HYDROGEOLOGIC FRAMEWORK OF THE MESILLA BASIN IN NEW MEXICO AND WESTERN TEXAS

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ABSTRACT

The two major objectives of this study of the Mesilla Basin between Las Cruces, New Mexico and the International Boundary zone west of El Paso, Texas were (3.) to develop a detailed conceptual model of the basins hydrogeologic framework that is baaed on a synthesis of available geological, geophysical, and geochemical data, and (2) to present that information in a format suitable for use by the U.S. Geological Survey, Water Resources Division (USGSWRD) in developing an up-to-date numerical model of the groundwater flow system. The basins hydrogeologic framework is graphically portrayed in terms of (1) the lithologic character, geometry, and geologic history of basin-fill deposits; and (2) the bedrock units and structural features that form the basin boundaries and influence intrabasinal depositional environments. The basic "architecture" of mappable subdivisions of basin deposits that can be defined in terms of their aquifer properties is characterized in the conceptual model.

The Santa Fe Group forms the bulk of basin-filling deposits and the major aquifer system of the region. It comprises a very thick sequence of alluvial, eolian, and lacustrine sediments deposited in intermontane basins of the Rio Grande rift structural province during an interval of about 25 million years starting in late Oligocene time. Widespread filling of several structural subbasins, which in aggregate form the Mesilla Basin, ended about 700,000 years ago (early Middle Pleistocene time) with the onset of Rio Grande (Mesilla) Valley incision. Post-Santa Fe deposits include (1) inset valley fill of the ancestral Rio Grande and tributary arroyos that forms terraces bordering the modem floodplain, and (2) river and arroyo alluvium that has been deposited since the last major episode of valley incision in late Pleistocene time (about 15,000 to 25,010 years ago).

The three basic hydrogeologic components of the Mesilla Basin model comprise: 1. Structural and bedrock features that include basin-boundary mountain uplifts, bedrock units beneath the basin fill, fault zones within and at the edges of basin that influence sediment thickness and composition, and igneous-intrusive and -extrusive rocks that penetrate or are interbedded with basin deposits. 2. Hydrostratigraphic units which are mappable bodies of basin and valley fill that are grouped on the basis of origin and position in a stratigraphic sequence. Genetic classes include ancestral-river, present river-valley, basin-floor playa, and piedmont alluvial fan deposits. Rock-stratigraphic classes include units deposited during early, middle and late stages of rift-basin filling (i.e. lower, middle and upper Santa Fe Group), and post-Santa Fe valley fills (e.g. channel and floodplain deposits of the Rio Grande, and fan alluvium of tributary arroyos) . 3. Lithofacies subdivisions are the basic building blocks of the model. In this study, basin deposits are subdivided into ten lithofacies (I through X) that are mappable bodies defined on the basis of grain-size distribution, mineralogy, sedimentary structures, and degree of post-depositional alteration. They have distinctive geophysical, geochemical, and hydrologic attributes.

The hydrogeologic framework of the Mesilla Basin area is graphically presented in map and cross-section format (Plates 1, 16 and 17). Supporting stratigraphic,

lithologic, petrographic, geophysical, and geochemical data from 61 wells are illustrated in stratigraphic columns and hydrogeologic sections (Plates 2 to 15). A new computer-generated graphics system was utilized in the presentation of these data. Tables 4a and 4b summarize the subsurface information used in this study, including (1) well location and depth; (2) ground-water levels; (3) drill-stem sample intervals; (4) selected data on ground-water chemistry; and (5) data sources. Major hydrostratigraphic units and aquifer zones sampled are also identified in Tables 4a and 4b.

The report has four major narrative sections (I. Introduction; II. Geologic Setting; III. Sand-Fraction Petrography; and IV. Conceptual Model), a comprehensive reference list, and two appendices (A. Basic petrographic data, and B. Preliminary hydrogeologic cross sections extending into adjacent parts of the Jornada del Muerto and Hueco basins). Previous work on basin hydrogeology and study methods are covered in Section I. A team approach was used in the analysis of borehole (geological, geophysical, and geochemical) data to develop the final conceptual model of hydrostratigraphic and lithofacies unit distribution.

Section II provides a general geological overview of the Mesilla Basin region including the structure of flanking mountain uplifts and relationship to contiguous basin areas in New Mexico, Texas, and Chihuahua. Emphasis is on the past 25 million years of geologic time when major structural and topographic elements of the present landscape formed. The interval was characterized by regional extension of the earth's crust, and differential uplift, subsidence and tilting of individual crustal blocks along major fault zones to form internally complex basins and ranges. This continental "rifting" process produced the Rio Grande rift structural zone that extends from southern Colorado to western Texas and northern Chihuahua. A major contribution of this study has been the significant improvement in definition of the physical limits of the Mesilla Basin and its component subbasins. Much of the information on bedrock distribution and geologic structure was derived from published maps and cross sections, with supplemental data from unpublished geophysical and geothermal surveys. Seismic reflection profiles specially prepared for the USGS-WRD at two sites in the lower Mesilla Valley have also been utilized in this study.

Rift basin fill comprising the Santa Fe Group has a maximum thickness of about 3,000 ft (915 m) in the Mesilla Basin. The lower and middle parts of the Santa Fe form the bulk of the basin fill and were deposited in an internally drained complex of three subbasins that were initially separated by a central (north-trending) intrabasin uplift (Eastern, Northwestern, Southwestern subbasins, and Mid-basin uplift on Plate 1) Eolian sands and fine-grained playa-lake sediments are major lithofacies. These units are locally well indurated and only produce large amounts of good quality ground water from buried dune sands (lower Santa Fe) in the eastern part of the basin beneath the Mesilla Valley. Poorly consolidated sand and pebble gravel deposits in the middle to upper part of the Santa Fe Group form the most extensive aquifers of the area. Widespread channel deposits of the ancestral Rio Grande first appear in upper Santa Fe beds that have been dated at about 3.5 million years (Ma) in southern New Mexico and 2.5 Ma in western (Trans-Pecos) Texas.

Expansion of the Rio Grande (fluvial) system into upstream and downstream basins, and integration with Gulf of Mexico drainage in the early to middle part of the Quaternary (Ice-Age) Period about 700,000 years ago led to rapid incision of the Mesilla Valley and termination of widespread basin aggradation (ending Santa Fe Group deposition in the Mesilla Basin). Cyclic stages of valley cutting and filling are represented by a stepped-sequence of valley border surfaces that flank the modern valley floor. Fluvial sand and gravel deposited during the last cut-and-fill cycle form a thin, but extensive shallow aquifer zone below the Rio Grande floodplain. Recent fluvial sediments are locally in contact with ancestral river facies in the upper Santa Fe Group, particularly in the northern Mesilla Valley. They form the major recharge and discharge zones for the basin's ground water, and are quite vulnerable to pollution in this urban-suburban and irrigation-agricultural environment.

Structural deformation along subbasin boundaries and changes in topographic relief between deeper basin areas and flanking uplifts continued throughout the late Cenozoic. During early stages of basin filling (lower Santa Fe deposition) many of the present bounding mountain blocks had not formed or had relatively low relief. Thickest basin-fill deposits (up to 1500 ft [455 m] of the middle Santa Fe Group) were emplaced between 4 and 10 million years ago during most active uplift of the Organ-Franklin-Juarez range and the Robledo Mountains, and subsidence of the Eastern (La Union-Mesquite) subbasin. The major basin-bounding fault zone (Mesilla Valley) is now covered by the recent river floodplain deposits.

The petrographic investigations described in Section III emphasize the fundamental properties of rock fragments and mineral grains that in aggregate form the various lithofacies subdivisions of the five hydrostratigraphic units (Tables 1 and 2). Cuttings from the Afton (MT1), Lanark (MT2), La Union (MT3), and Noria (MT4) were analyzed initially with a binocular microscope in order to construct a stratigraphic column for each of these key wells (Plates 12-15) and to determine intervals (approximately every 100 ft, 30 m) where subsamples of representative sands would be collected for thin-section petrographic analyses. Samples were also collected from representative sandy intervals in the two wells in the Canutillo Field (CWFLD and 4D) and from six outcrops of the Upper and Middle Santa Fe units. Petrographic analysis of sand samples analyzed from the six water wells and from outcrop areas in the Mesilla Basin shows that the basin fill was derived from more than one source terrane. The abundance of plagioclase (zoned and twinned) and andesitic lithic fragments strongly suggest an intermediate volcanic source area for most of the detrital material. Chert, chalcedony, and abundant quartz (many well rounded with overgrowth rims) indicate reworked sedimentary units as another major source. A granitic source area is also suggested by the presence of microcline, strained quartz, and granitic rock fragments. The paucity of metamorphic-rock fragments and tectonic polycrystalline quartz rules out a metamorphic terrane as a major sediment source.

It appears that even in early to middle Santa Fe time (Miocene) the central Mesilla Basin area was receiving sediment from a very large watershed. A much larger source region was also available for sand and finer grain-size material when the mechanism of eolian transport is taken into account. By middle Pliocene time the ancestral Rio Grande was delivering pebble-size material to the basin from source terranes as far away as northern New Mexico (e.g. pumice and obsidian from the Jemez and Mount Taylor areas). In most cases, visual and binocular microscopic examination of the gravel-size (>2mm) fraction is still the best way to establish local versus regional provenance of coarse-grained fluvial and alluvial deposits.

The conceptual hydrogeologic model is described in detail in Section IV and illustrated on Plates 1, 16, and 17 with supporting data and interpretations on Plates 2 to 15.The basic hydrogeologic mapping unit used in conceptual model development is the *hydrostratigraphic unit*. It is defined in terms of (1) environment of deposition of sedimentary strata, (2) distinctive combinations of lithologic features (lithofacies) such as grain-size distribution, mineralogy and sedimentary structures, and (3) general time interval of deposition. The attributes of four major classes into which the area's basin and valley fills have been subdivided are defined in Table 1. The Upper, Middle, and Lower hydrostratigraphic units of the Santa Fe Group roughly correspond to the (informal) upper, middle and lower rock-stratigraphic subdivisions of Santa Fe Group described in Section II. The other major hydrostratigraphic unit comprises Rio Grande alluvium of late Quaternary age (<15,000 yrs) that forms the upper part of the regional shallow-aquifer system.

The ten lithofacies subdivisions that are the fundamental building blocks of the model are defined primarily on the basis of sediment texture (gravel, sand, silt, clay, or mixtures thereof), degree of cementation, and geometry of bodies of a given textural class and their relative distribution patterns. Lithofacies I, II, III, V, and VI are unconsolidated or have zones of induration (strong cementation) that are not continuous. Clean sand and gravel bodies are major constituents of facies I, II, V, and VI; while clay or cemented sand zones form a significant part of facies III and IV. Subdivision IV is characterized by thick eolian sand deposits of the lower Santa Fe unit (LSF) that are partly cemented with calcite. Coarse-grained channel deposits of the modern and ancestral Rio Grande (lithofacies I and II) are the major components of the upper Santa Fe (USF) and river-alluvium (RA) hydrostratigraphic units. They form the most important aquifers and potential enhanced-recharge zones in the basin. Lithofacies VI and VIII are partly to well indurated piedmont-slope deposits; while facies IX and X comprise thick sequences of fine-grained basin-floor sediments that include playa-lake beds.

Unconsolidated deposits make up the bulk of the middle and upper Santa Fe Group and all of the recent valley fill in the Mesilla Basin. Textural classes include sand, gravelly-sand, silt-clay, and sandy to gravelly materials with a silt-clay matrix Secondary calcite and gypsum are the primary cementing agents in the basin fill; however, continuously indurated zones are uncommon except in basal parts of the Santa Fe section. Coarse-grained fan alluvium and debris-flow deposits, with gravel primarily in the pebble- to cobble-size range (<10 in., 25 cm), are confined to narrow piedmont zones near the basin margins (lithofacies V-VIII). Indurated parts of these deposits comprise facies VII and VIII. Widespread fluvial deposits of the ancestral Rio Grande form much of the upper Santa Fe Group (unit USF, facies Ib and II) as well as the upper Quaternary fill of the inner Mesilla Valley (unit RA, facies IV). Fluvial materials beneath the Rio Grande Valley floor constitute the major shallow aquifer system Outside the valley area, however, most of the ancestral river deposits are in the vadose zone.

Interbedded sand and silt-clay deposits of the Middle Santa Fe Unit (MSU; primarily lithofacies III) form the basin's thickest and most extensive aquifer system (the "medial" aquifer in this report; Tables 4a and b). This unit is as much as 1000 ft (305 m) thick in the eastern (La Union-Mesquite) subbasin (Plates 3-5, 10, 11, 16b-d, 17a). Well-sorted fine to coarse sand deposits of lithofacies IV make up a significant part of the lower Santa Fe Unit (LSU) and are here interpreted as being primarily of eolian origin. These partly-indurated beds are as much as 600 ft (185 m) thick in the eastern (La Union-Mesquite subbasin); and they may be 900-1000 ft (275-305 m) thick in the southwestern subbasin immediately east of the east Potrillo fault zone (Plates 3-5, 7, 10, 11, 16b-e, 17a).

All basin fill units (USF, MSF, LSF) become finer grained to south; and fine- to medium-grained basin-floor facies, with only minor amounts of gravel, dominate the basin fill section in the international boundary zone west of Cerro de Cristo Rey (Plates 6, 7, and 16e; facies III, IX and X). Most of the Upper Santa Fe hydrostratigraphic unit (USF) in that area is in the vadose zone; and sand beds in the basal Upper Santa Fe unit and upper part of the Middle Santa Fe unit (MSF, lithofacies III) appear to be the only major aquifer east of the Mid-Basin uplift. Lithofacies IV in the Lower Santa Fe hydrostratigraphic unit (LSU) may also be a potential deep aquifer in the Southwestern subbasin; but this zone has not yet been tested for either quantity or quality of ground water production.

Assignment of specific hydraulic conductivity ranges to individual lithofacies subdivisions is beyond the scope of this investigation. However, as a first approximation, the following general ranges appear to be reasonable: 1. Conductivities of lithofacies I and II are relatively high (30 to 300 ft/day, 10-100 m/day); 2. Lithofacies IX and X, and well-cemented sandstone and fanglomerate zones in facies VII and VIII will definitely have very low conductivities (usually much less than 0.3 ft/day, 0.1 m/day); 3. Conductivities in uncemented sand layers in lithofacies III and IV, and sand and gravel beds in facies V through VIII should primarily be in the intermediate range (0.3 to 30 ft/day, 0.1-10 m/day).

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I. INTRODUCTION

With ever-increasing demands on the ground-water resources of the Mesilla Basin there is a continuing need for a better understanding of the hydrogeologic framework of deposits that form one of the major aquifer systems of the region. The area (Fig. 1) includes the major centers of population and potential economic growth in the southern New Mexico, Trans-Pecos Texas and north-central Mexico region (Las Cruces, El Paso, and Ciudad Juarez). From a water-supply perspective, both the private and public sectors of society (except for irrigation agriculture) rely solely on ground water.

At a minimum, characterization of basin hydrogeology should include detailed descriptions of major lithologic, stratigraphic, structural, and geochemical subdivisions, and accurate delineation of basin boundaries and major recharge areas. Suitable numerical models of the ground-water flow system must be based on a conceptual model that is a synthesis of this type of baseline information (Frenzel and Kaehler, 1990; Kernodle, 1992b). Such modeling efforts are particularly important because of the potential for saline-water encroachment and land subsidence due to ground-water withdrawals in some parts of the basin (Contaldo and Mueller, 1992; Kernodle, 1992a, MacMillan et al., 1976).

This report describes the results of a hydrogeologic study by the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) of the Mesilla Basin and Valley fill between Las Cruces, New Mexico and the International Boundary west of El Paso, Texas (Fig. 1). The investigation, done in cooperation with the Water Resource Division of the U.S. Geological Survey (USGS-WRD) and the New Mexico State Engineer Office (NMSEO), was originally proposed (1986) because there needed to be better utilization of hydrogeologic information in the management of the area's ground-water resources. The two major objectives of the study were (1) to provide a synthesis of available geological, geophysical and geochemical data that can be used to create a detailed conceptual model of the basin's hydrogeologic framework, and (2) to construct that model in a format suitable for use in developing the best possible numerical models of the ground-water flow system.

Funding for the initial phase of data compilation and model development in 1987 was jointly provided by the NMBMMR and USGS-WRD, contract number 14-08-D001-G-726; and subsequent support has been furnished by the NMBMMR. Information in this open-file report will ultimately be integrated with geologic, geophysical, and geochemical data from adjacent parts of the Jornada del Muerto Basin north and east of Las Cruces. A final report on the area will then be published by the NMBMMR as part of its Hydrologic Report series.

Background

The Mesilla Basin has thick fill deposits, locally as much as 3000 ft (915 m), that are mostly unconsolidated and include the major fresh-water aquifers of the region. Of particular importance, with respect to both water-supply and ground-water recharge, are

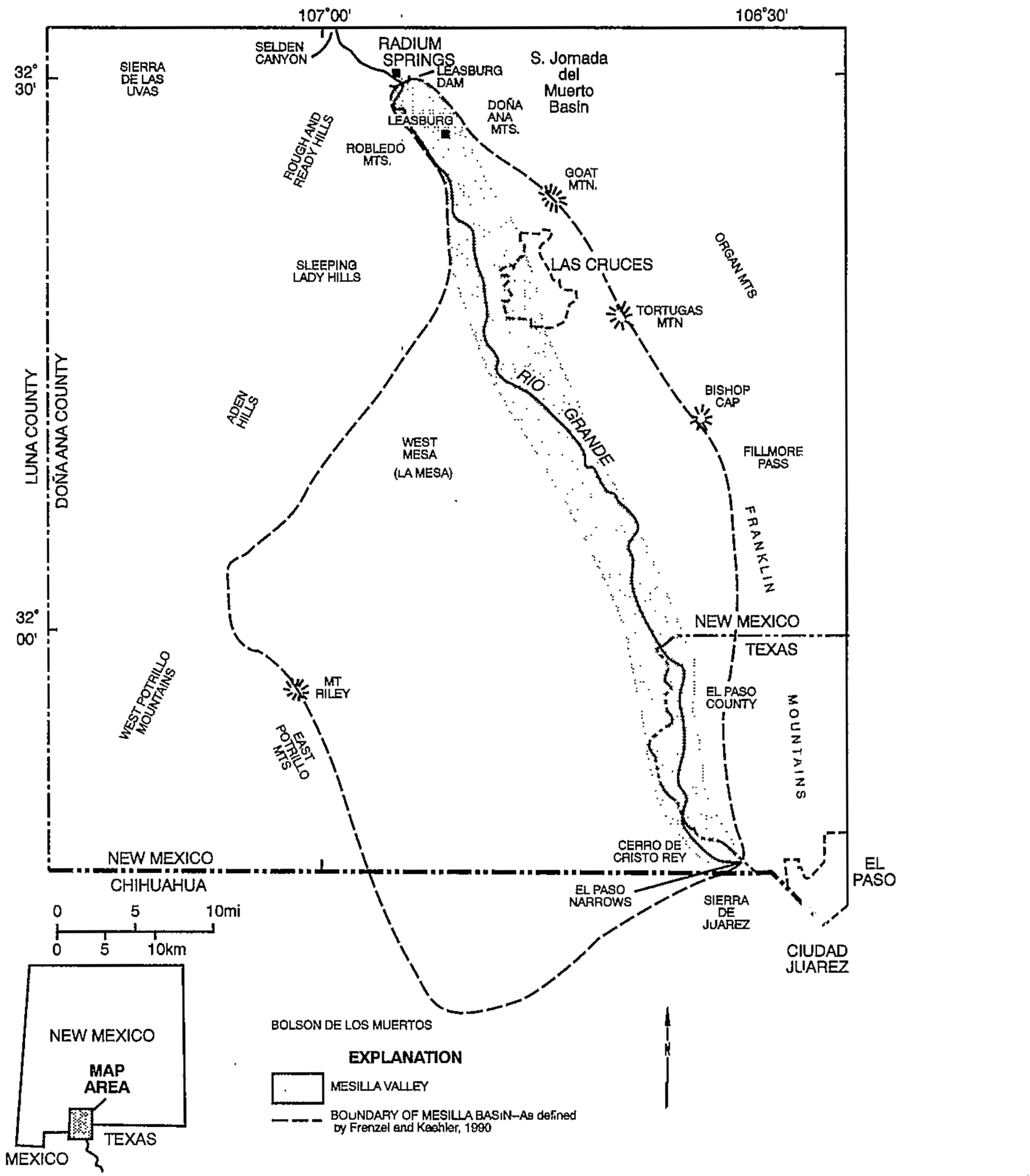


Figure 1. Location of study area.

widespread channel deposits of the modern and ancestral Rio Grande system that are a major component of the upper fill sequence. A large body of subsurface geologic information (e.g. borehole samples, geophysical logs, and geochemical data) has been collected, particularly since 1980 when a significant increase in development of the basin's ground-water resources was proposed by the City of El Paso. Prior to this study, however, much of this information had not been analyzed or organized within the framework of a conceptual model that accurately describes the "architecture" of basin deposits with respect to the distribution of geological units that have distinct differences in structural, lithostratigraphic, and hydrologic properties.

The model developed here has three basic components:

1. **Structural and bedrock features** include basin-bounding mountain uplifts, bedrock units beneath the basin fill, fault zones within and at the edges of the basin that influence sediment composition and thickness, and distribution of igneous intrusive and extrusive (volcanic) rocks that penetrate, cap or are interbedded with basin and valley fills. The locations of major structural features and bedrock units in the study area are shown on Plates 1-11, 16 and 17. Bedrock units, including volcanic rocks associated with upper Cenozoic basin and valley fills, are identified in Table 2.
2. **Hydrostratigraphic units** include major mappable subdivisions of the basin and valley fill that are defined on the basis of genetic origin and age of a stratigraphic sequence of deposits (Table 1). Genetic classes include ancestral-river, recent river-valley, basin-floor alluvial and playa-lake, and piedmont alluvial-fan environments. Time-stratigraphic classes include units deposited during early, middle and late stages of basin filling (lower, middle, and upper Santa Fe Group); and deposits of the present Rio Grande (Mesilla) Valley system. Distribution patterns of hydrostratigraphic units are shown on Plates 2-11, 16 and 17.
3. **Lithofacies units** are the fundamental building blocks of the model. Ten major lithofacies subdivisions of the basin-filling sequence have been identified in this study (Table 3). These units are mappable bodies that have distinctive compositions, depositional and post-depositional environments, distribution patterns, geophysical and geochemical properties, and hydrologic characteristics. Distribution patterns of lithofacies units are also shown on Plates 16 and 17.

Previous Work on Basin Hydrogeology

The present Mesilla Basin study is part of a more comprehensive investigation of the hydrogeologic framework of southern Rio Grande rift basins initiated by the senior author in 1962. Work was initially supported by the U.S. Soil Conservation Service (SCS), Soil Survey Division in cooperation with the New Mexico State University (NMSU) College of Agriculture (1962-1974) and subsequently funded by the NMBMMR (Soil Survey Investigations-Desert Project). Early research emphasis was on the influence of hydrogeologic factors on the genesis of desert soils, particularly on the development of secondary carbonate, clay, silica, and gypsum accumulation in basin-fill

Table 1. Key to informal hydrostratigraphic units in the Mesilla Basin (Plates 2 to 17, Tables 3 and 4)

Unit	Description
	Valley-Fill Deposits -- Post Santa Fe Group
RA	River alluvium; channel and floodplain deposits of inner Mesilla Valley; as much as 100 ft thick. Map unit "Qvyf" of Seager et al. (1987). Lithofacies subdivision Iv* is the major hydrogeologic component. Forms much of the "shallow aquifer" of Leggat et al. (1962), and "flood-plain alluvium" of Wilson et al. (1981). Holocene to late Pleistocene
VA	Valley-border alluvium; tributary arroyo (and thin eolian) deposits in areas bordering the inner Mesilla valley (river floodplain), with locally extensive river-terrace deposits; as much as 140 ft thick. Map unit "Qva" of Seager et al. (1987); Fillmore, Leasburg (Ft. Selden), Picacho, and Tortugas morphostratigraphic units of Gile et al. (1981). Includes lithofacies subdivisions Iv and V. Most of unit is in the unsaturated (vadose) zone. Holocene to middle Pleistocene
	Basin-Fill Deposits -- Santa Fe Group
	Rio Grande rift basin fill in New Mexico and adjacent parts of Texas, Chihuahua (MEX) and Colorado. Includes alluvial, eolian, and lacustrine deposits; with interbedded volcanic rocks (basalts and silicic tuffs). In the Mesilla Basin area the Santa Fe Group may locally exceed 2,500 ft in thickness. The group comprises four lithostratigraphic units - Hayner Ranch, Rincon Valley, Fort Hancock, and Camp Rice Formations (Hawley et al., 1969; Seager et al., 1987). It also includes the major aquifers of the area (King et al., 1971; Wilson et al., 1981; Hawley, 1984) and is subdivided into three informal hydrostratigraphic units:
USF	Upper Santa Fe Unit; coarse- to medium-grained deposits of the ancestral Rio Grande intertongue mountainward with piedmont-alluvial (fan) facies, and southward with fine-grained lake and playa sediments; volcanic rocks (mostly basalt) and sandy eolian deposits are locally present; as much as 750 ft thick. Unit includes the Camp Rice (CR) and upper Fort Hancock (FH) Formations (Strain, 1966; Hawley, 1978; Gustavson, 1991); also includes lithofacies subdivision Ib; much of facies II, V, and VI; and parts of facies III and VIII. Forms lower part of the "shallow aquifer" in the northern Mesilla Valley, and the upper aquifer zone outside the Valley area where much of the unit is above the water table. Middle Pleistocene to middle Pliocene

MSF

Middle Santa Fe Unit; alluvial, eolian, and playa-lake facies; interbedded sand and silt-clay basin-floor sediments intertongue mountainward with piedmont-alluvial (fan) deposits, and southward with fine-grained lake and playa facies; basaltic volcanics and sandy eolian sediments are locally present; as much as 1500 ft thick.

Unit includes basin fill that correlates with much of the Fort Hancock (FH) and Rincon Valley Formations, whose type areas are in the Hueco Bolson and western Jornada del Muerto (Rincon) Basin, respectively; also includes much of lithofacies subdivisions III, and parts of facies II, V, VI, VII, VIII and IX. Forms major part of "medium aquifer" of Leggat et al. (1962).

Middle Pliocene to middle Miocene

LSF

Lower Santa Fe Unit; eolian, playa-lake, and alluvial facies; sandy to fine-grained basin-floor sediments, which include thick dune sands and gypsiferous sandy mudstone, intertongue with conglomeratic sandstones and mudstones near the basin margins (early-stage piedmont alluvium); as much as 1000 ft thick.

Unit includes basin fill that correlates with much of the Hayner Ranch and the lower Rincon Valley Formations, whose type areas are in the western Jornada del Muerto (Rincon) Basin; also includes much of lithofacies IV and X, and parts of facies VII, VIII and IX. Forms major part of "deep aquifer" of Leggat et al. (1962).

Middle Miocene to late Oligocene

* Lithofacies subdivisions of hydrogeologic units are defined in Table 3

TABLE 2 Key to bedrock units and upper Cenozoic volcanics (Plates 2-17)

These rocks are primarily hydrogeologic boundary units with very low hydraulic conductivities. However, limestones may locally be highly permeable in zones with solution-enlarged joints and fractures. Fractured sandstone, conglomerate, welded tuffs, and lavas also form aquifers in a few areas.

