstone, locally will yield significant amounts of water. The Capitan crops out in and underlies a band about 4-5 miles (6-8 km) wide in the Apache Mountains (fig. 7) and is as much as 900 feet (270 m) thick (Wood, 1968). The Cox Sandstone crops out in three places north of the Wylie Mountains (fig. 7) and probably underlies much of Wildhorse Flat just north of the Wylie Mountains. In the Wylie Mountains and the hills to the south, the Cox Sandstone is from 130-550 feet (40-170 m) thick (Hay-Roe, 1957). The test hole at the county airport penetrated 60 feet (18 m) of permeable Cox Sandstone (Gates and White, 1976, p. 59).

Most wells in the basin fill of Wildhorse and Michigan Flats yield between 400 and 1,200 gal/min (25-76 L/s), with the largest yields obtained in Michigan Flat and in northwestern Wildhorse Flat. Two aquifer tests reported by Myers (1969, p. 115) and data in the files of the Geological Survey indicate that the transmissivity of the basin fill is from 2,700-12,000 ft^2/d (250-1,100 m^2/d). The specific capacities of the wells range from 5 to 50 (gal/min)/ft [1.0-10 (L/s)/m], and the median of 14 (gal/min)/ft [2.9 (L/s)/m] suggests an average transmissivity of about 4,600 ft^2/d (430 m^2/d).

The specific yield of the basin fill is probably about 10-15 percent. About 1.1 million acre-feet (1.4 km^3) of sediment was dewatered by pumping during a 19-year period from 1954 through 1972. During this period, an annual average of about 10,000 acre-feet (12.3 million m^3) was pumped for a total of 190,000 acre-feet (230 million m^3). If it is assumed that three-fourths of the water was derived from storage and one-fourth (2,500 acre-feet or 3.1 million m^3 per year) was derived from local recharge and subsurface inflow, the specific yield is about 13 percent. These estimates were made by excluding Michigan Flat because water-level declines in this area are not accurately known. If Michigan Flat is included, the total pumpage is estimated to be about 195,000 acre-feet (240 million m^3), and the specific yield would be 11.5 percent.

Few data are available on the Capitan Limestone and Cox Sandstone in this area, but several wells that tap the Capitan in the Apache Mountains yield from 400 to 1,100 gal/min (25-69 L/s). Many wells on the eastern side of Wildhorse Flat tap both the basin fill and the Cretaceous rocks, probably the Cox Sandstone. Most of these wells yield from 400 to 900 gal/min (25 to 57 L/s). A few wells that tap only the Cox Sandstone yield less than 200 gal/min (13 L/s).

Recharge to Wildhorse and Michigan Flats occurs around the margins of the basin and along the channels of Wildhorse Creek and other ephemeral streams. The basin fill is probably also recharged by subsurface inflow from Lobo Flat and from the drainage area south of Michigan Flat. By using the relation between recharge, precipitation, and drainage area, recharge to the Salt Basin south of Bitter Well Mountain is estimated to be on the order of 17,000 acre-feet (21 million m^3) per year, of which about 7,800 acre-feet (9.6 million m^3) is derived from Lobo Flat and Ryan Flat; 3,700 acre-feet (4.6 million m^3) from Michigan Flat; 2,500 acre-feet (3.1 million m^3) from the immediate Wildhorse-Michigan Flats area; and 3,000 acre-feet (3.7 million m^3) from the area between Wildhorse Flat and Bitter Well Mountain. However, the underflow from Lobo and Ryan Flats, based on estimates of the transmissivity and hydraulic gradient, is only about 1,000 acre-feet (1.2 million m^3) per year. The estimate of hydraulic gradient may be erroneous, however, because the water levels have been affected by pumping in the Van Horn and Wildhorse Flat areas.

Figure 8 shows the water levels in Wildhorse and Michigan Flats in January 1973. The water-level contours show that much of the ground water now moves into two water-table depressions--one in Wildhorse Flat and one in Michigan Flat, where it is withdrawn for irrigation. Water north of Wildhorse Flat moves toward and discharges at the salt flat between Sierra Diablo and the Delaware Mountains.

Water-level contours east of Wildhorse Flat also suggest that some ground water discharges out of the basin into the Pecos River drainage area to the east, possibly through the Capitan Limestone in the Apache Mountains. Water levels in the Apache Mountains, however, are about 1,000 feet (300 m) deep and are difficult to measure accurately. Many of the water levels used to construct the map (fig. 8) are reported data and could be erroneous; however, if in error by less than 10-20 feet (3-6 m), they do indicate movement of the water to the east.

Other data also suggest subsurface discharge from this part of the Salt Basin. The water-level contours on figures 5 and 8 indicate the occurrence of a ground-water divide near Bitter Well Mountain, because ground water to the north discharges at the Salt Flats, while the only area of natural discharge to the south is the small salt flat east of Sierra Diablo. The drainage area of the Salt Flats is about 5,000 square miles (13,000 km^2), which is about 1.8 times the 2,760-square-mile (7,150-km^2) drainage area of the rest of the Salt Basin. The Salt Flats at the northern end of the basin, in contrast, are approximately seven times larger than the small salt flat east of the Sierra Diablo; which suggests that about three-fourths of the recharge to the Salt Basin south of Bitter Well Mountain could have discharged from the basin in the subsurface prior to development.

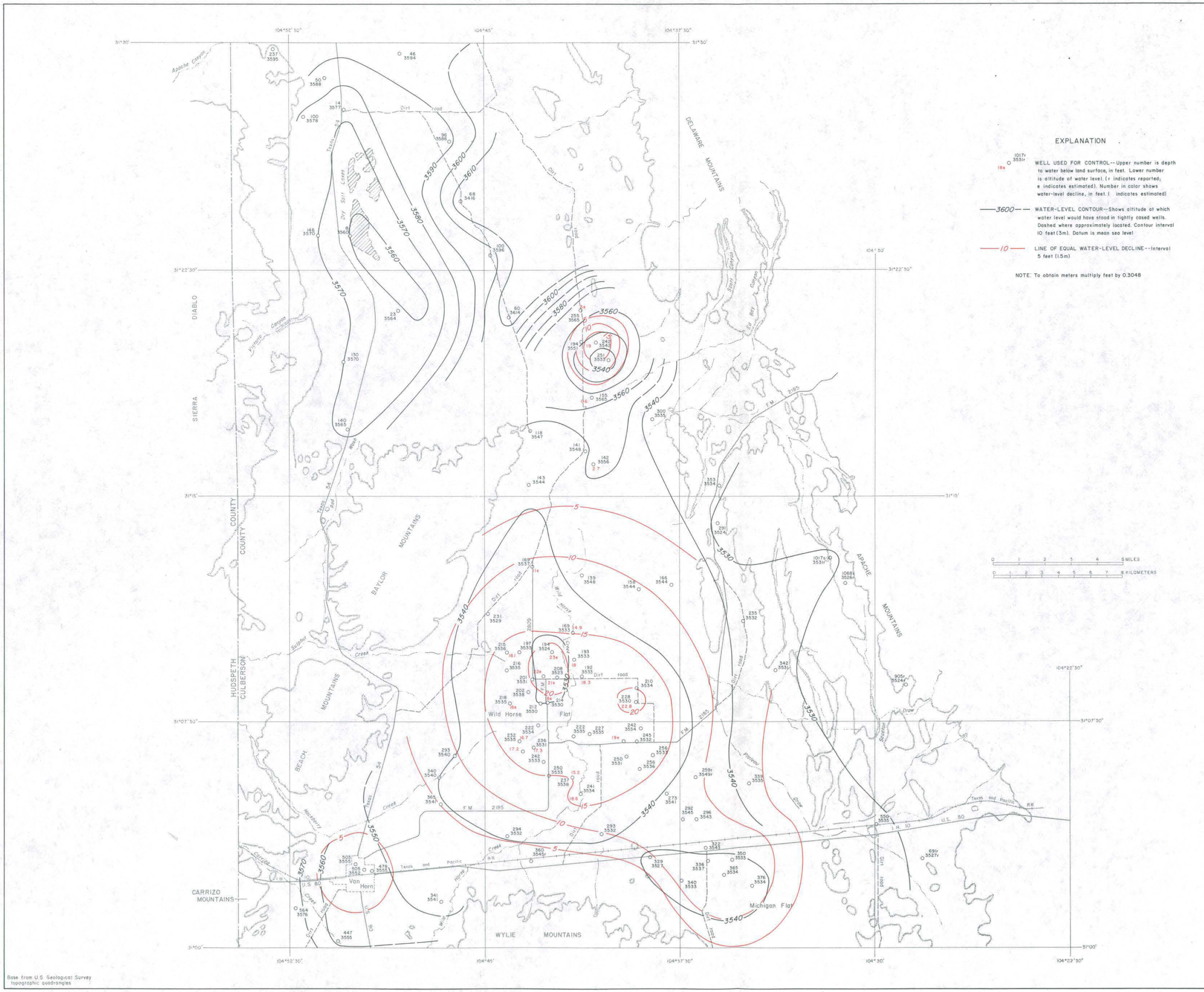

FIGURE 8.-Water levels in 1973 and water-level declines during 1954-73 in Wildhorse and Michigan Flats

In addition, before development began, water levels in Wildhorse Flat were apparently at the same altitude or slightly lower than water levels in the salt flat east of Sierra Diablo, suggesting that only the ground water north of Wildhorse Flat (About 18 percent of the area of the Salt Basin south of Bitter Well Mountain) discharged at the salt flat, and that much of the ground water in Wildhorse Flat and areas to the south discharged by subsurface flow to the east. Pumping at Wildhorse Flat, however, has probably lowered water levels enough to intercept some of this subsurface discharge and may in time induce subsurface inflow into the Salt Basin.

Quality of Ground Water

Figure 9 shows the quality of ground water in the Wildhorse and Michigan Flats area. At the northern end of the area, around the salt flat, ground water in the basin fill is fresh to slightly saline along the western edge of the basin, slightly to moderately saline along the eastern side, and probably very saline or poorer quality under most of the salt flat, where it has been concentrated by evapotranspiration. On the western side of Wildhorse Flat and in Michigan Flat, where the basin fill is thickest and probably coarser grained, the ground water is fresh, containing 350-500 mg/L dissolved solids in Michigan Flat and around Van Horn, and 600-1,000 mg/L in northwestern Wildhorse Flat.

On the eastern side of Wildhorse Flat, where the fill is thinner and possibly finer grained, the ground water is slightly saline, containing 1,000-2,000 mg/L dissolved solids. Some of the wells in this area probably also tap the Cox Sandstone, which may contain slightly saline water. The water-quality data indicate that fresh ground water flows into the area from Lobo Flat and from the southern end of Michigan Flat, and becomes more mineralized as it moves toward the north.

The map (fig. 9) also shows available data on the quality of water in the consolidated rocks on the edges of the basin. The Delaware Mountain Group in the foothills of the Delaware Mountains contains slightly to moderately saline water, and the Capitan Limestone in the Apache Mountains contains fresh to slightly saline water. The Geological Survey test hole at the county airport obtained freshwater from the Cox Sandstone, and another well obtains slightly saline water from the Cox.

Development of Ground Water, Volumes of Fresh and Slightly Saline Water in Storage, and Problems Associated with Future Development

Pumping for irrigation in the Wildhorse Flat area began late in 1949, increased during the 1950's, and since then has been fairly stable. In 1967, 38 wells produced about 11,500 acre-feet (14.2 million m^3). Pumping for irrigation in Michigan Flat began in 1970. In 1972, 43 wells in Wildhorse and Michigan Flats withdrew about 10,000 acre-feet (12.3 million m^3) to irrigate 4,020 acres (16 km^2) of cotton, feed grains, alfalfa, and vegetables, for an average of about 2.5 acre-feet per acre (0.76 m^3/m^2). This estimate is based on relations between water production and fuel or power consumption for 13 wells, basin-wide fuel and power consumption,

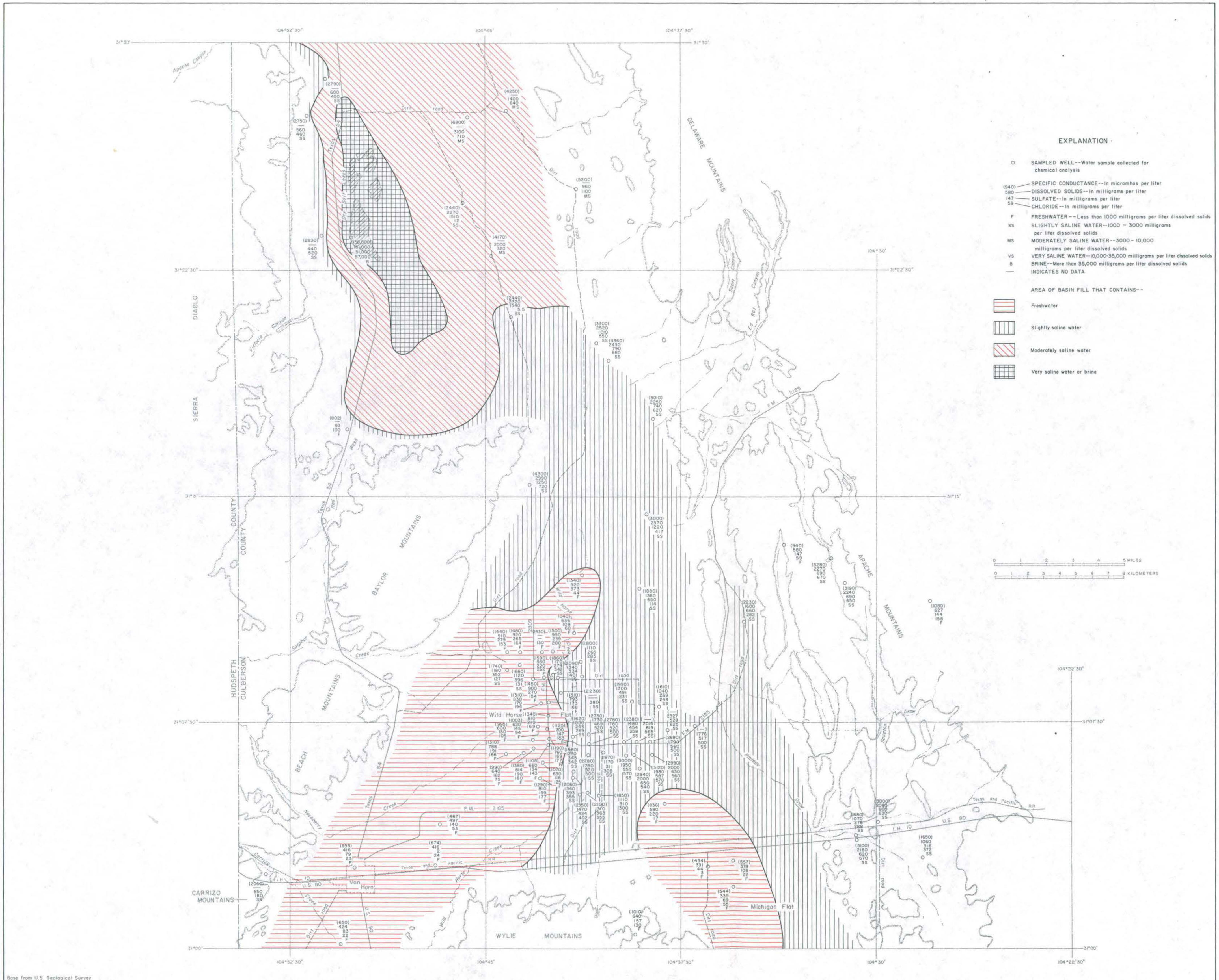

FIGURE 9.-Quality of ground water in Wildhorse and Michigan Flats

and irrigated acreage. It is estimated that the total pumpage for the 23 years from 1950 through 1972 was about 230,000 acre-feet (280 million m^3), which would be an average of 10,000 acre-feet (12.3 million m^3) per year.

Figure 8 shows that water levels declined 15 to 20 feet (4.6 to 6 m) or more over much of Wildhorse Flat in the 19 years between 1954 and 1973, an average of about 1 foot (0.3 m) per year. The maximum decline between 1949 and 1973 was about 25 to 30 feet (7.6 to 9 m). Declines in Michigan Flat were about 1-3 feet (0.3-0.9 m) per year between 1970 and 1973. The long-term and widespread decline in water levels in response to annual withdrawals of about 10,000 acre-feet (12.3 million m^3) indicates that recharge is less than 10,000 acre-feet (12.3 million m^3) per year. However, recharge may be larger if substantial quantities of water are discharged from the basin in the subsurface.

The amount of freshwater remaining in the basin fill is about 1.52 million acre-feet (1.87 km^3) in Wildhorse Flat and about 0.42 million acre-feet (520 million m^3) in Michigan Flat, for a total of about 1.94 million acre-feet (2.4 km^3). In addition, about 1.03 million acre-feet (1.3 km^3) of slightly saline water is in storage on the east side of Wildhorse Flat. The areas in which these volumes of water are stored are shown on figure 7. Because the thickness of the fill is poorly known around the edges of the basin, only those areas where the fill is at least 500 feet (150 m) thick were included in the estimates. The only exception is the area of shallow bedrock between Wildhorse and Michigan Flats, where the fill thickness is fairly well defined.

The freshwater estimates are based on fill thicknesses of 700 to 800 feet (210 to 240 m) and saturated thicknesses of 250 to 600 feet (76 to 180 m) over 49 square miles (130 km^2) of Wildhorse Flat, and average fill thicknesses of 600 to 750 feet (180 to 230 m) and saturated thicknesses of 180-400 feet (55-120 m) over 17 square miles (44 km^2) of Michigan Flat. The estimates of slightly saline water are based on average fill thicknesses of 300 to 800 feet (91 to 240 m) and saturated thicknesses of 25 to 600 feet (8 to 180 m) over 49 square miles (130 km^2). Although the specific yield of the upper part of the basin fill is about 13 percent, the average specific yield was assumed to be 10 percent because the deeper sediments have a lower porosity. The logs of the test hole at the county airport indicated that permeability, porosity, and specific yield decreased below 740 feet or 226 m (Gates and White, 1976, p. 59).

The volumes of water stored in the Capitan Limestone and the Cox Sandstone were not estimated because few data are available on the extent and thickness of the permeable zones in these consolidated-rock aquifers. Water levels in the Capitan Limestone in much of the Apache Mountains area are deep, and it is not likely that this water could be economically withdrawn for irrigation.

The problems associated with pumping ground water from the basin fill in Wildhorse and Michigan Flats include encroachment of saline water from the north and water-level declines. Contamination by the encroachment of water of poor quality would probably be minor, however, because the fine-grained basin fill north of Wildhorse Flat would release water slowly, and the distance of saline water to the center of pumping is about 15 miles (24 km).

At present, water levels are declining about 1 foot (0.3 m) per year in Wildhorse Flat and 1-3 feet (0.3-0.9 m) per year in Michigan Flat, in response to an average of 10,000 acre-feet (12.3 million m^3) of annual pumpage. Withdrawals of 30,000 acre-feet (37 m^3) per year would cause annual declines of at least 3 to 9 feet (0.9 to 3 m). Declines for a given rate of withdrawal will increase as the basin is dewatered because the deeper sediments have lower porosity and permeability and because the area of the basin decreases with depth.

Ground Water in the Capitan Limestone Between the Beacon Hill Area and the Apache Mountains

The position of the Capitan Limestone between the Beacon Hill irrigation area and the Apache Mountains is not known. The circumstances of deposition are considered to be either one or some combination of the following: (1) The Capitan was not deposited entirely across this area because there was a channel through the reef to the Delaware Basin; (2) it was deposited partly over the present Sierra Diablo and subsequently eroded; or (3) it was faulted down into the Salt Basin and underlies the basin fill. Hiss (1973, fig. 1), who has studied the Capitan in other areas of southeastern New Mexico and west Texas, assumed that the formation was deposited between the Guadalupe and Apache Mountains.

Figure 10 shows the inferred position of the Capitan on the assumption that it was deposited as a continuous unit between the Beacon Hill area and the Apache Mountains and then downfaulted into the Salt Basin graben. The Capitan was located in the Beacon Hill area and in areas near the Apache Mountains where it is tapped by water wells. Between these known occurrences, the Capitan was located west of the area in which sands in the Delaware Mountain Group equivalent to the Capitan crop out (King, 1949).

The Capitan could not be detected beneath the basin fill by using resistivity and seismic data across its inferred position (figs. 3a, 3b, and 3s). The Capitan is a difficult target for geophysical exploration (1) because if it is present, it is beneath 800 to 2,400 feet (240 to 730 m) of fine-grained fill containing salty water; (2) because of its narrow width and internal variations in porosity and water quality; and (3) because of a possible lack of contrast in electrical and other properties between the Capitan and laterally equivalent formations.

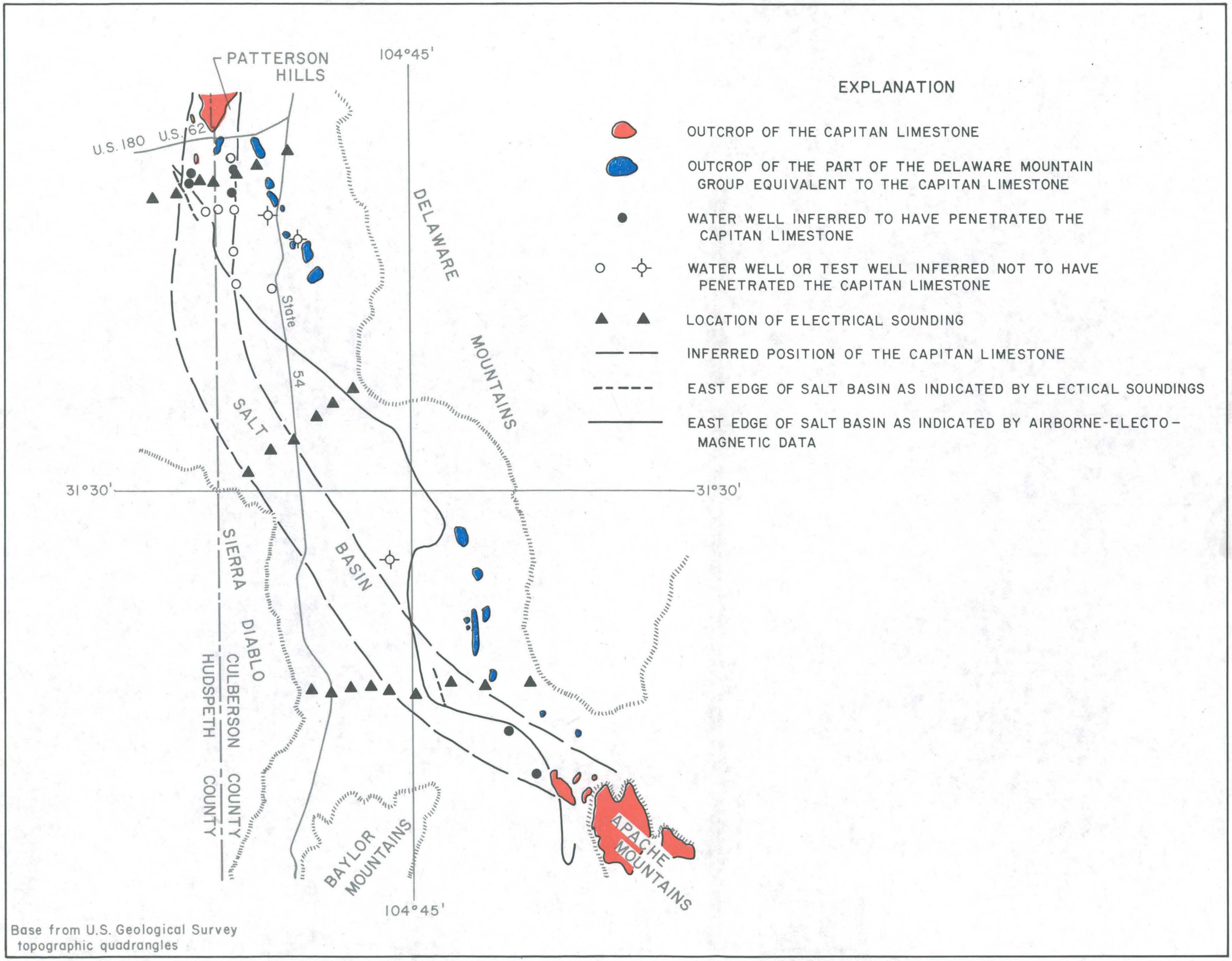

FIGURE 10.-Inferred position of the Capitan Limestone between the Beacon Hill area and the Apache Mountains

If the Capitan does underlie the Salt Basin, it probably contains salty water. Recharge to the Capitan would be small, and ground-water circulation would be limited if it is completely or partly separated by faulting from its outcrop or occurrences at shallow depths in the Beacon Hill and Apache Mountains areas. Movement of the ground water would be slow because of the depth of the Capitan and because ground water, at least in the northern half of the area, probably discharges slowly upward from the Capitan through a thick section of fine-grained basin fill. The water would become mineralized because of its slow movement.

LOBO FLAT AND ADJACENT AREAS

Lobo Flat and adjacent areas, shown on figure 11, consist of the Lobo Flat part (including Chispa Flat) of the Salt Basin, the hills and mountains south of the Wylie Mountains and west of the Davis Mountains, and the southern end of Michigan Flat. The Lobo Flat part of the Salt Basin extends from a few miles south of Van Horn to Rubio Dome, 5 miles (8 km) northwest of Valentine. Lobo Flat itself extends from the northern end of the Van Horn Mountains to about the Culberson-Jeff Davis County line; the area between the county line and Rubio Dome is locally called Chispa Flat.

