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CREATION OF A DIGITAL HYDROGEOLOGIC FRAMEWORK MODEL OF THE MESILLA BASIN AND SOUTHERN JORNADA DEL MUERTO BASIN

WRRI Technical Completion Report No. 332

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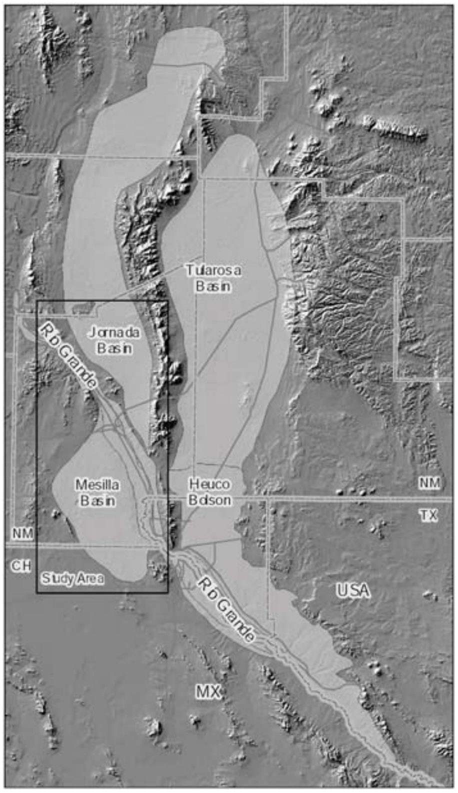

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CREATION OF A DIGITAL HYDROGEOLOGIC FRAMEWORK MODEL OF THE MESILLA BASIN AND SOUTHERN JORNADA DEL MUERTO BASIN

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Lower Rio Grande Water Users Organization

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EXECUTIVE SUMMARY

The primary purpose of this project was to create a digital hydrogeologic-framework model for the Mesilla Basin and contiguous parts of the southern Jornada del Muerto (Jornada) Basin (Plates 1 to 7). The binational, tri-state study area is mostly in Doña Ana County, New Mexico, but it also includes parts of the El Paso-Ciudad Juárez metropolitan area in Texas and Chihuahua, Mexico. The scope of work was dictated by requirements of the Lower Rio Grande Water Users Organization and New Mexico Interstate Stream Commission for best-available hydrogeologic information that will provide a sound basis for ongoing modifications and updates of the existing groundwater-flow model for the Lower Rio Grande-Mesilla Basin area. Our long-term objective is to develop a state-of the-art hydrogeologic model that will lead to significant improvements in future geohydrologic models of the entire study region and ultimately increase their utility as water-resource management tools. Report emphasis is on 1) the hydrogeologic framework of the Rio Grande rift-basin and river-valley fills that collectively form the major aquifer systems; and 2) how basin-fill composition and structural-boundary controls influence groundwater flow and geochemical/geothermal conditions. Geographic Information System (GIS) methodology (ARCINFO® platform) is used to portray and integrate the major framework components of aquifer-system lithology and stratigraphy, basin boundaries, and internal basin structure.

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The New Mexico Water Resources Research Institute and the Environmental Protection Agency, Region 6, provided support for this work. Rick Lozinsky (Fullerton College, Division of Natural Resources, Fullerton, CA) provided invaluable assistance with his work on thin-section petrology and well-log interpretation. Hard-copy and digital maps were provided by Jane Love and Glen Jones of the New Mexico Bureau of Geology and Mineral Resources. Graduate and undergraduate students assisted in the creation of the digital surface geology maps and subsurface hydrogeologic cross-sections and with the creation of the GIS (geographic information system) hydrogeologic framework model. The students are listed by employment date:
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ABSTRACT

The primary purpose of this project was to create a digital hydrogeologic-framework model for the Mesilla Basin area, including the Mesilla to Rincon section of the Rio Grande Valley and adjacent parts of the southern Jornada del Muerto (Jornada) Basin (Plates 1 to 7). The binational, tri-state study area is mostly in Doña Ana County, New Mexico; but it also includes parts of the El Paso-Ciudad Juárez metropolitan area in Texas and Chihuahua, Mexico. Scope of work was dictated by requirements of the Lower Rio Grande Water Users Organization and New Mexico Interstate Stream Commission for a state-of-the-art hydrogeologic model that will provide a sound basis for ongoing modifications and updates of the existing groundwater-flow model for the Lower Rio Grande-Mesilla Basin area. Project emphasis is on 1) the hydrogeologic framework of the Rio Grande rift-basin and river-valley fills that collectively form the major aquifer systems; and 2) how basin-fill composition and structural-boundary conditions influence groundwater flow and chemistry.

Geographic Information System (GIS) methodology (ARCINFO® platform) is used to portray and integrate the major framework components of aquifer-system lithology and stratigraphy, basin boundaries, and internal basin structure. The hydrogeologic-framework model "template" is three-dimensional and has a combined hydrogeologic-map—fence-diagram format (Plates 1 to 7). Map-scale is 1:100,000, model base elevation is 1,000 ft asl (above mean sea level), and vertical exaggeration of the 17 cross-sections is 10x.