Qb	Basaltic volcanics, mostly flows, with local cindercone and conduit material, that cap or are interbedded with the upper and middle Santa Fe Group. Quaternary and upper Pliocene
Tb	Basaltic plugs and minor flows that penetrate, cap, or are interbedded with the lower and middle Santa Fe Group. Miocene
Tr	Rhyolitic volcanics, with some interbedded sandstone and conglomerate mostly ashflow tuff and lava. Oligocene
Tri	Rhyolitic igneous-intrusive complexes; mostly sills, plugs and associated lava domes. Oligocene
Ti	Silicic to intermediate intrusive rocks. Oligocene and Eocene
Tv	Andesitic and other intermediate volcanic and volaniclastic rocks, including lava flows and laharic breccias and mudstones. Eocene and Oligocene
Tvi	Undivided Tv and intermediate intrusive rocks.
Tvs	Intermediate volcaniclastic rocks, with minor lava flows and intrusive units; primarily Palm Park Formation. Eocene and Oligocene
Trv	Undivided Tr and Tv or Tvs
Tl	Mudstone, sandstone, and conglomerate with local gypsum beds. Lower Tertiary, mainly Eocene
Tvl	Undivided Tv and Tl
K	Cretaceous rocks--undivided; includes limestone, sandstone and mudstone.
TK	Undivided Ti, Tv, Tl, K.
KP	Undivided Cretaceous and Permian rocks.
Pu	Upper Paleozoic rocks (Pennsylvanian and Permian); includes limestone, shale, sandstone, and mudstone, with local gypsum beds.
P	Undivided Paleozoic and Precambrian rocks of the southern Franklin Mountains; includes limestone, shale, sandstone, metamorphosed sedimentary and volcanic rocks, and granite.

Table 3 Lithofacies subdivisions of basin- and valley-fill and their occurrence in rock-stratigraphic and hydrostratigraphic units in the Mesilla Basin.

	Subdivision Descriptions	Rock-stratigraphic units and correlative lithofacies (Table 1)	Informal hydrostratigraphic units and aquifer systems (Table 1)
I.	Sand and gravel, river-valley and basin-floor fluvial facies; recent and ancestral Rio Grande channel and floodplain deposits underlying 1) the modern river-valley floor--facies Iv, 2) river-terrace surfaces-- deposits primarily in the vadose zone, and 3) relict or buried basin-floor fluvial plains--facies Ib. The latter surfaces include the La Mesa geomorphic surface (Gile et al. 1981). Gravel is characterized by sub-rounded to well-rounded pebbles and small cobbles of resistant rock types (mainly igneous and metamorphic) derived in part from extra-basin source areas.		
	Iv. Sand and pebble to cobble gravel, with thin, organic-rich silty sand to silty clay lenses; indurated zones of carbonate cementation rare or absent; as much as 100 feet thick.	Younger valley fill, river-floodplain and channel deposits	River alluvium, upper part of shallow aquifer system
	Ib. Sand and pebble gravel, with thin discontinuous beds and lenses of sandstone, silty sand, and silty clay; extensive basin-floor fluvial facies; usually nonindurated, but with local zones that are cemented with calcite (common), and other minerals (uncommon) including silicate clays, iron-manganese oxides, gypsum, silica, and zeolites; 200 to 400 feet thick in central basin areas.	Major component of the Camp Rice Fm (Upper Santa Fe Group); intertongues with facies II, III, V, and locally IX	Major component of upper Santa Fe hydrostratigraphic unit; mostly in vadose zone in basin areas outside the Mesilla Valley; occurs in lower part of shallow aquifer system in northern Mesilla Valley; and forms part of the upper aquifer system outside the valley.
II.	Sand, with discontinuous beds and lenses of pebbly sand, silty sand, sandstone, silty clay, and mudstone; extensive basin-floor fluvial facies and local eolian deposits; gravel composition as in facies I; usually nonindurated, but local cemented zones as in facies Ib; clean sand and pebbly-sand bodies make up an estimated 65-85 percent of unit; 300 to 750 feet thick in central basin areas.	Major component of Camp Rice Formation, and present in the Fort Hancock Fm (Middle to Upper Santa Fe Group) in the Mesilla Basin; intertongues with facies Ib, III, V, and locally IX	Major component of upper Santa Fe hydrostratigraphic unit; partly in vadose zone in basin areas outside the Mesilla Valley; occurs in lower part of shallow aquifer system in northern Mesilla Valley; forms parts of the upper and medial aquifer systems throughout the basin.
III.	Interbedded sand, silty sand, silty clay, and sandstone; with minor lenses of pebbly sand and conglomeratic sandstone; basin-floor alluvial and playa-lake facies; clay mineralogy of silty clay beds as in unit IX; usually nonindurated, but with local cemented zones as in facies Ib and II; secondary carbonate and gypsum segregations locally present in silty clay beds; common sheet-like to broadly-lenticular strata 10 to 40 feet thick; clean sand layers make up an estimated 35 to 65 percent of unit; 300 to 1,000 feet thick in central basin areas.	Major component of Fort Hancock Formation, and present in the Camp Rice Formation; intertongues with facies II, V, IX, and locally Ib.	Major component of middle Santa Fe hydrostratigraphic unit, and minor constituent of unit upper Santa Fe; sand, pebbly sand and silty sand beds in facies III form a major part of the medial aquifer system.
IV.	Sand to silty sand, with lenses or discontinuous beds of sandstone, silty clay, and mudstone; eolian and alluvial facies primarily deposited on basin floors and contiguous piedmont slopes; nonindurated to partly indurated, with cementing agents including calcite (common), silicate clays, iron-manganese oxides, gypsum, and zeolites (uncommon); clean fine to medium sand makes up an estimated 35 to 65 percent of unit; as much as 600 feet thick.	Major component of unnamed formation in the Lower Santa Fe Group; probably correlative with parts of the Rincon Valley and Hayner Ranch Formations in northern Dona Ana County; intertongues with facies VII and X	Major component of lower Santa Fe hydrostratigraphic unit; sand and silty sand beds in facies IV form a large part of a deep aquifer system.

V.	Gravelly sand-silt-clay mixtures (loamy sands to sandy clay loams) interstratified within discontinuous beds and lenses of sand, gravel, loamy sand an silty clay; distal to medial piedmont-slope alluvial facies (mainly coaleascent fan deposits), with minor compoonent of eolian sediments; gravel primarily in the pebble and small cobble size range, and clast composition reflects character of source bedrock terrane; usually nonindurated, but with thin discontinuous layers that are cemented with calcite; clean sand and gravel makes up an estimated 25 to 35 percent of unit; as much as 600 feet thick.	Major component of Camp Rice and Fort Hancock Formations; intertongues with facies II, III, VI, and IX	Component of both upper and middle Santa Fe hydrostratigraphic units; clean to loamy sand and gravel lenses in facies V form parts of the medial and upper aquifer systems.
VI.	Coarse gravelly sand-silt-clay mixtures (loamy sand and sandy loams to loams) interstratified with lenses of sand and gravel; proximal to medial piedmont-slope alluvial facies--fan and coalescent fan deposits; gravel primarily in the pebble to cobble range (up to 10 inches); clast composition reflects lithologic character of source bedrock terranes; usually nonindurated, but with discontinuous layers that are cemented with calcite; clean sand and gravel lenses make an estimated 15 to 25 percent of unit; as much as 300 feet thick.	Component of Camp Rice and Fort Hancock Formations; intertongues with facies V and VIII.	Component of both upper and middle Santa Fe hydrostratigraphic units; clean sand and gravel lenses in facies VI form parts of the medial and upper aquifer system.
VII.	Conglomeratic sandstone, silty sandstone, and mudstone with lenses and discontinuous beds of conglomerate, sand, gravel, and gravelly sand-silt-clay mixtures (as in unit V); distal to medial piedmont-slope alluvial facies, with minor component of eolian sediments; coarse clast sizes and composition as in unit V; moderately-well to poorly indurated; cementing agents include calcite (common) and silicate clays, iron-manganese oxides, silica and zeolites (uncommon); clean weakly-cemented sand and gravel beds make up an estimated 5 to 15 percent of unit; as much as 600 feet thick.	Major component of unnamed formation in lower part of Santa Fe Group; probably correlative with piedmont facies of the Rincon Valley and Hayner Ranch Formations; intertongues with facies IV, VIII and X.	Major component of lower Santa Fe hydrostratigraphic units; weakly-cemented sand and gravel beds in facies VII form part of the deep aquifer system.
VIII.	Coarse conglomeratic sandstone and silty-sandstone, fanglomerate, and minor lenses of sand and gravel; proximal to medial piedmont-slope alluvial facies--and coalescent fan deposits; coarse clast sizes and compositions as in unit VI; moderately to well indurated; cementing agents as in unit VI; moderately to well indurated; cementing agents as in unit VII; clean, weakly-cemented sand and gravel lenses make up an estimated 5 to 10 percent of unit, as much as 300 feet thick.	Component of basal Camp Rice and Fort Hancock Formations, and unnamed formations in lower part of Santa Fe Group (as in units VII and IV); intertongues with facies V, VI and VII	Minor component of all three Santa Fe hydrostratigraphic units; weakly-cemented sand and gravel beds in facies VIII form small parts of the upper, medial and deep aquifer systems.
IX.	Silty clay interbedded with thin silty sand, sand, sandstone, and mudstone beds; basin-floor playa-lake and alluvial-flat facies; clay mineral assemblage includes calcium smectite, mixed layer illite-smectite illite, and kaolinite (Anderholm, 1985); secondary deposits of calcite, gypsum, sodium-magnesium-sulfate salts, and zeolites are locally present; weakly-cemented fine to medium sand and silty sand makes up an estimated 5-10 percent of unit; as much as 600 feet thick in central basin areas.	Major component of the Fort Hanckco Formation and locally present in the Camp Rice Formation; intertongues with facies III, II, V, and locally Ib; grades downward into unit X in central basin areas	Makes up fine-grained part of middle Santa Fe hydrostratigraphic unit; sand and silty sand beds in facies IX form very minor to negligible component of the medial aquifer system.
X.	Mudstone and claystone interstratified with thin sandstone and silty sandstone beds; basin floor playa-lake and alluvial-flat facies; clay mineral and non-clay secondary mineral assemblages as in facies IX; weakly cemented fine to medium sand and silty sand makes up an estimated 0 to 5 percent of unit; as much as 600 feet thick in central basin area.	Major component of unnamed formation in lower part of the Santa Fe Group; probably correlative with basin-floor facies of the Rincon Valley and Hayner Ranch Formations; intertongues with facies IV and VII	Major component of lower Santa Fe hydrostratigraphic unit; weakly-cemented sand and silty sand beds in facies X form very minor to negligible component of deep aquifer system.

deposits. This work included geological logging of commercial and domestic water wells being drilled in the Mesilla and Jornada del Muerto Basins, and developing a water-well database that ultimately could be used to update existing ground-water reports by Sayre and Livingston (1945), Conover (1954), Knowles and Kennedy (1958), and Leggat et al. (1962); and complement ongoing studies by the City of El Paso (Cliett, 1969). Reports summarizing stratigraphic and geomorphic aspects of this research were published in 1969 (Hawley; Hawley and Kottlowski; Hawley et al.).

In 1965, a formal study of geology and groundwater resources of central and western Doña Ana County was initiated by the NMSU Earth Science Department in cooperation with the SCS and funded by the New Mexico Water Resources Research Institute and the U.S. Department of Agriculture. W. E. King was Principal Investigator and Hawley was responsible for geological aspects of the research. This study was completed in 1968 and published by the NMWRRI and NMBMMR (King et al., 1971). A threefold division of basin-fill aquifers into lower, intermediate (medium), and upper (shallow) zones, originally proposed by Leggat and others (1962) and Cliett (1969) was recognized as being characteristic of lithofacies distribution patterns that are widespread in the Santa Fe Group, at least in the southeastern Mesilla Basin.

These early investigations demonstrated the need for a much more comprehensive and quantitative evaluation of the area's water resources. In 1972, the USGS-Water Resources Division established a field office in Las Cruces and initiated ground-water investigations under the direction of C. A. Wilson. The results of this major continuing effort, now headed by R. G. Myers, have been published by the NMSEO and the USGS (Wilson et al., 1981; Wilson and White, 1984; Myers and Orr, 1985; Nickerson, 1986, 1989; Frenzel and Kaehler, 1990).

After the untimely death of Clyde Wilson in 1980, a new effort on integrating all available subsurface geological and geophysical data on the Mesilla and southern Jornada Basins was initiated by Hawley, now Senior Environmental Geologist with the NMBMMR. This work was primarily funded by the Bureau of Mines and partly supported by the NMWRRI through a grant to the New Mexico Tech Geoscience Department (Dr. Raz Khaleel, P.I.). A set of 17 hydrogeologic sections (1x and ~10x vertical exaggeration) and a map (1:125,000) showing major boundary faults were prepared for that study and published as an appendix to a WRRI report by Peterson, Khaleel, and Hawley (1984) on "Quasi Three-Dimensional Modeling of Ground Water Flow in the Mesilla Bolson, New Mexico." The hydrogeologic sections and base map were also published as NMBMMR Open-File Report 190, which is included in the present report as Appendix B. The provisional 10-unit classification of lithofacies distribution in basin and valley fills and the hydrogeologic cross sections developed for the 1984 study have been used in the present investigation; but they have been modified considerably (compare Appendix B and Plates 1, 16 and 17).

Continued research on basin hydrogeology also included cooperation with staff and graduate students at NMSU and the University of Texas System working in the areas of geology and geophysics, and with L. H. Gile (SCS soil scientist-retired) on Desert Project soil-geomorphology studies. Syntheses of geologic and geophysical aspects of these studies are published as Geologic Maps 53 and 57 (Seager et al., 1982, 1987) of the New Mexico Bureau of Mines and Mineral Resources. Desert Project research publications include Bureau Memoir 39 (Gile et al., 1981), and Gile (1987, 1989). Research reports and graduate theses have been completed by Figuers (1987), Gross and Icerman (1983), Mack (1985), Snyder (1985), Vanderhill (1986), and Wen (1983). Related work on siting of future radioactive-waste disposal facilities has also been done under contract with the U.S. Geological Survey, Basin and Range Working Group (Bedinger et al., 1989). This study included preparation of hydrogeologic sections of basins and ranges in the Mesilla-Hueco Bolson area of New Mexico and western Texas.

Methods and Techniques

Data Collection and Analysis

The initial step of the 1987 investigation was to collect and review all pertinent geologic and hydrologic information on the Mesilla Basin. This was done in order to develop a comprehensive database from which the hydrogeologic framework was constructed. Much of this information had already been collected for the earlier modeling study by New Mexico Tech (Appendix B; Hawley, 1984; Peterson et al., 1984). Key sources of surface and borehole data were identified and located on base maps of the Mesilla Basin (scales 1:24,000 and 1:100,000) for use as control points. These data include borehole cuttings and geophysical logs, geothermal and geochemical reports, and geologic maps. Six water-test wells drilled by the USGS and the City of El Paso as part of this study provided supplemental information. The Afton, Lanark, La Union, and Noria test wells (MT 1 to 4) were drilled in the basin area west of Mesilla Valley (La Mesa surface). The other two wells (CWF1D and 4D; Nickerson, 1987, 1989) are located in the Canutillo Well Field area on the Rio Grande floodplain west of Vinton, Texas. Subsurface data were supplemented by detailed seismic reflection profiles made at two sites near the Canutillo Well Field (C. B. Reynolds and Associates, 1986, 1987).

Drill Cutting and Thin Section Analysis

Cuttings from the Afton, Lanark, La Union, and Noria test wells (MT 1 to 4) were initially analyzed with a binocular microscope in order to construct a geologic log for each well and to determine sample intervals for thin section work. No preliminary cutting analysis was performed on samples from the Canutillo Field (CWF1D and CWF4D) because these wells were drilled very late in the study. Color, grain size, and other major characteristics of the sediments were noted on the geologic logs. Cuttings were analyzed in approximate 10 ft (3 m) intervals. Geophysical and driller logs aided in the initial examination of the cuttings.

Based on the cutting analysis, samples for thin section study were collected at approximately 100 ft (30 m) intervals from representative sand beds in the Afton, Lanark, La Union, and Noria wells. Samples were also collected from sandy intervals within the CWF1D and CWF4D wells, and from Santa Fe Group outcrops in the area. Locations of sampled wells and outcrops are shown on Plate 1. Forty-six thin sections were analyzed using criteria described by Dickinson (1970) in order to determine detrital modes and provenance. Thin-section petrographic data and interpretations are presented in Section III and Appendix A. Four hundred framework grains per thin section were point counted using a petrographic microscope. Ternary diagrams were constructed based on the point counts and data were also plotted on the geologic-petrographic logs of the Afton, Lanark, La Union and Noria Test Wells (Plates 12-15).

Digitizing Borehole Geophysical Logs

Concurrently with the cutting and petrographic analysis, borehole geophysical data from selected key wells were digitized and then plotted onto computer-generated worksheets with a basin cross-section format. The borehole data were plotted to an altitude datum of 4,500 ft (1372 m) above MSL (vertical scale 1 in = 100 ft, 1 cm = 12.2 m). Digitizing of geophysical logs and plotting of cross-section worksheets was done at the USGS-WRD District Office in Albuquerque. The computer-generated graphics system utilized in this study for integrating geophysical, geologic and hydrologic data (Plates 2-15) was developed by Ken Stevens, formerly with that office.

Hydrostratigraphic Unit Correlation and Hydrogeologic Framework

The basic approach of this investigation was the correlation of borehole-electric (resistivity), geologic-petrographic, and driller logs. Plates 12-15 summarize this information for the four test wells (MT 1 to 4) drilled as part of this study in representative areas of the central and southern parts of the basin. After detailed review of geophysical and geologic-petrologic data, and supplemental geothermal and geochemical information (Tables 4 to 6), initial correlations were made between these key boreholes and other wells in the basin (Plate 1). Ken Stevens of the USGS-WRD and Francis West of the NMSEO collaborated in this phase of the study. Preliminary cross section plots based on analyses of these data were prepared and reviewed prior to preparation of ten representative hydrogeologic sections of the basin. The sections, with selected borehole geophysical and geochemical data, are illustrated in Plates 2 and 11. Plates 1, 16 and 17, with supporting data in Tables 1 to 3, integrate the above information into a conceptual model of the basin's hydrogeologic framework. The model's base elevation is 1,000 ft (305 m) above mean sea level.

Well-Numbering Systems

Wells in New Mexico are identified by a location-number system based on the township-range system of subdividing public lands. The location number consists of four segments separated by periods, corresponding to the township, range, section, and tract within a section (Fig. 2a). The townships and ranges are numbered according to their location relative to the New Mexico base line and the New Mexico principal meridian. The smallest division, represented by the third digit of the final sequent, is a 10-acre (4 ha) tract. If a well has not been located precisely enough to be placed within a particular section or tract, a zero is used for that part of the location number.

Wells in Texas are officially given a well number consisting of five parts (Fig. 2b). The first part is a two-letter prefix used to identify the county, with El Paso County

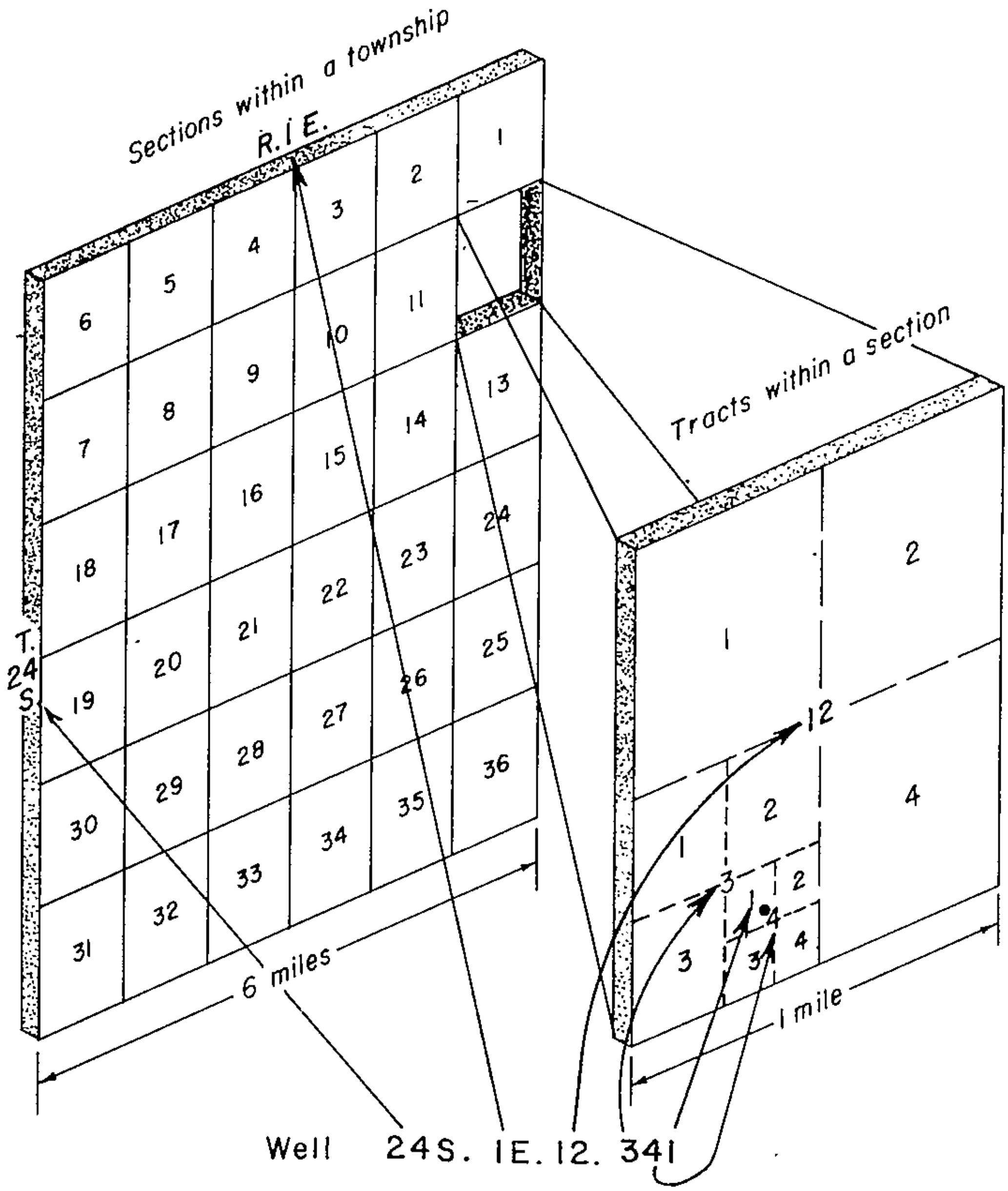


Figure 2a. Well numbering system: Diagram showing system of numbering wells in New Mexico.

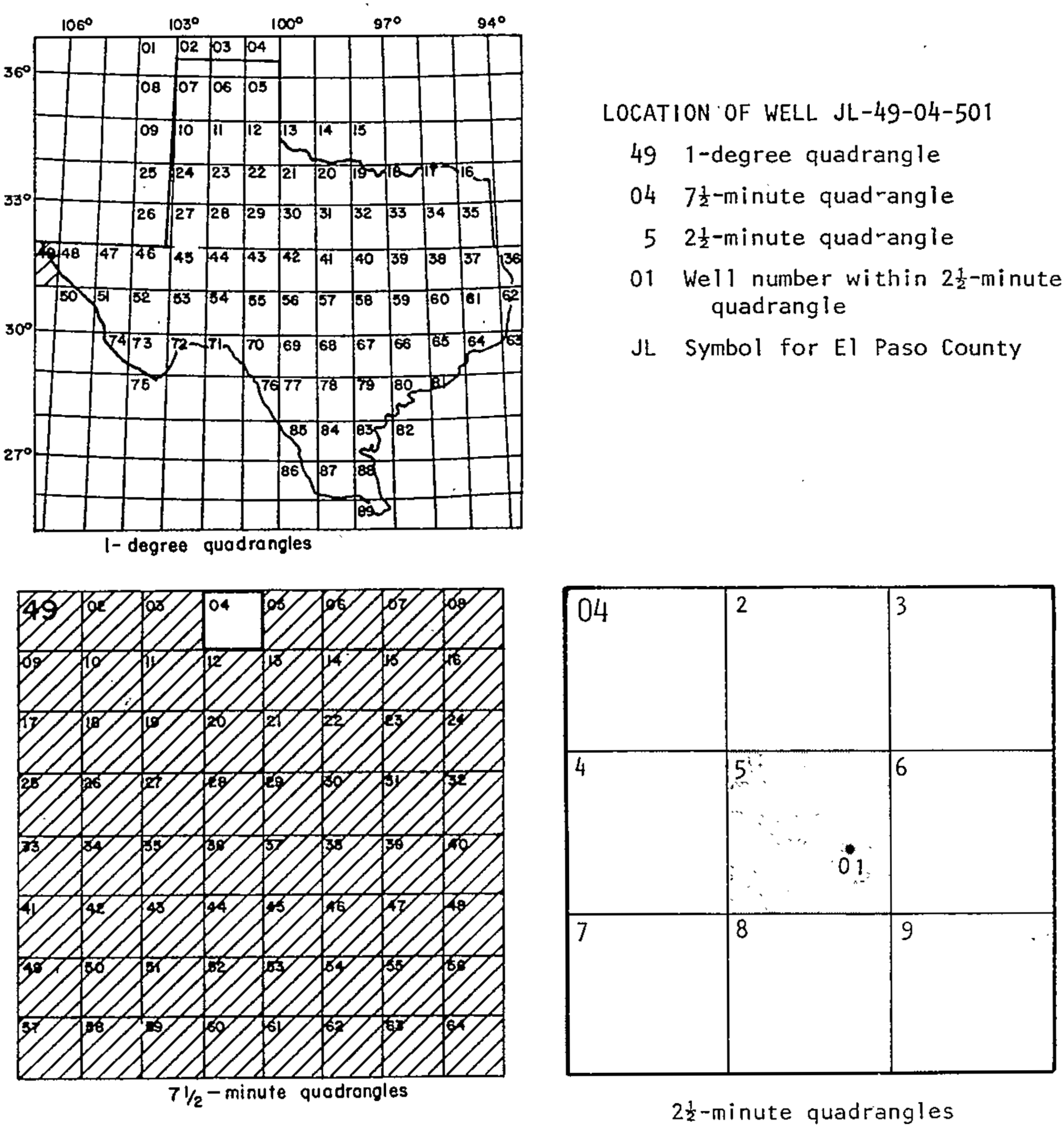


Figure 2b. Well numbering systems: Diagram showing system of numbering wells in Texas.

being represented by JL. The second part of the number has two digits indicating the 1-degree quadrangle. Each 1-degree quadrangle is divided into 64 7½-minute quadrangles. This is the third part of the well number. The first digit of the fourth part indicates the 2½-minute quadrangle, and the last two digits comprise a sequence number that identifies the well from others in the same 2½-minute quadrangle. As an example (Fig. 2b), well JL-49-04-501 is in El Paso County (JL), in 1-degree quadrangle 49, in 7½-minute quadrangle 04, in 2½-minute quadrangle 5, and was the first well inventoried in this 2½-minute quadrangle.

Acknowledgments

Numerous individuals and organizations provided assistance during the course of this study and earlier related investigations. Valuable contributions have been personally made by a large number of the authors of cited references. Many of the basic concepts on the area's geology have been developed by F. E. Kottlowski and W. R. Seager. Other important collaborators on geological and geophysical aspects of the study include R. E. Clemons, L. H. Gile, Tom Gustavson, G. R. Keller, Shari Kelley, Greg and Pamela Mack, Paul Morgan, C. B. Reynolds, Jay Snyder, W. S. Strain, and Jim Vanderhill.

The conceptual model of the basin's hydrogeologic framework was developed over a period of three decades in collaboration with Tom Cliett, W. E. King, Bob Myers, Dave Peterson, Andrew Taylor, and the late Clyde Wilson. Ken Stevens, formerly with the U.S. Geological Survey-Water Resources Division, Francis West of the New Mexico State Engineer Office, and Tom Cliett, formerly with the El Paso Water Utilities Department, were the driving forces behind the present study; and they played a key role in defining the geological, geophysical and geohydrologic elements that are basic building blocks of the conceptual model. Special acknowledgment is due to Ken Stevens who developed the computer-generated graphics system used in this study.

Logistical and financial assistance by the U.S. Geological Survey-Water Resources Division (Albuquerque, Las Cruces and El Paso offices), El Paso Water Utilities Department, Elephant Butte Irrigation District, International Boundary Commission, New Mexico Bureau of Mines and Mineral Resources, New Mexico State Engineer Office, and New Mexico Water Resources Research Institute is gratefully acknowledged. Bob Myers, Ed Nickerson and Don White of the USGS Las Cruces and El Paso offices have been particularly helpful, as have Peter Frenzel, Charles Haywood, and Mike Kernodle of the USGS Albuquerque office.