Ground-Water Hydrology

The aquifers in the Lobo Flat area include the basin fill, the underlying volcanic-clastic deposits, and locally may include the adjacent or underlying volcanic rocks. Probably all these aquifers are in hydraulic continuity. The basin fill is the principal aquifer, and except for some sections of clay, is water bearing and permeable throughout the area.

The volcanic clastics probably are permeable where they are mostly fluvial and well-sorted. Volcanic rocks, including flows and ash-flow tuffs, have low permeability except where they are highly fractured; although weathered interflow zones are commonly permeable. Ash-fall tuffs generally have low permeability, especially if many of the grains have been altered to clay. Volcanic rocks and volcanic clastics are known to be water bearing and permeable in parts of westernmost Texas. Six wells near Marfa, Texas, about 60 miles (97 km) southeast of Lobo Flat, yield from 400 to 1,200 gal/min (25 to 76 L/s) from volcanic clastics, ash-flow tuff, and basalt (Davis, 1961, table 3).

Most of the geologists who have mapped volcanic rocks and volcanic clastics in westernmost Texas, such as Twiss (1970) and Underwood (1963), have considered them to be older than the upper Tertiary and Quaternary basin fill. In the east-central part of Lobo Flat (fig. 11), drillers' logs of wells indicate that volcanic rocks were penetrated at depths as shallow as 100 feet (30 m), and were interbedded with basin fill below 100 feet (30 m). If these thin beds of "hard rock," "lava rock," "black lime," "lime," or "red rock" are actually volcanics, the underlying unconsolidated material could be volcanic clastics.

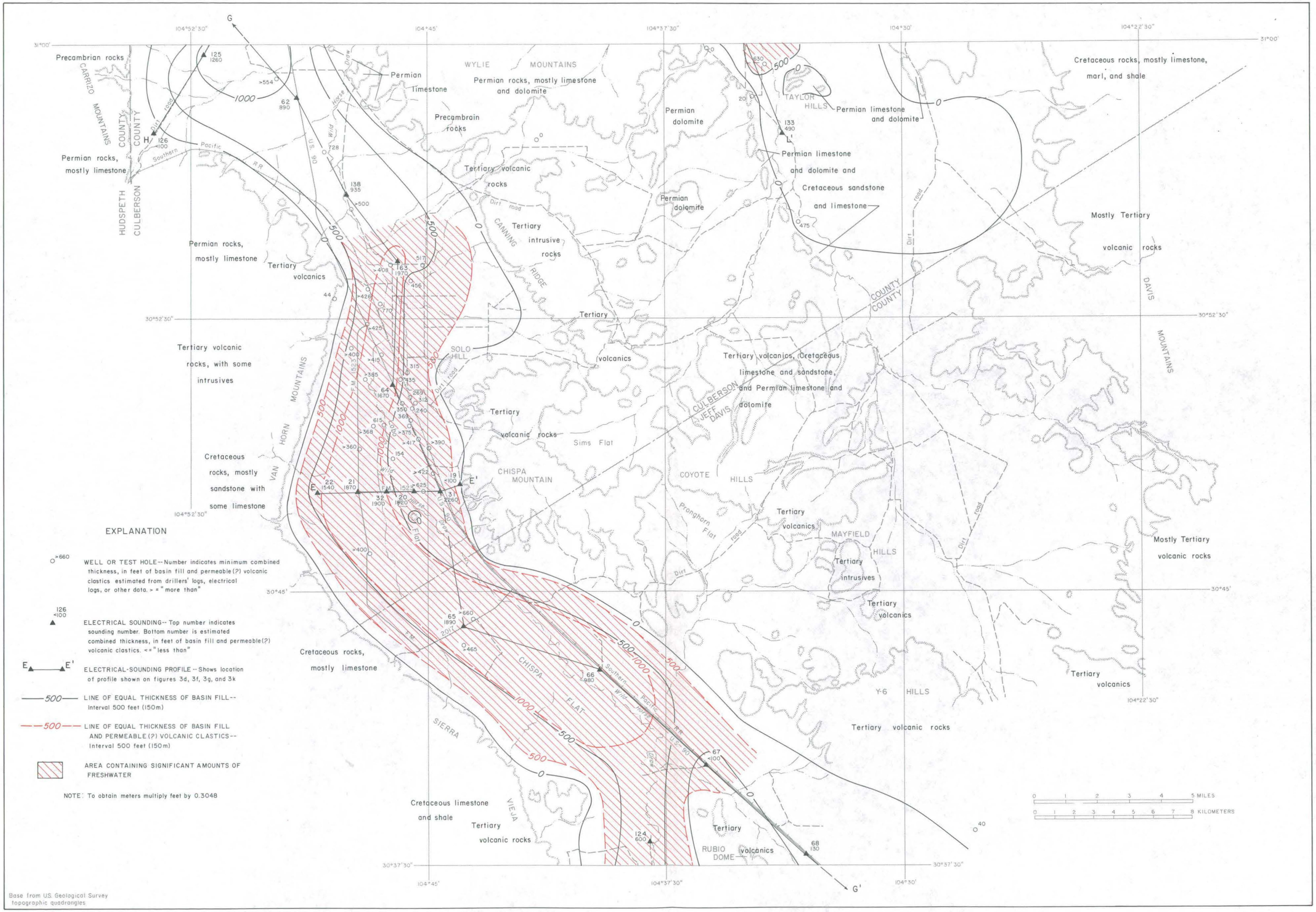

FIGURE 11.-Hydrologic data for Lobo Flat and adjacent areas and locations of electrical soundings

The basin fill and volcanics are difficult to distinguish by using resistivity or available hydrologic data. The basin fill, volcanic clastics, unaltered ash-fall tuff, and alternating volcanic flows or ash-flow tuff and ash-fall tuff all have about the same average range (10-60 ohm-meters) of resistivities. In addition, there is no significant difference in the quality of the water in the fill and the volcanics. Only where the basin fill or volcanic clastics are underlain by a thick series of volcanic flows and ash-flow tuffs can any division be made. In turn, resistivity data are usually inadequate to determine the base of water-bearing and permeable zones in volcanic clastics. For example, Gates and White (1976, p. 43-45) reported that the U.S. Geological Survey's Clay Evans test hole, drilled about 30 miles (48 km) southeast of Lobo Flat on Ryan Flat, penetrated about 385 to 555 feet (117-169 m) of basin fill, then permeable reworked volcanic clastics to a depth of about 1,250 feet (381 m). Below a depth of about 1,250 feet (381 m), the materials were volcanic rocks and altered ash-fall tuff, probably of low permeability. Data from an electrical sounding near the test hole, used apart from the test-hole data, did not clearly indicate the base of the fill or the base of the permeable material.

Figure 11 shows the estimated depths of the basin fill and the permeable water-bearing material, including the basin fill and volcanic clastics. Figure 3d (profile E-E'), which is an east-west section of resistivity across Lobo Flat, shows that the combined section of fill and all types of volcanics extends to depths of 1,400 to 3,200 feet (430 to 980 m). Figure 3f (profile G-G'), which is a north-south section of resistivity along the Lobo Flat part of the Salt Basin, shows a combined section (soundings 62 to 67) of basin fill and volcanics to depths of 900 to more than 4,000 feet (270 to more than 1,220 m). The depth of the basin fill was estimated mostly from drillers' logs of wells, and the maximum thickness was generally assumed to be between 500 and 1,000 feet (150 and 300 m). The maximum thickness of permeable material was assumed to be on the order of 1,000 feet (300 m) because six wells in the Lobo Flat area have been drilled through 600 to 830 feet (183 to 253 m) of fill and volcanic clastics, most of which is permeable.

At the northern edge of the Lobo Flat area, between the Carrizo and Wylie Mountains, resistivity data on the southwest end of the cross section on figure 3g and a driller's log of the well on figure 7 just north of its boundary with figure 11, indicate the occurrence of about 1,200 feet (370 m) of basin fill. Some of this material, however, may be Cretaceous sandstone and shale because the well yields in this area suggest that it has low to moderate permeability. The basin fill at the north end of the Lobo Flat area probably is not underlain by volcanics north of sounding 63.

On the east side of Lobo Flat, between Solo Hill and Chispa Mountain, drillers' logs of wells and resistivity data at soundings 20 and 31 indicate that volcanic rock occurs at depths of 100 to 450 feet (30 to 140 m). Three-fourths of a mile (1.2 km) south of sounding 20, a knob of andesite projects through the basin fill on the floor of Lobo Flat (Twiss, 1959).

The logs of several nearby wells and the resistivity data, however, indicate that the volcanic rocks are interbedded with and underlain by volcanic clastics.

In the Chispa section of the Lobo Flat area, south of the Culberson-Jeff Davis County line, few well data are available. However, several wells penetrated more than 450 feet (140 m) of permeable material; and resistivity data at soundings 65 and 66 (fig. 3f) indicate the occurrence of a thick section of basin fill and volcanic clastics. Rubio Dome, at the southern end of the area, is composed of basalt, and sounding 67 north of the dome indicates that solid volcanic rocks occur at shallow depth.

Most wells in the Lobo Flat area yield from 400 to 1,400 gal/min (25 to 88 L/s), with low- and high-yield wells located in most parts of the area in no particular pattern. However, three of the four wells that yield more than 1,200 gal/min (76 L/s) are in east-central Lobo Flat, where volcanic rocks occur at shallow depths, and these wells may tap permeable zones in the volcanics. Two aquifer tests in the Lobo Flat area compiled by Myers (1969, p. 116) gave transmissivities of 3,700-4,100 ft^2/d (340-380 m^2/d). Specific capacities range from 4 to 46 (gal/min)/ft [0.8 to 9.5 (L/s)/m], and the median of 24 (gal/min)/ft [5.0 (L/s)/m] suggests an average transmissivity of about 7,900 ft^2/d (730 m^2/d). Well yields and specific capacities have probably declined because of the large declines in water levels in Lobo Flat (p. 62), and transmissivities have probably decreased because the saturated thickness of the aquifers has decreased.

On the basis of ground-water withdrawals and water-level declines, the specific yield of the basin fill is estimated to be about 6 percent. About 5.2 million acre-feet (6.4 km^3) of sediment was dewatered by pumping during the 22-year period 1951 through 1972, as estimated from the contours of water-level declines (fig. 12). During this period, about 340,000 acre-feet (420 million m^3) of water was pumped. If under natural conditions about 1,600 acre-feet (2.0 million m^3) per year of water flows through Lobo Flat (see p. 59), and about 1,000 acre-feet (1.2 million m^3) of this subsurface flow is discharged by pumping, the specific yield is the ratio of pumpage (minus intercepted natural discharge) to the volume of dewatered sediment, which is about 6 percent.

This value of specific yield is lower than that for Wildhorse Flat, and may indicate that the basin fill of Lobo Flat is finer grained or less sorted. The low specific yield is partly a result, however, of incomplete drainage of the sediments, either because (1) the fill is less permeable vertically than horizontally, (2) because clay lenses result in locally perched bodies of ground water, or (3) because clay makes up a significant part of the fill and yields little water. During the winter (nonpumping season), water in many wells can be heard cascading from shallow perforations to the water surface, indicating that some shallow zones are not completely drained. Also, several stock and domestic wells still produce water from shallow zones above the current (1977) water table. Drainage probably will be incomplete throughout the progressive dewatering of the basin, and the "effective" specific yield may always be low.

Recharge to the Lobo Flat area occurs around the margins of the basin and along the channel of Wildhorse Creek. Ground water also flows into Lobo Flat from Ryan Flat to the south. By using the relation between recharge and drainage area (p. 14), recharge to the Ryan Flat part of the Salt Basin is about 5,800 acre-feet (7.2 million m^3) per year and recharge to the Lobo Flat area is about 2,000 acre-feet (2.5 million m^3) per year. The total of 7,800 acre-feet (9.6 million m^3) should flow through the Lobo Flat area. However, on the basis of a transmissivity of 4,000 ft^2/d (370 m^2/d); an average hydraulic gradient, derived from a number of 1943 water-level measurements, of 12 ft/mi (2.3 m/km); and a width of flow of 4 miles (6.4 km); the flow through Lobo Flat is only about 1,600 acre-feet (2.0 million m^3) per year.

The water-level contours on figure 12 show that ground water moves northward from Ryan Flat through Lobo Flat to Wildhorse Flat. Pumping has distorted the water-level contours and created shallow cones of depression in northern Lobo Flat and Chispa Flat. These small depressions are not shown on the water-level map because of the large contour interval.

Quality of Ground Water

Figure 13 shows the quality of ground water in the Lobo Flat area. Ground water in the basin fill and in the upper part of the volcanic rocks, with the exception of samples from two wells, is uniformly fresh, mostly containing water with a dissolved-solids concentration of 300 to 400 mg/L. The low dissolved-solids concentration is probably related to the high proportion of relatively insoluble volcanic rock in the basin fill and volcanic clastics and to a lack of natural discharge by evapotranspiration that would concentrate salts in the water.

The two samples of slightly saline water were from wells perforated at depths as shallow as 80-100 feet (24-30 m). The shallow ground water is locally perched and may be slightly saline because of the infiltration of irrigation water in which salts have been concentrated by evapotranspiration. Figure 13 shows that the ground water is generally fresh in the consolidated rocks and in the shallow alluvium in the hills and the upper Michigan Flat drainage area east of Lobo Flat.

Development of Ground Water, Volumes of Freshwater in Storage, and Problems Associated with Future Development

Pumping for irrigation of feed grains, alfalfa, and cotton in the Lobo Flat area began in 1949, increased rapidly in the early 1950's, and remained fairly stable since the 1950's. In 1949, about 7,500 acre-feet (9.2 million m^3) was pumped to irrigate 2,500 acres (10 km^2); and in 1950, 17,000 acre-feet (21 million m^3) was applied to 7,000 acres or 28 km^2 (Hood and Scalapino, 1951, p. 6). In 1967, about 11,500 acre-feet (14.2 million m^3) was pumped from 39 wells (Davis and Gordon, 1970, p. 2). In 1972, about 16,000 acre-feet (20 million m^3) was pumped from 61 wells to irrigate about 6,400 acres (26 km^2), which is an average of about 2.5 acre-feet per acre (0.76 m^3/m^2).

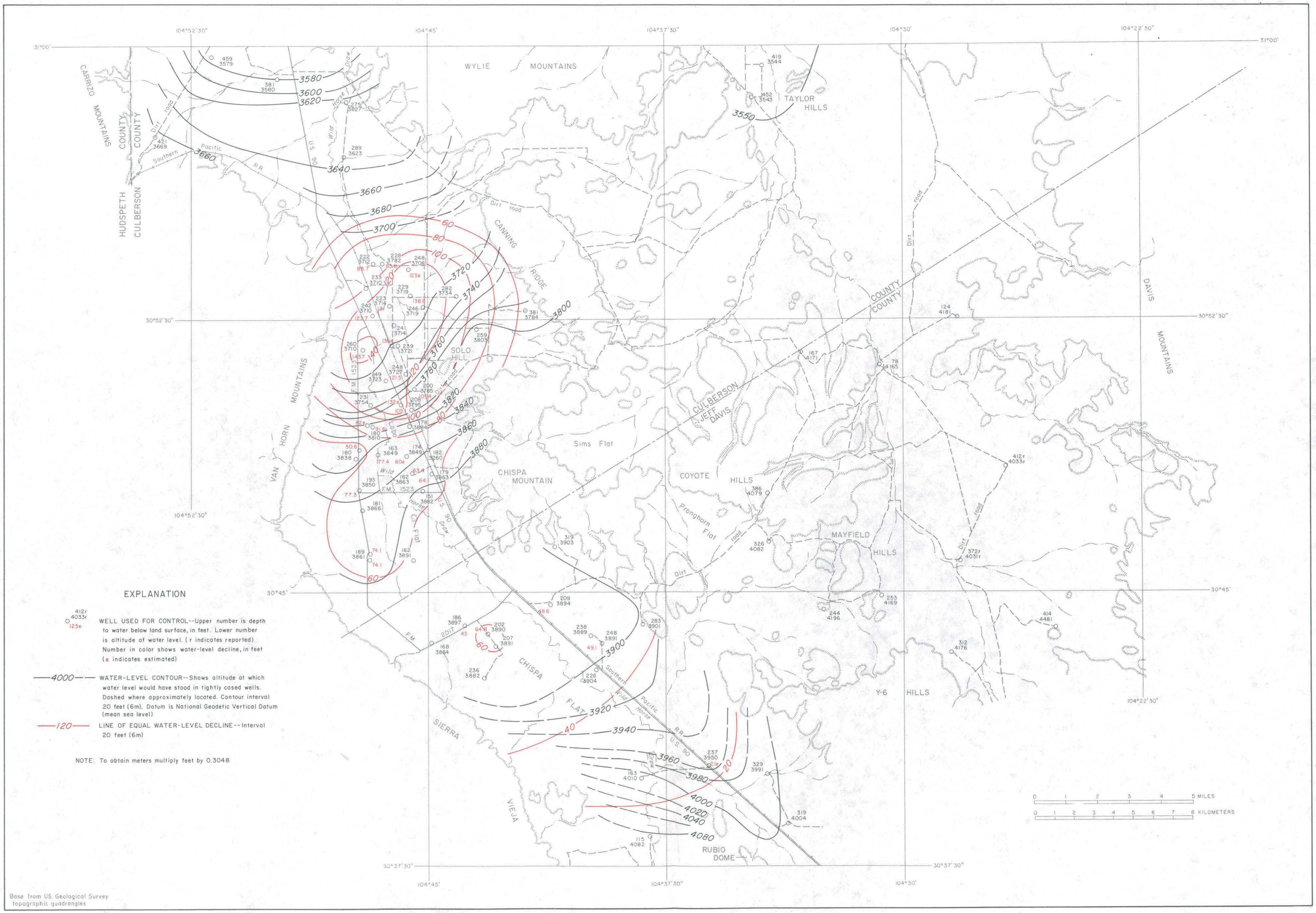

FIGURE 12.-Water levels in 1973 and water-level declines during 1951-73 in the Lobo Flat area

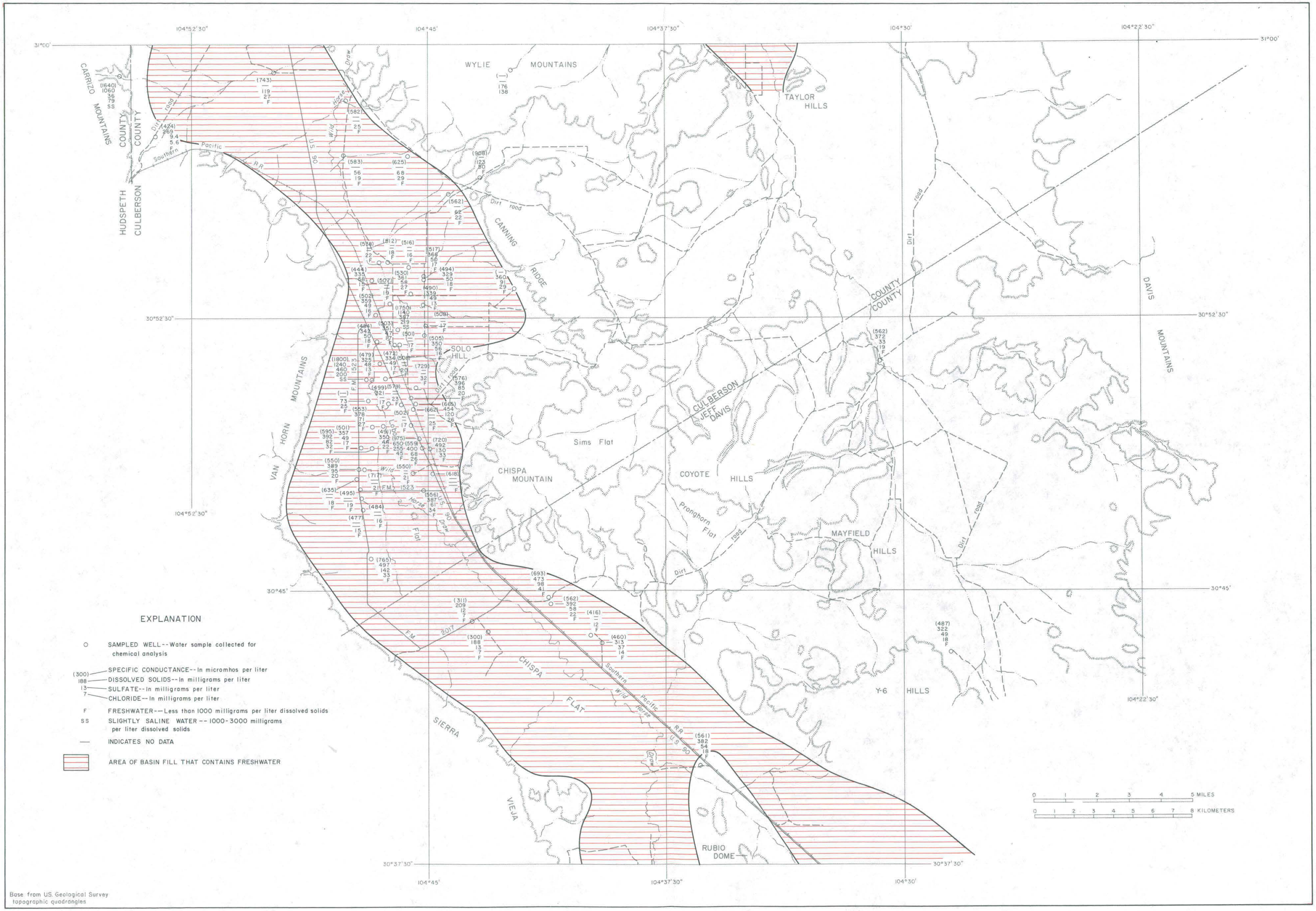

FIGURE 13.-Quality of ground water in the Lobo Flat area

This estimate of pumping is based on the ratios of water production and fuel or power consumption for 24 wells, basin-wide fuel and power consumption, and irrigated acreage. The estimated total pumpage for the 24 years from 1949 through 1972 was about 360,000 acre-feet (444 million m^3), or an average of about 15,000 acre-feet (18.5 million m^3) per year.

Figure 12 shows that water levels in the Lobo Flat area declined from 22 to 144 feet (6.7 to 44 m), or 1 to 6.5 feet (0.3 to 2 m) per year in the 22 years from 1951 to 1973. Declines were more than 100 feet (30 m) over much of Lobo Flat and 40-60 feet (12-18 m) over Chispa Flat. The large water-level declines probably result from the low specific yield of the basin fill, and to a lesser extent from the small area of the basin.

The amount of freshwater remaining in the basin fill and in the permeable volcanic clastics was estimated for several subareas of the Lobo Flat area (fig. 11). No estimates were made for the northern end of the area between the Carrizo and Wylie Mountains because well logs and yields indicate that the permeability of the subsurface material is low.

Estimates for the other subareas were made in three categories: (1) Where development of ground water has been significant and where hydrologic data and geophysical data are available; (2) where ground-water development has been minor and limited hydrologic and geophysical data are available; and (3) where ground water has not been developed and only geophysical data are available.

In the heavily-developed northern and central parts of Lobo Flat, extending south to FM Highway 1523, both hydrologic and geophysical data are available. These data indicate that about 540,000 acre-feet (666 million m^3) of freshwater is in storage. In the southern part of Lobo Flat, from FM Highway 1523 to the Culberson-Jeff Davis County line, and in the Chispa Flat area, ground-water development is less extensive and limited hydrologic data and geophysical data are available. On the basis of the available data, however, it is estimated that about 730,000 acre-feet (900 million m^3) of freshwater is stored in this subarea. At the southeastern end of Lobo Flat, northwest and west of Rubio Dome, ground water has been developed only for stock supply, and only geophysical data are available. In this subarea, it is estimated that about 230,000 acre-feet (284 million m^3) of freshwater is in storage. The estimated total volume of fresh ground water in 97 square miles (250 km^2) of the Lobo Flat area is about 1.5 million acre-feet (1.85 km^3).

These estimates of the amounts of freshwater in storage were made by using an average thickness of the basin fill and permeable volcanic clastics of 750 feet (230 m) in Lobo Flat and Chispa Flat, and 500 feet (150 m) in the areas around Rubio Dome. The saturated thicknesses were assumed to be 520 to 575 feet (158 to 175 m) in Lobo and Chispa Flats and 350 to 400 feet (110 to 120 m) around Rubio Dome. A specific yield of 5 percent was used in the calculations. The estimates of the thickness of the fill and permeable volcanic clastics may be conservative because no wells have been drilled through the entire permeable section. Six wells, however, have been drilled through 600 to 830 feet (183 to 253 m) of fill and volcanic clastics, most of which is probably permeable. The specific yield of 5 percent for the entire section was estimated to be slightly less than the 6 percent specific yield of the material already dewatered because the deeper material, much of which may be volcanic clastics, may be less porous.

A major problem in pumping ground water from the Lobo Flat area at the present or higher rates are the large water-level declines resulting chiefly from the low specific yield of the reservoir. If, for example, 30,000 acre-feet (37 million m^3) per year, which is about double the past average, were withdrawn, the maximum annual water-level decline would be 13 feet (4 m) or more. No poor quality ground water is adjacent to or is known to underlie the fresh groundwater of the Lobo Flat area; therefore, the freshwater would not be contaminated by the encroachment of salty water during progressive development.