Baseline information for about 160 "key wells" is used in design of the 17 hydrogeologic sections (Plates 3 to 6). The data base includes 60 digital borehole geophysical logs, driller and drill-cutting logs, and groundwater head and chemical data, as well as interpretations of the major lithologic, stratigraphic and structural elements of basin-bounding bedrock units (Appendix, Tables A1 to A4, Plates A1 to A9). GIS-framework components include area features (polygons), such as those showing the spatial extent of geologic-mapping units, line features such as fault-zones, and point features showing locations of key wells and other sites with detailed information on subsurface geology. This digital template is a significant advance over previous work, because hydrogeologic databases and interpretations were presented in a wide variety of

map and section formats with inconsistent scale, spatial coverage, organization, quality, and flow-model utility.

The primary aquifer systems of the study region are the thick (up to 3,000-ft) sedimentary fills of the Mesilla and Jornada Basins that are linked by the valley of the Rio Grande (Plate 1). Alluvial, eolian, and playa-lake sediments of the Santa Fe Group (Late Cenozoic) form most of the basin fill and include an upper sequence of ancestral river deposits. Thin (<80 ft), upper Quaternary alluvium of the inner-river valley is the only other major aquifer. Basin aquifer systems have three hydrogeologic components: lithofacies assemblages (LFAs), hydrostratigraphic units (HSUs), and bedrock and structural-boundary controls. Fluvial and eolian LFAs with excellent aquifer potential are very thick and extensive in Santa Fe Group HSUs of the central Mesilla Basin.

The Rio Grande Valley provides the only inter-basin connection for both surface and shallow-subsurface flow between the Rincon, Mesilla and southern Jornada Basins. Selden Canyon and El Paso del Norte "narrows," respectively at the north and south ends of the Mesilla valley, form very effective barriers to significant inter-basin groundwater flow from aquifer systems of the Rincon Valley and to the Hueco Bolson. In much of the northern Mesilla Basin, upper to middle parts of the basin- and valley-fill aquifer systems are well connected with respect to the surface and shallow-groundwater flow regimes of the inner-river valley. There is also a substantial (but still unquantified) "paleo-recharge" contribution to groundwater flow in the southernmost Mesilla Basin from the very large basin of "pluvial-Lake" Palomas in northwestern Chihuahua. The ultimate discharge zone for the entire (regional and local) groundwater-flow system is in the lower Mesilla Valley area between Anthony (NM-TX) and El Paso de Norte.

The Jornada Basin aquifer system has a groundwater-flow regime that is isolated from the Rio Grande Valley recharge sources. The very small amount of underflow discharge to the Mesilla Valley is restricted to a few shallow saddles in a partly buried bedrock "high" that separates the Jornada and Mesilla structural basins. The only area with mountain-front recharge sources and potential for long-term, moderate-yield production is limited to the southernmost basin area between the Doña Ana Mountains and Organ-southern San Andres range. Gypsiferous playa-lake sediments and brackish-water conditions characterize Santa Fe HSUs in the basin fill to the north, with minor underflow discharge to the Rincon Valley occurring only in the area between the Rincon Hills and San Diego Mountain.

Keywords: Hydrogeologic framework, GIS, Geographic Information Systems, Mesilla Basin, Jornada del Muerto Basin

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1.0 INTRODUCTION

1.1 PURPOSE AND SCOPE

The main purpose of this project was to create a digital hydrogeologic framework model for the Mesilla Basin and contiguous parts of the southern Jornada del Muerto Basin (Plates 1 to 7. The primary geohydrologic linkage between these major basin-fill aquifer systems of the south-central New Mexico border region is provided by the Mesilla and lower Rincon Valley sections of the Rio Grande Valley. The scope of work reflects requirements for the best-available hydrogeologic information that will support the Lower Rio Grande Water Users Organization and the New Mexico Interstate Stream Commission in their efforts to improve the groundwater-flow model of the Lower Rio Grande – Mesilla Basin system. In this context, ongoing work by T. Maddock and others to refine components of the current flow model, and model updating supported by the Office of the State Engineer, are contributing new information that requires continued integration with a hydrogeologic model that is ”state of the art” in terms of upgrade capabilities. Our ultimate objective is to provide a platform for significant improvements in geohydrologic modeling as a water-resource management tool in the south-central New Mexico region.