This report is dedicated to the memory of Clyde A. Wilson, who headed the USGS-WRD office in Las Cruces from 1971 until his untimely death in 1980. Clyde was an unassuming and highly motivated public servant who played a key role in putting ground-water hydrology and hydrogeology of the Mesilla Bolson area on a sound technical and scientific footing. His expertise and common-sense approach to water-resource investigations are greatly missed.

II: GEOLOGIC SETTING OF THE MESILLA BASIN

Introduction

The Mesilla Basin (Figs. 1 and 3) is at the southern end of a north-trending series of structural basins and flanking mountain uplifts that comprise the Rio Grande rift (Chapin and Seager, 1975; Seager and Morgan, 1979; Chapin, 1988). The rift extends through New Mexico from the San Luis Basin of south-central Colorado to the Hueco Bolson and Bolson de los Muertos area of western Texas and northern Chihuahua (Hawley, 1978). The rifting process began in Oligocene time, about 25 to 30 million years ago (Ma), and is continuing at present. During this long interval, extensional forces have stretched the earth's crust, causing large basin blocks to rotate and sink relative to adjacent mountain uplifts. All rift basin fill that was deposited prior to formation of the Rio Grande Valley in the early to middle Pleistocene (1.7 to 0.7 Ma) is included in the Santa Fe Group (Bryan, 1938; Spiegel and Baldwin, 1963; Hawley et al., 1969; Hawley, 1978; Chapin, 1988).

The upper Rio Grande now flows southward through a series of valleys cut along the deeper parts of most of the rift basins as far as El Paso. Beyond the Paso del Norte gap (El Paso "Narrows" between the Franklin and Juarez uplifts, Fig. 1) at the southern end of the Mesilla Basin, the river flows southeastward down the Hueco Bolson axis along the International Boundary toward the Big Bend area of Trans-Pecos Texas. Intermontane-basin and river-valley fills of the Rio Grande rift comprise the major aquifer systems of the region and are the principal subject of this report.

The Mesilla Basin, covering an area of about 1,000 sq mi(2590 km^2), is in the southeastern part of the Basin and Range physiographic province (Fig. 3; Hawley, 1986). It extends southward about 60 mi (100 km) from the upper Mesilla Valley between the Robledo and Doña Ana Mountains to a poorly defined ground-water divide near the International Boundary west of El Paso and Ciudad Juarez. Basin width varies from about 5 mi (8 km) at its northern end to about 25 mi (40 km) in its central part. Flanking mountain uplifts (Juarez-Franklin-southern Organ on the east and East Potrillo-Robledo on the west; Plate 1) are narrow and relatively low-lying (less than 8,000 ft, 2440 m, elev.) in comparison with ranges of the northern and central Rio Grande rift (Hawley, 1978).

Broad plains with low topographic relief (less than 500 ft, 150 m) characterize much of the basin area (Hawley, 1975; Gile et al., 1981). The single major erosional feature is the broad Mesilla Valley of the Rio Grande located on the east side of the basin (Fig. 1). An extensive remnant of the basin-floor surface that predates river-valley incision is preserved between the Mesilla Valley and the East Potrillo and Robledo uplifts. This geomorphic surface is called "La Mesa" in many earlier reports on the area (Conover, 1953; King et al., 1971; Gile et al., 1981) but is simply designated the "West Mesa" in recent water resources publications (Wilson et al., 1981; Myers and Orr, 1986).

Basin Structure and Bedrock Units

The internal structure of Mesilla Basin is complex (Figs. 3 and 4, Plates 1, 16, and 17). Structural interpretations in this report are based on oil and geothermal test-well, water-well, and both surface and borehole geophysical data (Plates 2-15, Table 4).

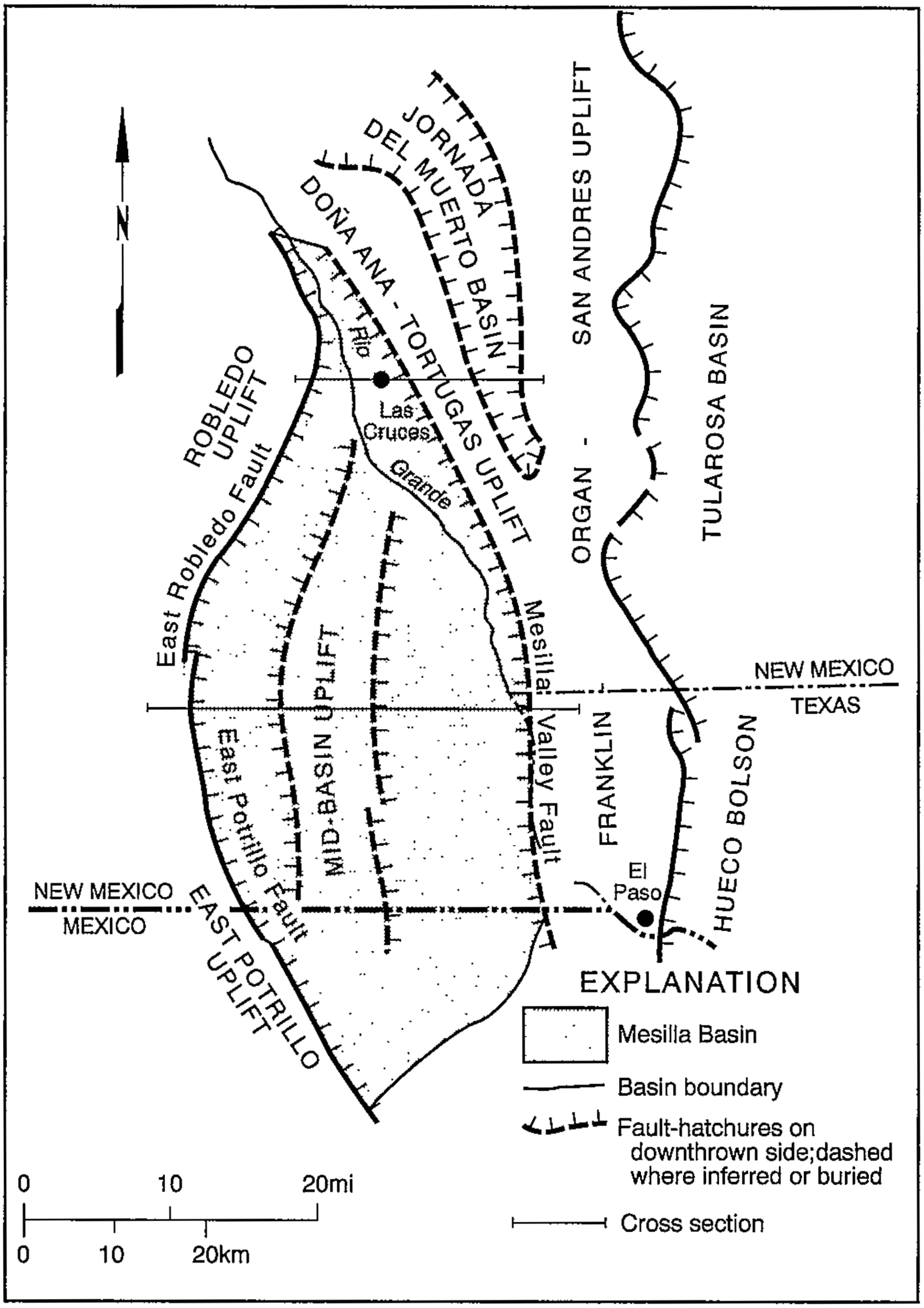


Figure 3. Index map of Mesilla Basin area showing locations of major boundary and intrabasin faults, adjacent mountain uplifts, and geologic cross sections (Fig. 4).

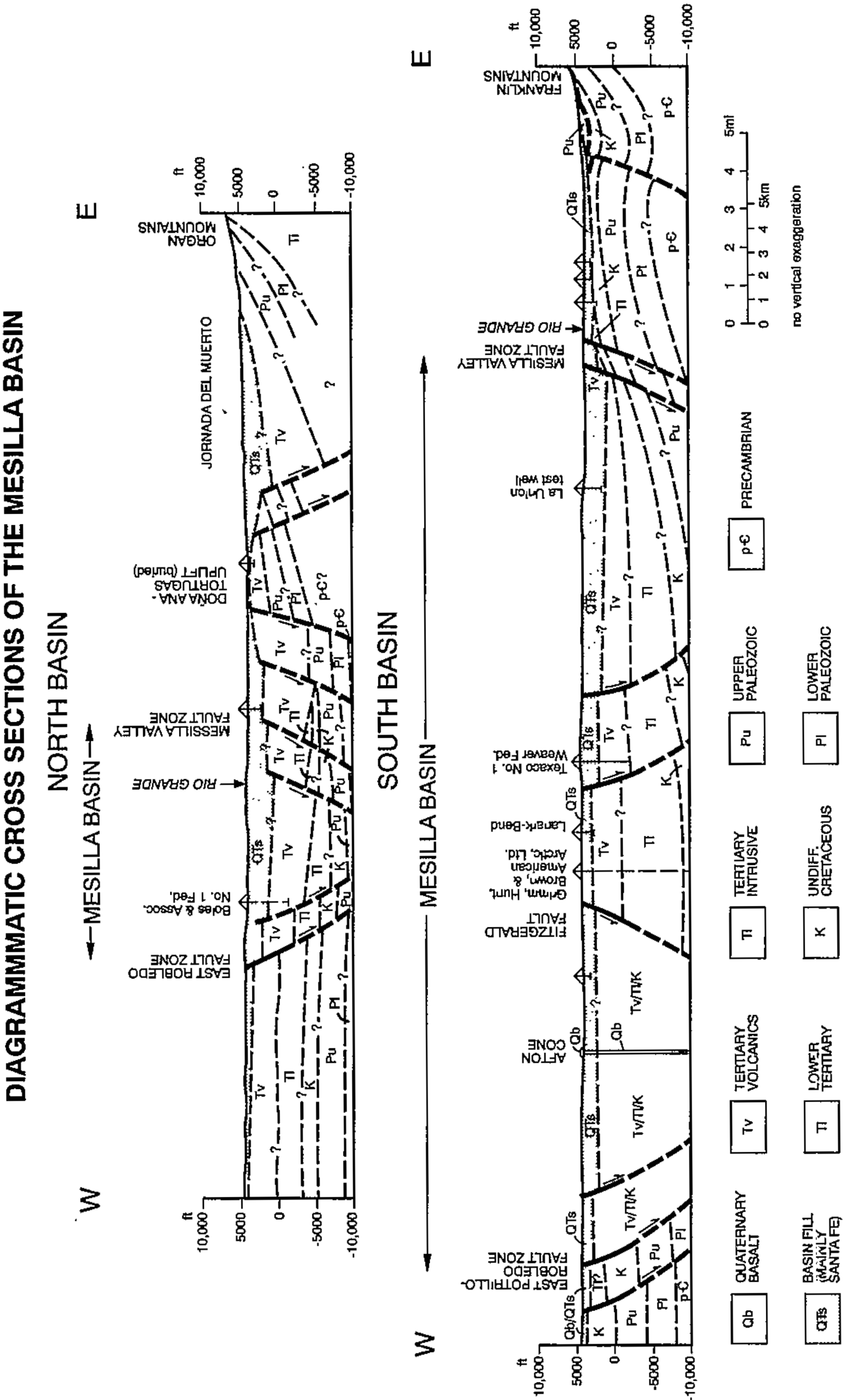


Figure 4. Diagrammatic geologic cross sections of the northern and central Mesilla basin.

The major structural elements include three large subbasins (eastern, southwestern, northwestern), with general north-south trends, a buried mid-basin uplift, and an inferred south-central basin that extends into Chihuahua west of the Cristo Rey (Sierra Juarez) uplift. The northeastern boundary of the Mesilla Basin is formed by a partly-buried bedrock ridge, designated the Doña Ana-Tortugas uplift on Plate 1. Topographically, the basin merges northward with the Jornada del Muerto Basin, northeast of Las Cruces, and southward with the Bolson de Los Muertos plains, southwest of El Paso-Ciudad Juarez (Figs. 1 and 3).

All boundaries between the major subbasins and flanking uplifts appear to be formed by zones of high-angle normal faults. Many of the exposed mountain blocks are strongly tilted, and at least some of the basin blocks have a tilted half-graben morphology and listric boundary faults that are typical of most continental rift basins (Rosendahl, 1987; Seager, 1989; in press; Seager et al., 1984; 1987). Dips are usually very low in the central basin area, however; and the major subbasins and intrabasin uplifts are here interpreted as only slightly tilted graben and horst blocks which are bounded by high-angle normal faults that may or may not flatten significantly with depth (Fig. 4, Plates 16 and 17).

Basin subsidence was initiated in late Oligocene time, but maximum differential displacement between the major basin and range structural blocks probably occurred between 4 and 10 million years ago (late Miocene to early Pliocene). By late Miocene time rock debris eroded from adjacent highlands, and possibly from adjacent parts of the Rio Grande rift, had filled existing subbasins (mostly half grabens) to the point where intrabasin uplifts (horsts) were buried by lower and middle Santa Fe Group deposits. The broad topographic basin formed by this infilling process continued to aggrade as a single (upper Santa Fe) unit through the early middle Pleistocene when widespread basin filling ceased due to entrenchment of the Rio Grande Valley system. The thickest Santa Fe Group fills in the Mesilla Basin (about 3000 ft, 900 m) are located in areas adjacent to the most active segments of major boundary fault zones—the Mesilla Valley, East Potrillo, and East Robledo (Figs. 3 and 4, Plates 16 and 17).

Bedrock Units of Basin-Margin Uplifts

The Mesilla Basin, in contrast to many basins of the northern and central Rio Grande rift, is not bounded by continuous ranges of high mountains (Hawley, 1978; Chapin, 1988). Onlap of basin fill has buried most of the Doña Ana-Tortugas and southern Organ-Bishop Cap uplifts on the northeastern basin margin, and the East Potrillo and Robledo uplifts to the west. Only the Franklin and Juarez uplifts at the basin's southeastern edge form well-exposed structural highlands (Fig. 1).

Tertiary igneous intrusives (granites to monzonites) and volcanics (rhyolites to andesites) are the dominant rocks exposed in the Doña Ana and southern Organ Mountains (Seager et al., 1976; Seager, 1981). Marine sedimentary rocks, mainly carbonate types, of Paleozoic and early Cretaceous age are the dominant lithologic units exposed in the Tortugas, Bishop Cap, Franklin, Juarez, East Potrillo, and Robledo uplifts (Harbour, 1972; Kelley and Matheny, 1983; LeMone and Lovejoy, 1976; Lovejoy, 1979; Seager et al., 1987; Seager and Mack, in press). A variety of sedimentary and intermediate-intrusive rocks of Cretaceous and early Tertiary age crop out in the Paso del Norte area between Franklin Mountains and Sierra de Juarez, which includes Cerro de Cristo Rey on the Chihuahua-New Mexico border (Fig. 1; Lovejoy, 1976).

Middle Tertiary volcanic and intrusive rocks of intermediate to silicic composition are exposed in isolated upland areas such as the Sleeping Lady and Aden Hills in the western part of the Robledo uplift, and Mount Riley northwest of the East Potrillo Mountains (Fig. 1; Seager, in press).

No additional information on the configuration of the basin's buried northeastern boundary (Doña Ana-Tortugas-Bishop Cap trend) was collected during the present study. Provisional interpretations in Hawley (1984; Appendix B, Plate H-H') will be revised in a future report after surface geophysical surveys and test drilling programs in that area have been completed by the U.S. Geological Survey.

Bedrock Units Beneath the Basin Fill

Analyses of drill cuttings and geophysical logs from a few deep test wells (oil and gas, water, and geothermal), and surface geophysical surveys are the only sources of information on the lithologic character and structure of bedrock units beneath the rift-basin fill. Oil and gas test holes described by Seager and others (1987), including wells 25.1.32.141 and 26.1.35.333 in the central part of the basin (this report), encountered a thick sequence of lower to middle Tertiary volcanics and lower Tertiary sedimentary rocks. The latter unit of continental origin was deposited in deep, northwest-trending basins of Laramide age (Seager et al., 1986). The lower Tertiary section is only exposed in a few places along the northern and eastern basin margins (Seager et al., 1987). Cretaceous and upper Paleozoic underlie the middle to lower Cenozoic sequence at great depth in most parts of the basin; but Cenozoic units may rest directly on lower Paleozoic or Precambrian rocks in a few areas (Seager 1989; Seager et al., 1986).

All deep test drilling to date indicates that lower to middle Tertiary volcanic and volcaniclastic rocks of intermediate to silicic composition are the dominant units that immediately underlie Santa Fe Group basin fill. Besides the previously mentioned oil tests, water test wells that have definitely penetrated these units include wells 24.1.8.123, 25.1.6.333, and 27.1.4.121 in the central part of the basin; and wells 24.2.4.334, 29.3.2.243, and 49-04-109 east of the Mesilla Valley fault zone near the east edge of the basin (Plates 1, 16 and 17).

Basin-Fill Stratigraphy

Middle and upper Cenozoic sedimentary deposits of the Rio Grande rift can be subdivided into two major units: 1) Santa Fe Group basin fill of late Oligocene to middle Pleistocene age, and 2) post-Santa Fe, river-valley and basin deposits of middle and late Quaternary age. These sediments are locally interbedded with and capped by basalt and andesite flows and pyroclastic (vent) deposits. Associated with these extrusive rocks are intrusive bodies that include feeder dikes, plugs, sills and breccia pipes. Dated basalts in the southwestern New Mexico region include scattered occurrences of middle Miocene to Pliocene age and extensive lava fields of Quaternary age. Pleistocene basalt flows and associated vent units (e.g. cinder cones, lava shields, and maars) form a widespread cover on the upper Santa Fe Group in the west-central Mesilla Basin area, and they also cap large parts of the southern Robledo and East Potrillo uplifts (Hoffer, 1976; Seager et al., 1987; Seager, 1989, in press). Basaltic andesites of late Oligocene age, which are interbedded with lower Santa Fe beds and extensively exposed the Sierra de Las Uvas area of northwestern Doña Ana County (Fig. 1), may be present in the basal part of the Mesilla Basin fill.

Volcanic layers of basaltic to andesitic composition have been reported in drilling records of two water wells in the northern basin area including the Mesilla Valley near Las Cruces (24.1.13.411) and may be either flows of sills interbedded with or intruded into the basin fill. A new well drilled at the Las Cruces waste-water treatment plant (about 1.5 mi, 2.4 km, WSW of 23.1.13.411) reportedly encountered a basalt layer at a depth of about 880 ft (270 m) in the middle to lower part of the basin-fill section (R. G. Myers, oral communication 7-14-92).

Santa Fe Group

The Santa Fe Group (Spiegel and Baldwin, 1963; Hawley et al., 1969; Chapin, 1988) is the major fill component of Rio Grande rift basins. In southern New Mexico and western Trans-Pecos Texas the Group ranges in age from about 25 to 0.7 Ma and includes alluvium derived from adjacent structural uplifts and nearby rift-basin areas, and locally thick eolian and playa-lake sediments. Fill thickness in most of the central basin area (between the Mesilla Valley and East Potrillo-Robledo fault zones) ranges from 1,500 to 2,500 ft (460-760 m). In this report, the Santa Fe Group is subdivided into informal *lower*, *middle* and *upper* lithostratigraphic units defined on the basis of general lithologic character, depositional environments, and diagenetic features related to age and post-depositional history. Generally-equivalent hydrostratigraphic units are discussed in Section IV.

The *lower* Santa Fe Group is dominated fine-grained basin floor sediments that intertongue with alluvial fan deposits beneath the distal piedmont slopes that border adjacent mountain uplifts. Sandy eolian sediments locally form thick sheets and lenses that are interbedded with both basin-floor and piedmont-slope deposits. Buried dune complexes as much as 500 ft (150 m) thick have been identified beneath the Mesilla Valley in the Anthony-Canutillo area (Cliett, 1969; Hawley, 1984) and are probably preserved in other parts of the eastern (La Union-Mesquite) subbasin (Plate 1). Thick eolian deposits possibly also occur in the deeper parts of the southwestern subbasin east of the East Potrillo fault zone.

Lower Santa Fe beds probably range in age from 25 to 10 Ma and were deposited in a closed-basin setting prior to the final interval of deep basin subsidence and uplift of the higher flanking range blocks (e.g. Organ, Franklin, East Potrillo, and Robledo Mountains). Formal lithostratigraphic subdivisions of the *lower* Santa Fe Group have not yet been proposed for the Mesilla Basin. However, the unit is generally correlative with the Hayner Ranch Formation and the lower part of the Rincon Valley Formation mapped in the Jornada del Muerto-Rincon Valley area of northern Doña Ana County (Seager and Hawley, 1973; Seager et al., 1971, 1982, 1987).

The *middle* Santa Fe Group was deposited between about 10 and 4 Ma when rift tectonism was most active and deposition in subbasins adjacent to the major boundary fault zones (Mesilla Valley, East Potrillo, East Robledo) was most rapid. In many areas erosion of uplifted basin borders and deposition on adjacent piedmont slopes also accelerated relative to early Santa Fe time. Rapidly aggrading central basin plains were characterized by broad alluvial flats that terminated in extensive playa lakes; and, most mid-basin uplifts are deeply buried by Middle Santa Fe deposits. Alternating beds of clean sand, silty sand, and silt-clay mixtures are the dominant lithofacies (Sections III and IV) in much of the central basin area. Eolian sediments also continued to accumulate in leeward (eastern) basin area; but the thickest buried dune sequences appear to be confined to the *lower* Santa Fe Group.

Formal lithostratigraphic subdivisions have not yet been proposed; but the *middle* Santa Fe unit probably correlates with at least the upper part of the Rincon Valley Formation (Seager et al., 1982, 1987) and the lower Fort Hancock Formation, which has a type area in the southeastern Hueco Bolson (Strain, 1966; Hawley et al., 1969; Gustavson, 1991).

The *upper* Santa Fe Group contrasts markedly with older Santa Fe units in terms of lithologic character. About 3 to 4 million years ago, the floor of the Mesilla Basin was transformed from an internally-drained feature to the broad fluvial plain of a throughgoing river. Braided distributary channels of the ancestral upper Rio Grande spread southward across the basin-floor and ultimately terminated in large playa-lake plains in the Bolson de los Muertos of north-central Chihuahua and the southern Tularosa Basin-Hueco Bolson area of New Mexico and western Texas (Hawley et al., 1969, 1976; Hawley, 1975, 1981; Gile et al., 1981; Seager et al., 1984, 1987).

Sandy deposits of this complex fluvial-deltaic system continued to accumulate on the Mesilla Basin floor through early Pleistocene time. Recent research on basin-fill magnetostratigraphy (Vanderhill, 1986; Mack et al., 1991) and dating of volcanic ash lenses in the upper part of the Santa Fe sequence (Gile et al., 1981) demonstrate that widespread fluvial aggradation of the Mesilla Basin floor (and Santa Fe Group deposition) had ceased by about 0.7 Ma. By 0.6 Ma, significant incision of upstream and downstream canyon areas (Selden and El Paso) had already occurred; and entrenchment of the Mesilla Valley by the ancestral Rio Grande had begun.

The uppermost part of the Santa Fe Group in the south-central New Mexico and western Texas area, and the main *upper* Santa Fe component, is the Camp Rice Formation of Strain (1966). It has now been recognized and mapped in detail from the southern Palomas and Jornada del Muerto Basins, across the Mesilla and southern Tularosa Basins, and throughout the Hueco Bolson to its type area near Fort Hancock in Hudspeth County, Texas (Hawley et al., 1969; Seager et al., 1971, 1976, 1982, 1987; Hawley, 1975, 1978; Gile et al., 1981; Gustavson, 1991). Camp Rice deposits are very well preserved throughout most of the Mesilla Basin, with significant erosion only occurring in the Mesilla Valley and valleys of a few major arroyos. The formation's thickness ranges from about 300 to 700 ft (90-215 m) in central basin areas.

The dominant lithofacies of the Camp Rice Formation is the complex of fluvial sand and pebbly sand deposits laid down by the ancestral Rio Grande. However, because of complex channel shifts (influenced by both tectonism and climatic factors) in the ancestral river system during the long interval of basin-floor aggradation, fine-grained (slack-water) facies are locally present. The other important Camp Rice lithofacies is a piedmont-slope facies assemblage that is primarily composed of fan alluvium and associated debris-flow deposits. To the south and southeast, the basal Camp Rice of the Mesilla Basin area appears to intertongue with and overlap fine-grained alluvial and playa-lake deposits of the upper Fort Hancock Formation of Strain (1966). In their type areas near Fort Hancock in Hudspeth County, Texas, the Camp Rice/Fort Hancock Formation contact has been dated at about 2.5 Ma (Vanderhill, 1986; Gustavson, 1991).

Post Santa Fe Deposits

Post-Santa Fe Group sedimentary units of middle and late Quaternary age were deposited in two contrasting geomorphic settings: (1) valleys of the Rio Grande and tributary arroyo system, and (2) extensive intermontane-basin areas still not integrated with the river (Hawley and Kottlowski, 1969; Hawley, 1975; Gile et al., 1981). Valley-fill units were deposited during repeated episodes of river incision separated by intervals of partial backfilling that produced the present landforms of the Mesilla Valley. The stepped-sequence of geomorphic surfaces (mainly alluvial terraces and fans) that border the inner-valley (floodplain) area are mainly the product of valley-entrenchment episodes during Pleistocene glacial (pluvial) stages, and subsequent intervals of valley aggradation during interglacial (pluvial) stages. The 60 to 100 ft (18-30 m) of medium- to coarse-grained alluvium beneath the modern river floodplain ("flood-plain alluvium" of Frenzel and Kaehler,1990) is a product of (1) valley cutting by a high-energy fluvial system during the late Wisconsinan (full) glacial substage about 15 to 25 thousand years ago (Ka), and (2) valley filling during the late-glacial and ongoing, Holocene interglacial stage that started about 10 Ka. Tributary alluvial systems have delivered more sediment to the valley floor than the river could transport out of the drainage basin during this ongoing period of fluvial aggradation.

The shallow aquifer system in the Mesilla Valley is formed by (1) the saturated part of the inner-valley fill, and (2) channel sands and gravels in underlying beds of the upper Santa Fe Group that were deposited by the ancestral Rio Grande during the mid- to late Pliocene interval of basin filling. Older valley fills, of the tributary arroyo systems as well as the ancestral river, that are preserved in terrace remnants on the valley borders ("valley-border surfaces"), are generally above the water table and are not described in this report. Thin (<30 ft, 10 m) alluvial, eolian, and playa-lake sediments deposited in areas of the Mesilla Basin still not integrated with the Rio Grande are also not discussed. They are included with the *upper* Santa Fe unit in the hydrogeologic cross sections (Plates 2-11, 16-17) that are covered in Section IV. Younger valley and basin fills, and soil-geomorphic relationships are described in detail by Gile et al. (1981) and Seager et al. (1987).

III: SAND-FRACTION PETROGRAPHY

Introduction

Prior to the present study, no detailed geologic or geophysical information had ever been collected from deep water test wells in the central and southern basin area west of the Mesilla Valley. The four test wells drilled in 1986 for the U. S. Geological Survey and the City of El Paso at the Afton, Lanark, La Union, and Noria sites (Plate 1, 25.1.6.333, 27.1.4.121, 27.2.13.331, and 28.1.34.414) were specifically designed to provide baseline information on general basin fill lithology, sand-fraction petrography, borehole geophysics, and ground-water quality at selected drill-stem sample intervals. Because no core samples were taken, lithologic and petrographic analyses could only be done on sets of drill-cuttings carefully collected at ten-foot intervals from these test wells.

Sand-fraction petrographic interpretations described in this section have been integrated with selected borehole lithologic and geophysical data in four geologic columns (Plates 12-15). These columns illustrate basic hydrogeologic characteristics of basin-fill deposits in the area of the four test holes; and they demonstrate that correlation of the major lithostratigraphic subdivisions of the Santa Fe Group (lower, middle, upper) described in Section II is possible throughout much of the Mesilla Basin. The hydrostratigraphic units described in detail in Section IV, which generally correspond to these basin-fill subdivisions, are also shown on Plates 12 through 15.