RYAN FLAT AND ADJACENT AREAS ALONG THE RIO GRANDE

Ryan Flat is the southern end of the Salt Basin drainage area, and extends southeast from Rubio Dome to the drainage divide 10 miles (16 km) northwest of Marfa, Texas (figs. 1 and 14). Capote Draw extends south from Ryan Flat more than 20 miles (32 km) between Capote Mountain and Cuesta Del Burro. Most of the highlands around Ryan Flat are composed of volcanic rocks of Tertiary age. Southwest of Rubio Dome is a small basin area tributary to Chispa Flat, separated from Ryan Flat by Rubio Dome and other outcrops of volcanic rocks to the south.

The narrow valley of the Rio Grande is also shown on figure 14, from the Cretaceous rocks of Sierra de Pilares on the western edge of the area, into the northern end of the Presidio bolson. The area between the Rio Grande and Ryan Flat is composed of volcanic rocks--ash-flow and ash-fall tuffs, rhyolite, and volcanic clastics, underlain by rocks of Cretaceous age. No structural basins with thick deposits of basin fill occur between the southern end of the Green River Valley, just east of the Sierra de Pilares, and the Presidio bolson; this area contains only shallow erosional valleys with thin alluvial deposits along ephemeral streams tributary to the Rio Grande. Some rocks of Permian age crop out beneath the volcanics between Capote Draw and the northern end of Presidio bolson.

The Tertiary volcanics of the Ryan Flat area are mostly thick flows north and east of Ryan Flat in the Davis Mountains, Y-6 Hills, and Chispa Mountain, and thinner ash-flow tuffs and flows interbedded with thick ash-fall tuffs and volcanic clastics around Ryan Flat. Walton (1975, fig. 2) published the most recent stratigraphic section of the volcanics. In descending order, the upper part (rocks of Oligocene age) includes the Petan Basalt, the Mitchell Mesa Ignimbrite (the Brite Ignimbrite of Twiss, 1970, fig. 8), the Capote Mountain Formation, the Bracks Rhyolite, the Chambers Formation, and the Buckshot Ignimbrite. The Mitchell Mesa and Buckshot Ignimbrites are ash-flow tuffs, and the Capote Mountain and Chambers Formations are predominantly volcanic clastics, mostly fine-grained

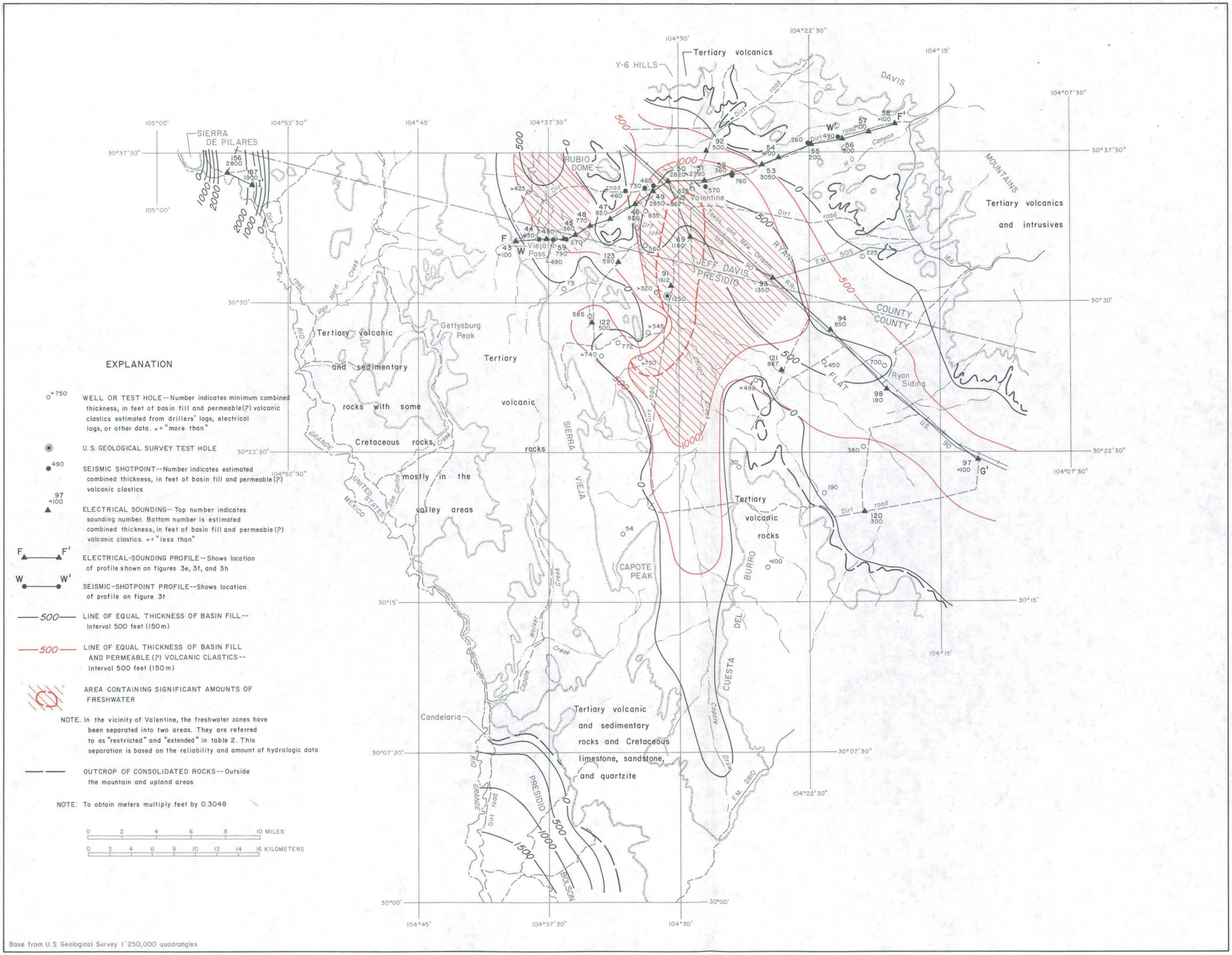

FIGURE 14.-Hydrologic data for Ryan Flat and adjacent areas along the Rio Grande and locations of electrical soundings and seismic shotpoints

tuffaceous sediments, but include nonmarine limestone and conglomerate. Twiss (1970, fig. 8) gives an approximate thickness of 300 feet (91 m) for the Petan, 50 feet (15 m) for the Mitchell Mesa, 1,800 feet (549 m) for the Capote Mountain, 150 feet (46 m) for the Bracks, 600 feet (183 m) for the Chambers, and 50 feet (15 m) for the Buckshot.

Ground-Water Hydrology

The principal aquifers of Ryan Flat are the basin fill and the water-bearing, permeable sections of the underlying volcanic clastics. The principal aquifer in the Rio Grande Valley is the alluvium underlying the flood plain.

The basin fill and volcanic clastics of the Ryan Flat area are probably similar in lithology to those of Lobo Flat, although the fill may be thinner in Ryan Flat. Figure 14 shows the estimated thickness of both the basin fill and the estimated total thickness of the water-bearing, permeable material, including the basin fill and the volcanic clastics. The thicknesses were estimated by using resistivity and seismic-refraction data; and drillers' logs and data from water wells, oil tests, and the U.S. Geological Survey Clay Evans test hole, 5 miles (8 km) south of Valentine, Texas (fig. 14).

Figure 3e (profile F-F') is a resistivity section across Ryan Flat through Valentine; figure 3t (profile W-W') is a cross section of seismic velocity constructed by using data from a seismic-refraction survey along the resistivity profile; and the southeast end (soundings 68-97) of figure 3f (profile G-G') is a cross section of resistivity across Ryan Flat along U.S. Highway 90. As in Lobo Flat, the basin fill cannot be distinguished easily from the volcanic clastics, or can the fill and permeable volcanic clastics be distinguished easily from low-permeability volcanic clastics. It is possible, however, to distinguish the basin fill, volcanic clastics, and ash-fall tuff from the massive volcanic flows or ash-flow tuffs of high resistivity and higher seismic velocity. This differentiation is useful only locally in delineating ground-water reserves.

Figures 3e and 3f show that the total thickness of the basin fill and volcanic rocks of various types ranges from about 740 feet (230 m) near the Davis Mountains to 4,300 feet (1,310 m) near Valentine. In comparison, the O. W. Killam Cole A. Means No. 1 oil test, 1 mile (1.6 km) northeast of Valentine, reportedly (Woodward, 1954, p. 15) penetrated basin fill to a depth of 528 feet (161 m) and volcanic rocks to 6,560 feet (1,999 m). Figure 3t suggests that the total thickness of low-velocity material, which probably includes the basin fill, volcanic clastics, and ash-fall tuffs, ranges from 270 to 490 feet (82 to 149 m) southwest of Rubio Dome and from 360 to 760 feet (110 to 232 m) in Ryan Flat.

The Geological Survey test hole south of Valentine yielded the most reliable data on the depth of permeable material in the Ryan Flat area. According to Gates and White (1976, p. 37-53), the test hole penetrated basin fill to a depth of either 385 or 555 feet (117 or 169 m)--mostly clay to 210 feet (64 m), permeable sand and gravel to 385 feet (117 m), and clay or altered ash-fall tuff to 555 feet (169 m). From 555 (169 m) to about 1,250 feet (381 m), the test penetrated mostly medium-grained, fairly well-sorted, permeable sand and some thin volcanic flows. The sand is probably reworked and redeposited tuffaceous material and is a volcanic-clastic deposit. From 1,250 to 1,465 feet (381 to 447 m), the rocks are volcanic flows interbedded with tuffs; and below 1,465 feet (447 m), the materials are altered tuff and tuff. The base of the permeable material is at a depth of about 1,250 feet (381 m).

The volcanic-clastic deposits and thin volcanic flows between 555 and 1,250 feet (169 and 381 m) in the test hole probably are younger than the volcanic sequence defined by Twiss (1970) and Walton (1975); although they may be included in or may be equivalent to the interval of the Petan Basalt and Mitchell Mesa Ignimbrite. The volcanic flows and tuffs from about 1,250 to 2,006 feet (381 to 611 m) probably are equivalent to at least part of the interval from the Petan Basalt through the Capote Mountain Formation. The Mitchell Mesa Ignimbrite and Capote Mountain Formation crop out about 2 miles (3.2 km) west of the test-hole site.

Data from routine computer interpretation of an electrical sounding made 0.5 mile (0.8 km) north of the test hole could not be directly correlated by the digital-computer program with the electrical log of the test hole, although the sounding interpretation can be constrained so that it will approximately match the log due to a range of equivalent models. This problem illustrates the difficulty in interpreting the thickness of the basin fill or permeable material by using only the resistivity data.

Figure 14 shows that the maximum estimated thickness of the basin fill is more than 500 feet (150 m) and that the maximum thickness of the permeable fill and volcanic clastics is between 1,000 and 1,500 feet (300 and 460 m). These estimates are based on limited and somewhat ambiguous data--a few drillers' logs of water wells, the test hole south of Valentine, and selected resistivity and seismic-velocity data. The thickest sections of basin fill are in the valley southwest of Rubio Dome and under Ryan Flat between Valentine and Ryan Siding. The thickest sections of permeable material are probably southwest of Rubio Dome and in Ryan Flat from Valentine south to Cuesta Del Burro.

The thickness of the alluvium underlying the flood plain of the Rio Grande is probably 100 to 200 feet (30 to 60 m) or less. Just east of the Sierra de Pilares, at the southern end of the Green River Valley structural basin, a thickness of as much as 2,800 feet (850 m) of basin fill was estimated from resistivity data (soundings 156 and 157 at the southern end of figure 3h). This material is mostly clay, but may include tuff at depth. At the northern end of the Presidio bolson, just south of Candelaria, the thickness of the basin fill was estimated to be as much as 1,500 feet (460 m) on the basis of resistivity sounding 105, located 10 miles (16 km) south of Candelaria (fig. 23). Data from this sounding, shown at the north end of figure 3m, indicate that the basin fill in the northern end of Presidio bolson is mostly clay but possibly includes tuff at depth.

Most wells in the Ryan Flat area pump small amounts of water for stock or domestic use. Three irrigation wells in the area, two west of Rubio Dome and one 9 miles (14 km) south of Valentine, yield between 250 and 1,400 gal/min (16 and 88 L/s). Two wells drilled in 1975 will be pumped to irrigate an area 2 to 3 miles (3 to 5 km) southwest of Valentine. These wells reportedly yielded 1,250 to 1,400 gal/min (79 to 88 L/s) during tests.

The few specific-capacity and aquifer-test data available in the Ryan Flat area indicate a wide range in transmissivity. The irrigation well south of Valentine, which, as inferred from the driller's log, taps sand similar to the volcanic-clastic material penetrated by the Geological Survey test hole, has a reported specific capacity of about 50 (gal/min)/ft [10 (L/s)/m]. This specific capacity indicates a transmissivity on the order of 17,000 ft^2/d (1,600 m^2/d). In contrast, a test hole drilled 8.5 miles (14 km) southwest of Valentine, near the Sierra Vieja, yielded 16 gal/min (1.0 L/s) from ash-fall tuff and poorly reworked volcanic clastics. The specific capacity of this test well was 0.15 (gal/min)/ft [0.03 (L/s)/m], and aquifer-test data indicated a transmissivity of about 14 ft^2/d (1.3 m^2/d). No data are available on the specific yield of the basin fill and volcanic clastics of the Ryan Flat area. A reasonable estimate for Ryan Flat, however, is about 7.5 percent. The specific yield for Ryan Flat probably is not as high as the 10 percent assumed for Wildhorse Draw because parts of the volcanic-clastic deposits may have a lower specific yield; however, the specific yield may not be as low as the 6 percent estimated for Lobo Flat.

About 13 irrigation wells (of which 9 are in the Presidio bolson) tap the alluvium along the Rio Grande and yield from 300 to 2,000 gal/min (19 to 126 L/s). The few reported specific-capacity data suggest transmissivities on the order of 7,000-13,000 ft^2/d (650-1,200 m^2/d).

Two oil tests, UW-51-43-101 and 201, drilled between the Sierra Vieja and the Rio Grande about 12 miles (19 km) northwest of Capote Peak, have been converted to a stock and an irrigation well respectively (White and others, 1977). Well UW-51-43-101, which taps Cretaceous limestone at a depth of about 2,800-2,900 feet (850-880 m), reportedly flows 1,000 gal/min (60 L/s) of slightly saline water with a temperature of about 160-180°F (70-80°C). Well UW-51-43-201, which probably also taps Cretaceous limestone at about 3,000 feet (910 m), reportedly flows 2,200 gal/min (140 L/s) of slightly saline water with a temperature of 160-180°F (70-80°C). Data from these wells are not sufficient to estimate the size of the ground-water reservoir or to predict its sustained yield.

Recharge to Ryan Flat occurs in the foothills of the highlands bordering the flat and probably along the channels of ephemeral streams crossing the flat. By using a rough relationship between recharge and drainage area, recharge to Ryan Flat is estimated to be about 5,800 acre-feet (7.2 million m^3) per year. The water-level contour map (fig. 15) indicates that ground water generally flows toward the axis of Ryan Flat and northwest toward Lobo Flat. However, the flow through Lobo Flat was estimated

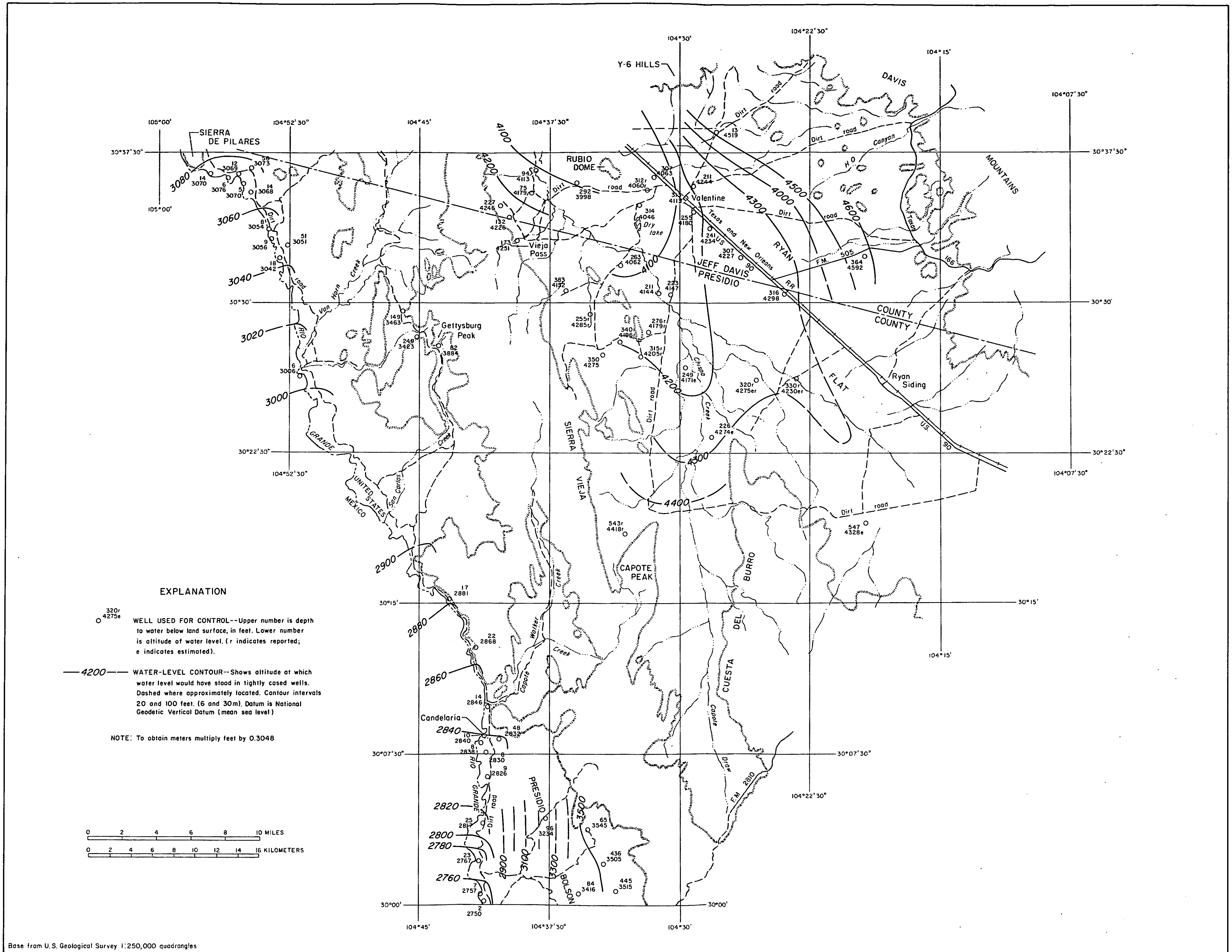

FIGURE 15.-Water levels in 1972-74 in Ryan Flat and adjacent areas along the Rio Grande

to be only about 1,600 acre-feet (2.0 million m^3) per year (p. 59). Some ground water also moves westward and discharges through springs along the western base of the Sierra Vieja. Capote Spring, 5 miles (8 km) south of Capote Peak, discharges about 1,000 acre-feet (1.2 million m^3) per year, which may represent a large part of the ground water recharged to upper Capote Draw. Other springs discharge along the Sierra Vieja to the north, and the discharge by springs from the Ryan Flat area to the Rio Grande drainage area may be on the order of 2,000 acre-feet (2.5 million m^3) per year.

The water-level contours on figure 15 are approximate because the number of measured water levels are insufficient to map the area in detail. The contours near Valentine represent general conditions because water levels in deep wells are lower than those in shallow wells, possibly because of zones of perched water or because of vertical movement of water. Water-level contours are not continuous between the Valentine area and the valley west of Rubio Dome because hydrologic continuity between these areas appears to be poor, possibly because the shallow volcanic rocks at and south of Rubio Dome have low permeability.

Recharge to the alluvium along the Rio Grande is derived mostly from surface flow in the river and tributary ephemeral streams, but some recharge is derived from subsurface flow under the phemeral streams. Water levels along the Rio Grande show that ground water west of the Sierra Vieja generally moves toward and discharges into the river. Ground water under the flood plain moves downstream and toward the river.

Quality of Ground Water

Figure 16 shows the quality of ground water in Ryan Flat and adjacent areas along the Rio Grande. Ground water in the basin fill and in the upper part of the volcanic sequence in Ryan Flat is uniformly fresh, mostly containing a dissolved-solids concentration of 200 to 400 mg/L. As in Lobo Flat, the low dissolved-solids concentration probably is related to the high proportion of relatively insoluble volcanic rock in the basin fill and volcanic clastics and to the lack of evapotranspiration, which would concentrate salts in the ground water. Most samples of ground water from the volcanic rocks in the highlands around Ryan Flat and between Ryan Flat and the Rio Grande are also fresh. The few samples of poorer quality water were obtained mostly from Cretaceous rocks.

Most ground water along the Rio Grande ranges in quality from slightly to moderately saline. The water is salty because the flood plain has been an area of ground-water discharge since drainage by the river was established, probably in early Pleistocene time. Much of the ground water that is discharged along the flood plain, especially during periods of low flow or no flow, evaporates from the land surface or is transpired. These processes concentrate salts in the remaining water. The reach of the Rio Grande between the Hueco bolson and the Presidio bolson has no major tributaries and is commonly dry for extended periods of time. The river lacks the volume of flow necessary to transport salts out of this part of the basin.

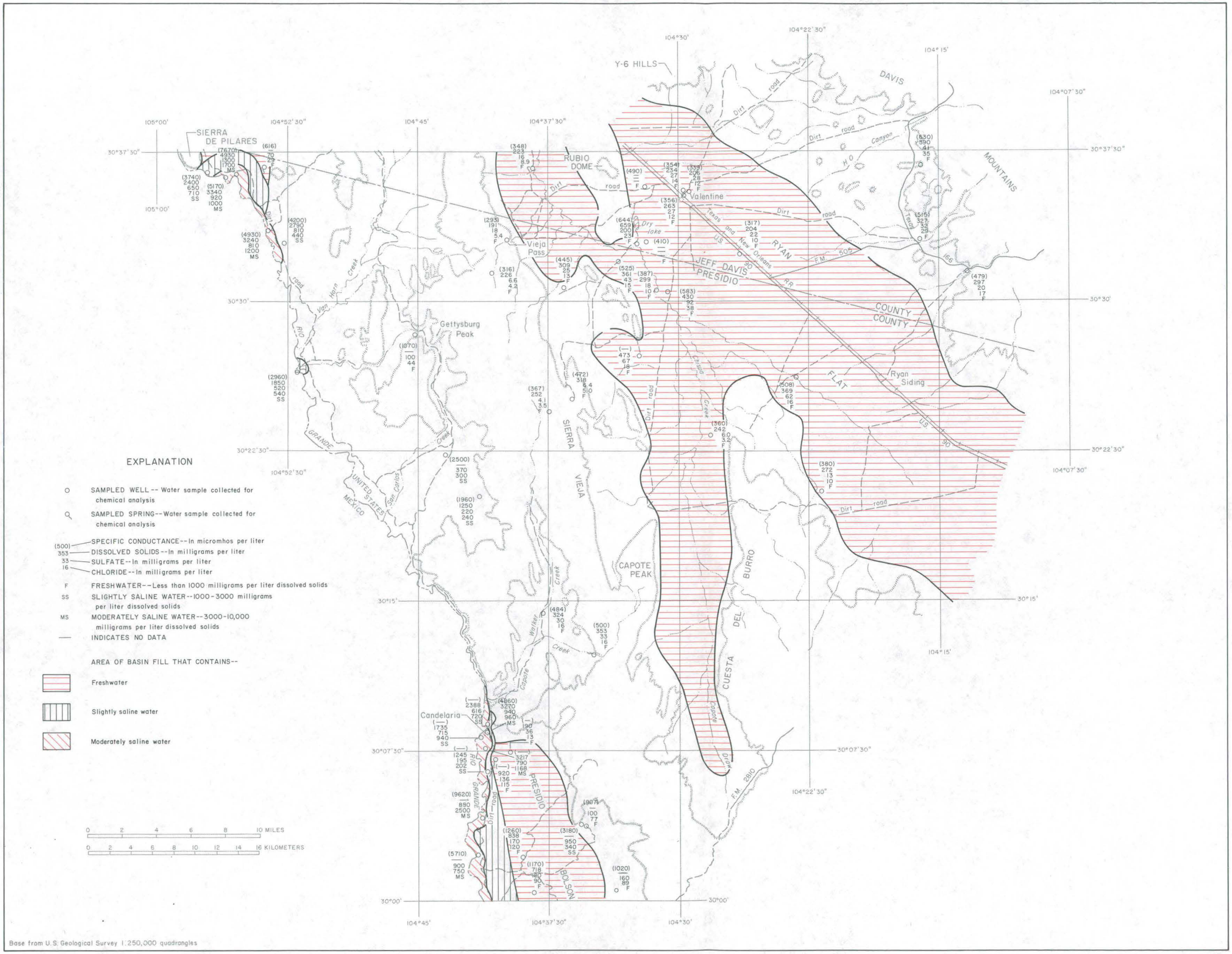

FIGURE 16.-Quality of ground water in Ryan Flat and adjacent areas along the Rio Grande

Ground water from springs and shallow wells in the northern end of the Presidio bolson and above the Rio Grande flood plain is mostly fresh, but resistivity data collected to the south (fig. 3m) indicate that the deeper basin fill is composed mostly of clay and contains salty water.