Supplemental analyses of sand-fraction petrography from two recent test holes in the Canutillo Well Field (CWF 1D and 4D; JL-49-04-481; Nickerson, 1989) were also done as part of this study. This is the area where Santa Fe Group basin fill was originally subdivided into "lower, medium, and upper" aquifer zones by Leggat and others (1962; Cliett, 1969).

Methods and Techniques

Preliminary Drill-Cutting Analyses

Cuttings from the Afton, Lanark, La Union, and Noria test wells were analyzed initially with a binocular microscope in order to construct a stratigraphic column for each well and to determine intervals where subsamples of representative sands and sandstones would be collected for thin section analyses. Color, grain size, and other major characteristics of the sediments were noted on the stratigraphic columns. Cuttings were analyzed in approximate 10 ft (3 m) intervals. Geophysical and driller logs aided in the initial analyses of the cuttings.

Thin Section Sample Collection and Preparation

Based on the cutting analysis, thin section samples were collected in approximate 100 ft intervals from the above four wells. Samples were also collected from sandy intervals penetrated by the Canutillo Well Field test holes (CWF1D and CWF4D). In addition, samples from representative Santa Fe Group outcrops were collected to use as a standard for comparison with the subsurface samples. Locations of sampled outcrops are given in Appendix A.

Wherever possible, medium- to coarse-grained sand was sampled. Finer-grained samples were used only when coarser samples were unavailable. Ingersoll et al. (1984) have shown that sand grain size does not affect point counting results. Sand samples were sieved (2.0-0.125 mm) to collect only the sand fraction. To guard against possible contamination, the sieved sand was re-examined with a binocular microscope to remove foreign material (i.e., wood, cement, seeds, drill bit shavings). Next, the sand samples were impregnated with epoxy and cut into standard thin sections. The final step in thin section preparation was to stain half the thin section slide with sodium cobaltinitrite to facilitate potassium feldspar identification.

Thin Section Analysis

Thin sections of the well cuttings and outcrop samples were analyzed using criteria described by Dickinson (1970) in order to determine detrital modes and provenance. Other workers (i.e., Mack, 1984; Lozinsky, 1987) have shown that point counting is a powerful tool for analyzing Santa Fe Group deposits. A total of 46 thin sections were examined; 37 from well cuttings and 9 from outcrops. Four hundred framework grains per thin section were counted using a Nikon binocular polarizing microscope and a Swift digital point counter. Counts were primarily made at 100X, but other magnifications were sometimes used. Nicols were usually crossed, except for occasional glances at plain light. Parameters counted and used to define petrofacies are listed on Table 5. Only framework grains were counted. Matrix and interstitial space were not counted because most samples were loosely consolidated and broken apart in the drilling process. After each point count, the thin section was further examined to determine grain size, sorting, roundness, and other important features. Point count results are summarized in Table 6 and listed in Appendix A. Ternary diagrams (Figs. 5-7) were constructed based on the thin section point counts.

Table 5. Point-count grain parameters. Modified from Dickinson (1970)

Counted parameters

Qm = monocrystalline quartz
Qpt = tectonic polycrystalline quarts
Qpn = nontectonic polycrystalline quartz (inc. chert)
P = plagioclase feldspar
K = potassium feldspar
Lv = volcanic lithic fragments
Lm = metamorphic lithic fragments
Ls = sedimentary lithic fragments (silt and shale)
Lc = carbonate lithic fragments
M = phyllosilicates

Recalculated parameters

Qp = Qpt + Qpn
Q = Qm + Qp
F = P + K
Lsc = Ls + Lc
Lst = Qp + Lsc
L = Lv + Lm + Lsc
QFL%Q = 100Q/(Q + F + L)
QFL%F = 100F/(Q + F + L)
QFL%L = 100L/(Q + F + L)
LmLvLsc%/Lm = 100Lm/L
LmLvLsc%/Lv = 100Lv/L
LmLvLsc%/Ls = 100Ls/L
LvLstLm%Lm = 100Lm/Lm + Lv + Lst
LvLstLm%Lv = 100Lv/Lm + Lv + Lst
LvLstLm%Lst = 100Lst/Lm + Lv + Lst

Table 6. Means (x) and standard deviations (s) of point counts on water well and outcrop samples. N = number of samples.

Water Wells		Qm	Qpt	Qpn	P	K	Lv	Lm	Ls	Lc
Afton (25.1.6.333) MT-1; N = 7	x	43.8	.35	2.1	28.0	7.0	17.6	.03	.5	.42
	s	4.2	.37	.5	3.2	2.1	2.8	.09	.27	.34
M1-021		11	0	.8	26	3.8	58	0	.25	.25
Lanark (27.1.4.121) MT-2; N = 5	x	42.4	.45	3.0	26.3	9.1	18.1	.1	.25	.4
	s	3.3	.45	.9	4.4	.8	4.4	.14	.30	.28
M2-015		0	0	0	0	0	100	0	0	0
La Union (27.2.13.331) MT-3; N = 7	x	47.0	.46	2.5	26.2	8.3	13.6	0	.6	.8
	s	2.6	.3	1.1	3.2	3.5	5.8	0	.2	.5
Noria (28.1.34.414) MT-4; N = 5	x	43.8	.45	2.9	29.1	8.5	14.6	.05	.45	.2
	s	1.9	.1	.38	3.7	1.3	4.7	.1	.3	.1
CWF 4D	x	47.8	.15	2.4	21.9	12.2	14.1	.05	.7	.5
(JL-49-04-469)	s	2.2	.12	.9	1.9	.8	2.9	.1	.45	.3
CWF 1D	x	49.1	0.3	2.4	20.4	16.3	10.3	0	.6	.4
(JL-49-04-481) N = 5	s	2.9	0.4	1.4	0.8	1.8	2.6	0	.13	.28
1D-009		6.0	0	4.0	3.0	1.0	30	0	1.0	55

Outcrops		Qm	Qpt	Qpn	P	K	Lv	Lm	Ls	Lc
Upper Santa Fe Gp	x	43.8	.2	2.3	21.7	11.6	19.4	.1	.8	.1
N = 7	s	4.2	.3	3.2	3.5	1.8	2.3	.2	.4	.1
Middle Santa Fe Gp	x	17	0	.75	34.0	14.6	32.8	0	.4	0
N = 2	s	2.2	0	.3	4.9	2.2	.2	0	.2	0

Sand Petrography of Selected Samples of Well Cuttings

Well cuttings analyzed petrographically consist of loosely consolidated, moderately to well sorted sands that can be classified as lithic arenites and litharenites after Folk (1974). Sand grains are fine- to coarse-grained and subangular to subrounded. As shown on Table 6, monocrystalline quartz (42-49%) and plagioclase (20-29%) are the dominant detrital grains in the well cuttings. Many quartz grains are clear, exhibit rapid extinction and overgrowth rings. Detrital plagioclase and plagioclase phenocrysts occurring in rock fragments range in composition from oligoclase to labradorite, but most are andesine (determined by the Michel-Levy method). These grains usually display twinning and sometimes oscillatory zoning. Most feldspar grains are fresh, but some show sericitic alteration. Volcanic-rock fragments (10-16%) are the dominant lithic fragment. They exhibit porphyritic and microlitic textures and appear to be mainly andesitic. Most potassium feldspars are orthoclase and sanidine, but significant amounts of microcline are also present. Minor amounts of detrital chert (2-3%), carbonate-rock fragments (<1%), sedimentary-rock fragments (<1%), and metamorphic-rock fragments (<<1%) occur.

When the point counting results are plotted on the various ternary diagrams (Figs. 5 and 6), little variation in sand composition is seen with depth except for a slight increase in lithic fragments (L) and a decrease in potassium feldspar (K). Most of the point counts cluster in the same general field. The only exceptions are samples M1-021 (Afton), M2-015 (Lanark), and CWF 1D-009 on Fig. 5 and Table 6. These samples contain very high percentages of lithic fragments and represent pre-Santa Fe or basal Santa Fe Group deposits.

On the QFL plots, wells CWF 1D and CWF 4D have the highest mean quartz percentages (51.8 and 50.4) whereas wells MT 1 and 2 (Afton and Lanark) have the lowest (46.3 and 45.8). Feldspars averaged between 34-37% in all wells, with K-feldspar being relatively abundant only in the Canutillo Well Field (CWF, Table 6, Appendix A), particularly in well CWF 1D located east of the Rio Grande at the base of the Franklin Mountain block. Lithic fragment percentages are highest in wells MT 1 and 2 (19 and 18.7) and lowest in wells MT 4 (Noria) and CWF 4D (11.3 and 14.7). Except for the bottom sample from CWF-1D, the LvLsLm plots show no groupings, as more than 90% of all lithic fragments are volcanic in origin with 3-5% being sedimentary and <1% metamorphic. Similarly, the LvLstLm plots also show a concentration of points in one general field as samples from all wells contained about 2-3% chert.

Comparison with Santa Fe Group Outcrops

Results of point counts on the outcrop samples are also summarized on Table 6, listed in Appendix A, and plotted on Fig. 7. Except for the two Rodey samples, all outcrop samples plot within the same fields on the ternary diagrams as the well cutting samples. All outcrop samples in the Mesilla and Palomas (T or C area) Basins are from the upper Santa Fe Group whereas the two Rodey samples are from the middle Santa Fe - Rincon Valley Formation. The Rodey samples also had source areas that differed from those of the middle Santa Fe units penetrated by test wells in the Mesilla Basin.

Figure 5. Ternary diagrams of sand-fraction petrography (thin-section point-count data, Tables 5 and 6) for well cuttings from representative Santa Fe hydrostratigraphic units at: Afton (MT 1), Lanark (MT 2), and Canutillo Well Field (CFW 1D).

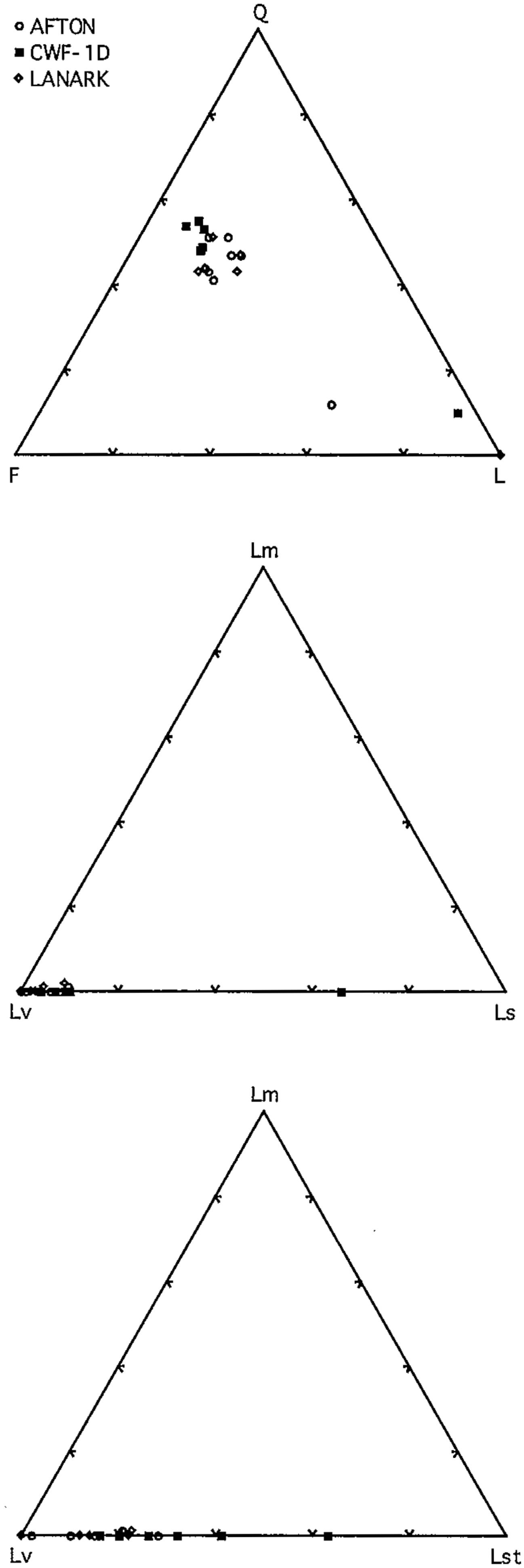
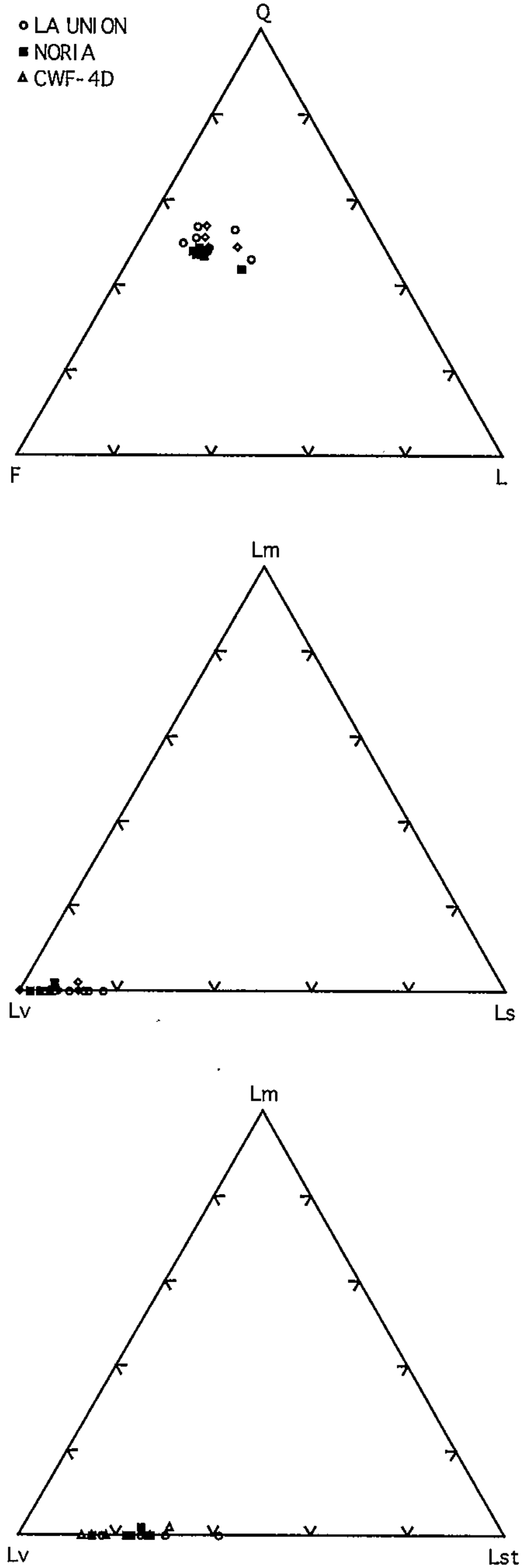

AFTON
CWF-1D
LANARK
Q
F
L
Lm
Lv
Ls
Lm
Lv
Lst

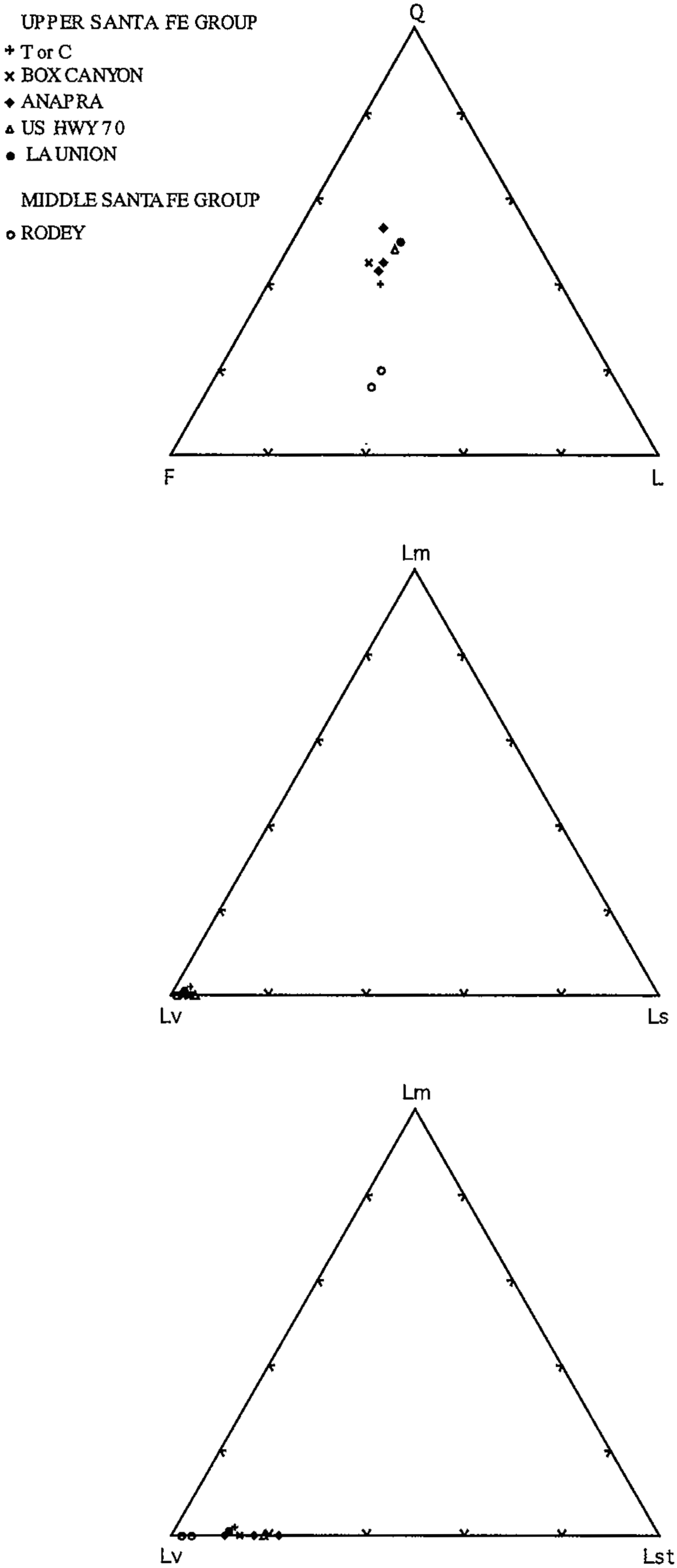
Figure 6. Ternary diagrams of sand-fraction petrography (thin-section point-count data, Tables 5 and 6) for well cuttings from representative Santa Fe hydrostratigraphic units at: La Union (MT 3), Noria (MT 4), and Canutillo Well field (CWF 4D).



LA UNION
NORIA
CWF-4D
Q
F
L
Lm
Lv
Ls
Lm
Lv
Lst

Figure 7. Ternary diagrams of sand-fraction petrography (thin-section point-count data, Tables 5 and 6) for samples from representative Santa Fe Group outcrops.

Fig. 7


UPPER SANTA FE GROUP
T or C
BOX CANYON
ANAPRA
US HWY 70
LA UNION
MIDDLE SANTA FE GROUP
RODEY
Q
F
L
Lm
Lv
Ls
Lm
Lv
Lst

Overall, point counts (Figs. 5-7) from this study are consistent with counts by Mack (1984) of samples from Santa Fe Group sandstone outcrops near Las Cruces.

Provenance

Sand samples analyzed from the six water wells and from the outcrop areas (except the two Rodey samples) were derived from more than one source terrain. The abundance of plagioclase (zoned and twinned) and andesitic lithic fragments strongly suggest an intermediate volcanic source area for most of the detrital grains. Chert, chalcedony, and abundant quartz (many well rounded with overgrowth rims) indicate reworked sedimentary units as another major source. A granitic source area is also suggested by the presence of microcline, strained quartz, and granitic rock fragments. The paucity of metamorphic-rock fragments and tectonic polycrystalline quartz rules out a metamorphic terrane as a major source area. In the middle Santa Fe Group Rodey samples, the abundance of plagioclase and intermediate volcanic lithic fragments and the paucity of quartz, chert and sedimentary lithic fragments strongly suggest an intermediate volcanic terrane as the only major source area.

Due to lack of paleoflow indicators, it is difficult to determine the exact source area for these deposits. However, it appears that even in early to middle Santa Fe time (Miocene) the central Mesilla Basin area was receiving sediment from a very large watershed area. A much larger source region was also available for sand and finer grain-size material when the mechanism of eolian transport is taken into account. By middle Pliocene time the ancestral Rio Grande was delivering even pebble-size material to the basin from source terranes as far away as northern New Mexico (e.g. pumice and obsidian from the Jemez and Mount Taylor? areas). In most cases, visual and binocular microscopic examination of the gravel-size (>2mm) fraction is still the best way to establish local versus regional provenance of coarse-grained fluvial and alluvial deposits.

IV: A CONCEPTUAL HYDROGEOLOGIC MODEL OF THE MESILLA BASIN

Introduction

The conceptual model of the Mesilla Basin's hydrogeologic framework and its development are described in this section. Emphasis is on stratigraphic and lithologic characteristics of basin and valley fills, intrabasin geologic structures, and basin-bounding bedrock features that influence the movement, storage, recharge, discharge, and quality of ground water. The area covered extends from the Mesilla Valley on the east, the Robledo and East Potrillo uplifts on the west, I-10 (west of Las Cruces) on the north, and the International Boundary (west of El Paso) on the south (Plate 1). The base of the model is at 1000 ft (305 m) above mean sea level (Plates 16 and 17); and the water table elevation in the area ranges from about 3750 to 4000 ft (1145-1220 m). Highest basin elevations are about 4400 ft (1340 m), and vadose zone thickness exceeds 400 ft (120 m) in a few areas outside the Mesilla Valley. Much of the zone of saturation occurs in basin fill that ranges from unconsolidated sand, silt, clay and gravel to partly indurated deposits with layers of sandstone, mudstone and conglomerate. The major aquifers in the area are in the upper 1500 ft (455 m) of the saturated section.

The conceptual model is presented in a combined map and cross-section format (Plates 1, 16, 17), with supporting lithologic, stratigraphic, petrographic, geophysical and geochemical data illustrated in Plates 2-15, and listed in Tables 1 to 4. Information on thin-section petrography of the sand-size fraction was discussed in the preceding section (III), with supplemental data in Appendix A. A three-dimensional view of basin hydrogeology is provided by eight cross sections, comprising five cross-basin profiles (approx. west to east; Plate 16) and three longitudinal sections that have a general south to southeast orientation (Plate 17). Horizontal scale is 1:100,000 (approx. 0.6 in per mi) and vertical exaggeration is 10X (approx. 1.2 in per 1000 ft, 1 cm = 100 m). Supporting geological, geophysical (resistivity-log) and geochemical data on individual wells are graphically illustrated in columnar diagrams with a vertical scale of 1 in = 100 ft (1 cm = 12.2 m) and unspecified horizontal scale (Plates 2 to 11). The spatial arrangement of wells on these diagrams corresponds to the cross-section format of Plates 16 and 17.

The basic geologic elements that form the model's framework were described in Section II; and historical development of hydrogeologic concepts was outlined in the discussion of previous work (Section I). Earlier descriptions of basin hydrogeology (Conover, 1954; Leggat et al., 1962; King et al., 1969; Wilson et al., 1981; Hawley, 1984) were based on limited subsurface data. With the exception on a few deep oil-test holes (e.g. 25.1.32.141, and 26.1.35.333) and a water well at the ASARCO site (25.1.16.111), deep exploration of the Santa Fe Group was confined to areas in or close to the Mesilla Valley. Inferences on basin-fill thickness and aquifer characteristics were, for the most part, based on interpretations of *uncalibrated* surface geophysical data (Akerman, 1982; Birch, 1980; Figuers, 1987; Gates et al. 1980; Wen, 1983; Wilson et al., 1981; Zohdy, 1969; Zohdy et al., 1976).

The present investigation is the first attempt to systematically analyze borehole geophysical and petrographic characteristics of the Santa Fe Group over a large part of the Mesilla Basin. The conceptual model discussed in this section also contains many of the hydrogeologic features observed in other Rio Grande rift basins (e.g. Gustavson, 1991; Hawley and Haase, 1992; Hearne and Dewey, 1988; Lozinsky, 1987, 1988), and it is important to note that, throughout the region, current estimates of thickness and areal extent of major aquifer units within the Santa Fe Group are significantly less than earlier interpretations. For example, compare Haase and Hawley (1992) with Bjorkland and Maxwell (1961) in the Albuquerque Basin; and King and others (1971), Wilson and others (1981), and Hawley (1984; Appendix B) with Plates 2 to 10, 16 and 17 in this report. Still further improvements in characterization of basin hydrogeology will only be possible when additional borehole geophysical data are available in a digital format, where there is more depth-specific geochemical information, and when representative core samples have been obtained from the major aquifer units and confining beds. The electrical resistivity logs (standard, single-point, and dual induction), drill-cutting sample suites, seismic-reflection profiles, and drill-stem geochemical data used in the present study clearly need to be supplemented with more sophisticated subsurface and surface information.

Hydrostratigraphic Subdivisions of Basin and Valley Fills

The basic hydrogeologic unit used in conceptual-model development is the hydrostratigraphic unit. This informal geologic-material subdivision is analogous to a rock-stratigraphic unit of formational rank: the basic mappable body of rocks (sedimentary, igneous, and metamorphic) or unconsolidated earth materials. The hydrostratigraphic-unit concept used here (as well as in other parts of North America; Back et al., 1988; Barrash and Morin, 1987) requires that it be definable in terms of environment of deposition (of sedimentary strata) or emplacement (of igneous bodies), distinctive lithologic features (textures, mineralogy, sedimentary structures), and general time of deposition or emplacement (in a dated sequence of strata or igneous events). Geohydrologic characteristics must be definable, and a hydrostratigraphic unit must be mappable in subsurface, as well as at the surface, at a useful map scale in terms of ground-water resource management (e.g. 1:24,000 to 1:250,000).

The attributes of four major hydrostratigraphic units (RA, USF, MSF, LSF) and one minor (VA) unit, into which basin deposits have been subdivided, are described in Table 1. The major subdivisions of Santa Fe Group basin fill (Upper, Middle and Lower units - USF, MSF, LSF) broadly correspond to the informal rock-stratigraphic subdivisions discussed in Section II. The river alluvium (RA) unit forms the upper part of shallow aquifer system in the Mesilla Valley. The eight diagrammatic cross sections of the Mesilla Basin (Plates 16 and 17) illustrate representative distribution patterns of hydrostratigraphic units in subsurface.

Because of the large (10X) vertical exaggeration and diagrammatic nature of the cross sections (Plates 16 and 17), the inclination (dip) of faults and stratified sequences cannot be accurately shown. Fill units, however, are highly deformed only in narrow zones adjacent to major faults. True dips of even basal Santa Fe units rarely exceed 10-20°, and the Upper Santa Fe Unit (USF) is nearly level (Fig. 4; Appendix B - Hawley, 1984).

Lithofacies Subdivisions of Basin and Valley Fills

The second major feature of the hydrogeologic model is the subdivision of basin deposits into distinct material categories (lithofacies) that are defined primarily on the basis of sediment texture, degree of induration, geometry of bodies of a given textural class, and distribution pattern of zones of contrasting texture. They form the basic building blocks of the conceptual model developed for this study. The ten-unit lithofacies classification system used here (Table 3) is a modification of a scheme originally developed by Hawley (1984; Appendix B) to facilitate numerical modeling of groundwater systems in the Mesilla Bolson area between Las Cruces and El Paso by the New Mexico Water Resources Research Institute (Peterson et al., 1984). The lithofacies categories and their subdivisions are defined in Table 3; and a distribution pattern of these units in Mesilla Basin fill is illustrated on Plates 16 and 17.

These fundamental hydrogeologic components of basin and valley fills have also been recognized in all major basins of the Rio Grande rift in New Mexico and adjacent parts of Colorado, Texas and Chihuahua (Spiegel and Baldwin, 1963; Hawley et al., 1969; King et al., 1971; Hawley, 1978; Seager and Morgan, 1979; Gile et al., 1981; Wilson et al., 1981; Seager et al., 1982, 1987; Chapin, 1988; Hearne and Dewey, 1978; Brister, 1990; Gustavson, 1991; Lozinsky and Tedford, 1991). They have been formally defined, however, only in the Albuquerque and Mesilla Basins (Hawley and Haase, 1992; this report). Anderson's (1989) paper on "hydrogeologic facies models" relating to "glacial and glacial fluvial sediments" is an excellent account of how lithofacies-unit concepts are being used in ground-water research in other geographical areas.

Lithofacies units I,II,III,V and VI are unconsolidated or have only discontinuous zones of induration. With the exception of subdivision III, clean sand to pebbly sand bodies are major components of these units and have relatively high hydraulic conductivity. Clay, silty sand, and weakly indurated sandstone beds interstratified with fine to coarse sand layers characterize lithofacies III and IV. The latter facies is mainly composed of thick, well-sorted sands that are partly cemented with calcite. Lithofacies VII to X are partly to well-indurated units with significant amounts of fine-grained material (silt-clay beds or a sand to gravel framework with clay-silt-fine sand matrix).

Channel deposits of the modern and ancestral Rio Grande (facies I and II), which are the major components of hydrostratigraphic units RA and USF, form the most important aquifer and potential enhanced-recharge zones in the basin. Coarse-grained distributary channel deposits of large alluvial fans in the Middle and Upper Santa Fe units (MSF and USF; parts of facies V and VI) may also have good aquifer potential in local areas. Thick, buried dune-sand deposits in the Lower Santa Fe unit (LSF, facies IV) are demonstrably a major "deep" aquifer in the Canutillo Well Field area. Units with very limited potential for ground-water production are partly- to well-indurated piedmont deposits (facies VII and VIII), and thick sequences of fine-grained and locally saline basin-floor sediments that include extensive playa-lake beds in the southern part of the basin (facies IX and X).

Inferred subsurface distribution patterns of lithofacies within the five hydrostratigraphic units at specific sites in the Mesilla Basin are shown on Plates 16 and 17. Documentation of these patterns varies from good (where petrographic analysis of drill cutting, bore-hole geophysical logs, and detailed drilling records are available) to strictly inferential (where few or no field data exist). This variation in basic data quality is clearly illustrated in the lithofacies interpretations given on Plates 2-11, 16 and 17. In the large areas and/or depth zones without adequate subsurface control only the most general features of the major hydrostratigraphic units can be shown, and the resultant conceptual model is based only on inference (i.e. best guesses). However, one important generalization can be made: All basin-fill units become finer grained to the south; and fine- to medium-grained basin-floor facies are dominant in the international-boundary zone west of Cerro de Cristo Rey (Plate 16e; facies III, IX and X. How far this fining trend in basin-fill deposits continues into the Bolson del Muertos area of northern Chihuahua is not known. Major aquifers in the border region south of Santa Teresa (Plates 6 and 9) will probably be confined to the upper Middle Santa Fe unit (facies II and III, Plate 16e) since the Upper Santa Fe is almost entirely in the vadose zone.

The next step in characterization of lithofacies components of hydrostratigraphic units, and one that is beyond the scope of this report, will be to formally assign ranges of hydraulic conductivity values to individual lithofacies or groups of facies in cooperation with other members of the USGS-WRD, NMSEO and NMBMMR staffs. In the present conceptual model, extensive, thick-bedded deposits of fluvial sand and gravel deposits (lithofacies I and II) are considered to have relatively high hydraulic conductivities (e.g. in the 30 ft to 300 ft/day, 10-100 m/day range), while playa-lake clays, silts and mudstones (lithofacies IX and X) or well-cemented sandstones and fanglomerates (facies VII and VIII) have very low conductivities (commonly much less than 0.3 ft/day, 10 cm/day). Lithofacies III to VI should be expected to have average conductivities in the moderate to low range (about 30 to 0.3 ft/day, 10-0.1 m/day). See Frenzel and Kaehler, 1990; and Kernodle, 1992 for detailed information on expected ranges in hydraulic conductivity values and other parameters in ground-water-flow systems.

In many valley-border areas, coarse-grained river channel deposits of the Upper Santa Fe and younger valley-fill units (USF, VA and RA) are in direct contact (Gile et al., 1981). This relationship has a very negative context in terms of waste management problems (Stone, 1984); but it also offers exciting possibilities for much more efficient conjunctive use of surface- and ground-water resources (e.g. artificial recharge) at a number of sites.

Structural and Bedrock Elements of Hydrogeologic Framework

The third major component of the basin's hydrogeologic framework includes the bedrock units and structural features that form important boundary zones with respect to saturated- and vadose-zone processes (Table 2). Igneous-intrusive bodies and associated extrusive (volcanic) units within the basin-fill sequence are also locally significant parts of the hydrogeologic framework. Structural interpretations are based on geologic studies reviewed in Section II, and geophysical and geothermal-resource investigations, some of which are unpublished (Akermann, 1982; Cunniff, 1986; De Angelo and Keller, 1988; Figuers, 1987; Gross and Icerman, 1983; Reynolds & Assoc., 1986, 1987; Snyder, 1986; Wen, 1983; Zohdy, 1969; Zohdy et al., 1976). Areal distribution of major structural elements is shown on Plate 1. Surficial geology for most of the area (at a 1:125,000 scale) has already been, or will soon be published (Seager et al., 1987; in press). Igneous and sedimentary bedrock units form the basin floor and margins, and vertical to near vertical lines on the cross sections (Plates 2-11, 16, 17) show major boundary and intrabasin faults and a volcanic feeder conduit (plug or dike).

One of the most significant results of the present study is that there is now much better definition of the basin-fill/bedrock contact. Compare Plates 16 and 17 with interpretations by Wilson and others (1981) and Hawley (1984; Appendix B). However, additional drilling and geophysical studies, including seismic reflection surveys, will lead to significant refinements in identification of basin-boundary conditions, particularly in the northeastern and south-central basin areas.

Bedrock units (Precambrian to middle Tertiary, Section II) are generally considered to be low-permeability boundary zones in ground-water-flow models (Frenzel and Kaehler, 1990; Kernodle, 1992). However, upper Paleozoic (Pennsylvanian-Permian) and Cretaceous carbonate rocks such as are present in the East Potrillo, Robledo, Franklin and Juarez uplifts may locally provide conduits for significant amounts of ground-water movement. A temperature log in carbonate rocks at the south end of the East Potrillo uplift (Snyder, 1986; Plate 7, Table 4a, 29.1W.6.410) which has isothermic profile segment indicates significant ground-water flow (at least in that local area).

Basin-Boundary Faults and Santa Fe Group Thickness

The structural segmentation of the basin into three major sub-basins (NW, SW, and E) and the mid-basin uplift is discussed in Section II. Basin fill thickness exceeding 2000 ft (610 m) is well documented by borehole data only in the Eastern (La Union-Mesquite) and southernmost Southwestern subbasins (Plates 1, 3-7, 16 b-e, 17, Table 4a). Significant thinning of basin fill over the Mid-basin uplift (to about 1500 ft, 455 m) is also well documented (Plates 3, 4, 7-9, 16 b-c, 17 b-c). Estimates of basin-fill thickness in most parts of the Northwestern and Southwestern subbasins are based in the premise that deposits in those areas, even near the East Potrillo and Robledo faults, will not be thicker than fills in parts of the Eastern subbasin that are adjacent to the relatively large mountain masses of southern Organ and Franklin uplifts.

Structural Influences on Intrabasin Sedimentation Patterns

Because the Mesilla Basin is part of an active tectonic zone (Rio Grande rift) that has been evolving for more than 25 million years (Section II), the distribution pattern of hydro-stratigraphic units and lithofacies in space and time (Plates 16 and 17) must be interpreted in terms of ongoing crustal extension and basin subsidence. Active local extension of the earth's crust and differential movement, including rotation, of basin and range blocks are the basic structural controls on basin sedimentation. As is evident from the impact on Quaternary geomorphic processes by climate change related to Quaternary glacial-interglacial cycles, forces other than rift tectonism can also materially influence erosion, sediment transport, and deposition (Frostick and Reid, 1989). However, on the geologic-time and space scale represented by Santa Fe Group deposition, structural deformation and associated igneous activity are the dominant factors that will be considered here in terms of controls on basin sedimentation.

The Lower Santa Fe hydrostratigraphic unit (early to middle Miocene) and associated lithofacies (primarily IV, VII, VIII, IX, and X) were deposited in a broad, shallow basin that predated major uplift of the flanking mountain blocks (uplifts) bounded by the Mesilla Valley, East Potrillo and East Robledo fault zones (Plates 1, 16, 17). The deepest and most actively subsiding part of this basin appears to have been in the "Southwestern" area east of the East Potrillo uplift (Plates 7 and 16e).

Petrologic studies of drill cutting and core discussed in Section III, as well as interpretations based on detailed analyses of samples and drillers logs (Plates 2-11, Tables 4a and 4b), indicate that depositional environments in the Lower Santa Fe hydrostratigraphic unit (LSU) contrast markedly with those in younger basin fill. During early stages of basin filling, the Mesilla Basin received a major influx of fine- to medium-grained sediments (muds to sands) from adjacent upland source areas that were sites of late Eocene and Oligocene volcanic activity. Since high mountain areas (such as the present Organ-Franklin-Juarez chain) had not yet formed, wedges of coarse-grained piedmont deposits were limited to the extreme basin margins. The most striking features of the Lower Santa Fe unit (LSF) are the thick deposits of clean, fine to coarse sand (lithofacies IV), noted in the Eastern (La Union-Mesquite) and Southwestern subbasins, that have been interpreted as buried dune fields in the Canutillo well-field area and elsewhere in the basin (Cliett, 1969; Wilson et al., 1981; Hawley, 1984). These partly-indurated beds are as much as 600 ft, (185 m) thick in the eastern (La Union-Mesquite subbasin); and they may be 900-1000 ft (275-305 m) thick in the southwestern subbasin immediately east of the east Potrillo fault zone (Plates 3-5, 7, 10, 11, 16b-e, 17a).

Distribution patterns of both piedmont-slope and basin-floor lithofacies (I,II,III,V to IX) in Middle and Upper Santa Fe hydrostratigraphic units (MSF and USF) have also been greatly influenced by differential subsidence of basin fault blocks between the Mesilla Valley fault zone on the east, and the East Robledo and mid-basin faults on the west (Plates 1, 16, 17). As has been previously noted (Section II) tectonic subsidence has been most active in areas adjacent to these fault zones particularly in the Eastern (La Union-Mesquite) subbasin.

The Middle Santa Fe unit was deposited during late Miocene to early Pliocene time when maximum differential movement occurred between the central basin blocks and the Doña Ana-Tortugas, southern Organ, Franklin, Juarez, East Potrillo, Robledo and Mid-basin uplifts. East of the Rio Grande Valley, both the Middle and Upper Santa Fe units (MSF and USF) are dominated by coarse clastic material (fan alluvium) derived from the rapidly rising southern Organ and Franklin uplifts (Lithofacies V to VIII). The developing Robledo and East Potrillo Mountains contributed fan sediments to the western subbasins during the same interval. Lithofacies III is the major component of the Middle Santa Fe unit in the broad central-basin area that extends west from the Mesilla Valley. It is as much as 1000 ft (305 m) thick in the eastern (La Union-Mesquite) subbasin (Plates 3-5, 10, 11, 16b-d, 17a). This sequence of interbedded sand and silt-clay beds also forms the basin's thickest and most extensive aquifer system ("medial aquifer" in this report, Tables 4a and b).

East of the Mesilla Valley fault zone, fan deposits (facies V and VII) prograded westward almost to present location of I-25 during much of the Middle Santa Fe interval. Similar but smaller alluvial aprons extended basinward from the Robledo and East Potrillo uplifts. Complex intertonguing of piedmont-slope and basin-floor sediments is observed in the Middle Santa Fe unit beneath the Mesilla Valley (Plate 17a; MSF; lithofacies II,III,V,VII, and IX). Analyses of drillers and sample logs shows a mixture of alluvial-fan and basin-floor facies derived from local sources. A precursor to the through-going (ancestral) Rio Grande system may have contributed a large volume of fluvial sand and mud to actively subsiding areas, at least in the northern part of the basin, during latest stages of Middle Santa Fe deposition. Basin-floor aggradation ultimately outpaced basin subsidence and a nearly-level alluvial plain with scattered playa-lake depressions extended across most of the basin area.

The Upper Santa Fe unit was deposited during a 2-3 million year interval when large volumes of sediment were washed into the basin by distributaries of the ancestral Rio Grande system that headed as far north as the San Juan and Sangre de Cristo Mountains of southern Colorado (Southern Rocky Mountain province). This fluvial system discharged at various times into playa-lake plains on the Tularosa Basin and Hueco Bolson (via Fillmore Pass, Fig. 1), as well as the Bolson de Los Muertos (Hawley, 1975, 1981; Hawley et al., 1976; Gile et al., 1981; Seager, 1981; Gustavson, 1991).

The final phase of widespread basin aggradation throughout the central and southern New Mexico region (lithofacies Ib and II) occurred during eruptions of the Jemez volcanic center that produced the Bandelier Tuff and the Valles caldera 1 to 1.6 million years ago (Smith et al., 1970; Gardner et al., 1986; Goff et al., 1989). At that time braided channels of the ancestral Rio Grande shifted across a broad fluvial plain that included most of the present Mesilla Valley and West Mesa (La Mesa) area (Fig. 1, Plate 1). Complex intertonguing of ancestral Rio Grande and piedmont slope-facies (I,II,III and V) characterize the upper Santa Fe Unit (USF)) east of the Mesilla Valley fault zone (Plates 16 and 17). At times progradation of alluvial fans from the Organ and Franklin uplifts was very active (lithofacies V), and the piedmont alluvial apron expanded across the Mesilla Valley fault zone as far west as the present central Mesilla Valley.

The patterns of Upper Santa Fe sedimentation are clearly influenced by both local and regional volcanic and tectonic processes, as well as by early Pleistocene and Pliocene climate cycles. Structural deformation has produced more than 2000 ft (610 m) of subsidence in the Eastern subbasin since middle Miocene time (past 10 million years). Hundreds of feet of basin subsidence have also occurred along the Mesilla Valley, East Potrillo and East Robledo faults in Pliocene and Quaternary time (past 4-5 million years) and clearly influenced the final position of the ancestral Rio Grande and the distribution patterns of lithofacies (I,II,III and V) in the Upper Santa Fe hydrostratigraphic unit (USF; Plates 16, 17). Differential movement along the major basin-bounding fault zones shown on Plate 1 continued in post-Santa Fe (Quaternary) time and has controlled the position of the inner Mesilla Valley and bordering river terraces from the Selden Canyon to Paso del Norte narrows (Fig. 1). Valley fills units (VA) are definitely offset by faults east of the Robledo Mountains (Gile et al., 1981).

V. SUMMARY

Introduction

This report describes the results of a hydrogeologic study by the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) in the Mesilla Basin between Las Cruces, New Mexico and the International Boundary west of El Paso, Texas. The two major study objectives were (1) to develop a detailed conceptual model of the basin's hydrogeologic framework that is based on a synthesis of all available geological, geophysical, and geochemical data, and (2) to present that information in a format suitable for use by the U.S. Geological Survey, Water Resources Division (USGS-WRD) in developing numerical models of the ground-water flow system. These modelling efforts will, in turn, provide a much more quantitative base for management decisions on future strategies for water-resource development and conservation. Predictive models are particularly important because of the potential for water quality degradation and land subsidence due to excessive ground-water withdrawals that have been proposed in some parts of the Mesilla Basin.

Funding for the initial phase of data compilation and model development in 1987 was jointly provided by the NMBMMR and the U.S. Geological Survey, Water Resources Division (USGS-WRD, contract no. 14-08-D001-G-726), and subsequent support has been furnished by the NMBMMR. Work was done in cooperation with personnel of the USGS-WRD Albuquerque, Las Cruces, and El Paso offices, New Mexico State Engineer Office, and El Paso Water Utilities Department.

In its simplest form, the conceptual model of a basin's hydrogeologic framework is a graphic portrayal of (1) the lithologic character, geometry, and geologic history of basin-fill deposits; and (2) the bedrock units and structural features that form the basin boundaries and influence intrabasinal depositional environments. When firmly based on adequate (geological and geophysical) data on subsurface conditions, the model characterizes the basic "architecture" of mappable subdivisions of basin deposits that can be defined in terms of their aquifer properties.

The fill of the Mesilla Basin has two basic hydrologic components: Santa Fe Group basin fill and Rio Grande Valley fill. In terms of volume and areal extent, the Santa Fe Group forms the bulk of basin-filling deposits. It comprises a very thick sequence of alluvial, eolian, and lacustrine sediments deposited in intermontane basins of the Rio Grande rift structural province during an interval of about 25 million years starting in late Oligocene time. Widespread filling of several structural subbasins, which in aggregate form the Mesilla Basin, ended about 700,000 years ago (early Middle Pleistocene time) with the onset of Rio Grande (Mesilla) Valley incision.

Post-Santa Fe Group valley fills include (1) inset deposits of the ancestral Rio Grande and tributary-arroyo systems that form terraces bordering the modern floodplain, and (2) river and arroyo alluvium of the inner valley area that has been deposited since the last major episode of Rio Grande Valley incision in late Pleistocene time (about 15,000 to 25,000 years ago).

The three basic hydrogeologic components of the Mesilla Basin model comprise:

1. **Structural and bedrock features**. They include basin-boundary mountain uplifts, bedrock units beneath the basin fill, fault zones within and at the edges of basin that influence sediment thickness and composition, and

igneous-intrusive and -extrusive rocks that penetrate or are interbedded with basin deposits.

2. **Hydrostratigraphic units**. These mappable bodies of basin and valley fill are grouped on the basis of origin and position in a stratigraphic sequence. Genetic classes include ancestral-river, present river-valley, basin-floor playa, and piedmont alluvial fan deposits. Time-stratigraphic classes include units deposited during early, middle and late stages of rift-basin filling (i.e. lower, middle and upper Santa Fe Group), and post-Santa Fe valley fills (e.g. channel and floodplain deposits of the Rio Grande, and fan alluvium of tributary arroyos).
3. **Lithofacies subdivisions**. These units are the basic building blocks of the model. In this study, basin deposits are subdivided into ten lithofacies (I through X) that are mappable bodies defined on the basis of grain-size distribution, mineralogy, sedimentary structures, and degree of post-depositional alteration. They have distinctive geophysical, geochemical, and hydrologic attributes.

Report Format

The report has four major narrative sections (I. Introduction; II. Geologic Setting; III. Sand-Fraction Petrography; and IV. Conceptual Model), a comprehensive reference list, and two appendices (A. Basic petrographic data, and B. Preliminary hydrogeologic cross sections that extend into adjacent parts of the Jornada and Hueco basins). The hydrogeologic framework of the Mesilla Basin area as defined by Frenzel and Kaehler (1990) is graphically presented in map and cross-section format (Plates 1, 16 and 17). Supporting stratigraphic, lithologic, petrographic, geophysical, and geochemical data from 61 wells are illustrated in stratigraphic columns and hydrogeologic sections (Plates 2 to 15). Tables 4a and 4b summarize the subsurface information used in this study, including (1) well location and depth; (2) ground-water levels; (3) drill-stem sample intervals; (4) selected data on ground-water chemistry; and (5) data sources. Major hydrostratigraphic units and aquifer zones sampled are also identified in Tables 4a and 4b.

Section I

The introductory section of this report outlines previous work on basin hydrogeology, particularly that done since 1962 when the senior author started his investigations in the Las Cruces area of Doña Ana County. Study methods and techniques are also covered in this section. Emphasis is on the team approach used in the analysis of borehole (geological, geophysical, and geochemical) data to develop the final conceptual model of hydrostratigraphic and lithofacies unit distribution.

Section II

Section II provides a general geological overview of the Mesilla Basin region including the structure of flanking mountain uplifts and relationship to contiguous basin areas. The area discussed comprises parts of the Jornada del Muerto, Tularosa, Hueco, and Los Muertos basins in New Mexico, Texas, and Chihuahua. Emphasis is on the relatively recent interval of geologic time (~ past 25 million years) when major structural and topographic elements of the present landscape formed (Seager and Morgan, 1979; Gile et al., 1981; Seager et al., 1984, 1987). The interval was characterized by regional extension of the earth's crust, and differential uplift, subsidence and tilting of individual crustal blocks along major fault zones to form internally complex basins and ranges. This continental "rifting" process produced the Rio Grande rift structural zone that extends from southern Colorado to western Texas and northern Chihuahua. Rift basin fills that predate Pleistocene entrenchment of the Rio Grande Valley system comprise the Santa Fe Group.

The Mesilla Basin is near the southern end of the rift zone and is relatively shallow in comparison to many other rift basins (Chapin, 1988, Lozinsky, 1987, 1988; Brister, 1990; Hawley and Haase, 1992). Maximum thickness of upper Cenozoic fill is about 3,000 ft (1900 m). The lower and middle parts of the Santa Fe Group form the bulk of the basin fill. These units were deposited in an internally drained complex of three subbasins that were initially separated by a central (north-trending) intrabasin uplift (Eastern, Northwestern, Southwestern subbasins, and Mid-basin uplift on Plate 1). Even though differential movement of intrabasin and basin-bounding faults continued throughout late Cenozoic time, the basin-filling process outpaced structural deformation; and individual fills of early-stage subbasins ultimately coalesced to form the widespread blanket of basin fill that characterizes the upper part of the Santa Fe Group.

Eolian sands and fine-grained playa-lake sediments are major lithofacies in the lower and middle Santa Fe Group. These units are locally well indurated and only produce large amounts of good-quality ground water from buried dune sands (lower Santa Fe) in the eastern part of the basin beneath the Mesilla Valley. Poorly consolidated sand and pebble gravel deposits in the middle to upper part of the Santa Fe Group form the most extensive aquifers of the area. Widespread channel deposits of the ancestral Rio Grande first appear in upper Santa Fe beds that have been dated at about 3.5 million years (Ma) in southern New Mexico and 2.5 Ma in western (Trans-Pecos) Texas.

Expansion of the Rio Grande (fluvial) system into upstream and downstream basins, and integration with Gulf of Mexico drainage in the early to middle part of the Quaternary (Ice-Age) Period about 700,000 years ago led to rapid incision of the Mesilla Valley and termination of widespread basin aggradation (ending Santa Fe Group deposition in the Mesilla Basin). Cyclic stages of valley cutting and filling correlate with expansion and contraction of Alpine glaciers and pluvial lakes in the southern Rocky Mountain, and Basin and Range region. These cycles are represented by a stepped-sequence of valley border surfaces that flank the modern valley floor. Fluvial sand and gravel deposited during the last cut-and-fill cycle form a thin, but extensive shallow aquifer zone below the Rio Grande floodplain. Recent fluvial sediments are locally in contact with ancestral river facies in the upper Santa Fe Group, particularly in the northern Mesilla Valley. They form the major recharge and discharge zones for the basin's ground water, and are quite vulnerable to pollution in this urban-suburban and irrigation-agricultural environment.

Structural deformation of subbasin boundaries and topographic relief between deeper basin areas and flanking uplifts continued to change over geologic time. For example, during early stages of basin filling (lower Santa Fe deposition) many of the present bounding mountain blocks had not formed or had relatively low relief. Thickest basin-fill deposits (up to 1500 ft, 455 m, of middle Santa Fe Group) were emplaced between 4 and 10 million years ago during most active uplift of the Organ-Franklin-Juarez range and the Robledo Mountains, and subsidence of the Eastern (La Union-Mesquite) subbasin. The major (Mesilla Valley) fault zone is now buried by the recent valley fill beneath the present Rio Grande floodplain.

Section III

The petrographic investigations described in Section III emphasize the fundamental properties of rock fragments and mineral grains that in aggregate form the various lithofacies subdivisions of the five hydrostratigraphic units (Tables 1 and 2). Tools needed to properly describe earth materials in fine detail include the binocular microscope for preliminary drill-cutting descriptions, the petrographic (light) microscope from rock and grain thin-section analyses, and x-ray equipment and the scanning electron Microscope for characterization of ultra-fine-scale features (e.g. grain-surface features, cementing agents, and porosity). Only the binocular and petrographic microscopes were used in this study to analyze the sand-size fraction from selected sets of drill cuttings and outcrop samples. Anderholm (1985) describes preliminary x-ray analyses of fine-grained materials from several Rio Grande Basins (including the Albuquerque and Mesilla Basins).

Cuttings from the Afton (MT1), Lanark (MT2), La Union (MT3), and Noria (MT4) were analyzed initially with a binocular microscope in order to construct a stratigraphic column for each of these key wells (Plates 12-15) and to determine intervals (approximately every 100 ft, 30 m) where subsamples of representative sands would be collected for thin-section analyses. Samples were also collected from representative sandy intervals in the two wells in the Canutillo Field (CWF1D and 4D) and from six outcrops of the Upper and Middle Santa Fe units.

Sand samples analyzed from the six water wells and from outcrop areas in the Mesilla Basin were derived from more than one source terrane. The abundance of plagioclase (zoned and twinned) and andesitic lithic fragments strongly suggest an intermediate volcanic source area for most of the detrital grains. Chert, chalcedony, and abundant quartz (many well rounded with overgrowth rims) indicate reworked sedimentary units as another major source. A granitic source area is also suggested by the presence of microcline, strained quartz, and granitic rock fragments. The paucity of metamorphic-rock fragments and tectonic polycrystalline quartz rules out a metamorphic terrane as a major source area. In the middle Santa Fe Group samples from the Rincon Valley area (Rodey site), the abundance of plagioclase and intermediate volcanic lithic fragments and the paucity of quartz, chert and sedimentary lithic fragments strongly suggest an intermediate volcanic terrane as the only major source area.

Due to lack of paleoflow indicators, it is difficult to determine the exact source area for these deposits. However, it appears that even in early to middle Santa Fe time

(Miocene) the central Mesilla Basin area was receiving sediment from a very large watershed area. A much larger source region was also available for sand and finer grain-size material when the mechanism of eolian transport is taken into account. By middle Pliocene time the ancestral Rio Grande was delivering even pebble-size material to the basin from source terranes as far away as northern New Mexico (e.g. pumice and obsidian from the Jemez and Mount Taylor areas). In most cases, visual and binocular microscopic examination of the gravel-size (>2mm) fraction is still the best way to establish local versus regional provenance of coarse-grained fluvial and alluvial deposits.

Section IV

The conceptual hydrogeologic model is described in detail in Section IV and illustrated on Plates 1, 16, and 17. These plates are published at a horizontal scale of 1:100,000 (1 cm = 1 km; approx. 0.6 in/mi), and cross sections have vertical exaggeration of 10X. The base elevation of the model is 1000 ft (305 m) above sea level and the water table in central basin areas ranges from about 4000 ft (1220 m) to the north and 3750 ft (1145 m) at the southeastern end of the basin. Outside the Mesilla Valley area the vadose (unsaturated) zone is commonly 300 to 400 ft (90-120 m) thick. Supporting geological, geophysical, and geochemical data above an elevation of 1500 ft (455 m) are shown on stratigraphic columns and hydrogeologic cross sections (Figs. 2-15) at a vertical scale of 1 in = 100 ft (1 cm = 12.2 m) and variable horizontal scale.

The basic hydrogeologic mapping unit used in conceptual model development is the *hydrostratigraphic unit*. It is defined in terms of (1) environment of deposition of sedimentary strata, (2) distinctive combinations of lithologic features (lithofacies) such as grain-size distribution, mineralogy and sedimentary structures, and (3) general time interval of deposition. The attributes of four major (RA, USF, MSF, LSF) and one minor (VA) classes into which the area's basin and valley fills have been subdivided are defined in Table 1. The Upper, Middle, and Lower hydrostratigraphic units of the Santa Fe Group roughly correspond to the (informal) upper, middle and lower rock-stratigraphic subdivisions of Santa Fe Group described in Section II. The other major hydrostratigraphic unit (RA) comprises Rio Grande alluvium of late Quaternary age (<15,000 yrs) that forms the upper part of the regional shallow-aquifer system.

The ten lithofacies subdivisions that are the fundamental building blocks of the model are defined primarily on the basis of sediment texture (gravel, sand, silt, clay, or mixtures thereof), degree of cementation, and geometry of bodies of a given textural class and their relative distribution patterns. Lithofacies I, II, III, V, and VI are unconsolidated or have zones of induration (strong cementation) that are not continuous. Clean sand and gravel bodies are major constituents of facies I, II, V, and VI; while clay or cemented sand zones form a significant part of facies III and IV. Subdivision IV is characterized by thick eolian sand deposits of the lower Santa Fe unit (LSF) that are partly cemented with calcite. Coarse-grained channel deposits of the modern and ancestral Rio Grande (lithofacies I and II) are the major components of the upper Santa Fe (USF) and river-alluvium (RA) hydrostratigraphic units. They form the most important aquifers and potential enhanced-recharge zones in the basin. Lithofacies VI and VIII are partly to well indurated piedmont-slope deposits; while facies IX and X comprise thick sequences of fine-grained basin-floor sediments that include playa-lake beds.