Development of Ground Water, Volumes of Freshwater in Storage, and Problems Associated with Future Development

Little ground water has been developed in Ryan Flat, and water levels have declined only in local areas. Two irrigation wells west of Rubio Dome have pumped about 300 acre-feet (0.4 million m^3) per year since 1949; and the irrigation well 9 miles (14 km) south of Valentine has withdrawn an estimated 700 acre-feet (0.9 million m^3) per year since 1971. Water levels west of Rubio Dome declined 8 feet (2.4 m) between 1955 and 1973, but part of this decline may have been caused by pumping in the Lobo Flat-Chispa Flat area. Pumping for irrigation along the Rio Grande probably has not caused any long-term water-level declines because infiltration from periodic flow in the river recharges the alluvium. Water levels in two observation wells near Candelaria showed no declines during 1957-76.

The amount of freshwater stored in the basin fill and in the water-bearing, permeable volcanic clastics of the Ryan Flat area was estimated in two categories: (1) Where limited hydrologic data and geophysical data are available; and (2) where only geophysical data are available.

In a narrow, restricted subarea of about 21 square miles (54 km^2) extending south from Valentine and including the Geological Survey test hole and the irrigation well 9 miles (14 km) south of Valentine (fig. 14), available hydrologic data show that the basin fill and permeable volcanic clastics extend to depths of as much as 1,250 feet (381 m). Assuming an average thickness of permeable material of 1,000 feet (300 m), a saturated thickness of 740 feet (230 m), and a specific yield of 7.5 percent, about 760,000 acre-feet (940 million m^3) of freshwater is stored in this subarea.

If this narrow subarea south of Valentine is expanded by 64 square miles (167 km^2) to include most of the area in which the thickness of fill and permeable volcanic clastics is potentially as much as 1,000 feet (300 m), an additional 2.1 million acre-feet (2.6 km^3) of freshwater is in storage (fig. 14). This value is based on a saturated thickness of 700 feet (210 m), and includes areas where only geophysical data were available to estimate the thickness of the permeable material. Parts of the area in which permeable material may be 1,000 feet (300 m) thick were not included because interpretations of the geophysical data were ambiguous.

In the valley west of Rubio Dome, about 220,000 acre-feet (270 million m^3) of freshwater is stored in the basin fill and permeable volcanic clastics in an area of about 17 square miles or 44 km^2 (fig. 14). This value is based on a thickness of permeable material of 500 feet (150 m), a saturated thickness of 400 feet (120 m), and a specific yield of 5 percent. In this subarea, few data, mostly geophysical, are available on the thickness of the permeable material. The specific yield was assumed to be 5 percent because this area is continuous with the Lobo Flat area to the north.

The total amount of freshwater stored in the basin fill and volcanic clastics of the central part of Ryan Flat is estimated to be about 2.9 million acre-feet (3.6 km^3). This estimate was made by assuming a relatively low specific yield of 7.5 percent, primarily because the material under Ryan Flat is probably similar to the material under Lobo Flat, where the effective specific yield of material dewatered during 1954-73 was about 6 percent. This estimated volume of water is too large if the specific yield is as low as in Lobo Flat, or if the thickness of the permeable material is significantly less than 1,000 feet (300 m) over a large part of Ryan Flat. The estimate could be too small if significant volumes of permeable material extend south up to Capote Draw or southeast toward Ryan Siding.

The total amount of freshwater stored in the entire Ryan Flat area, including the valley west of Rubio Dome, is estimated to be about 3.1 million acre-feet (3.8 km^3). The amounts of ground water stored along the Rio Grande west of Ryan Flat were not estimated because there is no evidence to indicate the occurrence of any large volumes of permeable alluvium or basin fill saturated with fresh or slightly saline water.

No problems are known to be associated with withdrawing freshwater from Ryan Flat, other than the potential of large water-level declines if the specific yield is low. Little water has been pumped from the flat, so the effects of large withdrawals are not known. Because of the probable wide range in permeability and specific yield, extensive test drilling would be required to evaluate the water-yielding potential of Ryan Flat.

EAGLE FLAT, NORTHERN RED LIGHT DRAW, AND ADJACENT AREAS

Eagle Flat extends from Sierra Blanca, Texas, southeastward toward the Carrizo and Van Horn Mountains; Red Light Draw extends south between the Quitman Mountains and Devil Ridge toward the Rio Grande. Eagle Flat originally drained to the Salt Basin, but the surface drainage of its northwestern end has been diverted to Red Light Draw around the ends of Devil Ridge. Red Light Draw drains to the Rio Grande, mostly southward down the draw. Figure 17 includes most of Eagle Flat and the northern end of Red Light Draw. The rest of Eagle Flat and Red Light Draw are shown on figure 20 and are discussed in a later section of this report.

Eagle Flat is bounded on the north by the Diablo Plateau, which is underlain by a relatively thin section of flat-lying Cretaceous sandstone, limestone, shale, and marl and older rocks deposited on the Diablo platform; and on the south by Devil Ridge and the Eagle Mountains, composed of a thicker section of folded and faulted Cretaceous limestone and sandstone and older rocks deposited in the Chihuahua trough, and Tertiary volcanic rocks and instrusives. At least part of the northern edge of Eagle

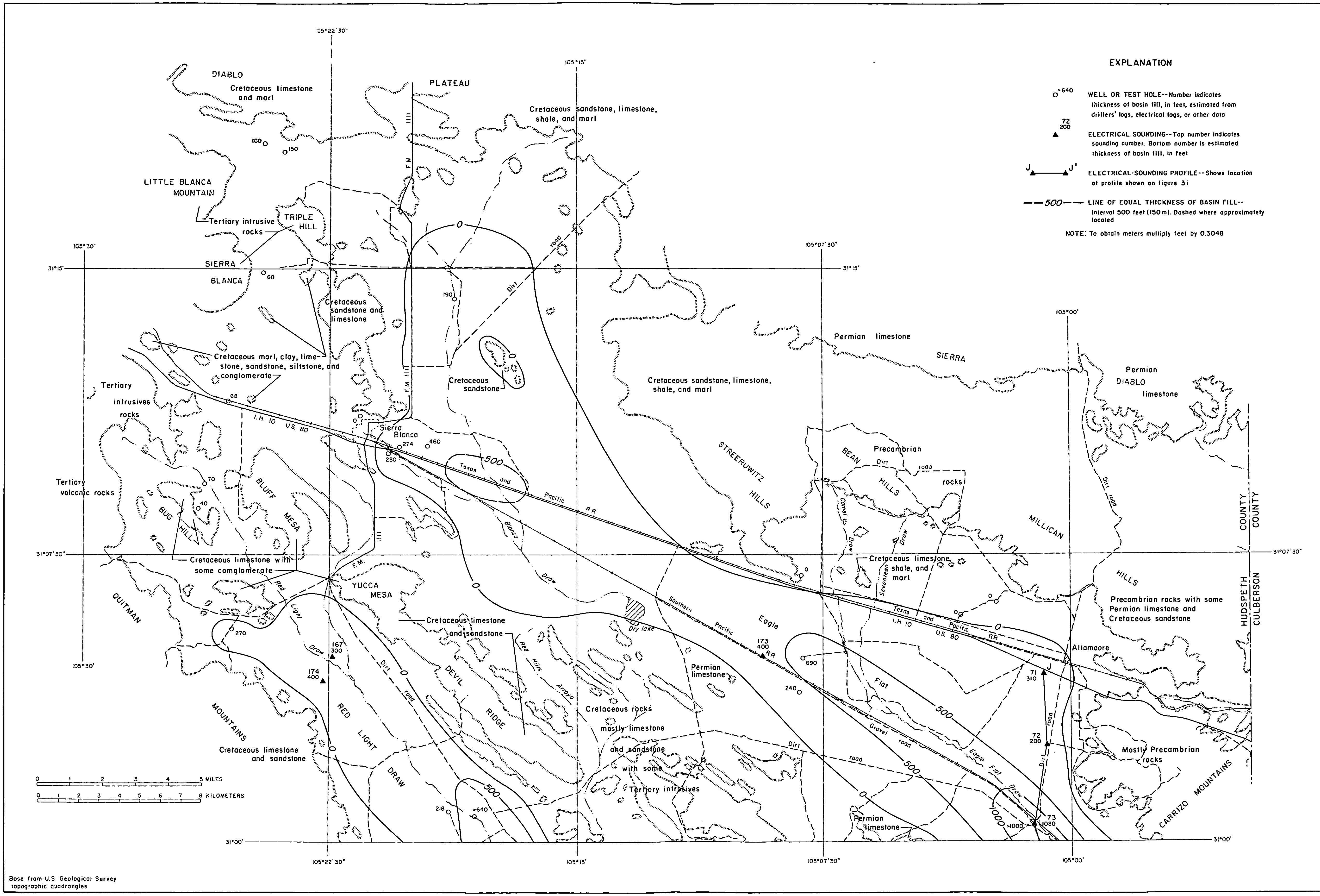

FIGURE 17.-Estimated thickness of basin fill and locations of electrical soundings in Eagle Flat and northern Red Light Draw

Flat is marked by a major fault, which separates the Diablo Plateau from the Chihuahua trough (Muehlberger and Wiley, 1970, p. 13), and is the northern boundary of the Eagle Flat graben. The graben therefore coincides with the stratigraphic and structural boundary that has been termed the "Texas Lineament." The northern end of Red Light Draw is bounded on the west by the Quitman Mountains and on the east by Devil Ridge, both of which are composed mostly of Cretaceous limestones and sandstones.

Ground-Water Hydrology

The basin fill in much of Eagle Flat is less than 500 feet (150 m) thick and is above the water table. Only at the southeastern end of the area (fig. 17), south of Allamoore, is there a significant thickness of fill, about half of which is saturated. The northern end of the resistivity section that extends south from Allamoore (fig. 3i) shows that the basin fill is thin and probably is underlain by Precambrian rocks to sounding 73, where the section crosses the fault on the north side of the graben. Farther south, the basin fill is about 1,100 feet (330 m) thick. In the northern end of Red Light Draw, the basin fill is also thin, generally less than 500 feet (150 m) thick and mostly unsaturated.

Most wells in and near the northwestern end of Eagle Flat and northern Red Light Draw obtain water from consolidated rocks of Cretaceous age underlying the basin fill. A number of wells in the Sierra Blanca vicinity tap the Cox Sandstone and underlying limestones such as the Bluff Mesa Limestone or its equivalent under the Diablo Plateau, the Campagrande Formation. These wells commonly yield less than 100 gal/min (6.3 L/s), although a well drilled 2 miles (3.2 km) east of Sierra Blanca in 1972 by the Sierra Blanca Corporation yields about 200 gal/min (13 L/s) of slightly saline water, reportedly from the Cox Sandstone; and a well drilled 9 miles (14 km) north of Sierra Blanca in 1973-74 by the Diamondhead Corporation yields about 500 gal/min (32 L/s) of slightly saline water, reportedly from the Campagrande Formation. Specific capacities of wells in this area commonly are less than 10 (gal/min)/ft [2 (L/s)/m], although the well 9 miles (14 km) north of Sierra Blanca reportedly has a specific capacity of 15 (gal/min)/ft [3.1 (L/s)/m]. South and northwest of Allamoore, wells commonly yield less than 100 gal/min (6.3 L/s), and most probably tap fractures in the Precambrian rocks underlying the thin basin fill.

The areas of recharge and the rates of recharge to the Cretaceous rocks in northwestern Eagle Flat are not known, but the rate is probably small. Water levels in Eagle Flat are commonly from 750 to 1,000 feet (230 to 300 m) below the land surface (fig. 18). The available water-level data are not sufficient to trace the movement of ground water in northwestern Eagle Flat, but the data suggest that the water may discharge through the Cretaceous rocks in the subsurface, probably toward the Rio Grande to the south.

South of Allamoore, ground water in the basin fill moves toward the southeastern end of Eagle Flat, where it may also discharge through the consolidated rocks. Ground water in northern Red Light Draw moves south toward the Rio Grande.

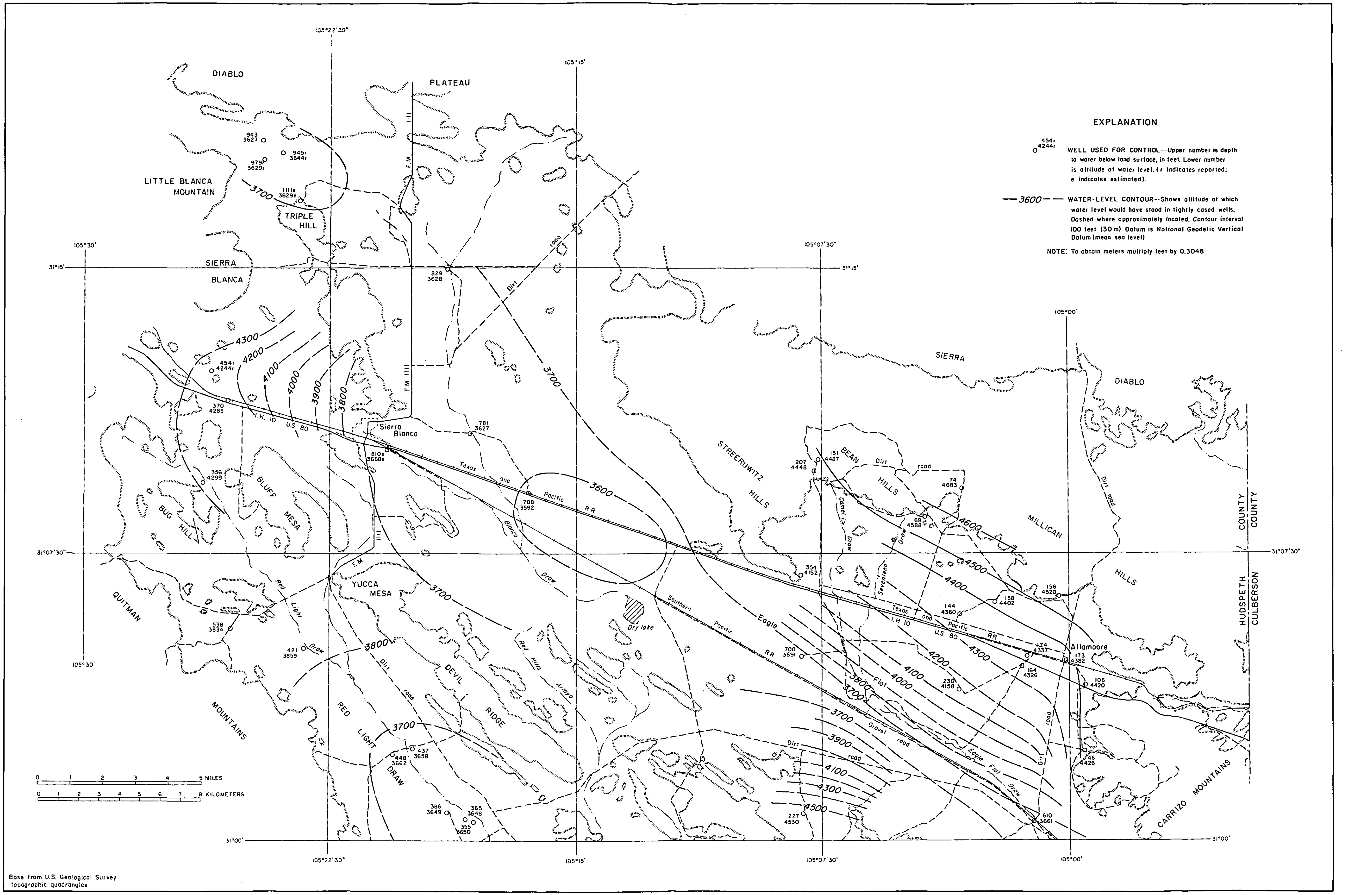

FIGURE 18.-Water levels in 1972-74 in Eagle Flat, northern Red Light Draw, and adjacent areas

Quality of Ground Water

Figure 19 shows the quality of ground water in Eagle Flat, northern Red Light Draw, and adjacent areas. The few samples of ground water collected from the basin fill and samples collected from the Precambrian rocks around Allamoore are all fresh. Ground water in the Cretaceous rocks in northwestern Eagle Flat ranges from fresh to moderately saline, but most of the water is slightly saline. The Cretaceous rocks contain more soluble material than the basin fill, and the ground water in the consolidated rocks is more mineralized.

Development of Ground Water and Potential for Future Development

Prior to 1972, ground water in the Eagle Flat-northern Red Light Draw area was pumped for livestock, domestic supply, and municipal supply for Sierra Blanca. During 1972-74, wells were drilled to supply water for the community planned by the Sierra Blanca Corporation east of Sierra Blanca and for the Diamondhead Corporation's planned Mile High community northwest of Sierra Blanca.

No significant volumes of fresh ground water are known to occur in the area, although small volumes of freshwater occur in the Allamoore area, northern Red Light Draw, and locally in Cretaceous rocks in the Sierra Blanca area. Sierra Blanca (Hudspeth County Water Control and Improvement District No. 1) drilled three wells northeast of Bug Hills, about 5 miles (8 km) southwest of Sierra Blanca, during 1970-73. These wells tapped the Bluff Mesa Limestone and initially yielded a total of about 200 gal/min (13 L/s) of freshwater. During 1973-74, however, the water levels and yields of these wells declined sharply. These declines and data from an aquifer test made in 1973, indicate that the total volume of the reservoir is small, even though the limestone underlying the well field is relatively permeable. The sustained yield of these wells reportedly is only 20 to 30 gal/min (1.3 to 1.9 L/s).

The volume of slightly saline water in the Cox Sandstone, Campagrande Formation, and other Cretaceous rocks around Sierra Blanca is not known because the extent and thickness of the water-bearing and permeable zones are not known. The yields and water levels in the wells of the Sierra Blanca Corporation and the Diamondhead Corporation east and north of Sierra Blanca reportedly have not declined significantly, indicating that the reservoirs tapped by these wells are larger than that of the well field near Bug Hill.

Ground Water in the Diablo Plateau Area

The Diablo Plateau is a large upland area between the Salt Basin and the Hueco bolson underlain by Cretaceous, Permian, and older rocks. The few wells on the plateau withdraw small amounts of water for stock and domestic use. Most of the water is slightly or moderately saline, and water levels are commonly on the order of 1,000 feet (300 m) below the

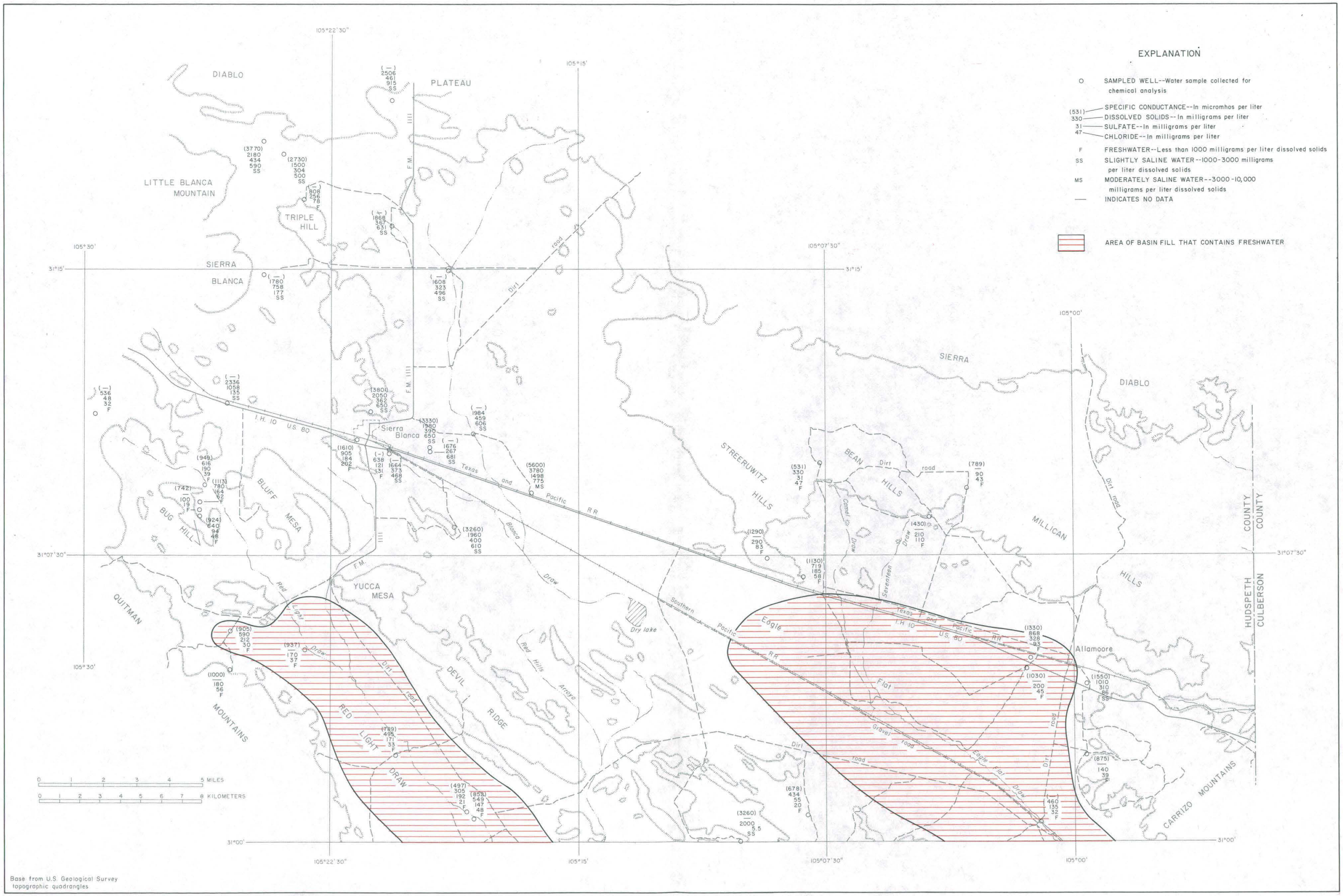

FIGURE 19.-Quality of ground water in Eagle Flat, northern Red Light Draw, and adjacent areas

land surface. El Paso Water Utilities drilled two test holes in the northwestern part of the Diablo Plateau in 1958-59 (Leggat, 1962, p. 12). One test, drilled to 2,613 feet (796 m), yielded moderately saline water at a depth of 2,242 to 2,308 feet (683 to 703 m); the other test did not penetrate any permeable zones in its total depth of 2,100 feet (640 m). Leggat (1962, p. 12) stated that available data did not indicate the occurrence of any large volumes of freshwater under the plateau.

RED LIGHT DRAW, SOUTHEASTERN EAGLE FLAT, AND GREEN RIVER VALLEY

Red Light Draw lies between the Quitman Mountains to the west, composed of Cretaceous limestone, sandstone, shale, and siltstone, and Tertiary volcanic rocks; and the Eagle and Indio Mountains to the east, composed of Cretaceous sandstone, limestone, conglomerate, and siltstone, and Tertiary volcanics and intrusives (fig. 20).

The southeastern end of Eagle Flat lies between the Eagle Mountains to the west, the Carrizo Mountains to the northeast, and the Van Horn Mountains to the southeast. The part of the Eagle Mountains bordering southeastern Eagle Flat is composed of Cretaceous limestone and sandstone, underlain by Permian limestone and Precambrian rocks. The Carrizo Mountains consist of Permian limestone and conglomerate and Precambrian rocks, and the part of the Van Horn Mountains bordering Eagle Flat is composed of Cretaceous conglomerate and sandstone, Permian limestone, and Precambrian rocks.

Green River Valley lies between the Indio and Van Horn Mountains, which are composed of Cretaceous sandstone, limestone, conglomerate, and siltstone, and Tertiary volcanics. Green River, which is an ephemeral stream, is tributary to the Rio Grande. At one time, Green River probably extended to the outcrops of Tertiary volcanics about 7 miles (11 km) north of its junction with the Rio Grande (fig. 20); but has subsequently extended north an additional 7 miles (11 km) by headward erosion and now drains a part of southeastern Eagle Flat.

Ground-Water Hydrology

The combined section of basin fill and volcanic clastics(?) in Red Light Draw thickens to the south, from about 500 feet (150 m) to as much as 3,600 feet (1,100 m) near the Rio Grande (fig. 20). Figures 3k (section M-M') and 3u show the resistivity and seismic velocity across and about midway up Red Light Draw, and figure 3ℓ shows the resistivity across the southern end of the Draw and along the Rio Grande. Figures 3k and 3u indicate that a thin section of basin fill overlies volcanic rocks on the west side of the draw, but that a thicker section of moderately resistive basin fill, volcanic clastics, and volcanics underlies the eastern side. As in Lobo Flat, the resistivity data cannot be used to distinguish basin fill from volcanic clastics or mixed volcanic clastics and volcanics, nor can the data be used to determine the depth of permeable material.

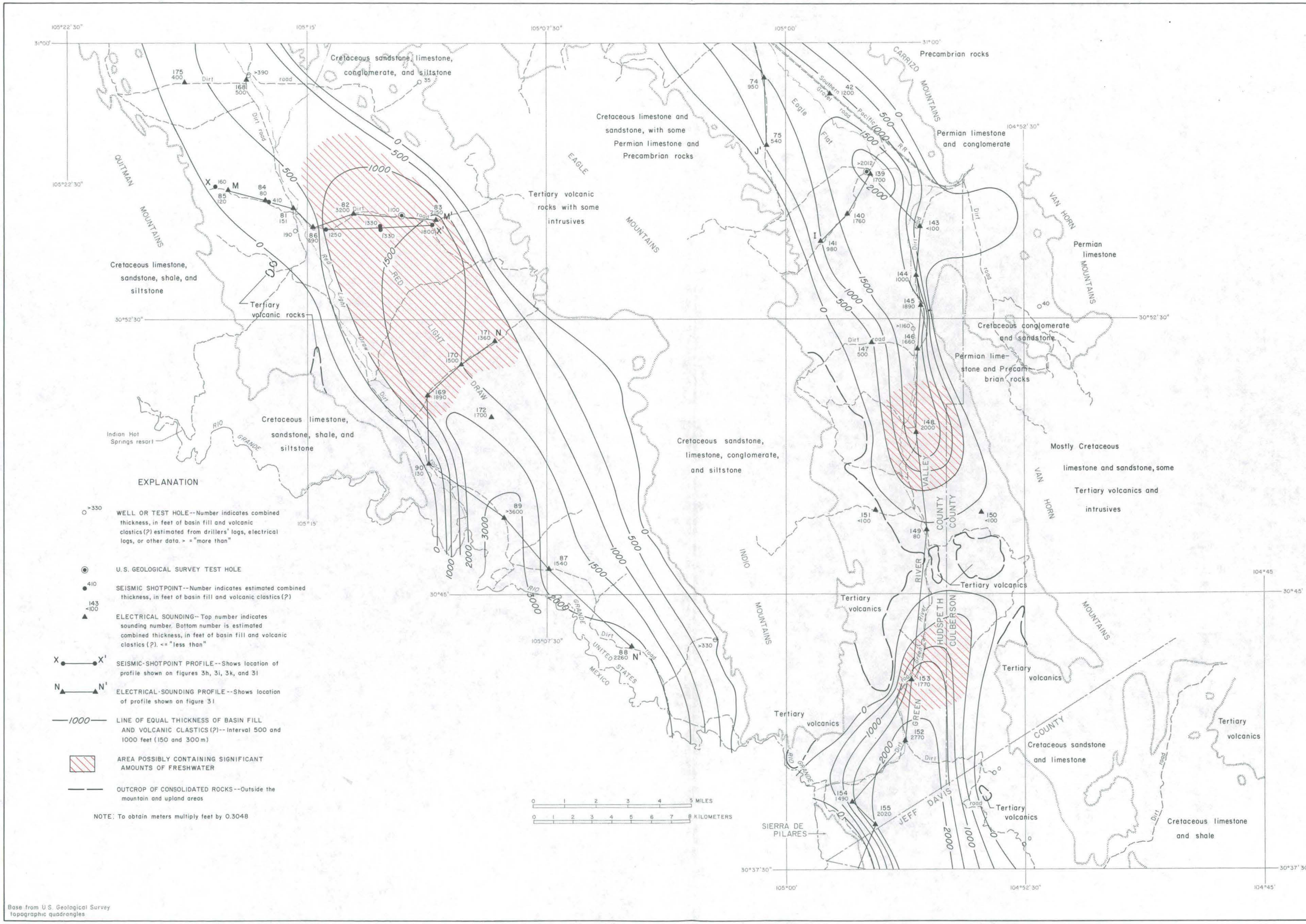

FIGURE 20.-Hydrologic data for Red Light Draw, southeastern Eagle Flat, and Green River Valley, and locations of electrical soundings and seismic shotpoints

The seismic-refraction data (fig. 3u) indicate velocities of about 8,400 ft/s (2,560 m/s) between depths of about 300 to 500 feet (90 to 150 m) and 1,200 to 2,000 feet (370 to 610 m) on the east side of the draw. This velocity is higher than the 5,000-ft/s (1,520-m/s) average that has been established for saturated alluvium (Zohdy, Eaton, and Mabey, 1974, p. 80), and suggests that this material has a higher elasticity coefficient, possibly because it is partly cemented.

The U.S. Geological Survey test hole Guerra No. 1, which was drilled between resistivity soundings 82 and 83 (fig. 20) penetrated mostly coarse-grained alluvial-fan deposits to a depth of 1,100 feet (335 m), where it probably penetrated a volcanic flow (Gates and White, 1976, p. 25-29). The seismic velocity data (fig. 3u) also indicate the occurrence of material with higher velocities, probably consisting of a greater proportion of volcanic flows, below depths of 1,000 to 2,000 feet (300 to 610 m) between electrical soundings 82 and 83.

Figure 3ℓ (profile N-N') in the southern part of the draw shows a thicker section, commonly greater than 1,500 feet (460 m) of basin fill and mixed volcanic clastics and volcanics. Along the Rio Grande, the basin fill is mostly fine grained, probably lacustrine clay and silt containing salty water and possibly including altered tuff at depth.

The basin fill in southeastern Eagle Flat is as much as 2,000 feet (610 m) thick (fig. 20). Figure 3h (profile I-I'), which shows the resistivity across the flat and along Green River Valley, indicates that the fill is coarse grained near the Eagle and Van Horn Mountains, but that it includes considerable fine-grained material along the axis of the flat at soundings 139 and 146. The thickness and lithology of the fill is difficult to interpret between soundings 143 and 146, probably because these soundings are along the Rim Rock Fault that bounds the west side of the Van Horn Mountains (Wiley, 1972). The U.S. Geological Survey Davis No. 1 test hole, near sounding 139, penetrated 2,012 feet (613 m) of basin fill without reaching consolidated rock. At this location, the fill was predominantly brown clay with thin beds of sand and gravel (Gates and White, 1976, p. 65-67).

In most of Green River Valley, the maximum thickness of the basin fill is between 1,700 and 2,000 feet (520 and 610 m), and probably includes a considerable amount of coarse-grained material on either side of the outcrops of volcanic rock about midway up the drainage. At these locations, however, the section may also include volcanic clastics and volcanics, especially at depth. Near the Rio Grande, the basin fill is more than 2,000 feet (610 m) thick, and is predominantly fine grained, probably consisting of lacustrine clay and silt containing salty water, and possibly including altered tuff at depth. The Green River Valley topographic depression extends south on the east side of the Sierra de Pilares (fig. 14), where it contains up to 2,800 feet (850 m) of mostly fine-grained basin fill and tuff(?).

Most wells in Red Light Draw, Eagle Flat, and Green River Valley are stock wells with small yields. Several irrigation wells that have been drilled along the flood plain of the Rio Grande at the lower ends of Red Light Draw and Green River Valley reportedly yield between 1,000 and 1,500 gal/min (63 and 95 L/s). Reported specific-capacity data indicate that the transmissivity of the alluvium along this reach of the Rio Grande is as much as 13,000 ft^2/d (1,200 m^2/d).

Recharge occurs around the margins of these basins and possibly along the channels of ephemeral streams. By using a rough relation between recharge and drainage area, annual recharge is estimated as follows: (1) About 3,000 acre-feet (3.7 million m^3) to Eagle Flat (including the northwestern part shown on figure 17); (2) about 2,000 acre-feet (2.5 million m^3) to Red Light Draw; and (3) about 1,000 acre-feet (1.2 million m^3) to Green River Valley.

Water-level contours in these basins are shown on figure 21. Ground water in Red Light Draw and in the lower end of Green River Valley moves toward the axis of each valley and then south where it discharges to the Rio Grande. Ground water in the area that includes Eagle Flat and the northern end of Green River Valley moves toward the axis of the flat and apparently discharges out of the basin through consolidated rock in the subsurface. The water level in a well 4 miles (6.4 km) south of the gap between the Carrizo and Van Horn Mountains indicates a shallow depression in the water table, and suggests that little ground water discharges through the gap to the Salt Basin.

Eagle Flat probably has been topographically closed and undrained by surface streams for much of its geologic history, but recently has been partly drained by ephemeral streams that have eroded headward from the Salt Basin and Red Light Draw. The clays penetrated by the Geological Survey Davis No. 1 test hole, however, do not appear to be the saline playa-lake deposits that are typical of the sediments in the center of an undrained basin. In addition, the fresh ground water sampled in the flat does not suggest the depositional environment of a playa lake. The basin underlying Eagle Flat may have been a topographically closed but drained basin, which as defined by Snyder (1962, p. 58-59), has deep water levels, deposits of buff or earthy-colored nonsaline clays, and fresh ground water. Such closed basins are drained by water discharging to adjacent basins through subsurface outlets. Eagle Flat is probably drained in the subsurface by discharge through consolidated rock underlying the flat, possibly to the Rio Grande basin to the south.

Quality of Ground Water

The quality of ground water in Red Light Draw, southeastern Eagle Flat, Green River Valley, and the adjacent uplands is shown on figure 22. Ground water in most of the basin fill is fresh, and contains less than 500 mg/L dissolved solids. Most of the samples of water collected from shallow wells and springs in consolidated rock in the adjacent uplands were also fresh, although two samples collected west of Red Light Draw, probably from wells tapping Cretaceous rocks, were slightly saline.

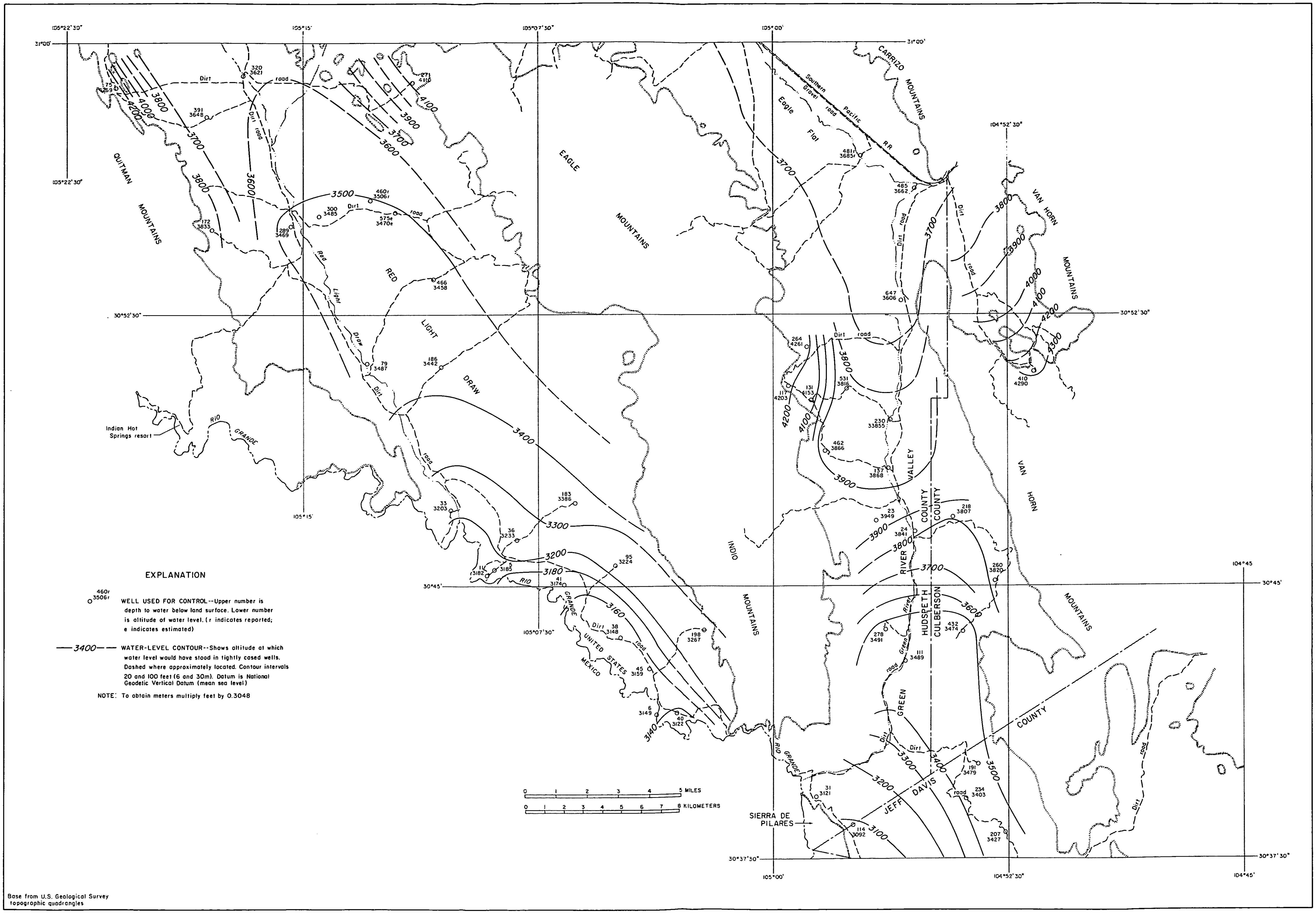

FIGURE 21.-Water levels in 1972-73 in Red Light Draw, southeastern Eagle Flat, and Green River Valley

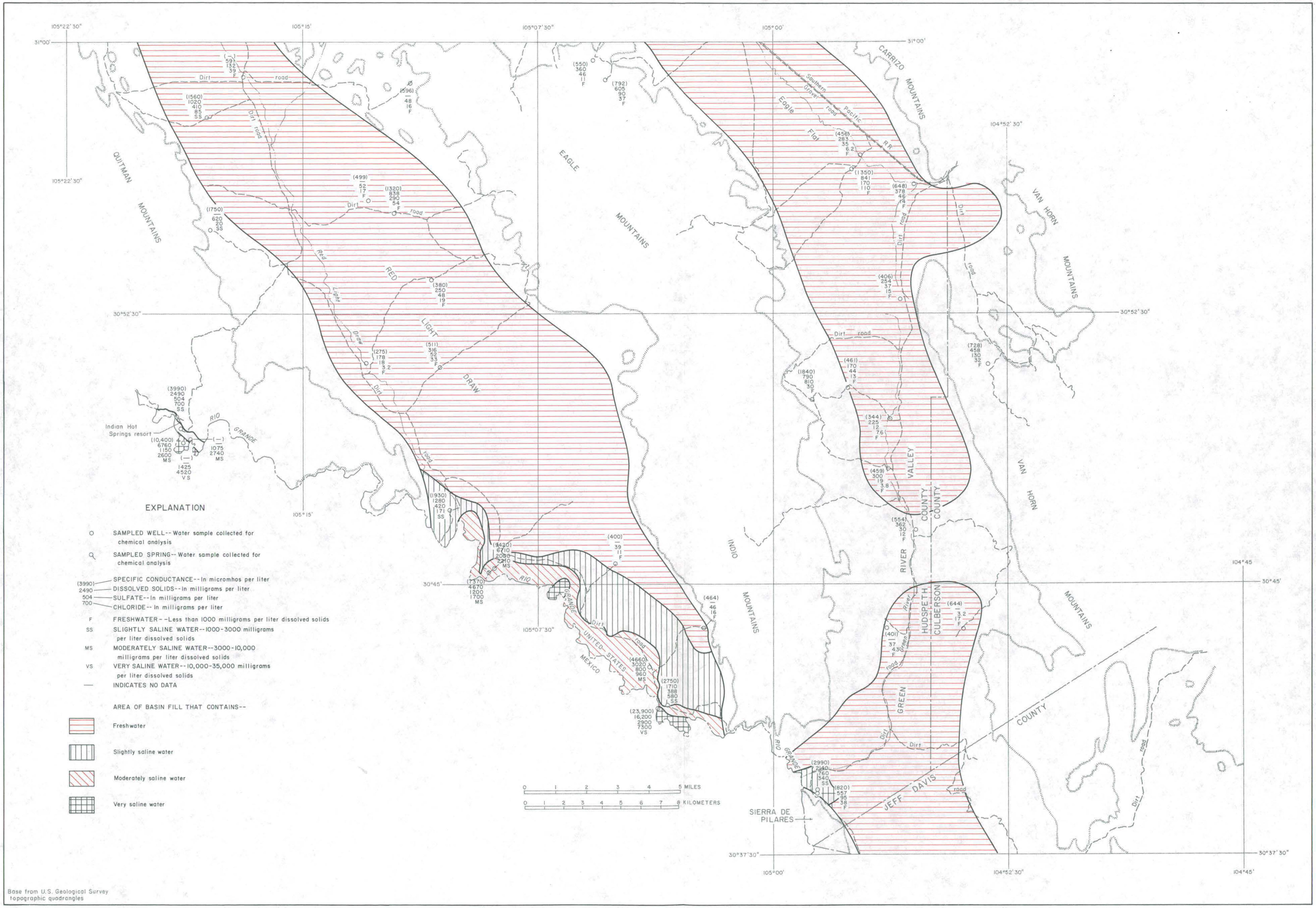

FIGURE 22.-Quality of ground water in Red Light Draw, southeastern Eagle Flat, Green River Valley, and adjacent areas

Ground water in the alluvium along the Rio Grande at the lower end of both Red Light Draw and Green River Valley is of poorer quality, commonly slightly to very saline. The high salt content probably results from evapotranspiration in the ground-water discharge zone along the river. However, in the Indian Hot Springs area, along the Rio Grande in the southeasternmost part of the Hueco bolson just west of lower Red Light Draw (fig. 22), part of the poor-quality ground water in the alluvium is hot, salty water that has leaked upward along faults. Most of the springs in the area are geothermal, and water is discharged at temperatures of 104 to 122°F (40 to 50°C).

Development of Ground Water, Volumes of Freshwater in Storage, and Problems Associated with Future Development

Little ground water has been developed in Red Light Draw, Eagle Flat, and Green River Valley. Most wells yield small amounts of water for stock and domestic use, although 10 wells have been drilled to irrigate local tracts of land along the Rio Grande from Indian Hot Springs to Green River. Water levels over the entire area probably have changed little since it was settled.

The areas where significant quantities of fresh ground water might be available are shown on figure 20. The volumes of water in storage were estimated by using geophysical data; therefore, these estimates are uncertain because few hydrologic data are available for correlation with the geophysical data, and the geophysical data are insufficient to determine the base of water-bearing, permeable basin fill and volcanic clastics.

About 600,000 acre-feet (740 million m^3) of fresh ground water may be stored in the south-central part of Red Light Draw, assuming an average thickness of permeable material of 750 feet (230 m), a saturated thickness of 350 to 450 feet (110 to 140 m), and a specific yield of 7.5 percent over an area of 32 square miles (83 km^2). Although the geophysical data indicate thicknesses of 1,000 to more than 2,000 feet (300 to more than 610 m) of permeable material, the Geological Survey test hole Guerra No. 1 penetrated only about 1,100 feet (335 m) of permeable material and the average thickness is probably less than 1,000 feet (300 m). Because much of the material may be volcanic clastics, similar to that in Lobo and Ryan Flats, the specific yield was assumed to be 7.5 percent.

In Green River Valley, limited geophysical data suggest significant thicknesses of potentially freshwater-bearing material on either side of the outcrops of volcanic rock midway up the valley. No hydrologic data are available in this area, but if the average thickness of the water-bearing material is assumed to be 750 feet (230 m), the saturated thickness is estimated to be 450 to 550 feet (140 to 170 m), and the specific yield is 7.5 percent over 12 square miles (31 km^2), about 280,000 acre-feet (345 million m^3) of freshwater is in storage.

The resistivity data, which indicate significant amounts of freshwater-bearing material in Green River Valley at soundings 148 and 153, also suggest that this material has low porosity and permeability. In thick sections of moderately coarse-grained and resistive material, the water table commonly can be detected as a decrease in resistivity if the porosity is high. The data from soundings 148 and 153 do not indicate the altitude of the water table; consequently, the potential water-bearing material may have low porosity and permeability, and possibly is tuff or interbedded tuff and volcanic flows.

Along the east front of the Eagle Mountains in southeastern Eagle Flat, resistivity data from soundings 140 and 141 indicate some potentially freshwater-bearing, permeable material. In this area, however, the water table is 500 to 1,000 feet (150 to 300 m) below the land surface, and the saturated material is probably thin.

No problems are known to be associated with developing ground water in Red Light Draw and Green River Valley. In both basins, the water levels in areas containing fresh ground water are 200 to 400 feet (60 to 120 m) higher than the water levels in areas of saline water along the Rio Grande. Encroachment of saline water should not be a problem until water-level declines are significant.

PRESIDIO BOLSON AND ADJACENT AREAS

The Presidio bolson extends along the Rio Grande from Candelaria, Texas, to outcrops of volcanic rock 6 to 10 miles (10 to 16 km) southeast of Presidio, Texas. The smaller Redford bolson continues along the Rio Grande for another 12 miles (19 km) southeast of the volcanic outcrops. Data on the northern end of the Presidio bolson are shown on figure 14; data on the rest of Presidio bolson and the Redford bolson are shown on figure 23. Both the Presidio and Redford bolsons are drained by ephemeral streams tributary to the Rio Grande. The southeastern end of the Presidio bolson is also drained by two streams that flow into the bolson from the north.

The Presidio bolson is bounded on the northeast by the Chinati Mountains, composed of Tertiary intrusive rocks and volcanics underlain by Permian siltstone, limestone, and sandstone, and Cretaceous limestone, shale, sandstone, and conglomerate. To the southeast, the bolson is bounded by the Cienega Mountains, the Black Hills, and other hills composed of Tertiary intrusive rocks, conglomerate, and volcanic clastics, underlain by Cretaceous limestone, shale, and sandstone; and by the Bofecillos Mountains, composed of Tertiary volcanics and volcanic clastics. The Redford bolson is bounded on the east by the Bofecillos Mountains, and the United States parts of the Presidio and Redford bolsons are bounded on the west by the Rio Grande.

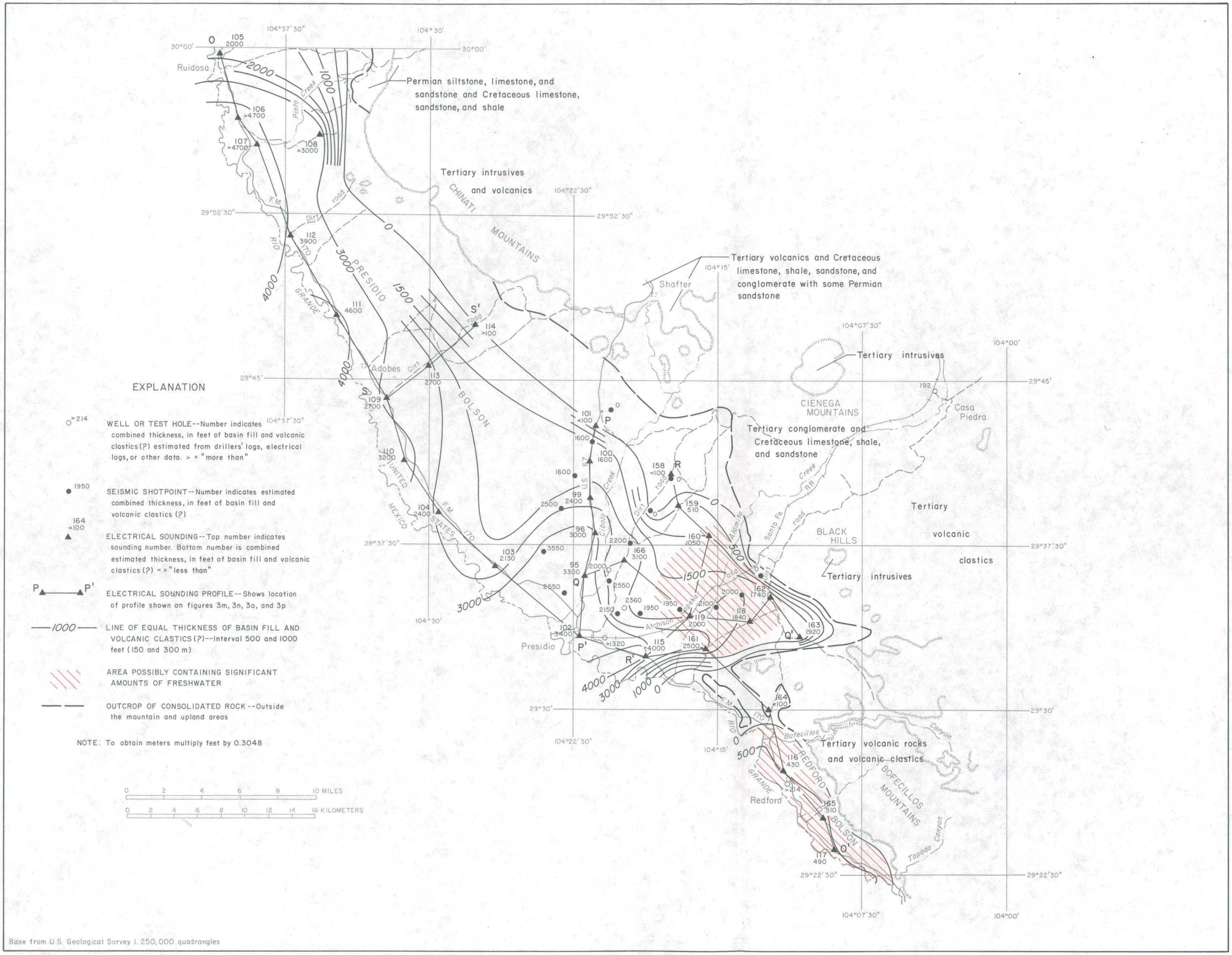

FIGURE 23.-Hydrologic data for the Presidio bolson and adjacent areas and locations of electrical soundings and seismic shotpoints

Ground-Water Hydrology

Much of the Presidio bolson is underlain by a thick section of fine-grained basin fill, most of which is probably lacustrine clay and silt containing salty water, and volcanic clastics(?). Figure 3m shows resistivity along the axis of the Presidio bolson near the Rio Grande from Ruidosa to Redford bolson. Figure 3n shows resistivity across the Presidio bolson from the Chinati Mountains to Presidio, and figure 3p (section S-S') shows resistivity between the Chinati Mountains and the Rio Grande. Figures 3o and 3p (sections Q-Q' and R-R') show resistivity roughly east-west and north-south across the southeastern part of the Presidio bolson in the Alamito-Cibolo Creeks area.