Assignment of specific hydraulic conductivity ranges to individual lithofacies subdivisions is beyond the scope of this investigation. However, as a first approximation, the following general ranges appear to be reasonable:

1. Conductivities of lithofacies I and II are relatively high (30 to 300 ft/day, 10-100 m/day)
2. Lithofacies IX and X, and well-cemented sandstone and fanglomerate zones in facies VII and VIII will definitely have very low conductivities (usually much less than 0.3 ft/day, 0.1 m/day)
3. Conductivities in uncemented sand layers in lithofacies III and IV, and sand and gravel beds in facies V through VIII should primarily be in the intermediate range (0.3 to 30 ft/day, 0.1-10 m/day)

In addition to delineation of major hydrostratigraphic units and lithofacies subdivisions in basin and valley fills, the other major contribution of this study has been the significant improvement in definition of the physical limits of the Mesilla Basin and its component subbasins. Most of this information on bedrock and structural geology was derived from geologic maps and cross sections, with supplemental data from geophysical and geothermal surveys, that have been recently published or are in press (Figuers, 1987; Seager, 1989, in press; Seager and Mack, in press; Seager et al., 1987; Snyder, 1986). Unpublished seismic reflection surveys done for the USGS-WRD in the lower Mesilla Valley have also been very useful (C. B. Reynolds & Assoc., 1986, 1987).

Unconsolidated deposits make up the bulk of the middle and upper Santa Fe Group and all of the recent valley fill in the Mesilla Basin. Textural classes include sand, gravelly-sand, silt-clay, and sandy to gravelly materials with a silt-clay matrix Secondary calcite and gypsum are the primary cementing agents in the basin fill; however, continuously indurated zones are uncommon except in basal parts of the Santa Fe section. Very coarse-grained alluvium, with gravel primarily in the pebble- to cobble-size range (<10 in, 25 cm), is confined to narrow piedmont zones near the basin margins (lithofacies V-VIII). Layers of these alluvial-fan deposits are the basal locally indurated (facies VII and VIII).

Widespread fluvial deposits of the ancestral Rio Grande form much of the upper basin fill (unit USF, facies Ib and II). In the northern half of the basin, fluvial materials constitute the major shallow aquifer system in conjunction with the inner Mesilla Valley fill (unit RA, facies IV). Outside the valley area, however, most of the ancestral river deposits are in the vadose zone.

Interbedded sand and silt-clay deposits of the Middle Santa Fe Unit (MSU, primarily lithofacies III) form the basin's thickest and most extensive aquifer system (the "medial" aquifer in this report; Tables 4a and b). This unit is as much as 1000 ft (305 m) thick in the eastern (La Union-Mesquite) subbasin (Plates 3-5, 10, 11, 16b-d, 17a). Well-sorted fine to coarse sand deposits of lithofacies IV make up a significant part of the lower Santa Fe Unit (LSU) and are here interpreted as being primarily of eolian origin. These partly-indurated beds are as much as 600 ft (185 m) thick in the eastern

(La Union-Mesquite subbasin); and they may be 900-1000 ft (275-305 m) thick in the southwestern subbasin immediately east of the east Potrillo fault zone (Plates 3-5 7, 10, 11, 16b-e, 17a).

All basin fill units (USF, MSF, LSF) become finer grained to south; and fine- to medium-grained basin-floor facies, with only minor amounts of gravel, dominate the basin fill section in the international boundary zone west of Cerro de Cristo Rey (Plates 6, 7, and 16e; facies III, IX and X). Most of the Upper Santa Fe hydrostratigraphic unit (USF) in that area is in the vadose zone; and sand beds in the basal Upper Santa Fe unit and upper part of the Middle Santa Fe unit (MSF, lithofacies III) appear to be the only major aquifer east of the Mid-Basin uplift. Lithofacies IV in the Lower Santa Fe hydrostratigraphic unit (LSU) may also be a potential deep aquifer in the Southwestern subbasin; but this zone has not yet been tested for either quantity or quality of ground water production.

Discussion

The conceptual model of the Mesilla areas's hydrogeologic framework developed for this report (Plates 1, 16, 17) is simply what its name implies:

1. It is only a general representation of a very complex real-world system (Kernodle, 1992, p. 6-7).
2. The intellectual construct that is a "concept" can only be as good as the quality of the scientific information used in its development.
3. The model's graphic portrayal is at least partly an artistic effort that reflects the talents of its creators (or lack thereof).

We believe that the major features of this portrayal of basin hydrogeology will stand the test of time; however, there will always be room for improvements. The positive feedback loops between assimilation of additional scientific information, better conceptualization, and improved artistic skill will be enhanced as the model is tested and further developed.

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APPENDIX A

Basic Petrographic Data: Thin section analyses of grain mounts of sieved sand from representative borehole and outcrop samples of Santa Fe Group sands and sandstones, Dona Ana and Sierra Counties, New Mexico.

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Part I. Composition of the 0.125 - 2 mm size fraction of sandy intervals in Santa Fe Group deposits penetrated by deep test wells in the Mesilla Basin. Refer to Table 5 for explanation of symbols.

Test Well Sample #	(Depth ft)	Unit	Q	F (P/K)	L	Lm	Lv	Ls	Lm	Lv	Lst
Afton, MT1 (25.1.6.333)											
000	(40')	USF	47	30 (25/5)	23	0	96	4	0	84	16
002	(190')	USF	47	32 (27/5)	21	0	94	6	0	85	15
006	(620')	MSF	44	39 (28/11)	17	1	90	9	1	79	20
010	(1050')	MSF	51	31 (24/7)	18	0	93	7	0	72	28
013	(1370')	MSF	51	35 (28/7)	14	0	93	7	0	80	20
016	(1670')	LSF	43	39 (33/6)	18	0	100	0	0	90	10
018	(1870')	LSF	41	39 (32/7)	20	0	96	4	0	84	16
021	(2180')	Tvs?	12	29 (25/4)	59	0	99	1	0	98	2
Lanark MT2 (27.1.4.121)											
000	(40')	USF	44	39 (30/9)	17	0	100	0	0	88	12
001	(380')	USF	43	33 (23/10)	24	0	98	2	0	86	14
004	(450')	MSF	43	41 (32/9)	16	2	90	8	1	77	22
008	(880')	MSF	47	30 (22/8)	23	1	95	4	1	77	22
011	(1170')	LSF	51	34 (24/10)	15	0	97	3	0	78	22
015	(1550')	Tv	0	0	100	0	100	0	0	100	0

Test Well Sample #	(Depth ft)	Unit	Q	F (P/K)	L	Lm	Lv	Ls	Lm	Lv	Ls*
La Union MT3 (27.2.13.331)											
000	(40′)	USF	46	29 (24/5)	25	0	93	7	0	83	17
003	(380′)	MSF	49	36 (29/7)	15	0	87	13	0	75	25
008	(830′)	MSF	53	29 (24/5)	18	0	95	5	0	73	27
011	(1170′)	MSF	51	38 (27/11)	11	0	86	14	0	70	30
014	(1470′)	MSF	50	41 (31/10)	9	0	83	17	0	59	41
018	(1840′)	LSF	48	37 (29/8)	15	0	90	10	0	85	15
020	(2020′)	LSF	54	36 (22/14)	10	0	95	5	0	74	26
Noria MT4 (28.1.34.414)											
000	(40′)	USF	49	38 (28/10)	13	2	92	6	2	74	24
001	(160′)	USF	44	32 (23/9)	24	0	96	4	0	85	15
006	(620′)	MSF	47	38 (30/8)	15	0	98	2	0	78	22
009	(970′)	MSF	48	40 (32/8)	12	0	94	6	0	73	27
012	(1250′)	MSF	47	39 (32/7)	13	0	96	4	0	77	23

Test Well Sample #	(Depth ft)	Unit	Q	F (P/K)	L	Lm	Lv	Ls	Lm	Lv	Ls*
CWF 1D (JL-49-04-481)											
002	(250′)	MSF	49	37 (21/16)	14	0	93	7	0	84	16
003	(320′)	MSF	48	38 (21/17)	14	0	91	9	0	80	20
004	(440′)	MSF	54	38 (19/19)	8	0	90	10	0	59	41
005	(550′)	LSF	55	35 (20/15)	10	0	91	9	0	74	26
008	(800′)	LSF	53	35 (21/14)	12	0	96	4	0	68	32
009	(900′)	KP	10	4 (3/1)	86	0	34	66	0	37	63
CWF 4D (JL-49-04-469)											
001	(120′)	MSF	49	36 (24/12)	15	2	87	11	2	68	30
002	(230′)	MSF	51	36 (24/12)	13	0	88	12	0	73	27
003	(350′)	MSF	49	30 (19/11)	21	0	92	8	0	85	15
004	(470′)	LSF	49	36 (23/13)	15	0	94	6	0	87	13
007	(700′)	LSF	54	34 (21/13)	12	0	100	0	0	82	18

Part II. Composition of the 0.125 - 2 mm size fraction of sandy intervals in outcrops of the Santa Fe Group. Refer to Table 5 for explanation of symbols.

Stratigraphic Unit	Q	F (P/K)	L	Lm	Lv	Ls	Lm	Lv	Lst
Upper Santa Fe Group									
AN-1a	43	36 (23/13)	21	0	97	3	0	89	11
AN-1b	45	34 (26/8)	21	0	96	4	0	83	17
AN-3	53	30 (20/10)	17	0	98	2	0	78	22
LU-1	50	28 (18/10)	22	1	97	2	1	88	11
70-1	48	28 (17/13)	22	0	98	5	0	81	19
BC-3	45	37 (24/13)	18	0	96	4	0	86	14
TC-1	40	37 (25/12)	23	2	95	3	2	86	12
Middle Santa Fe Group									
R-1	20	47 (31/16)	33	0	99	1	0	96	4
R-2	16	51 (38/13)	33	0	99	1	0	98	2

Part III. Locations of sampled Santa Fe Group outcrops, Dona Ana and Sierra Counties, New Mexico

Upper Santa Fe (Camp Rice and Palomas Formations)

Anapra	Includes 3 samples from upper Santa Fe Group outcrops located west of Sunland Park (AN - 1a, 1b and 2); 29S.4E.18.1131
La Union	Sample from upper Santa Fe Group deposits exposed just west of La Union (LU-1); 27S.3E.18.1411
US-70	Exposure along northside of US-70 just west of Las Cruces - ancestral river deposits (70-1); 23S.1E.20.223
Box Canyon	Sample from base of Ruhe's (1962) upper Santa Fe Group section west of Picacho Mountain (BC-3); 23S.1W.2.4323
T or C	Sample from Palomas Formation ancestral river deposits exposed in northern Truth or Consequences (TC-1); 13S.4W.28.211 (Sierra County)

Middle Santa Fe (Rincon Valley Formation)

Rodey	Two samples from middle Santa Fe Group (Rincon Valley Formation) deposits exposed south of Rodey, 1.5 mi southeast of Hatch (R-1,2); 19S.3W.15.344

EXPLANATION - PLATE 1

25.1.6.333	Key Water Test Wells, with petrographic analyses (Plates 12-15, Figures 4, 5, Table 4)
25.1.16.111	Other well-control points
	Upper Santa Fe Group outcrop sample sites (Appendix A, Part III)
Plates 3 & 16b	Hydrogeologic sections (Plates 2-11, 16-17)
Q-43 LU-1, VI-1 CA-1	Locations of seismic refraction lines (Reynolds & Associates, 1986, 1987)
	Major normal faults; bar and ball on downthrown side

EXPLANATION - PLATES 2 TO 17

Informal Hydrostratigraphic Units

Unit	Description
	Valley-Fill Deposits -- Post Santa Fe Group
RA	River alluvium; channel and floodplain deposits of inner Mesilla Valley; as much as 100 ft thick. Lithofacies subdivision Iv is the major hydrogeologic component. Forms much of the "shallow aquifer." Holocene to late Pleistocene.
VA	Valley-border alluvium; tributary arroyo (and thin eolian) deposits in areas bordering the inner Mesilla valley, with locally extensive river-terrace deposits; as much as 140 ft thick. Includes lithofacies subdivisions Iv and V. Most of unit is in the unsaturated (vadose) zone. Holocene to middle Pleistocene.
	Basin-Fill Deposits -- Santa Fe Group
	Rio Grande rift basin fill; includes alluvial, eolian, and lacustrine deposits; with interbedded volcanic rocks (basalts and silicic tuffs). In the Mesilla Basin area the Santa Fe Group comprises four lithostratigraphic units - Hayner Ranch, Rincon Valley, Fort Hancock, and Camp Rice Formations; and locally exceeds 2,500 ft in thickness. It includes the major aquifers of the area and is subdivided into three informal hydrostratigraphic units:
USF	Upper Santa Fe Unit; coarse- to medium-grained deposits of the ancestral Rio Grande intertongue mountainward with piedmont-alluvial (fan) facies, and southward with fine-grained lake and playa sediments; volcanic rocks (mostly basalt) and sandy eolian deposits are locally present; as much as 750 ft thick. Unit includes the Camp Rice (CR) and upper Fort Hancock (FH) Formations. It also includes lithofacies subdivision Ib; much of facies II, V, and VI; and parts of facies III and VIII. Forms lower part of the "shallow aquifer" in the northern Mesilla Valley, and the upper aquifer zone outside the Valley area where much of the unit is above the water table. Middle Pleistocene to middle Pliocene.

MSF Middle Santa Fe Unit; alluvial, eolian, and playa-lake facies; interbedded sand and silt-clay basin-floor sediments intertongue mountainward with piedmont-alluvial (fan) deposits, and southward with fine-grained lake and playa facies; basaltic volcanics and sandy eolian sediments are locally present; as much as 1500 ft thick. Unit includes basin fill that correlates with much of the Fort Hancock (FH) and Rincon Valley Formations, in the Hueco Bolson and western Jornada del Muerto (Rincon) Basin, respectively. It also includes much of lithofacies subdivisions III, and parts of facies II, V, VI, VII, VIII and IX. Forms major part of "medium aquifer" of Leggat et al. (1962). Middle Pliocene to middle Miocene.

LSF Lower Santa Fe Unit; eolian, playa-lake, and alluvial facies; sandy to fine-grained basin-floor sediments, which include thick dune sands and gypsiferous sandy mudstone, intertongue with conglomeratic sandstones and mudstones near the basin margins piedmont deposits; as much as 1000 ft thick. Unit includes basin fill that correlates with much of the Hayner Ranch and the lower Rincon Valley Formations, in the western Jornada del Muerto (Rincon) Basin. It also includes much of lithofacies IV and X, and parts of facies VII, VIII and IX. Forms major part of "deep aquifer" of Leggat et al. (1962). Middle Miocene to late Oligocene.

EXPLANATION - PLATES 2 TO 17

Bedrock Units and Upper Cenozoic Volcanics

Unit	Description
Qb	Basaltic volcanics, mostly flows, with local cindercone and conduit material, that cap or are interbedded with the upper and middle Santa Fe Group. Quaternary and upper Pliocene
Tb	Basaltic plugs and minor flows that penetrate, cap, or are interbedded with the lower and middle Santa Fe Group. Miocene
Tr	Rhyolitic volcanics, with some interbedded sandstone and conglomerate mostly ashflow tuff and lava. Oligocene
Tri	Rhyolitic igneous-intrusive complexes; mostly sills, plugs and associated lava domes. Oligocene
Ti	Silicic to intermediate intrusive rocks. Oligocene and Eocene
Tv	Andesitic and other intermediate volcanic and volaniclastic rocks, including lava flows and laharic breccias and mudstones. Eocene and Oligocene
Tvi	Undivided Tv and intermediate intrusive rocks.
Tvs	Intermediate volcaniclastic rocks, with minor lava flows and intrusive units; primarily Palm Park Formation. Eocene and Oligocene
Trv	Undivided Tr and Tv or Tvs
Tl	Mudstone, sandstone, and conglomerate with local gypsum beds. Lower Tertiary, mainly Eocene
Tvl	Undivided Tv and Tl
K	Cretaceous rocks--undivided; includes limestone, sandstone and mudstone.
TK	Undivided Ti, Tv, Tl, K.
KP	Undivided Cretaceous and Permian rocks.
Pu	Upper Paleozoic rocks (Pennsylvanian and Permian); includes limestone, shale, sandstone, and mudstone, with local gypsum beds.
P	Undivided Paleozoic and Precambrian rocks of the southern Franklin Mountains; includes limestone, shale, sandstone, metamorphosed sedimentary and volcanic rocks, and granite.

EXPLANATION - PLATES 2 TO 17

Lithofacies Subdivisions

Unit	Description
I.	Sand and gravel, river-valley and basin-floor fluvial facies; recent and ancestral Rio Grande channel and floodplain deposits underlying 1) the modern river-valley floor--facies Iv, 2) river-terrace surfaces--deposits primarily in the vadose zone, and 3) relict or buried basin-floor fluvial plains--facies Ib. The latter surfaces include the La Mesa geomorphic surface (Gile et al. 1981). Gravel is characterized by sub-rounded to well-rounded pebbles and small cobbles of resistant rock types (mainly igneous and metamorphic) derived in part from extra-basin source areas.
	Iv. Sand and pebble to cobble gravel, with thin, organic-rich silty sand to silty clay lenses; indurated zones of carbonate cementation rare or absent; as much as 100 feet thick.
	Ib. Sand and pebble gravel, with thin discontinuous beds and lenses of sandstone, silty sand, and silty clay; extensive basin-floor fluvial facies; usually nonindurated, but with local zones that are cemented with calcite (common), and other minerals (uncommon) including silicate clays, iron-manganese oxides, gypsum, silica, and zeolites; 200 to 400 feet thick in central basin areas.
II.	Sand, with discontinuous beds and lenses of pebbly sand, silty sand, sandstone, silty clay, and mudstone; extensive basin-floor fluvial facies and local eolian deposits; gravel composition as in facies I; usually nonindurated, but local cemented zones as in facies Ib; clean sand and pebbly-sand bodies make up an estimated 65-85 percent of unit; 300 to 750 feet thick in central basin areas.
III.	Interbedded sand, silty sand, silty clay, and sandstone; with minor lenses of pebbly sand and conglomeratic sandstone; basin-floor alluvial and playa-lake facies; clay mineralogy of silty clay beds as in unit IX; usually nonindurated, but with local cemented zones as in facies Ib and II; secondary carbonate and gypsum segregations locally present in silty clay beds; common sheet-like to broadly-lenticular strata 10 to 40 feet thick; clean sand layers make up an estimated 35 to 65 percent of unit; 300 to 1,000 feet thick in central basin areas.
IV.	Sand to silty sand, with lenses or discontinuous beds of sandstone, silty clay, and mudstone; eolian and alluvial facies primarily deposited on basin floors and contiguous piedmont slopes; nonindurated to partly indurated, with cementing agents including calcite (common), silicate clays, iron-manganese oxides, gypsum, and zeolites (uncommon); clean fine to medium sand makes up an estimated 35 to 65 percent of unit; as much as 600 feet thick.
V.	Gravelly sand-silt-clay mixtures (loamy sands to sandy clay loams) interstratified within discontinuous beds and lenses of sand, gravel, loamy sand an silty clay; distal to medial piedmont-slope alluvial facies (mainly coaleascent fan deposits), with minor compoonent of eolian sediments; gravel primarily in the pebble and small cobble size range, and clast composition reflects character of source bedrock terrane; usually nonindurated, but with thin discontinuous layers that are cemented with calcite; clean sand and gravel makes up an estimated 25 to 35 percent of unit; as much as 600 feet thick.

VI. Coarse gravelly sand-silt-clay mixtures (loamy sand and sandy loams to loams) interstratified with lenses of sand and gravel; proximal to medial piedmont-slope alluvial facies--fan and coalescent fan deposits; gravel primarily in the pebble to cobble range (up to 10 inches); clast composition reflects lithologic character of source bedrock terranes; usually nonindurated, but with discontinuous layers that are cemented with calcite; clean sand and gravel lenses make an estimated 15 to 25 percent of unit; as much as 300 feet thick.

VII. Conglomeratic sandstone, silty sandstone, and mudstone with lenses and discontinuous beds of conglomerate, sand, gravel, and gravelly sand-silt-clay mixtures (as in unit V); distal to medial piedmont-slope alluvial facies, with minor component of eolian sediments; coarse clast sizes and composition as in unit V; moderately-well to poorly indurated; cementing agents include calcite (common) and silicate clays, iron-manganese oxides, silica and zeolites (uncommon); clean weakly-cemented sand and gravel beds make up an estimated 5 to 15 percent of unit; as much as 600 feet thick.

VIII. Coarse conglomeratic sandstone and silty-sandstone, fanglomerate, and minor lenses of sand and gravel; proximal to medial piedmont-slope alluvial facies--and coalescent fan deposits; coarse clast sizes and compositions as in unit VI; moderately to well indurated; cementing agents as in unit VI; moderately to well indurated; cementing agents as in unit VII; clean, weakly-cemented sand and gravel lenses make up an estimated 5 to 10 percent of unit, as much as 300 feet thick.

IX. Silty clay interbedded with thin silty sand, sand, sandstone, and mudstone beds; basin-floor playa-lake and alluvial-flat facies; clay mineral assemblage includes calcium smectite, mixed layer illite-smectite illite, and kaolinite (Anderholm, 1985); secondary deposits of calcite, gypsum, sodium-magnesium-sulfate salts, and zeolites are locally present; weakly-cemented fine to medium sand and silty sand makes up an estimated 5-10 percent of unit; as much as 600 feet thick in central basin areas.

X. Mudstone and claystone interstratified with thin sandstone and silty sandstone beds; basin floor playa-lake and alluvial-flat facies; clay mineral and non-clay secondary mineral assemblages as in facies IX; weakly cemented fine to medium sand and silty sand makes up an estimated 0 to 5 percent of unit; as much as 600 feet thick in central basin area.

EXPLANATION - PLATES 2 TO 17

Special Symbols

Plates 2-11, 16-17	Drill-stem packer tests, water table, and faults
961	Top of sampled interval
510	Total dissolved solids (mg/L)
	Water table (cited literature)
	High angle normal faults, with direction of relative displacement indicated.

Plates 12-15	Lithologic Logs

LITHOLOGIC LOGS

- sand
- gravel
- silty sand
- silt
- clay
- volcaniclastic/ volcanic

Plates 16-17	Seismic Refraction Lines
Q-43 LU-1,VI-1 CA-1	Locations of profiles by Reynolds & Associates (1986, 1987)

Plate 1· Index Map, Mesilla Basin Well and Section Locations (draft)

Hawley and Lozinsky

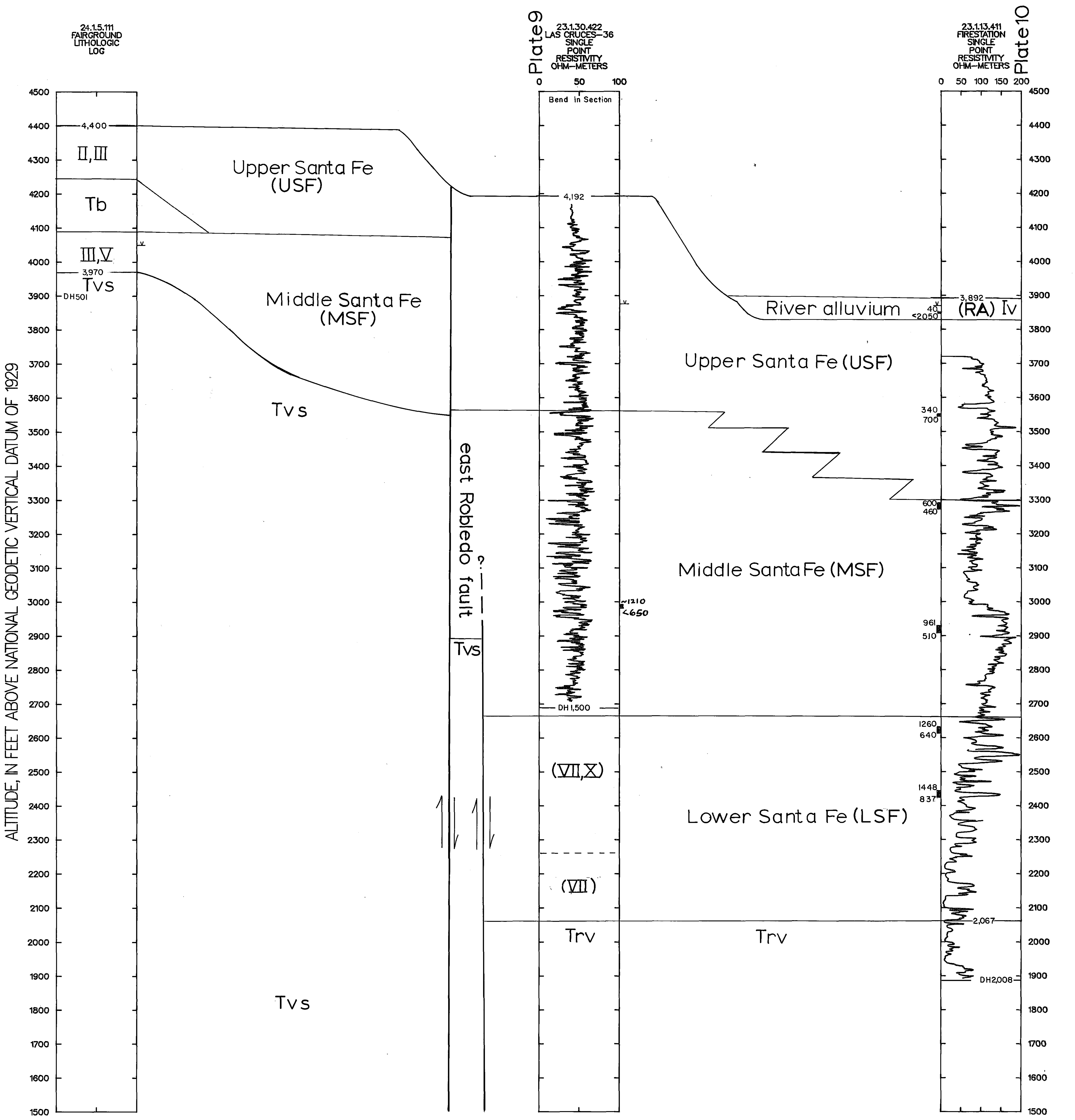

Plate 2. Hydrogeologic section Las Cruces Fairground to Firestation, with borehole geophysical data.

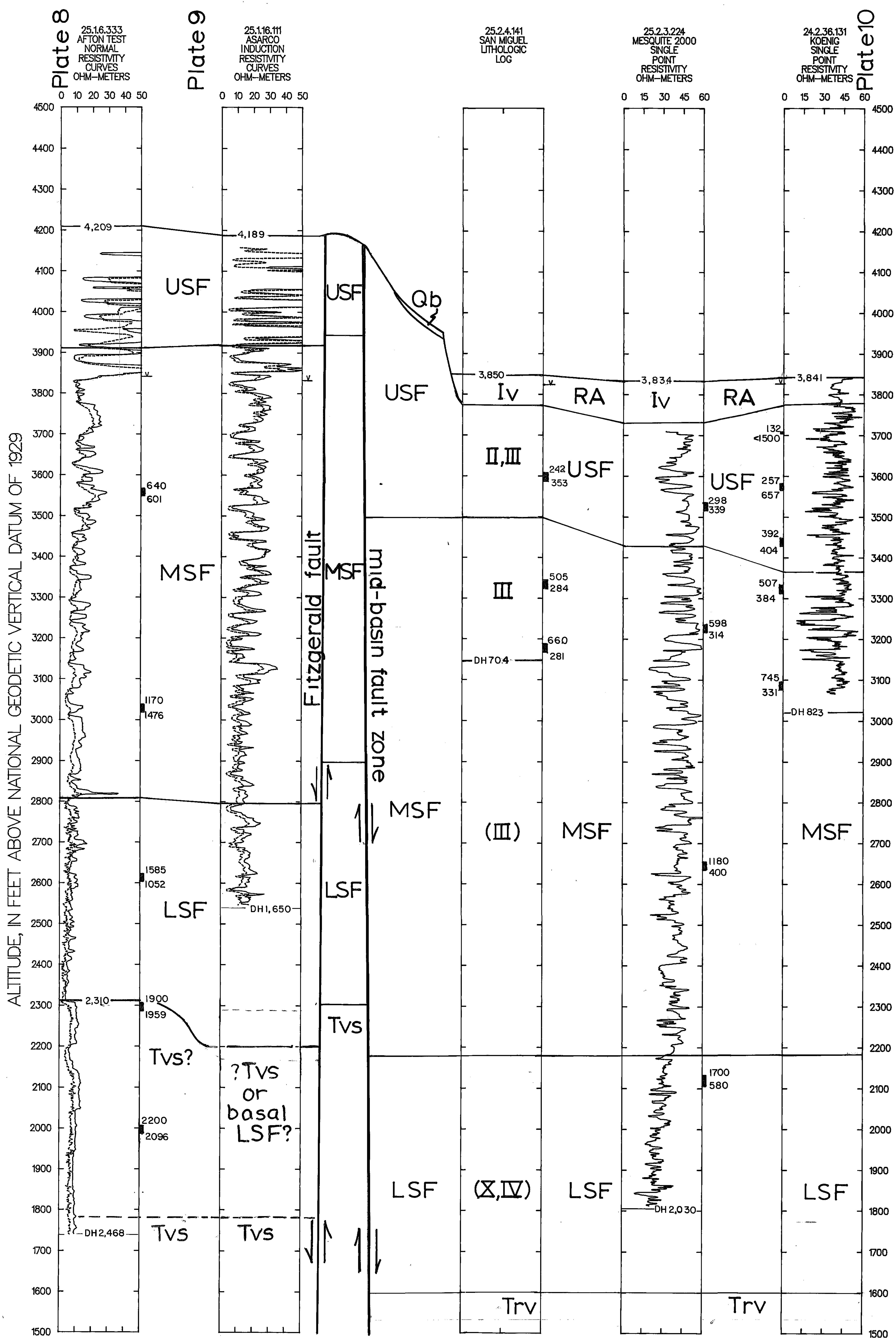

Plate 3. Hydrogeologic section Afton to Mesquite, with borehole geophysical data.

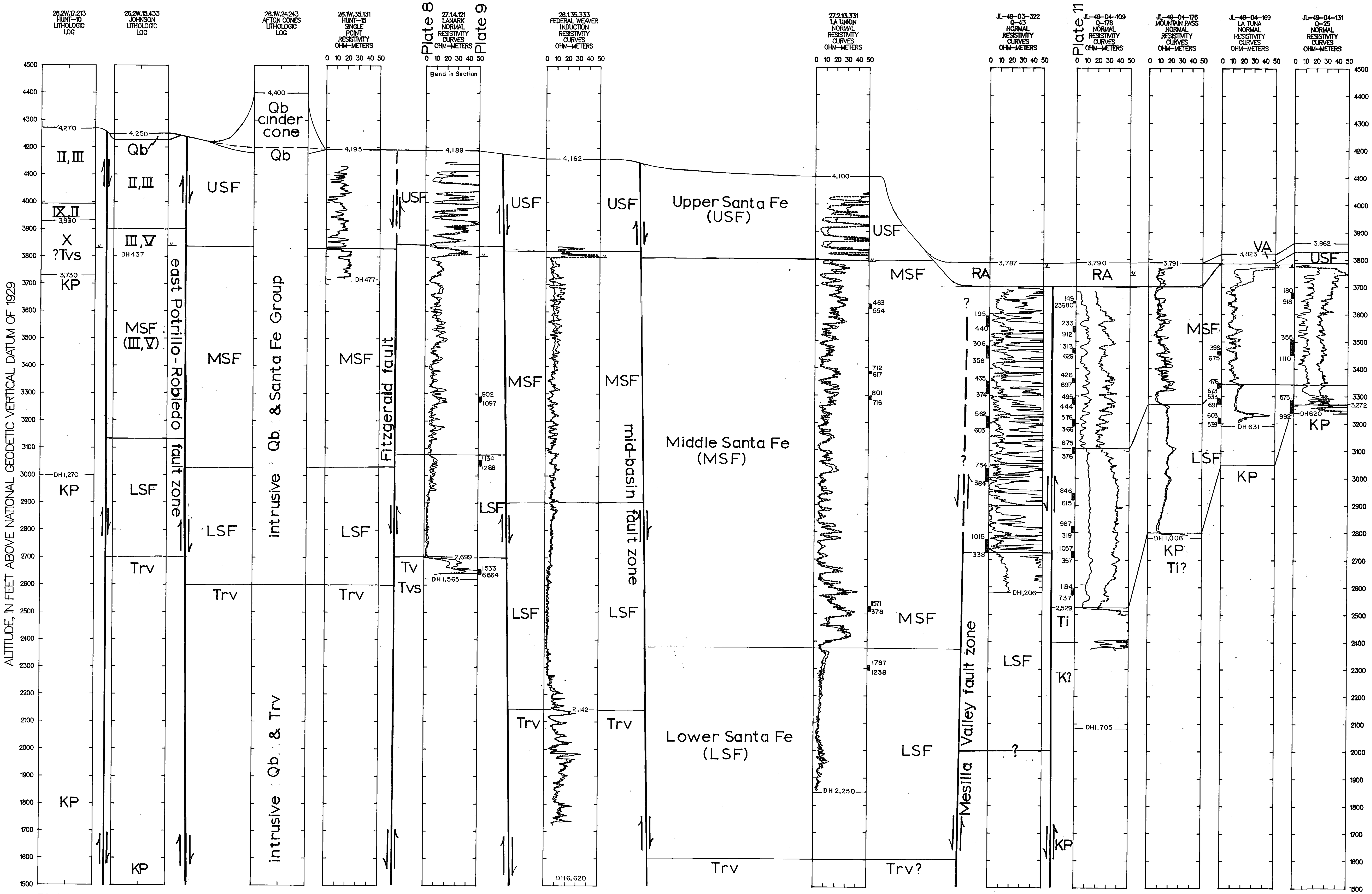

Plate 4. Hydrogeologic section Aden to La Tuna, with borehole geophysical data.

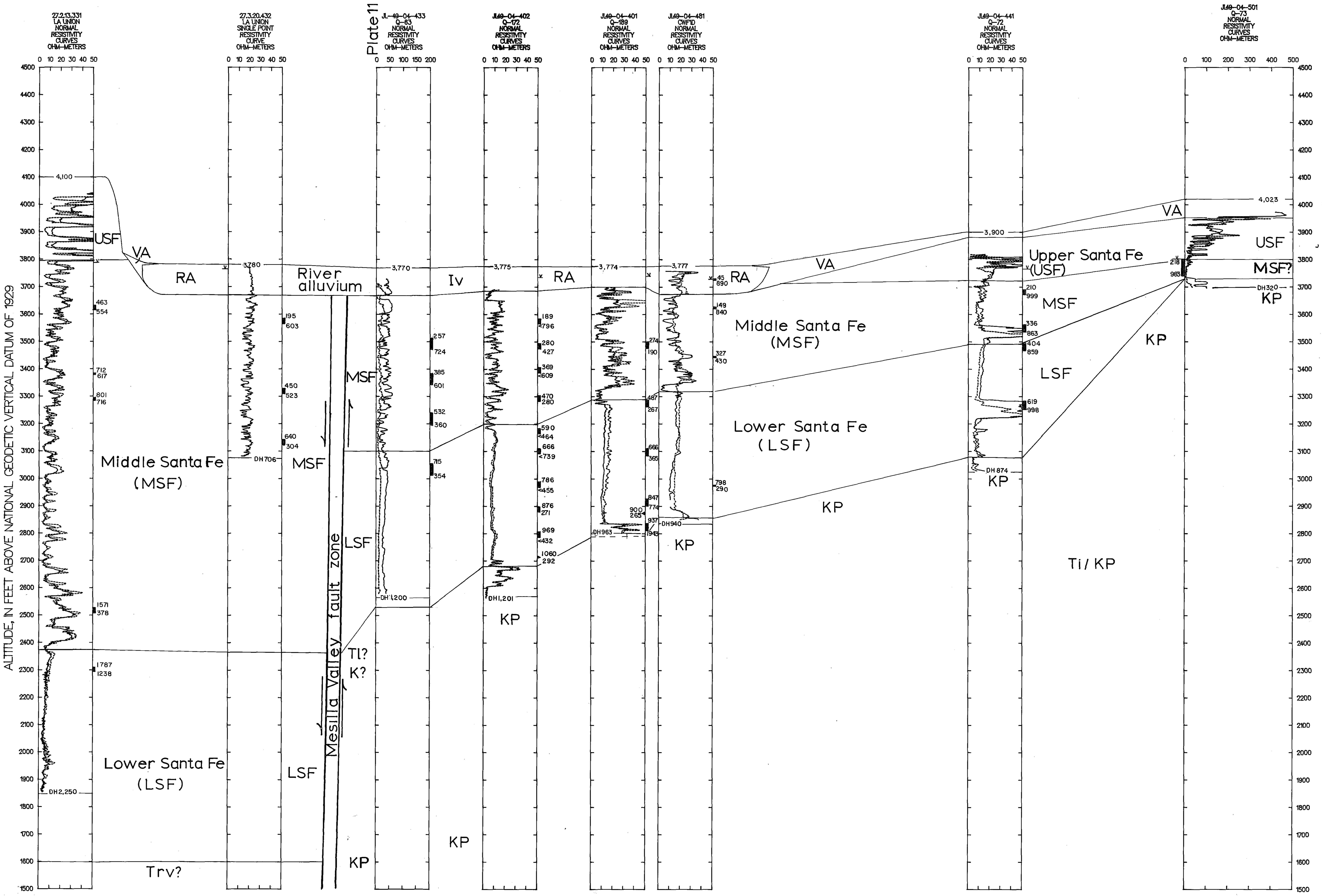

Plate 5. Hydrogeologic section La Union to Vinton, with borehole geophysical data.

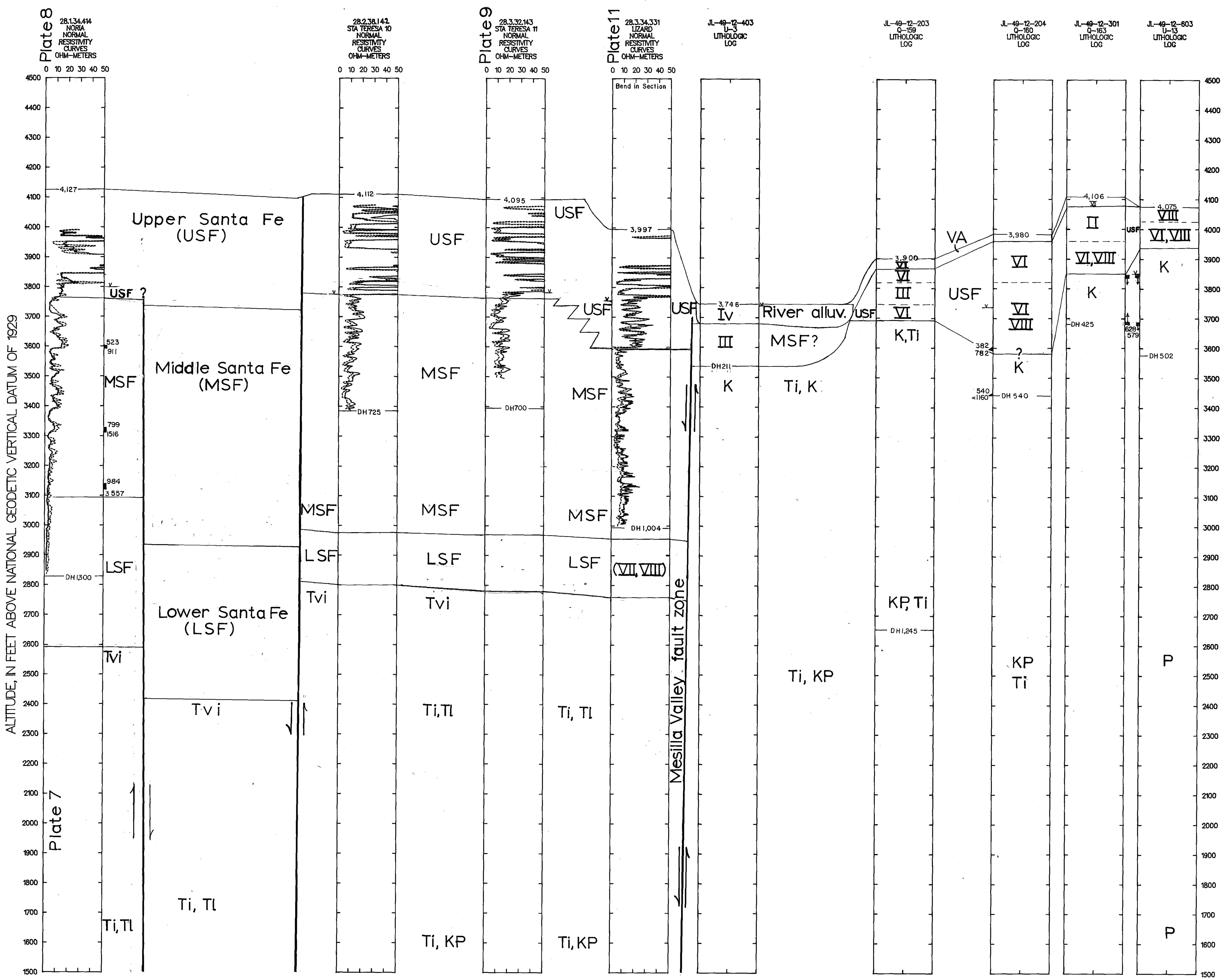

Plate 6. Hydrogeologic section Noria Test to Mesa Boulevard, with borehole geophysical data.

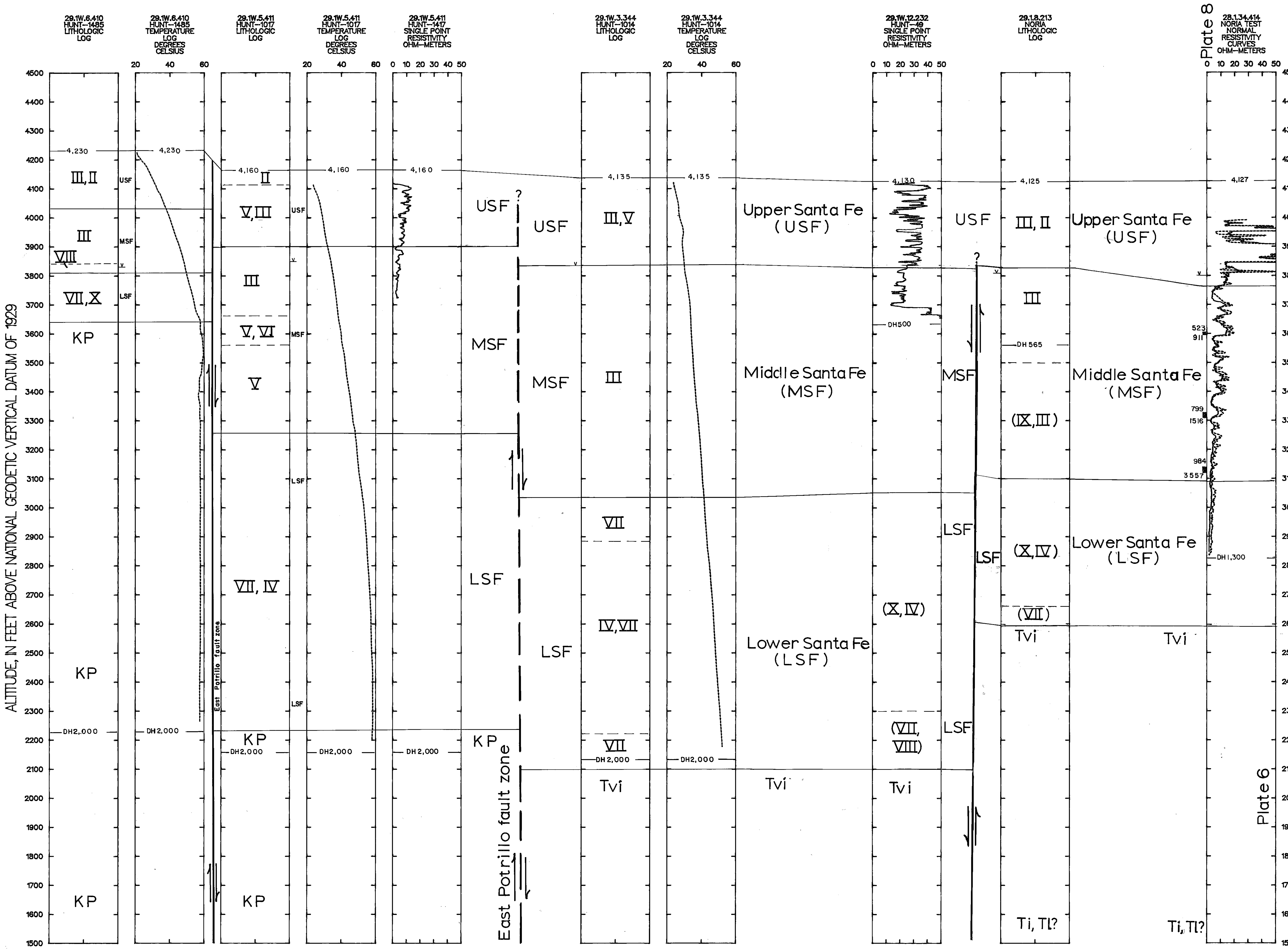

Plate 7. Hydrogeologic section Potrillo Mountains to Noria Test, with borehole geophysical data.

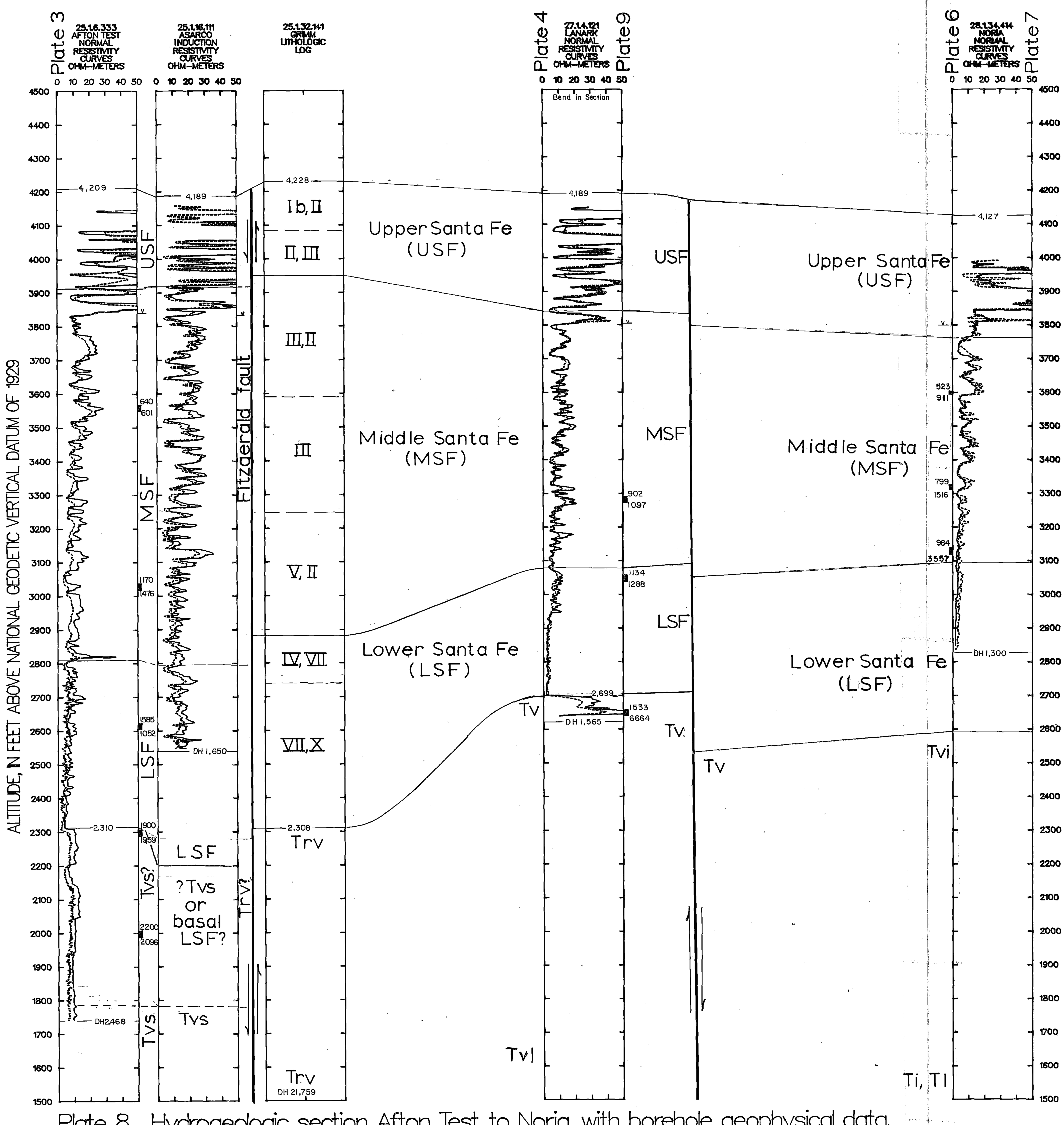

Plate 8. Hydrogeologic section Afton Test to Noria, with borehole geophysical data.

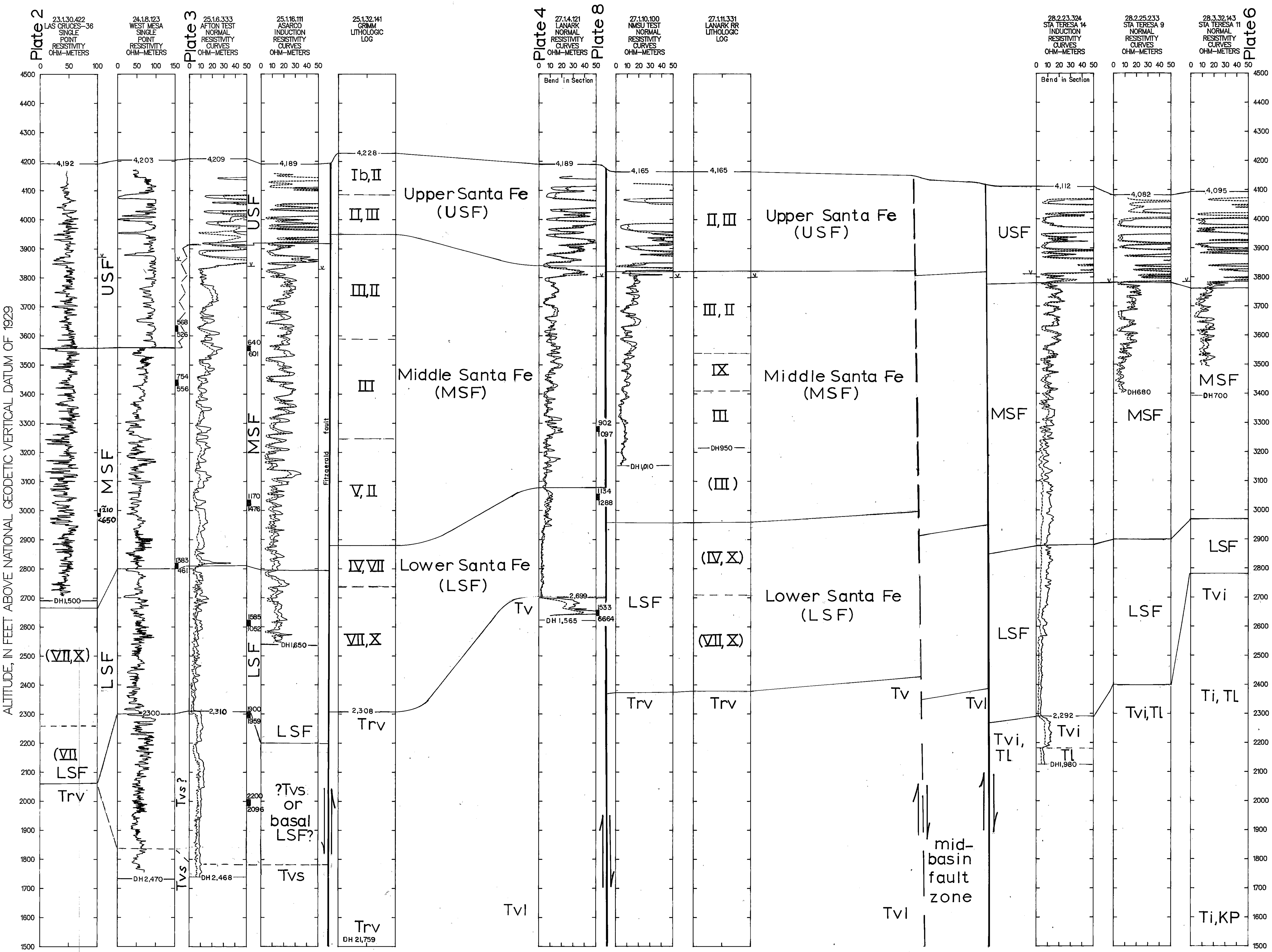

Plate 9. Hydrogeologic section Las Cruces to Santa Teresa, with borehole geophysical data.

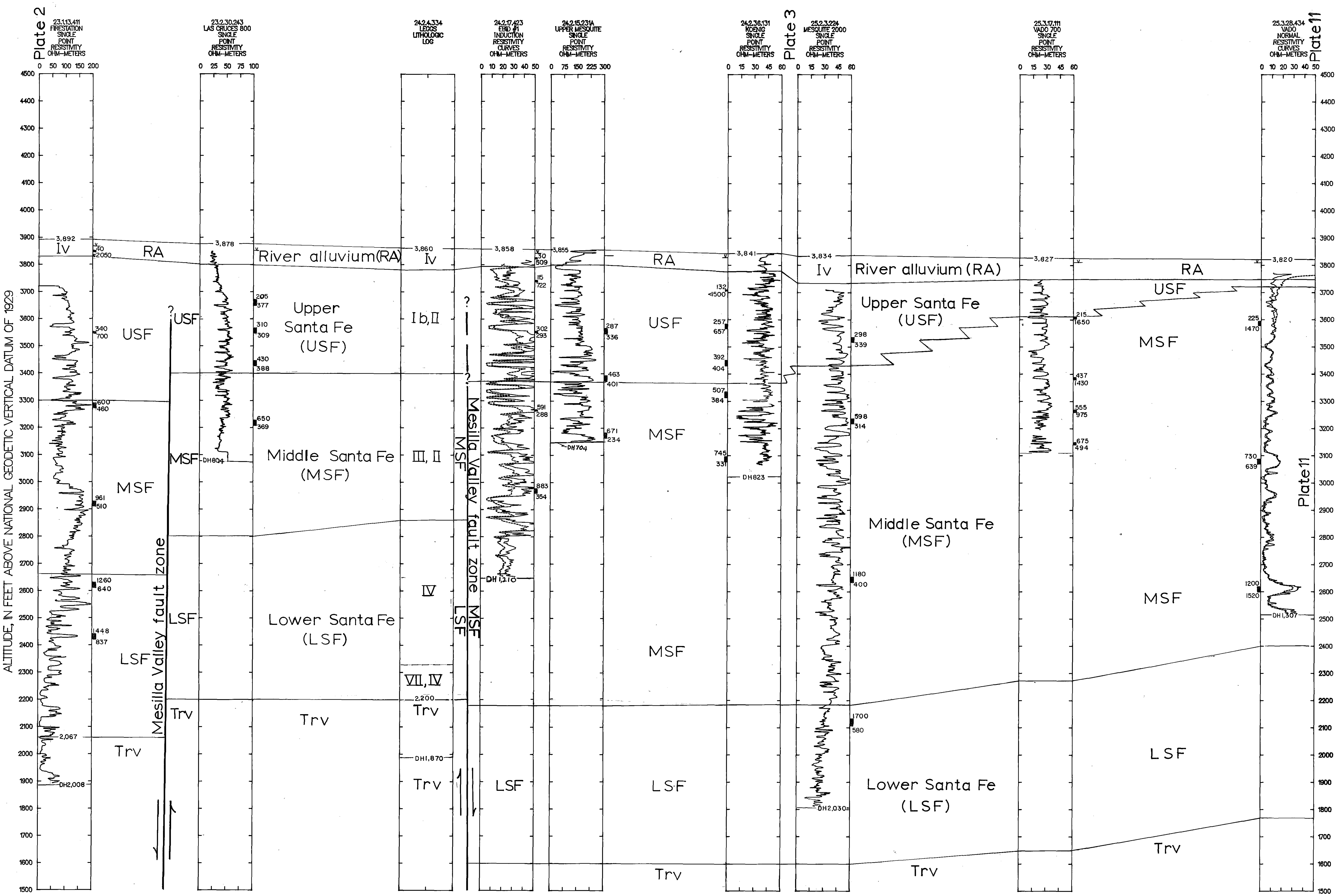

Plate 10. Hydrogeologic section Las Cruces Firestation to Vado, with borehole geophysical data.