Resistivity-sounding profiles O-O', P-P', Q-Q', R-R', and S-S' (figs. 3m-3p) indicate the occurrence of large maximum thicknesses of fine-grained material, ranging from about 1,600 feet (490 m) near the Chinati Mountains to as much as 5,000 feet (1,520 m) along the bolson axis. Near the mountains, as at soundings 101 on figure 3n and 114 on figure 3p, volcanic flows apparently occur at shallow depths, although some of this material could be coarse-grained alluvial-fan deposits derived from the mountains. Sounding 108, near the mountains at the northern end of the bolson (not shown on the resistivity sections), also indicated moderately resistive material to a depth of about 1,300 feet (400 m). This material is probably coarse-grained fan deposits, but may be volcanics.

Seismic-reflection data obtained from an oil company were used to estimate the thickness of the basin fill and volcanic clastics(?) at selected sites shown on figure 23. Most of these thicknesses are of the same order of magnitude as the thicknesses determined from the resistivity data.

Soundings 116, 165, and 117, at the southeast end of the section on figure 3m in the Redford bolson, indicate that the basin fill in this area is thinner, about 500 feet (150 m) thick, and coarser grained. Sounding 164 shows the shallow volcanic rocks separating the Presidio and Redford bolsons.

Figures 3o and 3p (section R-R') suggest that the basin fill and volcanic clastics(?) in the Alamito Creek area are coarser grained than in the rest of the Presidio bolson. Soundings 119 through 163 on figure 3o and 160 through 119 on figure 3p, as well as sounding 161 on figure 3m, show that the basin fill and volcanic clastics(?) range from 1,000 to 2,500 feet (300 to 760 m) thick and are moderately resistive, especially at soundings 118, 160, 161, and 162. Much of this material may be coarse-grained alluvial sediments deposited by Alamito Creek, although the deeper material may be tuff or interbedded tuffs and volcanic flows. As in Lobo and Ryan Flats, the resistivity data cannot be used to distinguish alluvium from volcanic clastics or permeable material from deposits of low permeability.

The resistivity data do not accurately indicate the thickness of the alluvium overlying the fine-grained bolson fill along the Rio Grande flood plain, although the data suggest that the alluvium is less than 100 feet

(30 m) thick. Because the alluvium generally contains ground water of poor quality, the resistivity of the coarser alluvium is as low as the resistivity of the bolson fill. The few drillers' logs available of wells along the river also indicate that the alluvium is less than 100 feet (30 m) thick.

Most wells in the Presidio bolson above the Rio Grande flood plain pump small amounts of water for stock or domestic use, but one irrigation well along Cibolo Creek and another well along Alamito Creek both reportedly yield 600 gal/min (38 L/s). About 80 large-diameter wells in the Presidio bolson, chiefly around Presidio, and 11 in the Redford bolson, most of which originally were dug or drilled for irrigation, were inventoried during this study. Most of these wells reportedly yield between 300 and 800 gal/min (19 and 50 L/s), although three wells in the northern end of the Redford bolson reportedly yield 1,200 to 1,500 gal/min (76 to 95 L/s). Reported specific-capacity data indicate that the transmissivity of the Rio Grande alluvium in the Presidio and Redford bolsons is about 5,000 to 21,000 ft^2/d (500 to 2,000 m^2/d).

Recharge to the Presidio and Redford bolsons occurs along the margins of the bordering mountains and in the channels of Cibolo and Alamito Creeks and ephemeral streams. The Rio Grande, during periods of high flow, locally recharges the alluvium along its flood plain. By using a rough relationship between recharge and drainage area, recharge to the Presidio and Redford bolsons, not including recharge by the Rio Grande or recharge in the drainage areas of Cibolo Creek and Alamito Creek outside the Presidio bolson, is about 7,000 acre-feet (8.6 million m^3) per year. Additional ground water enters the southeastern part of the Presidio bolson as underflow in the Alamito Creek Valley.

Water-level contours in the Presidio and Redford bolsons (fig. 24) indicate that ground water flows from the margins of the bolsons to the Rio Grande, where it discharges to the river. Water-level data are sparse outside of the Rio Grande flood plain, and much of the data are from shallow wells (less than 100-200 feet or 30-60 m deep) in or near the channels of ephemeral streams and Cibolo and Alamito Creeks. Water levels in these wells may be higher than would be typical of wells in the deeper bolson fill because of periodic recharge from the streams or because the water is perched.

Water levels in two wells that are 350-400 feet (110-120 m) deep, one next to the upper part of Cibolo Creek and one adjacent to Alamito Creek, were 140 to 160 feet (43 to 49 m) lower than water levels in the shallow wells, and may be more representative of conditions in the deeper bolson deposits. However, in much of the Presidio bolson northwest of Cibolo Creek, the deeper bolson fill is mostly fine-grained lacustrine deposits; and most ground-water circulation in this area probably is in the channel deposits along the ephemeral streams tributary to the Rio Grande.

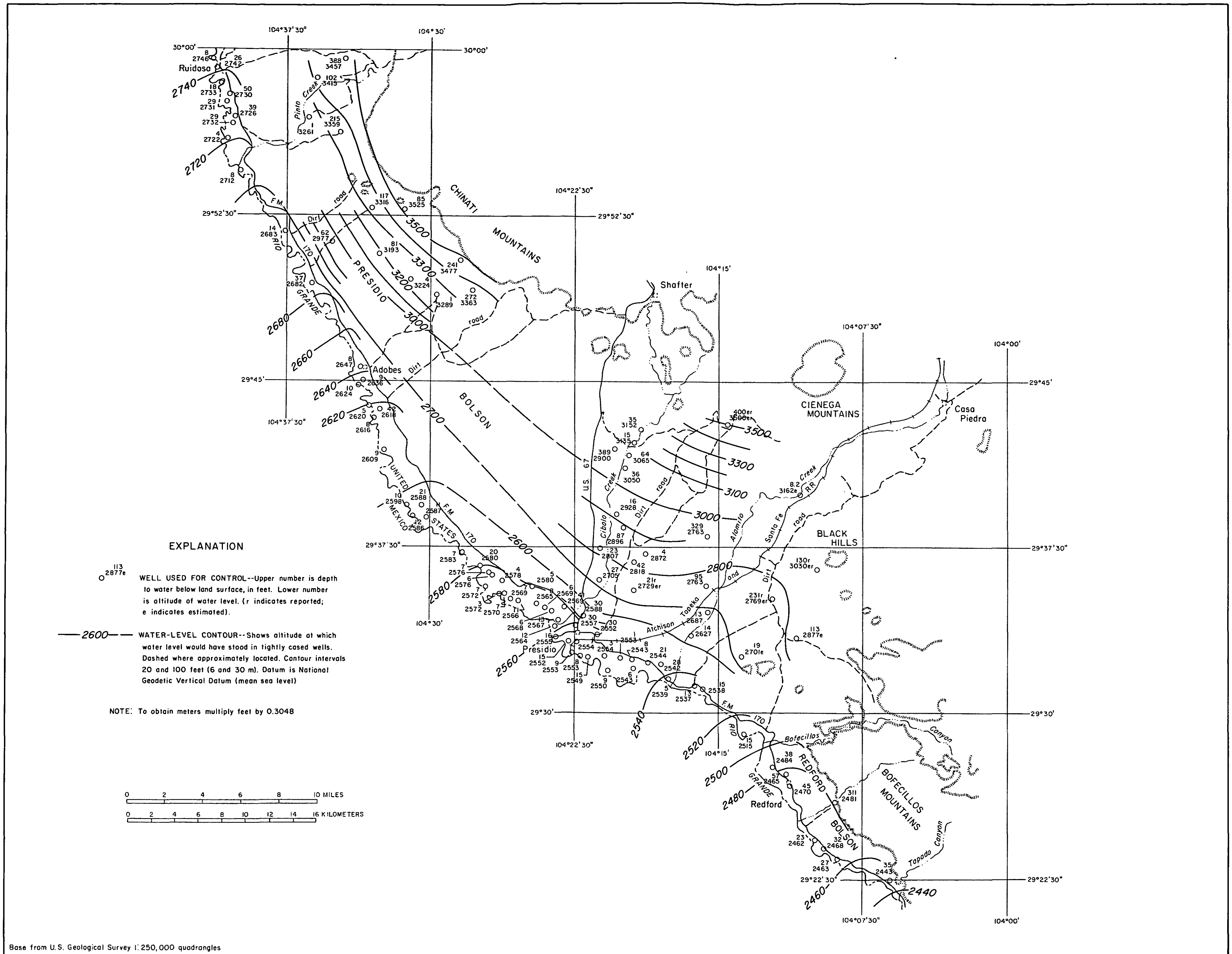

FIGURE 24.-Water levels in 1973-74 in the Presidio bolson and adjacent areas

Quality of Ground Water

The quality of ground water in the Presidio and Redford bolsons and adjacent areas is shown on figure 25. Almost all of the ground water sampled above the flood plain of the Rio Grande, both in the bolsons and in the adjacent hills and mountains, was fresh. However, in the area northwest of Cibolo Creek between the foothills and the flood plain, where the resistivity data indicate that the bolson fill is mostly lacustrine clay and silt, the ground water probably is fresh only in the alluvium along the stream channels. Water in the bulk of the fine-grained bolson fill probably is moderately saline or of poorer quality. In the Cibolo-Alamito Creek area, resistivity data indicate that the entire section of bolson fill is coarser grained and may contain freshwater.

In the alluvium along the Rio Grande northwest of Presidio, ground water ranges from fresh to very saline, but mostly is moderately saline. Below Presidio and in the Redford bolson, ground water in the alluvium generally is slightly saline. The Rio Grande above Presidio commonly has low flow or is dry; after the Rio Conchos enters the Rio Grande 4 miles (6 km) above Presidio, it becomes a perennial stream. In 1973, the Rio Grande had a discharge of 6,600 acre-feet (8.1 million m^3) at the gaging station 7 miles (11 km) northwest of Presidio while the discharge was 791,000 acre-feet (975 million m^3) at the station downstream from the Rio Conchos and Alamito Creek junctions (International Boundary and Water Commission, United States and Mexico, 1973, p. 16 and 19). The inflow from the Rio Conchos and Alamito Creek has maintained the ground water along the Rio Grande at a better quality below the confluence of the Rio Conchos.

The generally poor quality of ground water in the alluvium along the Rio Grande results from the discharge of ground water by evapotranspiration along the flood plain of the river. The quality of ground water in the alluvium, however, varies both with area and time, reflecting periodic recharge from the river. The alluvium locally contains fresh to slightly saline water, probably because of recharge from the river, subsurface inflow, or recharge from tributary streams, such as Pinto Creek, Cibolo Creek, and Alamito Creek.

Development of Ground Water, Volumes of Freshwater in Storage, and Problems Associated with Future Development

Ground water has been developed for irrigation along the flood plain of the Rio Grande and locally along Cibolo and Alamito Creeks; in other parts of the Presidio and Redford bolsons, ground water is withdrawn only for stock and domestic uses. Davis and Leggat (1965, p. U38) estimated that in 1960 about 5,400 acre-feet (6.7 million m^3) of water was pumped for irrigation above the confluence of the Rio Grande and Rio Conchos. Below the Rio Conchos, surface water is normally available and ground water is pumped only for supplemental irrigation supply.

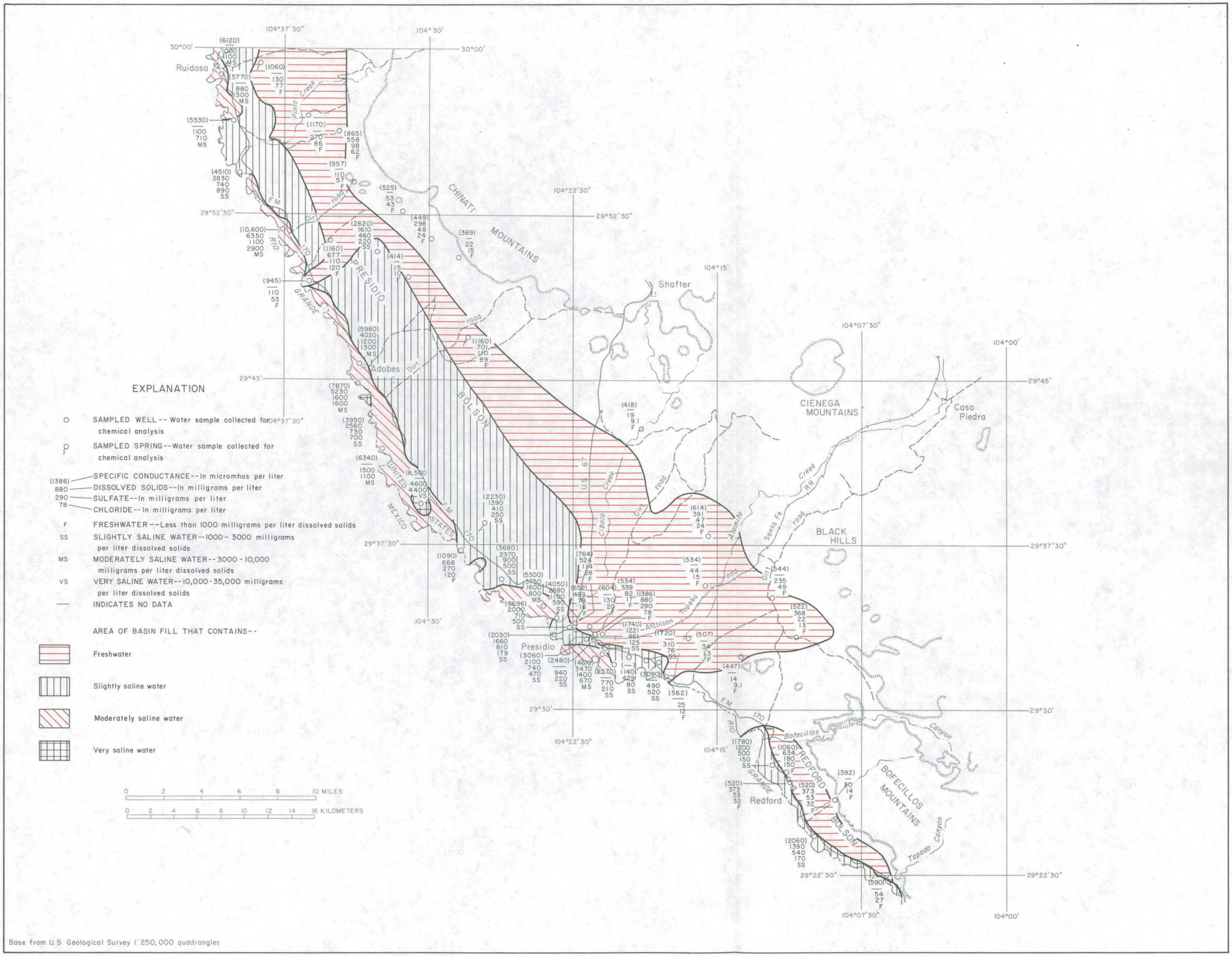

FIGURE 25.-Quality of ground water in the Presidio bolson and adjacent areas

Long-term water-level declines along the Rio Grande are probably small because pumping is minimal and high flows in the Rio Grande periodically recharge the alluvium. Two observation wells at Presidio and Redford showed no significant water-level changes during 1966-76.

The only areas where significant amounts of fresh ground water might be in storage are around Alamito Creek in the southeastern Presidio bolson and in the Redford bolson (fig. 23). The estimated amount of water stored in the Alamito Creek area was based only on geophysical data. This estimate is uncertain because no hydrologic data were available to verify the geophysical data, and because the base of the water-bearing and permeable material is not known. The estimate for the Redford bolson is slightly more reliable because some hydrologic data are available.

As much as 800,000 acre-feet (986 million m^3) of fresh ground water may be stored in the Alamito Creek area, assuming an average thickness of potentially permeable basin fill and volcanic clastics(?) of 750 feet (230 m), an average saturated thickness of 600 feet (180 m), and a specific yield of 7.5 percent over an area of about 29 square miles (75 km^2). About 200,000 acre-feet (247 million m^3) of fresh and slightly saline ground water may be stored in the Redford bolson, assuming an average basin-fill thickness of 350 feet (110 m), an average saturated thickness of 200 feet (60 m), and a specific yield of 10 percent over an area of 17 square miles (44 km^2). The specific yield was assumed to be 10 percent because the material to depths of about 500 feet (150 m) in the Redford bolson is bolson fill and probably does not include any volcanic clastics. Most of this water is fresh, because the slightly saline water occurs only in the river alluvium to depths of 100 feet (30 m) or less.

The volume of slightly saline water in the alluvium under the Rio Grande flood plain of the Presidio bolson was not estimated because it is probably insignificant. Most of the water in the alluvium of this reach of the river is moderately saline or poorer quality.

No problems are known to be associated with developing the fresh ground water in the Presidio and Redford bolsons. Water levels along the Rio Grande near Presidio are about 200 feet (60 m) lower than the average water level in the Alamito Creek area, so the poor-quality water in the alluvium would not move north unless development in the Alamito area lowered water levels more than 200 feet. The lack of hydrologic data in the Alamito Creek area, however, makes it impossible to accurately determine the potential of this area for the development of freshwater.

HUECO BOLSON

The Hueco bolson, an interstate and international ground-water reservoir, includes areas in Texas, New Mexico, and Mexico. The northern part of the bolson, in Texas and New Mexico, lies between the southern Organ Mountains and the Franklin Mountains on the west and the Hueco Mountains on the east; the southeastern part of the bolson, in Texas and Mexico, lies between several mountain ridges in Mexico on the west and the Diablo Plateau and the Finley, Malone, and Quitman Mountains on the east (fig. 26).

The Organ Mountains are composed of Tertiary intrusives and volcanics, Paleozoic limestones and dolomites, and Precambrian rocks; the Franklin Mountains are composed mostly of Precambrian rocks and Paleozoic limestones and dolomites; and the Hueco Mountains and the Diablo Plateau are composed mostly of limestone, sandstone, and shale of Paleozoic and Cretaceous age. The Finley and Malone Mountains are composed mostly of limestone, sandstone, and shale of Paleozoic, Jurassic, and Cretaceous age; and the Quitman Mountains are composed of Cretaceous limestones and Tertiary volcanics. The rocks of the mountain ranges bounding the bolson in Mexico are mostly limestone, sandstone, and siltstone of Cretaceous age (DeFord and Haenggi, 1970, p. 175).

The Rio Grande is entrenched about 200 to 250 feet (60 to 80 m) into the Hueco bolson. The relatively undissected and undrained surface of the bolson is commonly termed the "mesa," and the hilly eroded area between the edge of the mesa and flood plain of the Rio Grande is called, in this report, the "sandhills area" (fig. 26). The flood plain of the Rio Grande on the United States side of the river is locally called the El Paso Valley.

Ground-Water Hydrology

The primary water-bearing material of the Hueco bolson is the unconsolidated basin fill, which in previous hydrologic studies (Knowles and Kennedy, 1958, p. 19-20; and Alvarez and Buckner, 1974, p. 33-34) commonly has been divided into the Rio Grande alluvium, composed of the channel deposits of the modern course of the Rio Grande, and the older bolson deposits, mostly deposited before the Rio Grande drained the bolson.

In the northern part of the bolson, Davis and Leggat (1967, p. 8 and fig. 2) reported that on the basis of seismic-refraction, gravity, and resistivity data, the thickest section of basin fill occurs as a trough-shaped body adjacent and parallel to the Franklin Mountains. The total thickness of this section may be as much as 9,000 feet (2,740 m). In this area, a deep test hole drilled by El Paso Water Utilities about 12 miles (19 km) north of downtown El Paso penetrated 4,363 feet (1,330 m) of fill that was predominantly sand and gravel in the upper 600 feet (180 m), sand and clay in the interval from 600 to 2,300 feet (180 to 700 m), and mostly lacustrine clay with some evaporites below 2,300 feet or 700 m (Davis and Leggat, 1967, p. 14-16). Cliett (1969, fig. 2) identifies the upper 1,400 feet (430 m) as fluvial deposits and the material below 1,400 feet (430 m) as lacustrine deposits.

In the southeastern part of the bolson between El Paso and Clint, Davis and Leggat (1967, fig. 2) indicated that the basin fill is from 1,000 to 3,000 feet (300 to 910 m) thick. Gates and Stanley (1976, p. 34) interpreted resistivity data collected over much of the southeastern Hueco bolson between El Paso and Esperanza to indicate that the basin fill was

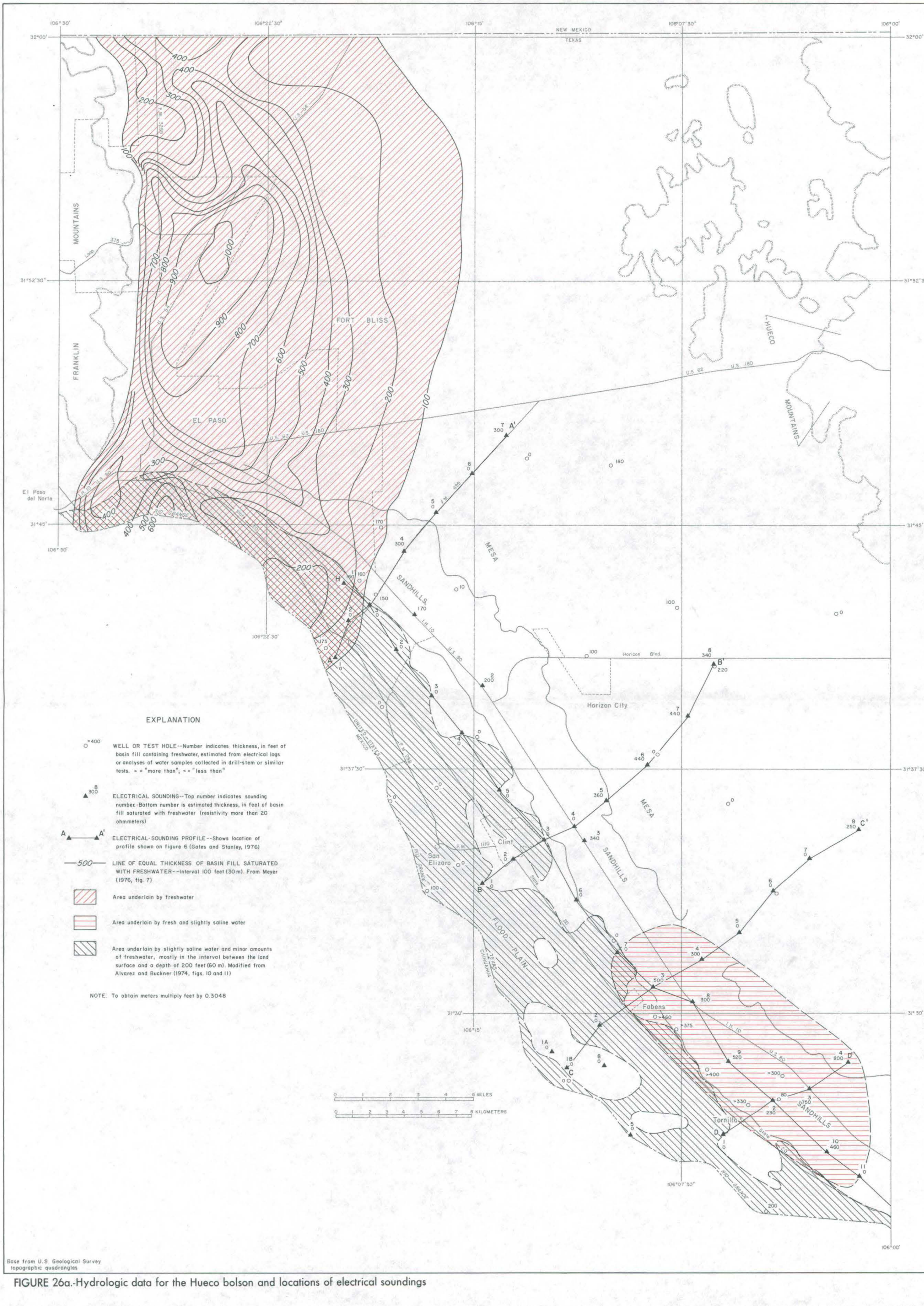

FIGURE 26a.-Hydrologic data for the Hueco bolson and locations of electrical soundings

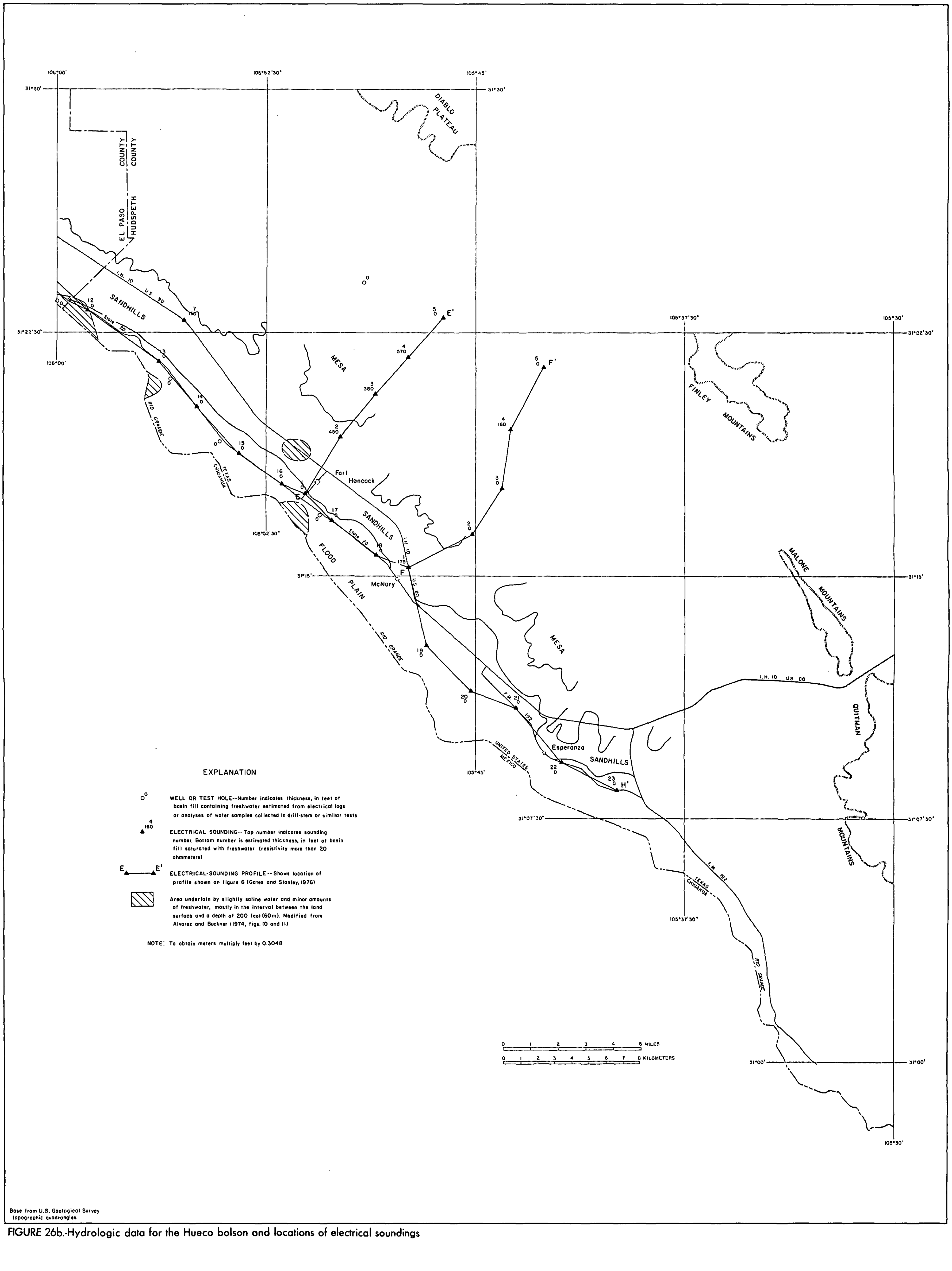

FIGURE 26b.-Hydrologic data for the Hueco bolson and locations of electrical soundings

from less than 1,000 feet (300 m) to about 5,000 feet (1,520 m) thick. An oil test drilled 2 miles (3.2 km) northeast of Tornillo (fig. 26a) reportedly penetrated about 9,000 feet (2,740 m) of basin fill (Alvarez and Buckner, 1974, p. 33). This thickness is anomalous for this part of the bolson and is not indicated by the resistivity data. However, the deep trough of fill adjacent to the Franklin Mountains may extend south into Mexico and possibly swings southeast into the United States near Tornillo. Gates and Stanley (1976, p. 35) stated that much of the basin fill in the southeastern part of the bolson has low resistivity and is composed of clay, probably playa-lake deposits, including some sand beds containing salty water.