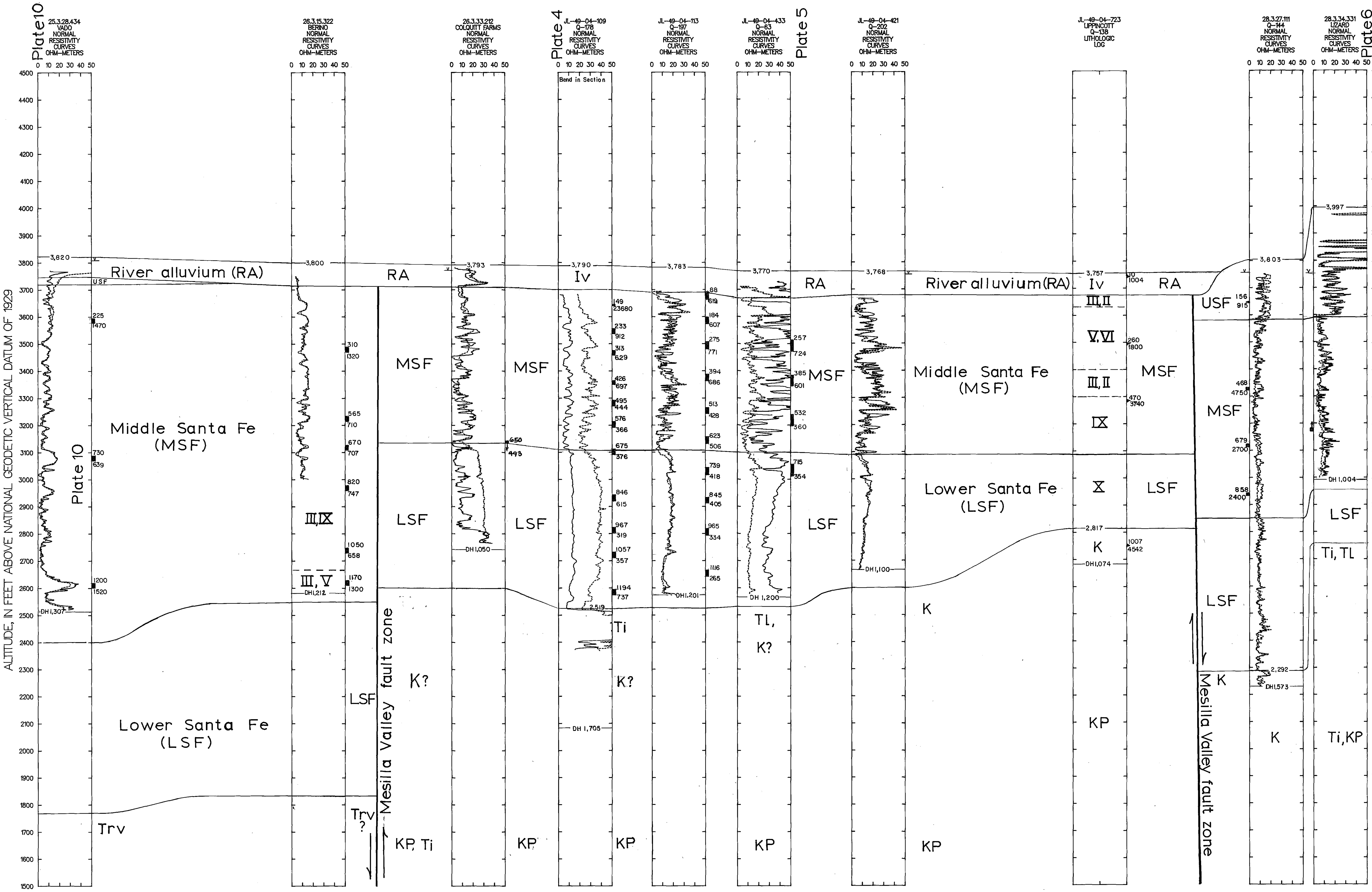

Plate 11. Hydrogeologic section Vado to Lizard, with borehole geophysical data.

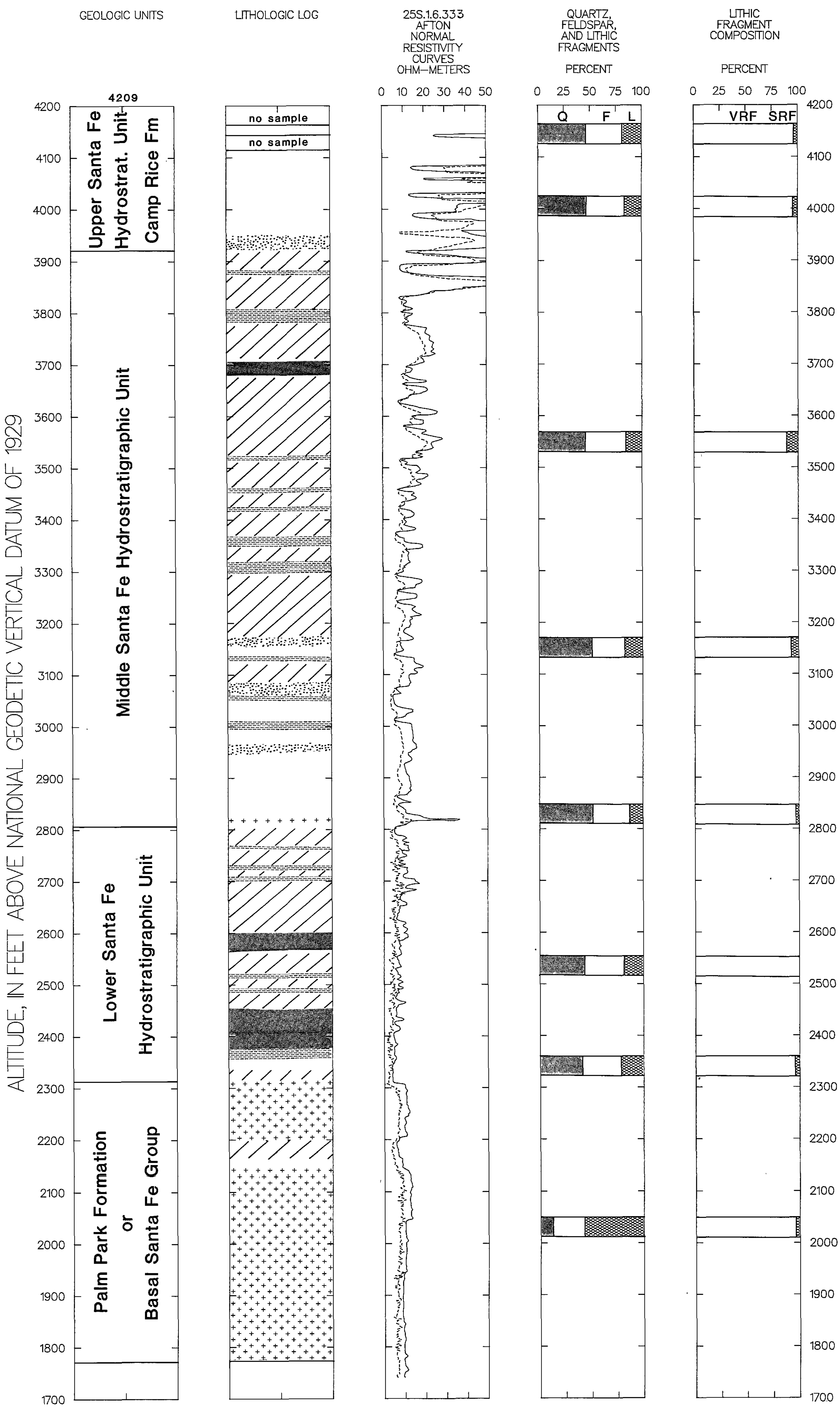

Plate 12. Geological data on Afton test well.

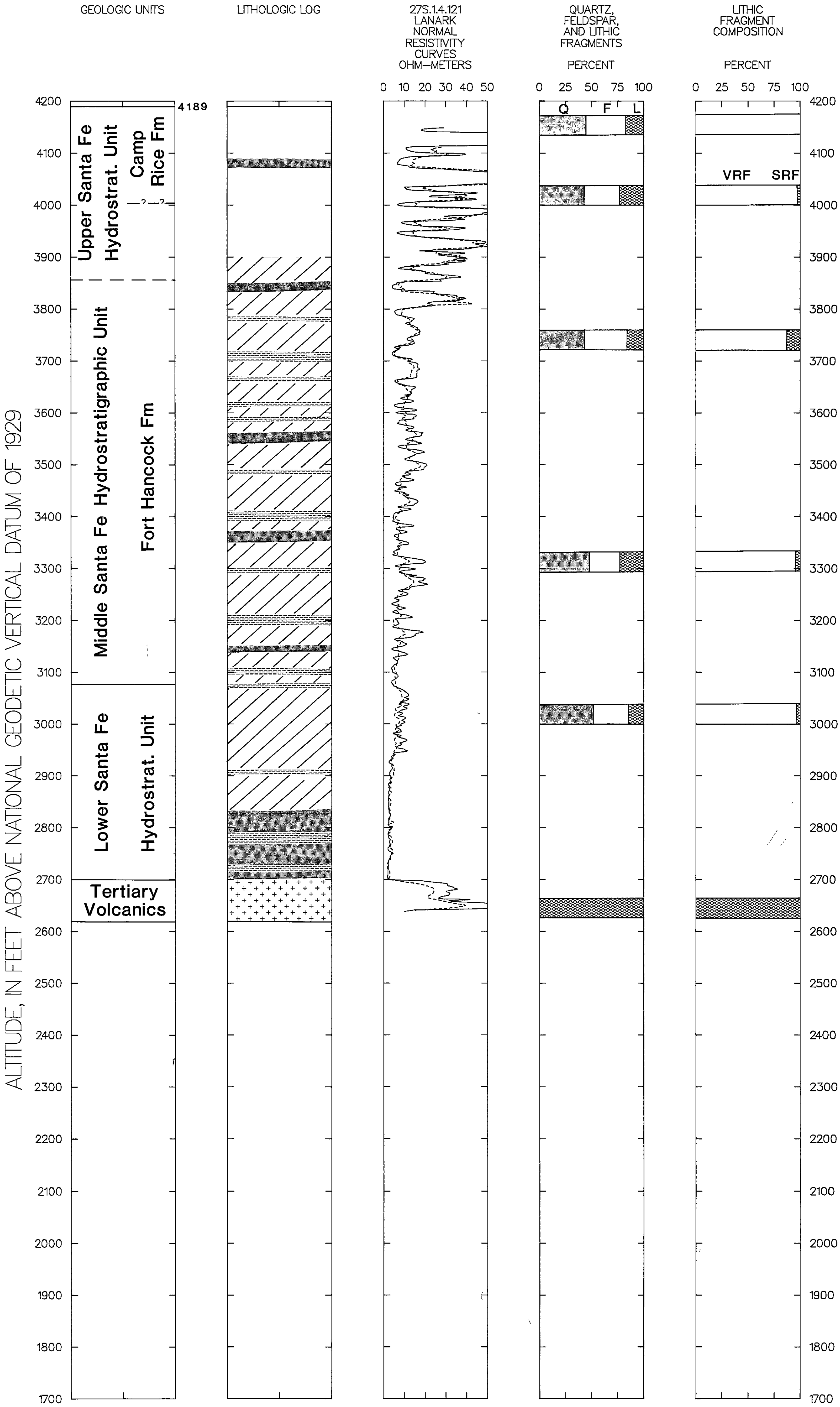

Plate 13. Geological data on Lanark test well.

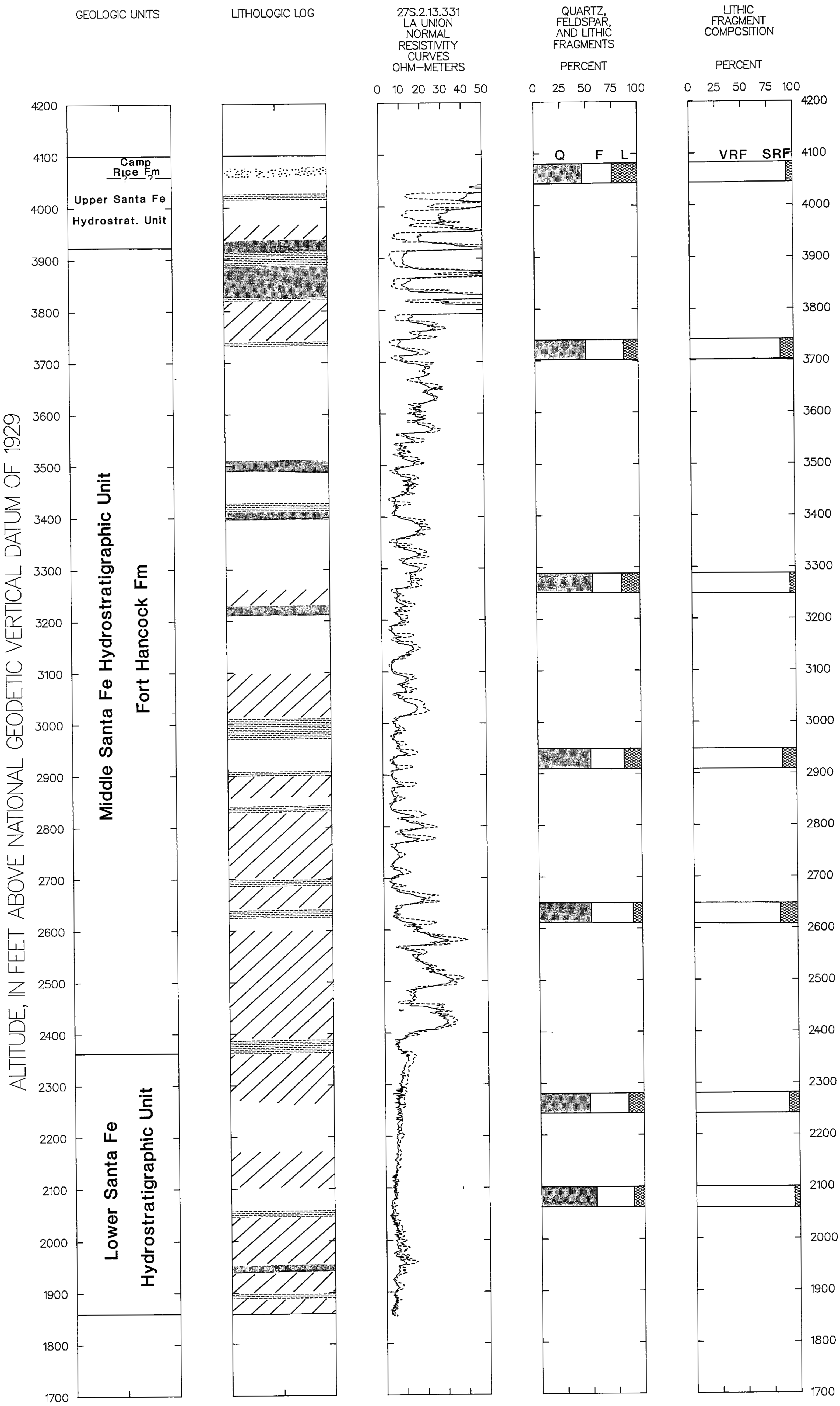

Plate 14. Geological data on La Union test well.

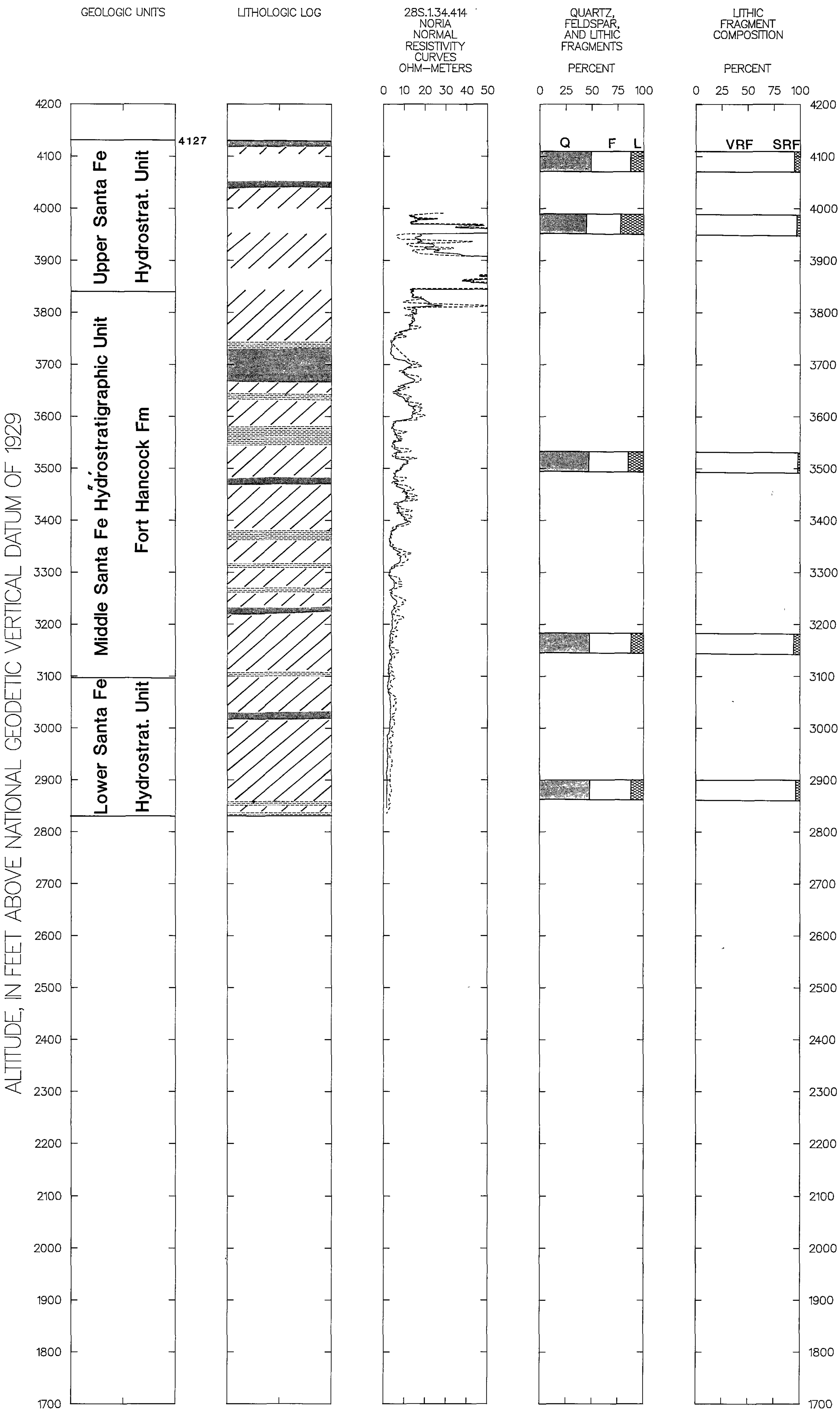

Plate 15. Geological data on Noria test well.

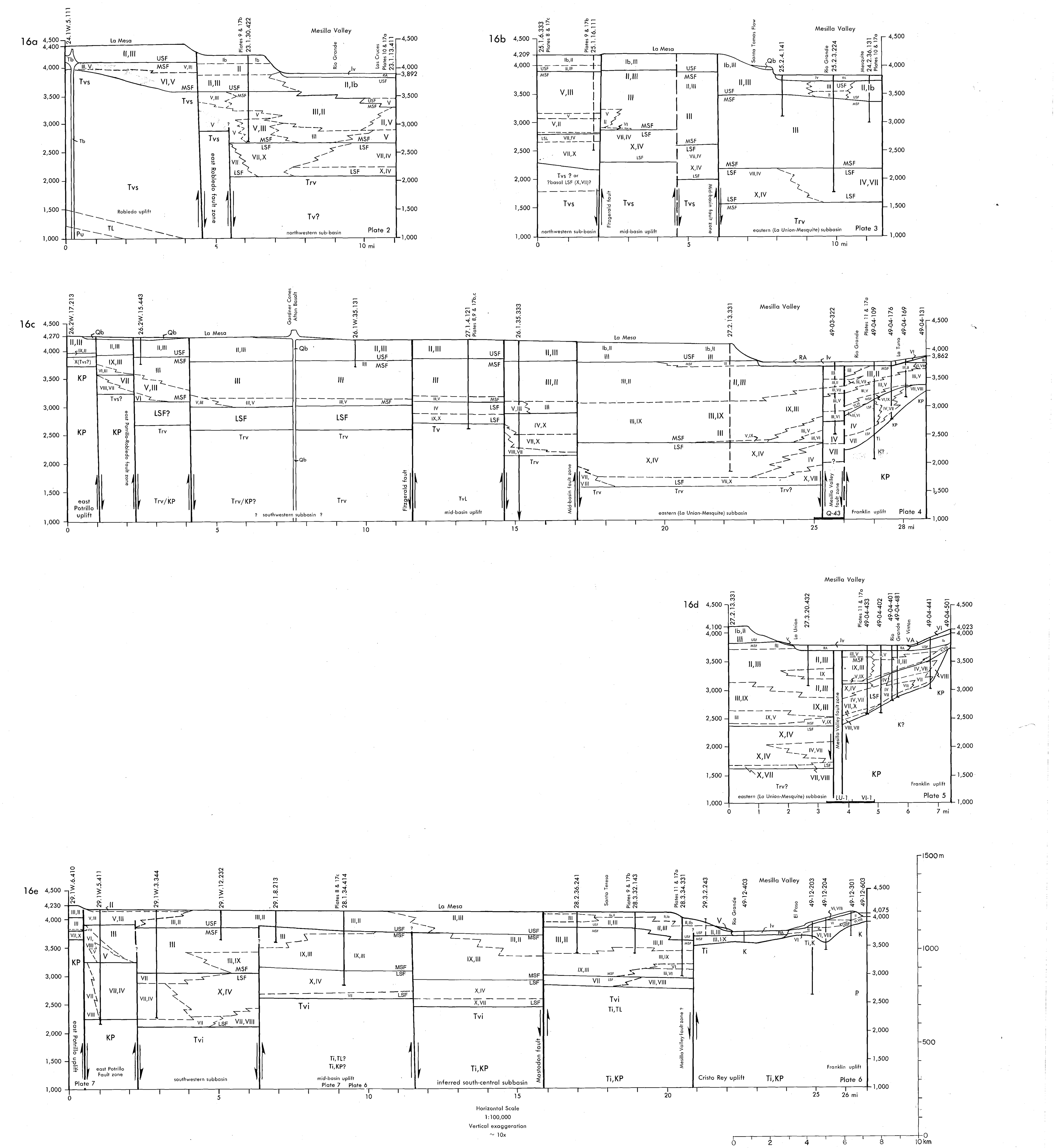

Plate 16. Hydrogeologic Sections of the Mesilla Basin, Las Cruces to El Paso Area, showing inferred distribution of major hydrostratigraphic and lithofacies units, and fault zones

J. W. Hawley and R. P. Lozinsky, 1992
NMBM&MR Open-file Report 323

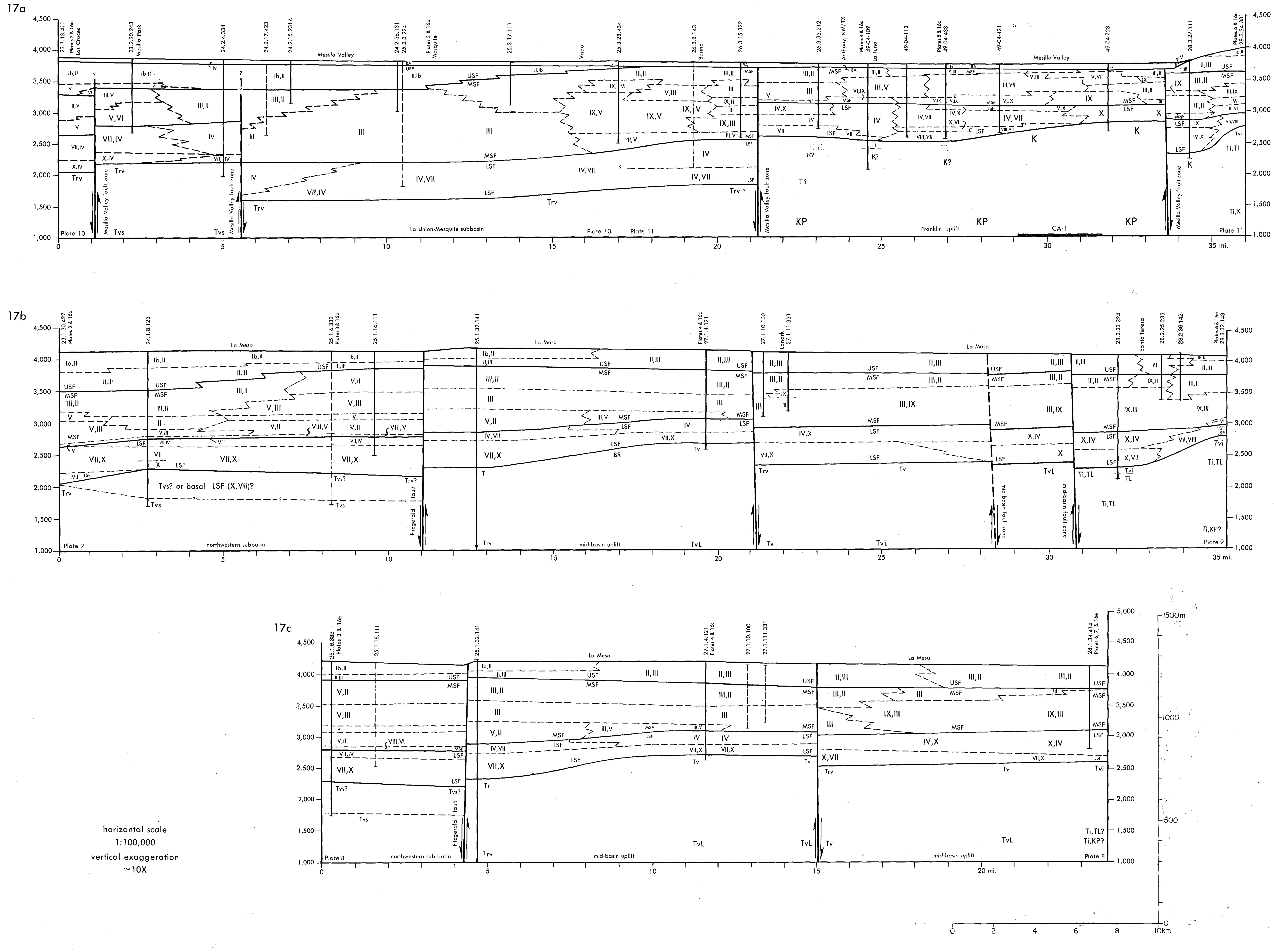

Plate 17 Hydrogeologic Sections of the Mesilla Valley and west central Mesilla Basin areas, showing inferred distribution of major hydrostratigraphic and lithofacies units, and fault zones

J. W. Hawley and R. P. Lozinsky, 1992
NMBM&MR Open-file Report 323