An ancient course of the Rio Grande probably extended into the Hueco bolson through Fillmore Pass between the Organ and Franklin Mountains and along the east front of the Franklin Mountains (Strain, 1966). Part of the uppermost 600-1,400 feet (180-430 m) of relatively coarse-grained basin fill east of the Franklin Mountains may be deposits of the ancestral Rio Grande. Airborne-electromagnetic and resistivity data from the southeastern part of the bolson indicate the occurrence of a band of resistive material several hundreds of feet (about 100-200 m) thick along the edge of the mesa roughly parallel to the Rio Grande (Gates and Stanley, 1976, figs. 5 and 7). This zone may represent a continuation of the coarse-grained material deposited by the ancestral Rio Grande on its course to the southeastern end of the bolson.

The Rio Grande alluvium is the material deposited by the Rio Grande along its present course through the bolson. Davis (1967, p. 5) estimated its maximum thickness at about 200 feet (60 m); Alvarez and Buckner (1974, p. 22) stated that in two test holes drilled along the river, the coarsest material, most of which is alluvium, extended to a depth of 250 feet (76 m).

Transmissivities of the bolson deposits along the Franklin Mountains range from 6,700 to 33,400 ft^2/d or 620 to 3,100 m^2/d (Meyer, 1976, fig. 8). No data are available on transmissivities in the southeastern part of the bolson or in the Rio Grande alluvium. The wells of El Paso Water Utilities, east of the Franklin Mountains, yield as much as 1,800 gal/min (113 L/s) with specific capacities of up to 40 (gal/min)/ft [8 (L/s)/ft]. Irrigation wells tapping the Rio Grande alluvium in the El Paso Valley yield as much as 2,000 gal/min (126 L/s).

Recharge to the Hueco bolson occurs along the mountains bordering the bolson, and at times locally along the Rio Grande. Meyer (1976, p. 18) estimated, from digital-model studies, that the annual recharge around the perimeter of the northern end of the bolson, including areas in New Mexico and around Ciudad Juarez in Mexico, was about 6,000 acre-feet (7.4 million m^3). By using a rough relationship between recharge and drainage area, and by assuming an annual average of 10 inches (254 mm) of precipitation, recharge to the entire United States part of the bolson, not including recharge from the Rio Grande, might be about 14,000 acre-feet (17.3 million m^3) per year.

Before the Rio Grande drained the Hueco bolson, ground water probably flowed to depressions or lakes in the lowest parts of the bolson, where it was discharged by evapotranspiration. After the river cut through the bolson, the flood plain served as the discharge zone. Meyer and Gordon (1972, fig. 8) showed estimated water-level contours for the northern part of the bolson in 1903, prior to significant ground-water development. These contours indicate that ground water moves generally south across the Texas-New Mexico State line toward the Rio Grande. A 1970 water-level map (Meyer and Gordon, 1972, fig. 4) shows that much of the ground water now flows into two cones of depression in the water table east of the Franklin Mountains, where it is discharged by municipal-supply and industrial wells.

Over most of the bolson, ground water occurs under water-table conditions. In the El Paso Valley, however, ground water is under water-table conditions in the Rio Grande alluvium and partially under artesian conditions where sands occur in the underlying bolson deposits. Along the Rio Grande flood plain between downtown El Paso and Ysleta, the water in the bolson deposits is under slight artesian pressure; and Davis and Leggat (1965, p. U38) defined this as the city artesian area. Within this area, the freshwater in the bolson deposits is overlain by slightly saline water and underlain by slightly saline and poorer-quality water. The freshwater zone is as much as 600 feet (180 m) thick and the top of the zone is at depths of 200 to 500 feet (60 to 150 m). The water in the city artesian zone is fresh because the recharge area is nearby, the fill is relatively coarse, and ground-water circulation is relatively rapid.

Davis and Leggat (1965, p. U40) envisioned the city artesian area to be a locality where ground water passes beneath beds of lower permeability and is confined under pressure. The clay beds in the deposits of the northern part of the bolson, however, are discontinuous lenses; consequently, there is no single confining bed in the city artesian area. The increase in pressure with depth in the city artesian area may be as much a result of the upward movement of ground water and low vertical permeability as it is a result of the water passing beneath confining beds.

In most of the city artesian area, pumping of ground water from the bolson deposits has lowered the water level below the water level in the overlying Rio Grande alluvium; and the original direction of ground-water movement has been reversed. Water now moves downward from the alluvium to the bolson deposits. This reversal of flow, together with the lining with concrete of a 4.35-mile (7.0-km) segment of the Rio Grande below El Paso del Norte in downtown El Paso in 1968, has in turn lowered water levels in the alluvium. In southeastern El Paso, downstream from the end of the lined section of the river, the Rio Grande is now a source of recharge to the alluvium rather than an area of discharge.

The digital model of the ground-water system of the northern part of the bolson indicated that the river furnished between 10,000 and 20,000 acre-feet (12.3 and 24.7 million m^3) per year of recharge to the alluvium between 1953 and 1973 (Meyer, 1976, table 1). The model indicated that the rate of recharge progressively increased, except just after the partial lining of the Rio Grande in 1968, when recharge decreased and subsequently continued to increase. This recharge, which did not occur before ground water was developed in the bolson, has been induced by water-level declines caused by pumping in the city artesian area. If this estimate of induced recharge is correct, the amount is substantially greater than the 6,000 acre-feet (7.4 million m^3) per year of recharge estimated to occur under natural conditions around the margin of the nothern end of the bolson.

El Paso Water Utilities drilled two test holes southwest of Fabens (one of these tests, 3.5 miles or 5.6 km southwest of Fabens, is shown on figure 26a) that penetrated a zone of alternating sands and clays between 1,300 and 1,900 feet (400 and 580 m). This zone, which yields slightly saline water (958 to 1,540 mg/L dissolved solids) under sufficient pressure to flow at the land surface, has been informally called the "Fabens artesian zone." In this zone, the pressure probably is the result of ground-water confinement. Electrical logs of the test holes indicate that the material overlying the artesian zone is predominantly clay, which probably forms an effective confining bed.

The Fabens artesian zone also has been tapped by wells drilled farther west in Mexico. Hydrologic and resistivity data from the Mexican side of the Rio Grande near Fabens (Hector A. Gameros, Secretaria de Recursos Hidraulicos, written commun., Apr. 24, 1975; and GeoFimex S. A., 1970) indicate that the top of the artesian zone is shallower there, perhaps at a depth of about 900 feet (270 m). The zone may be composed of coarser sediments eroded from the Sierra del Presidio, Sierra de Guadalupe, and Sierra de San Ignacio, which bound the bolson to the south in Mexico and rise to elevations of 6,000 to 7,000 feet (1,830 to 2,130 m) above mean sea level. Resistivity data collected in the Fabens area suggest that the artesian zone extends to a depth of 2,800 feet (850 m), and resistivity and hydrologic data suggest that it is limited in the United States to the area immediately south and west of Fabens (Gates and Stanley, 1976, p. 31; Davis and Leggat, 1965, p. U40).

Quality of Ground Water

Figures 26a,b show the areas of the Hueco bolson that are underlain by significant thicknesses of fresh and slightly saline ground water. The largest amount of freshwater in the Texas part of the bolson occurs in the northern part, in a trough-shaped body up to 1,000 feet (300 m) thick and about 7 miles (11 km) wide adjacent to the Franklin Mountains. This body of freshwater occurs in sediments that include coarse debris eroded from the mountains and alluvium deposited by the ancestral Rio Grande. Recharge occurs mainly by infiltration of runoff along the Franklin and Organ Mountains. The combination of a nearby source of recharge and coarse-grained and permeable sediments results in relatively rapid and deep circulation of freshwater. Water pumped from wells in this area commonly contains less than 500 mg/L dissolved solids.

East of the axis of the trough, toward the Hueco Mountains, the freshwater section thins to less than 100 feet (30 m). Along the eastern side of the southeastern part of the bolson, available well data also indicate that where present, the freshwater is generally in a zone less than 200 feet (60 m) thick (figs. 26a,b). In these areas, the fill is finer grained, less permeable, and probably contains more soluble material. The rate of recharge is less from the low Hueco Mountains and Diablo Plateau, ground-water circulation is slow, and the water contains a greater amount of dissolved minerals.

Ground water in the Rio Grande alluvium in the El Paso Valley is predominantly slightly saline in El Paso County and moderately saline or of poorer quality in Hudspeth County (fig. 26 and Alvarez and Buckner, 1974, figs. 10 and 11). In the city artesian area at the north end of El Paso Valley, the water in the Rio Grande alluvium is of poorer quality than the water in the underlying bolson deposits, but at many locations down valley, the water in the alluvium is of better quality than the water in the underlying fill. The poor quality of the water in the Rio Grande alluvium probably results from the concentration of salts through evapotranspiration of shallow ground water during the long period when the river was the zone of discharge for ground water in the Hueco bolson. In addition, irrigation in the valley has increased the concentrations of salt in the water.

Southeast of Ysleta, water in the bolson deposits beneath the Rio Grande alluvium is moderately to very saline, generally containing more than 5,000 mg/L dissolved solids (Alvarez and Buckner, 1974, fig. 14). Only 2 of the 15 deep test holes that have been drilled to depths of 600 to 3,500 feet (180 to 1,070 m) in the El Paso Valley southeast of Ysleta encountered any freshwater, and this water was limited to the upper 300 feet (90 m) of material penetrated, most of which was Rio Grande alluvium. Soluble material in the fine-grained, predominantly playa-lake bolson deposits, and the lack of ground-water circulation at depth probably accounts for the poor-quality water in the basin fill in the El Paso Valley.

Some fresh and slightly saline ground water occurs in the Rio Grande alluvium and underlying bolson deposits in the sandhills area between the flood plain and the mesa, most significantly between Fabens and Tornillo (fig. 26a). In this area, several wells penetrated sediments containing fresh and slightly saline water to depths of as much as 500 feet (150 m).

Development of Ground Water, Volumes of Fresh and Slightly Saline Water in Storage, and Problems Associated with Future Development

Pumping ground water from the Hueco bolson for municipal and industrial supplies began in the early 1900's. The rate of withdrawal has steadily increased along with the area's population and industrial growth. From 1906 through 1975, about 1.80 million acre-feet (2.2 km^3) was pumped from the Texas part of the northern Hueco bolson; and from 1925 through 1975, about 570,000 acre-feet (703 million m^3) was pumped from the Ciudad

Juarez area in Mexico, for a total of 2.37 million acre-feet (2.9 km^3). In 1975, 72,000 acre-feet (89 million m^3) was pumped from the Texas part of the northern bolson and about 40,000 acre-feet (49 million m^3) was pumped from the Ciudad Juarez area, for a total of 112,000 acre-feet (138 million m^3). From 1903 to January 1976, water levels declined as much as 60-70 feet (18-21 m) in the northern and southeastern part of El Paso and as much as 95 feet (29 m) in downtown El Paso and Ciudad Juarez (U.S. Geological Survey, unpublished records).

When the flow of the Rio Grande is low and little water is available for irrigation, large amounts of ground water are pumped from shallow wells in the Rio Grande alluvium for supplemental irrigation supplies. As much as 150,000 acre-feet (185 million m^3) per year has been pumped when surface water was in short supply, and less than 10,000 (12.3 million m^3) per year has been pumped when the surface-water supply was adequate (Alvarez and Buckner, 1974, table 7). Water levels decline in the alluvium during years of heavy pumping but recover when surface water is plentiful and recharges the alluvium. Except in the city artesian area, water levels in the Rio Grande alluvium have not shown any long-term declines.

Meyer (1976, table 2) estimated on the basis of digital-model studies that in 1973, about 10.6 million acre-feet (13.1 km^3) of fresh ground water was stored in the trough east of the Franklin Mountains. Gates and Stanley (1976, p. 28) estimated that 400,000 to 800,000 acre-feet (0.5 to 1 km^3) of fresh to slightly saline ground water occurs from Fabens to and southeast of Tornillo, mostly in the sandhills area (fig. 26a). This estimate was based on an average saturated thickness (50 percent sand) of 500 feet (150 m), a specific yield for the sands of 10 percent, and an area of 25 to 50 square miles (65 to 130 km^2).

In addition to these volumes of water, Knowles and Kennedy (1958, p. 37) estimated that 6.2 million acre-feet (7.6 km^3) of fresh ground water is stored in the part of the freshwater trough in New Mexico, which extends about 12 miles (19 km) north of the State line to the southern end of the Organ Mountains. Data are not available to estimate the volume of fresh ground water in the Mexican part of the Hueco bolson, although Meyer (1976, p. 14) made a rough estimate of 4 million acre-feet (5 km^3) in the Ciudad Juarez area.

At each electrical sounding (figs. 26a,b), the thickness of material potentially saturated with freshwater is shown. This thickness, which is defined as all intervals below the water table having a resistivity of more than 20 ohmmeters, was obtained from figure 6 of Gates and Stanley (1976). The resistivity data show little potentially freshwater-bearing material southeast of El Paso. With the exception of sounding H-H' north of Ysleta (fig. 26a), no soundings in the El Paso Valley showed any potential for the occurrence of freshwater. In the sandhills and mesa areas, with the exception of the Fabens-Tornillo area, most soundings indicate 200 feet (60 m) or less of freshwater-bearing material. Greater potential thicknesses of sediments containing fresh ground water occur at several localities--up to 300 feet (90 m) northeast of Ysleta, up to 440 feet (130

m) northeast of Clint, and up to 570 feet (170 m) northeast of Fort Hancock in Hudspeth County. However, wherever well or test-hole data are available near an electrical sounding in the southeastern Hueco bolson, they indicate that the resistivity data overestimate the thickness of sediments containing freshwater.

In addition to fresh ground water in storage, large volumes of slightly saline water are stored in both the Rio Grande alluvium and in the deposits of the Hueco bolson. Alvarez and Buckner (1974, p. 17) estimated that about 1.8 million acre-feet (2.2 km^3) of slightly saline water occurs to depths of about 200 feet (60 m) in the Rio Grande alluvium of the El Paso Valley. Most of the slightly saline water is in El Paso County (fig. 26a). Slightly saline and poorer-quality water also underlie the freshwater trough east of the Franklin Mountains. Meyer and Gordon (1972, p. 27 and 29) roughly estimated the volume of slightly saline water in the northern part of the bolson to be about 3.4 million acre-feet (4.2 km^3).

Continued withdrawals of ground water from the Hueco bolson will result in additional water-level declines, and will probably cause contamination of the freshwater by poorer-quality water, and could possibly cause land-surface subsidence. Meyer (1976, fog. 13) predicted, by use of a digital model, water-level declines of up to 110 feet (34 m) in El Paso and 140 feet (43 m) in Ciudad Juarez for 1903-91. The prediction for Juarez is probably conservative, because Meyer assumed an average annual pumping rate for 1973-91 of 36,000 acre-feet (44 million m^3) for Ciudad Juarez, and this amount was exceeded by 1974.

The freshwater trough is underlain by and adjacent to poorer quality water. In the deep test hole drilled by El Paso Water Utilities north of downtown El Paso, the bolson sediments contained freshwater to a depth of 960 feet (290 m). However, below that depth water quality deteriorated markedly. Water samples from depths of 1,225-2,856 feet (373-871 m) contained from 11,200 to 41,900 mg/L dissolved solids (Davis and Leggat, 1967, table 1). In addition, freshwater in the city artesian area is overlain by slightly saline water in the Rio Grande alluvium. As pumping lowers water levels in the bolson deposits, water in the Rio Grande alluvium will move down into the freshwater and will contaminate it to an unknown degree. Similarly, water-level declines could induce upward and lateral movement of poorer-quality water into the freshwater trough. The rate and extent of such contamination has not been predicted, but it will probably be gradual. Within limits, however, some mixing of fresh and slightly saline water would produce a large volume of usable water.

Large water-level declines have produced land-surface subsidence in parts of the United States (Poland, 1973) where aquifers include significant thicknesses of clay and the declines have induced drainage of water and compression of the clays. Subsidence has been predicted tentatively to accompany future water-level declines around Tucson, Arizona (Davidson, 1973, p. E51-E54), an area in which the geohydrologic characteristics have some similarity to those of the Hueco bolson. No land-surface subsidence has been recorded in the Hueco bolson and none has been predicted, but if water levels decline several hundreds of feet (about 100 m), some subsidence may occur, especially in the heavily pumped city artesian area in the U.S. and Mexico.

LOWER MESILLA VALLEY AND ADJACENT PARTS OF THE MESILLA BOLSON

The Mesilla Valley of the Rio Grande crosses the east side of the Mesilla bolson west of the Franklin and Organ Mountains. The lower Mesilla Valley is that part between the Texas-New Mexico State line at Anthony and El Paso del Norte between the Franklin Mountains and Sierra de Cristo Rey at the Mexican border (fig. 27). The Franklin Mountains to the east are composed of Precambrian rocks and Paleozoic and Cretaceous limestone, dolomite, and sandstone. Tertiary intrusives flanked by Cretaceous rocks form the Sierra de Cristo Rey and the hills southeast of Cristo Rey on the east side of the Rio Grande. The west side of the lower Mesilla Valley is La Mesa, the undissected surface of the Mesilla bolson that is underlain by basin fill of late Tertiary and Quaternary age.

The Mesilla bolson extends over a wide area of New Mexico, Texas, and Mexico, from Las Cruces, New Mexico, on the north to the salt flats in Mexico about 50 miles (80 km) south of the border. The western side of the bolson, opposite the lower Mesilla Valley, is about 15 miles (24 km) west of the area shown on figure 27. This boundary is formed by the East and West Potrillo Mountains, composed of Tertiary volcanic and intrusive rocks and Paleozoic and Cretaceous rocks that are mostly limestone.

Ground-Water Hydrology

Most of the Mesilla Valley and Mesilla bolson are underlain by thick sections of basin fill, which are probably underlain by thick sections of volcanic rocks. The basin fill of the Mesilla bolson is composed of clay, silt, sand, and some gravel and includes the Santa Fe Group of Miocene to Pleistocene age and the Rio Grande alluvium of Holocene age. Resistivity and well data indicate that a fault bounds the east side of the basin between Interstate Highway 10 and Texas Highway 20 (fig. 27). East of the fault, the bedrock that is encountered at depths of about 100 to 600 feet (30 to 180 m) is probably Paleozoic or Cretaceous limestone.

West of Texas Highway 20, a number of test holes and wells penetrated more than 1,000 feet (300 m) of basin fill. A test hole 1 mile (1.6 km) southwest of Anthony penetrated an igneous sill between 1,271 and 1,385 feet (387 and 422 m) but then apparently reentered unconsolidated fill and remained in it to its total depth of 1,705 feet or 520 m (Leggat, Lowry, and Hood, 1962, p. 14 and table 3). A well drilled 1 mile (1.6 km) southwest of Strauss reportedly penetrated 1,810 feet (552 m) of basin fill and from 1,810 feet to its total depth of 1,980 feet (604 m), the well penetrated 110 feet (34 m) of rock underlain by 60 feet (18 m) of clay, which may represent the bedrock.

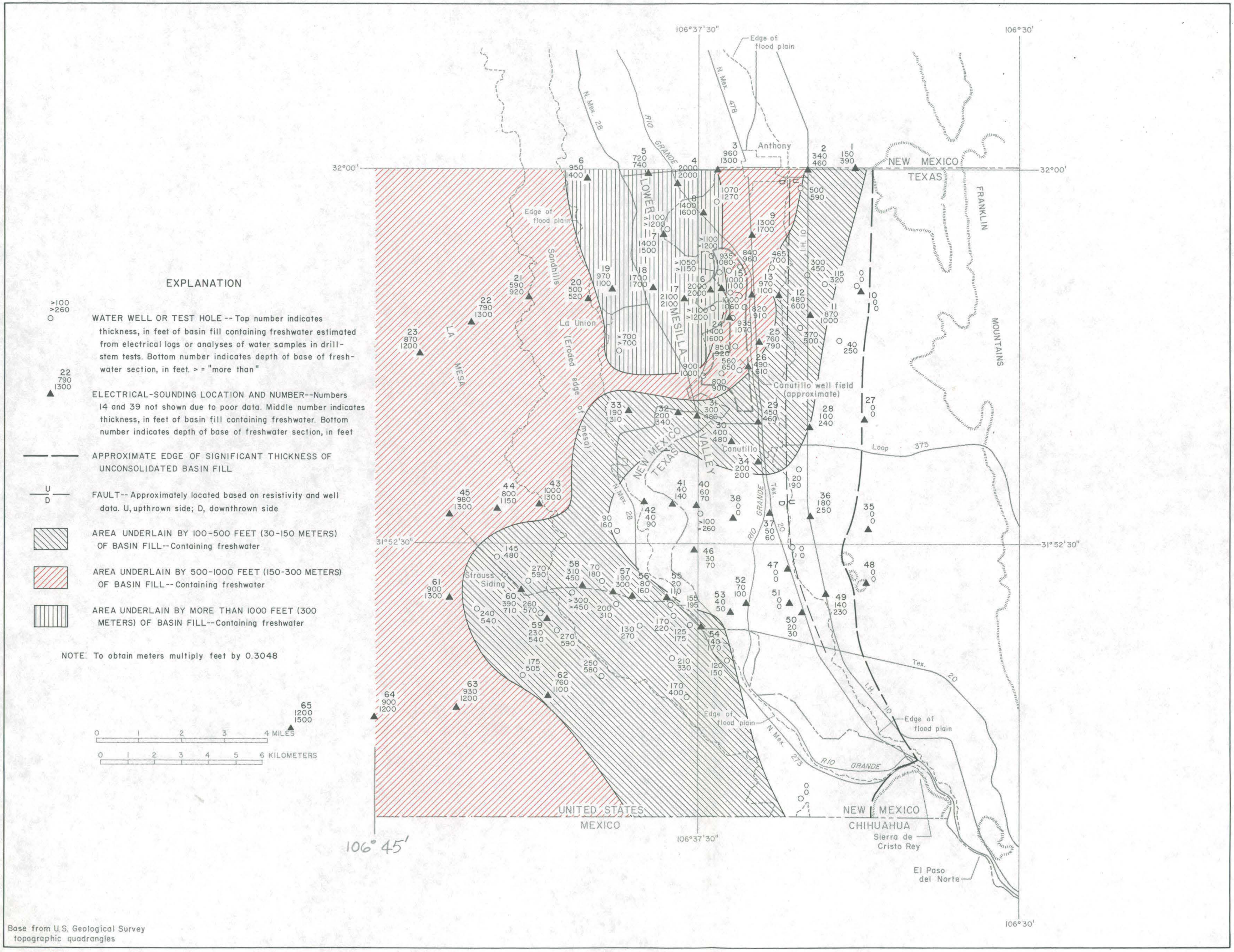

FIGURE 27.-Approximate thickness of basin fill containing fresh ground water and locations of electrical soundings in the lower Mesilla Valley, Texas and New Mexico

Kottlowski (1973, p. 42) stated that the Texaco No. 1 Weaver Federal oil test, 12 miles (19 km) west of Anthony, penetrated basin fill to a depth of 2,430 feet (741 m) and then volcanic rocks to a total depth of 6,620 feet (2,020 m). The electrical, sonic, and formation-density logs of the oil test, however, suggest that the change from basin fill to volcanics could also occur at depths between 1,800 to 2,000 feet (550 to 610 m). Kottlowski (1973, p. 42) described the volcanic sequence in the Texaco oil test as rhyolitic ash-flow tuffs and sediments, underlain by tuff breccias and flows that are interbedded with siltstones. Interpretation of resistivity data collected in the lower Mesilla Valley (Zohdy, Bisdorf, and Gates, 1976) indicates as much as 3,000 to more than 5,000 feet (900-1,520 m) of low-resistivity material under the valley, which probably includes the basin fill and underlying volcanics.

Much of the deeper part of the Santa Fe Group probably was deposited when the Mesilla bolson was a closed basin and is predominantly coarse grained around the margins of the bolson and fine grained in its center. Most of the upper part of the basin fill was deposited by the ancestral Rio Grande, which entered the bolson from the north, or was deposited in lakes that formed periodically in the Mesilla and adjacent bolsons (Strain, 1973, p. 33). The river deposits are mostly coarse grained and the lake deposits are mostly fine grained. The Rio Grande alluvium was deposited by the river after it established its present course through the Mesilla bolson to enter the Hueco bolson at El Paso del Norte. The alluvium underlies the flood plain of the river in the Mesilla Valley, and cannot be distinguished easily from the underlying Santa Fe Group. Leggat, Lowry, and Hood (1962, p. 15) estimated the thickness of the Rio Grande alluvium to be 150 feet (46 m) or less.

Leggat, Lowry, and Hood (1962, p. 10-15) defined three water-bearing zones (shallow, medium, and deep aquifers) in the unconsolidated rocks of the valley, mostly based on electrical logs of wells in El Paso Water Utilities' well field northwest of Canutillo (fig. 27). The shallow aquifer, which includes the Rio Grande alluvium and part of the underlying Santa Fe Group, is composed of sand and gravel with some silt and clay, and extends from the land surface to depths of 160 to 260 feet (49 to 79 m). The aquifer at medium depth, which includes most of the upper part of the Santa Fe Group, consists of alternating beds of sand and clay, and extends from the base of the shallow aquifer to depths of about 460 to 680 feet (140 to 210 m). The medium aquifer appears to thicken to the west and north (Leggat, Lowry, and Hood, 1962, figs. 4 and 5).

The deep aquifer is tapped by wells and defined only in the Canutillo-Anthony area, where it extends from the base of the medium aquifer locally to depths of more than 1,200 feet (370 m). In the deep test hole 1 mile (1.61 m) southwest of Anthony, the base of the deep aquifer may be the 114-foot (35-m) igneous sill encountered at 1,271 feet (387 m)--the water-bearing properties of the unconsolidated material below the sill are not known. The deep aquifer is a uniform, thick-bedded, fine to medium sand with relatively little clay. Electrical logs indicate that it thickens to the west, and the aquifer (or laterally equivalent beds) contains brackish water in the southern end of the valley.

The shallow, medium, and deep aquifers each yield as much as 2,000 to 3,000 gal/min (126 to 189 L/s) to wells; and their transmissivities are about 18,000, 5,000, and 8,000 ft^2/d (1,670, 460, and 740 m^2/d), respectively (Leggat, Lowry, and Hood, 1962, p. 31, and unpublished data supplied by El Paso Water Utilities). Specific capacities of irrigation wells in the shallow aquifer of the northern part of the valley averaged 46 (gal/min)/ft [9.5 (L/s)/m]. Wells in the medium aquifer of the Canutillo field had an average specific capacity of 16 (gal/min)/ft [3.3 (L/s)/m], and wells in the deep aquifer had an average specific capacity of 25 (gal/min)/ft [5.2 (L/s)/m].

Recharge to the Mesilla bolson occurs from infiltration of runoff around its margins. In and adjacent to the Mesilla Valley part of the bolson, recharge also occurs from flow in the channels of ephemeral streams tributary to the valley and as seepage from the Rio Grande, canals, and infiltration of excess irrigation water. Unpublished water-level maps prepared by the Geological Survey indicate that in general, ground water moves from north to south in the bolson parallel to the Rio Grande, and in the southern part of the bolson moves eastward into the lower Mesilla Valley, which serves as a discharge zone. Before irrigation and ground-water pumping began, the lower Mesilla Valley probably was a swampy area of ground-water discharge. The narrow outlet at El Paso del Norte restricts ground-water outflow from the valley, and results in most of the water being discharged by evapotranspiration. Water-level contours do not indicate that any significant amount of ground water moves south across the border toward the salt flats in Mexico (C. A. Wilson and R. R. White, U.S. Geological Survey, oral commun., Nov. 17, 1976).

Leggat, Lowry, and Hood (1962, p. 18) estimated that ground-water inflow to the three aquifers of the lower Mesilla Valley from La Mesa to the west, from the foothills of the Franklin Mountains to the east, and from the Mesilla Valley north of Anthony was about 18,000 acre-feet (22 million m^3) per year. This estimate was based partly on transmissivities and water-table gradients. If the lower Mesilla Valley is the major discharge zone for the entire Mesilla bolson, and if the transmissivity and gradient data are representative of actual conditions, this value may be the approximate recharge to the entire bolson.

Quality of Ground Water

The quality of ground water in the lower Mesilla Valley varies considerably, both areally and with depth. Ground water in the shallow aquifer is influenced by the quality of water in the Rio Grande because of irrigation and direct infiltration from the river and canals. In general, the water in the shallow aquifer is poorer in quality than the deeper ground water. North of Canutillo, water from the shallow aquifer contains from 260 to 2,300 mg/L dissolved solids, and south of Canutillo contains as much as 24,800 mg/L (Meyer and Gordon, 1972, fig. 14). Water from the medium and deep aquifers in the Canutillo-Anthony area is of better quality, the best of which, from the deep aquifer, commonly contains less than 300 mg/L dissolved solids. Leggat, Lowry, and Hood (1962, p. 40-41) observed that the base of the freshwater in the Santa Fe Group is progressively shallower toward the south and east, and that south of Canutillo, most ground water contains more than 1,000 mg/L dissolved solids. At the southern tip of the valley, wells commonly yield water containing more than 3,000 mg/L dissolved solids. Leggat, Lowry, and Hood (1962, p. 41) believed that the poor quality of ground water in the southern half of the valley is related to the lack of ground-water outflow. The narrow valley outlet at El Paso del Norte prevented flushing of the original and possibly poor-quality water from the Santa Fe Group, and forces most of the ground water to be discharged by evapotranspiration, which concentrates dissolved salts in the shallow ground water.

The temperature of the ground water in the intermediate and deep aquifers is abnormally high. Leggat, Lowry, and Hood (1962, p. 10) reported that the thermal gradient in the Canutillo well field ranged from 1°F per 33 feet to 1°F per 41 feet (1°C per 18 m to 1°C per 22 m), which is considerably more than the gradient of about 1°F per 50 feet (1°C per 27 m) in the Hueco bolson. Water typical of El Paso Water Utilities' Canutillo well field from depths of about 600 to 1,100 feet (180 to 340 m) has an average temperature of 96°F (36°C).

Development of Ground Water, Volumes of Freshwater in Storage, and Problems Associated with Future Development

Ground water is pumped from the lower Mesilla Valley for municipal supply, irrigation, and industrial use. The amount of land irrigated by surface and ground water is 14,000 to 15,000 acres (57 to 61 km^2), with about 1,000 acres (4 km^2) of that amount irrigated with ground water only (Meyer and Gordon, 1973, p. 7 and table 2). When surface-water supplies are insufficient, water is pumped from standby wells in the shallow aquifer for irrigation.

Most of the municipal pumpage in the valley is by the El Paso Water Utilities from the Canutillo field. During 1957-75, the city pumped an average of about 5,500 acre-feet (6.8 million m^3) annually from the shallow aquifer, 3,500 acre-feet (4.3 million m^3) from the medium aquifer, and 9,200 acre-feet (11.3 million m^3) from the deep aquifer. In 1975, withdrawals by the city were about 5,000 acre-feet from the shallow aquifer, about 1,400 from the medium aquifer, and about 12,700 from the deep aquifer (6.2, 1.7, and 15.7 million m^3, respectively).

Other wells in the valley withdraw water for municipal supply for the town of Anthony and the community of Westway, 3 miles (4.8 km) southeast of Anthony; for irrigation and municipal supply by the Federal Correctional Institution at La Tuna, 1.5 miles (2.4 km) southeast of Anthony, and Santa Teresa Development east of Strauss; and for industrial use by several firms, including El Paso Electric Co.'s Rio Grande station in the southern end of the valley. The pumpage for these uses totaled about 8,000 acre-feet (9.9 million m^3) in 1975, of which the major amounts were about 3,500 acre-feet (4.3 million m^3) pumped by El Paso Electric Co. from the shallow aquifer, 2,000 acre-feet (2.5 million m^3) by Santa Teresa Development from the Santa Fe Group (medium aquifer?), and 1,400 acre-feet (1.7 million m^3) by the Federal Correctional Institution from the shallow and medium aquifers.

In 1973-75, a period of adequate surface-water supply, 3,000-5,000 acre-feet (3.7-6.2 million m^3) per year was pumped for irrigation. However, during a period of drought such as the mid-1950's, when little or no surface water was available, as much as 40,000-50,000 acre-feet (49-62 million m^3) reportedly was pumped from the shallow aquifer for irrigation (Leggat, Lowry, and Hood, 1962, table 1). Current pumping for all uses from the lower Mesilla Valley is about 30,000 acre-feet (37 million m^3) per year, but during a severe drought, could be as much as 80,000 acre-feet (99 million m^3) per year.

Water levels in the shallow aquifer have had little long-term change because the aquifer is replenished by infiltration from canals, the river, and applied irrigation water. Water levels in observation wells in the medium and deep aquifers of the Canutillo well field declined during the initial period of development in 1957-60, and essentially have stabilized since 1960, indicating that pumping from the field is balanced by ground-water inflow. The most likely source of inflow is leakage (vertical percolation) from the shallow aquifer induced by water-level declines in the medium and deep aquifers. Initially, the water level in the deep aquifer was at or a few feet (about 1 m) above the land surface; the water level in the medium-depth aquifer was about 5 feet (1.5 m) lower. In January 1976, the water level in an observation well in the medium aquifer was 12 feet (3.7 m) below the land surface, and water levels in three observation wells in the deep aquifer ranged from 32 to 71 feet (10 to 22 m) below the land surface.

Figure 27 shows the approximate thickness of basin fill containing fresh ground water in the lower Mesilla Valley. This map was prepared by using electrical-log and water-sample data from wells and test holes, supplemented by interpretations of electrical-sounding data. The map shows the areas underlain by more than 1,000 feet (300 m), 500-1,000 feet (150-300 m), 100-500 feet (30-150 m), and less than 100 feet (30 m) of freshwater-bearing material.

The map shows that the thickest section containing freshwater, locally more than 1,000 feet (300 m), is in the northwest part of the valley. The freshwater section thins to the east and south, and in the southern end of the valley, little or no fresh ground water is available, probably because of evapotranspiration and possibly due to a lack of flushing. The Canutillo well field is on the southeast edge of the thickest freshwater section. Within the field, the section ranges from 560 to more than 1,100 feet (170 to more than 340 m) thick. In the sandhills and mesa areas, the top of the freshwater section generally coincides with the water table; while on the flood plain, the freshwater commonly is overlain by 50 to 230 feet

(15 to 70 m) of slightly saline water, mostly in the shallow aquifer. The occurrence of this poorer-quality water probably results from the concentration of salts by evapotranspiration and by recycling of pumped irrigation water.

About 820,000 acre-feet (1.0 km^3) of fresh ground water is stored under the Texas portion of the lower Mesilla Valley and the adjacent mesa to the east. This figure was estimated using the contours of figure 27 and assuming that the specific yield of the unconsolidated deposits is 0.10. About 4.7 million acre-feet (5.8 km^3) of fresh ground water is stored under the New Mexico part of figure 27. This includes the New Mexico portion of the lower Mesilla Valley and the mesa to the west, south of an east-west line extending from the Texas-New Mexico State line at Anthony, Texas. The estimated figure for the New Mexico part of the Mesilla Valley area is less reliable than the figure for the Texas part because fewer data are available in New Mexico. However, the total amount of fresh ground water stored in the New Mexico part of the entire Mesilla bolson doubtless is much larger than 4.7 million acre-feet (5.8 km^3) because it includes water in areas north and west of the boundaries of figure 27. Davis (1967, p. 5) estimated that about 450,000 acre-feet (555 million m^3) of water containing less than 2,500 mg/L dissolved solids occurs in the Rio Grande alluvium of the Texas part of the lower Mesilla Valley. This estimate includes the freshwater in the alluvium, so part of this volume is included in the freshwater estimate made in this report. The volume of slightly saline water in the Rio Grande alluvium in Texas is estimated to be about 300,000 acre-feet (370 million m^3).

The relatively stable water levels in the medium and deep aquifers indicate that the current rate of pumping is approximately balanced by ground-water inflow. If more ground water is pumped from these aquifers, water levels will decline. The Geological Survey is presently developing a digital model of the lower Mesilla Valley that will simulate the hydrologic conditions and will be used to estimate water-level declines resulting from various amounts of future withdrawals.

The slightly saline and poorer-quality water in the southern end of the valley may move northward and contaminate the freshwater in response to future water-level declines. The slightly saline water in the shallow aquifer that locally overlies the freshwater in the medium and deep aquifers also may move downward and contaminate the freshwater to some degree in response to water-level declines. In addition, poorer-quality water probably underlies the freshwater locally, and could move upward into the freshwater. Analyses of water from production wells in the medium and deep aquifers of the Canutillo field have not indicated any significant changes in water quality. However, the dissolved-solids concentration in water from an observation well in the deep aquifer in the southern end of the field has increased from 510 mg/L in 1957 to 1,260 mg/L in 1975. This increase may reflect vertical leakage around the well casing or encroachment of poorer-quality water from the south.

SUMMARY AND CONCLUSIONS

The most significant aspect of the ground-water hydrology of westernmost Texas is the amount of fresh and slightly saline water stored in the permeable sections of the unconsolidated alluvial fill of the basins of the area. The natural recharge and discharge are small fractions of the amount in storage; consequently, any significant withdrawals of ground water in these basins will easily exceed the natural recharge. Development of ground water, therefore, generally consists of "mining" the water; and the critical factors are the quantities of water in storage; the hydraulic properties of the aquifer, especially the specific yield; and the problems associated with increased withdrawals. The only exception is the pumping of ground water from the Rio Grande alluvium when surface water is in short supply. This water is replenished by the Rio Grande during periods of high flow and no long-term depletion has occurred.

The quality of water in the basin fill ranges from fresh to very saline, and is locally brine. Water in the consolidated rocks is generally slightly saline or of poorer quality. In the basin fill, the best quality water is found where the fill is coarse grained and near areas of significant recharge, such as in the northern Hueco bolson and southern Salt Basin. In areas where the coarse-grained fill is composed mostly of relatively insoluble volcanic material, the ground water is of exceptionally good quality, such as in the southern Salt Basin and in Red Light Draw. Areas of ground-water discharge, such as the Salt Flats in the northern Salt Basin and the flood plain of the Rio Grande, commonly have poor quality water, mostly because salts are concentrated by evapotranspiration. In areas in which the sediments are mostly fine-grained basin fill, as in parts of the closed basins that are or have been the sites of ground-water discharge, the water also tends to be of poor quality, such as the southeastern part of the Hueco bolson, the northern Salt Basin, and much of the Presidio bolson.

Table 2 summarizes current (1977) estimates of the volumes of fresh and slightly saline water stored in the permeable basin fill of westernmost Texas, and in one local, permeable, consolidated-rock aquifer, the Capitan Limestone in the northern Salt Basin. This table shows that more than 20 million acre-feet (25 km^3) of fresh ground water may be stored in the basin fill in the Texas parts of the Salt Basin, Red Light Draw, Green River Valley, the Presidio bolson, the Hueco bolson, and the lower Mesilla Valley. In addition, the basin fill of these areas, including the Rio Grande alluvium in the Hueco bolson and lower Mesilla Valley, and the Capitan Limestone contain about 7 million acre-feet (8.6 km^3) of slightly saline water. More than half of the freshwater, about 12 million acre-feet (15 km^3), and more than three-fourths of the slightly saline water, about 5.5 million acre-feet (6.8 km^3), is in storage in El Paso County in the Hueco bolson and lower Mesilla Valley. Future detailed exploration in the Salt Basin, Red Light Draw, Green River Valley, and the Presidio bolson may, however, delineate the occurrence of more fresh and slightly saline water than is shown in table 2. However, it is likely that El Paso

Table 2.--Estimated volumes of fresh and slightly saline ground water in aquifers of the Salt Basin, Red Light Draw, Green River Valley, Presidio and Hueco bolsons, and lower Mesilla Valley

Area	Aquifer	Volume of water (millions of acre-feet)		Remarks
		Fresh	Slightly saline	
Beacon Hill	Capitan Limestone	minor	0.5	Estimate based mostly on reported hydrologic and geologic data and is fair to good.
Wildhorse Flat and Michigan Flat.	Bolson fill	1.52 .42 (Subtotal 1.94)	1.03	Estimates based on extensive hydrologic data and geophysical data and are good.
Lobo Flat area: Northern and central Lobo Flat.	Bolson fill, volcanic-clastics, and possibly volcanic rocks.	.54	Insignificant	Estimate based on extensive hydrologic data and geophysical data and is good.
Southern Lobo Flat and Chispa Flat.		.73		Estimate based on limited hydrologic data and geophysical data and is fair.
Rubio Dome subarea		.23 (Subtotal 1.50)		Estimate based on geophysical data and is poor to fair.
Ryan Flat:	Bolson fill and volcanic-clastics.		Insignificant	
Ryan Flat (restricted subarea).		.76		Estimate based on limited hydrologic data and is fair.
Ryan Flat (extended subarea).		2.1		Estimate is based on geophysical data and is poor to fair.
Rubio Dome subarea		.22 (Subtotal 3.1)		Estimate is based on geophysical data and is poor to fair.
Red Light Draw	Bolson fill and volcanic-clastics(?).	.6	Insufficient data to estimate.	Estimate based on geophysical data and is poor.
Green River Valley	Bolson fill and volcanic-clastics(?).	.28	Insufficient data to estimate.	Estimate based on geophysical data and is poor.
Presidio bolson and	Bolson fill and volcanic-clastics(?).	.8	Insufficient data to estimate.	Estimate based on geophysical data and is poor.
Redford bolson (Texas only).	Bolson fill and Rio Grande alluvium.	.2 (includes some slightly saline) (Subtotal 1.0)	Insufficient data to estimate.	Estimate based on limited hydrologic data and geophysical data and is fair.
Hueco bolson (Texas only):				
Northern Hueco bolson	Bolson fill	10.6	3.4	Estimates of freshwater by Meyer (1976) based on extensive hydrologic data and digital-model studies and is good; estimate of slightly saline water by Meyer and Gordon (1972) based on hydrologic data and is fair to good.
El Paso Valley	Rio Grande alluvium	Insignificant	1.8	Estimate by Alvarez and Buckner (1974) based on extensive hydrologic data and is good.
Fabens-Tornillo area, in the sandhills and under the mesa.	Mostly in bolson fill, some in Rio Grande alluvium.	.4-.8 (includes both fresh and slightly saline)	--	Estimate by Gates and Stanley (1976) based on limited hydrologic data and geophysical data and is fair.
Lower Mesilla Valley	Bolson fill	.82	Insufficient data to estimate.	Estimate based on extensive hydrologic data and geophysical data and is good; includes some freshwater in the Rio Grande alluvium.
(Texas only)	Rio Grande alluvium	(approximately 0.10-0.15 included in freshwater estimate above)	.3	Estimate by Davis (1967) based on hydrologic data and is fair to good.
TOTAL		20.6	7.0	

County has a disproportionally large share of the total amount of usable water, and most of this water is stored in the freshwater trough east of the Franklin Mountains.

The Hueco bolson and lower Mesilla Valley also have the largest amounts of freshwater reserves that are considered as reliable estimates. Of the 13.9 million acre-feet (17.1 km^3) of freshwater reserves considered to be good estimates because they are based on extensive hydrologic data (table 2), 11.4 million acre-feet (14.1 km^3) occurs in the northern Hueco bolson and lower Mesilla Valley; 1.94 million acre-feet (2.4 km^3) occurs in Wildhorse and Michigan Flats; and 0.54 million acre-feet (0.67 km^3) occurs in northern Lobo Flat. Freshwater reserves considered to be fair estimates because they are based on limited hydrologic data and geophysical data total as much as 2.5 million acre-feet (3.1 km^3) in southern Lobo Flat, in the area around Valentine in Ryan Flat, in the Redford bolson, and in the Fabens-Tornillo area in the southeastern part of the Hueco bolson. Freshwater reserves considered to be poor to fair estimates because they are based only on geophysical data total 4.2 million acre-feet (5.2 km^3) in the areas between Lobo and Ryan Flats and in Ryan Flat, in Red Light Draw, in the Green River Valley, and in the Presidio bolson.

Large volumes of ground water also occur in the fine-grained basin fill in westernmost Texas, primarily in the Salt Basin north of Wildhorse Flat, in much of the Presidio bolson, at the southern ends of Red Light Draw and Green River Valley, and in the Hueco bolson east of the freshwater trough, and in the southeastern part of the Hueco bolson. This water, however, is moderately saline or of poorer quality and would be difficult to withdraw because most of the fill in these areas has low permeability. Significant volumes of moderately saline and poorer quality water also occur in the permeable Rio Grande alluvium from the lower Mesilla Valley to the Presidio bolson.

Ground water occurs in consolidated rocks in westernmost Texas, as in the Dell City and Sierra Blanca areas, under the Diablo Plateau, and in other mountain and upland areas. Freshwater occurs locally in consolidated rocks, but the total volume is not significant. Most of the water in the consolidated rocks is slightly saline or poorer quality, and much of it occurs in rock of low permeability. The only areas in which the rocks are known to yield moderate to large amounts of fresh to slightly saline water include the Beacon Hill area, from the Capitan and Goat Seep Limestones; the Apache Mountains area, from the Capitan; and the Sierra Blanca area, from Cretaceous limestones. In the Dell City area, the Bone Spring and Victorio Peak Limestones yield large amounts of slightly to moderately saline water.

Significant volumes of freshwater are also known to occur in parts of the Hueco and Mesilla bolsons outside of Texas. Approximately 6 million acre-feet (7.4 km^3) is in storage in the New Mexico part of the Hueco bolson, 4 million acre-feet (4.9 km^3) in the Ciudad Juarez area in the Mexican part of the Hueco bolson, about 4.7 million acre-feet (5.8 km^3)

in the New Mexico part of the lower Mesilla Valley and adjacent mesa to the west, and an unknown volume in the rest of the Mesilla bolson in New Mexico.

Development of ground water in the basins of westernmost Texas results in water-level declines because the water is mined from storage. In the El Paso area, municipal and industrial pumping caused as much as 95 feet (29 m) of decline during 1903-76; and pumping for irrigation caused up to 150 feet (46 m) of decline at Lobo Flat in the Salt Basin during 1949-73. Water-level declines have been especially large in Lobo Flat because the effective specific yield is low, and these declines have forced water users to deepen wells and(or) lower pumps. In other areas that have basin fill and volcanic-clastic deposits with hydraulic properties similar to Lobo Flat, but which are relatively undeveloped, such as Ryan Flat, Red Light Draw, Green River Valley, and the northeastern Presidio bolson, withdrawals of ground water may cause large water-level declines.

In most of the basins of westernmost Texas, fresh and slightly saline ground water is underlain and(or) adjacent to water of poorer quality, such as in the Beacon Hill area of the northern Salt Basin, Wildhorse Flat, Red Light Draw, Green River Valley, the Presidio bolson, the Hueco bolson, and the lower Mesilla Valley. Locally along the Rio Grande in the Hueco bolson and lower Mesilla Valley, freshwater also is overlain by slightly saline water in the Rio Grande alluvium. Withdrawals of large volumes of freshwater in these areas may lower water levels enough to induce migration of water of poorer quality vertically or laterally into freshwater areas. This process could ultimately degrade the remaining freshwater to the degree that it is unsuitable for municipal supply or industrial use. The only areas where significant amounts of poor-quality ground water are not known to occur are in Lobo and Ryan Flats.

Large water-level declines could result in land-surface subsidence in areas where the basin fill includes significant thicknesses of compressible clay, but there is no evidence that subsidence has occurred at the present (1977) time.

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