Recent advances in GIS—ARCINFO® methodology and expanded coverage and quality of geological-geophysical-geochemical databases also mandate upgrading of existing hydrogeologic-framework models. Our study represents the first synoptic integration of hydrogeologic information in the Mesilla-Jornada Basin area, which includes the tri-state, binational Las Cruces-El Paso-Ciudad Juárez metropolitan district. From a flow-modeler’s perspective, hydrogeologic databases and interpretations have, heretofore, only been available in a variety of formats with a wide range of interpretive quality and clarity. While all geology-based models tend to be “works in progress,” we believe that our digital-framework model represents a significant scientific and technological advance over previous work

This study is a continuation of a series of recent binational and multi-state investigations of “alluvial-aquifer” systems in the southwestern New Mexico border region. The common theme of all this work is emphasis on GIS coverages related to hydrogeology, geohydrology, and hydro-geochemistry (cf. Hibbs et al. 1997, 1998, 1999, 2003; Kennedy 1999; Kennedy et al. 2000; Hawley and Kernodle 2000; Hawley et al. 2000, 2001, 2002; Witcher et al. 2004). Emphasis here is on 1) the hydrogeologic framework of intermontane-basin (bolson) and river-valley fills, which collectively form the Mesilla and southern Jornada del Muerto Basin aquifer systems; and 2) the major hydrogeologic factors that influence groundwater flow and chemistry within this complex of basin deposits and bedrock-boundary units.

Until recently, conceptual and physical models of "alluvial-basin" hydrogeology have been designed primarily for use in numerical models of groundwater-flow systems; and many equally important attributes that influence geochemical and geothermal conditions have not been emphasized Therefore, the GIS-based, hydrogeologic-framework concepts used here (and in above-cited related work) are designed to integrate the major framework components (e.g., aquifer-system lithology, stratigraphy and structure) that influence geochemical/geothermal properties as well as flow regimes in local as well as regional geohydrologic systems. Our framework-model "template" is 3-dimensional and has a combined hydrogeologic-map—fence-diagram format (Plates 1 to 7) with a map-scale of 1:100,000; 10x vertical exaggeration of cross-sections, and a base elevation of 1,000 ft asl (above mean sea level). Plate 7, a structure-contour map, is a provisional working model of the base of Santa Fe Group basin fill in the Mesilla-southern Jornada basin area. Plate 6 and Figure 5-3 give a more detailed view of the bedrock topography of the lower Mesilla Valley-Paso del Norte area.

Baseline information from about 350 reference wells used in preparation of 17 (schematic) hydrogeologic sections (Plates 3 to 6, Fig. 5-3) includes: digitized borehole geophysical logs (60), driller and drill-cutting logs, groundwater head and chemical data, and interpretations of the major lithofacies, hydrostratigraphic and structural elements of the hydrogeologic framework (Appendix, Tables A1 to A4, Plates A1 to A9). GIS-framework-data components include area features (polygons), such as planimetric units that express the spatial extent of geologic-mapping units, line features representing the surface expression of fault-zones, and point features showing the location of important wells that provide detailed information on subsurface geology. These databases are essential components of all hydrogeologic models and require updating when new data is made available.

1.2 RELATED CONCURRENT STUDIES

Concurrent investigations that are already providing important new information to our expanding digital-hydrogeologic database include the following.

A recently completed study was supported by the New Mexico Interstate Stream Commission on sources of salinity in the Mesilla Basin (Witcher et al. 2004; Appendix—Tables A2 to A4, Plates A1 to A9). Project tasks included: 1) preliminary hydrogeologic-framework characterization; 2) collection of long-term surface-water quality data and evaluation of changes in surface-water salinity over time; 3) gathering new groundwater quality data and comparison of changes in groundwater salinity with respect to surface-water quality, and 4) identifying "packages" of groundwater, through the use of stable isotopic systems, that may have a significant impact on surface-water quality.

The U.S. Geological Survey cooperative long-term groundwater monitoring program continues to provide baseline information on key drain and canal seepage, river seepage, and groundwater levels throughout the basin. Of special importance is a cooperative study funded by El Paso Water Utilities that emphasizes groundwater-flow modeling in the Cañutillo well field area of the lower Mesilla Valley. It is already providing additional geophysical and hydrogeologic data from several deep boreholes for piezometer nests near La Union and Gadsden-Chamberino in Doña Ana County. A related project supported by the Lower Rio Grande Water Users Organization (LRGWUO) includes installation of a piezometer nest that will provide additional information on the geohydrology of the basin-fill aquifer system in the Las Cruces area.

The primary task of a GIS project funded by the Hewlett Foundation is the development of a "basemap-framework dataset" that shows locations of roads, streams, populated places, and administrative boundaries. Such databases are seen as a critical component to the regional watershed planning activities by entities in Las Cruces, El Paso, and Ciudad Juárez.

1.3 LOCATION AND PHYSIOGRAPHIC SETTING

1.3.1 Introduction

The Rio Grande Valley and intermontane-basin area covered in this report (Fig. 1-1) includes much of Doña Ana County, New Mexico, and the lower Mesilla Valley section of El Paso County, Texas. The study area includes the Las Cruces metro- area of the upper Mesilla Valley and extends into northern Chihuahua at the western edge of the El Paso-Ciudad Juárez “metroplex” (Fig. 1-2). Emphasis here is on the hydrogeologic framework of two contiguous topographic and structural basins (bolsons), Mesilla and Jornada del Muerto. Both basins and the surrounding region are located in the Mexican Highland section of the Basin and Range physiographic province (Fenneman 1931; Hawley 1986). Major river-valley segments and adjacent “bolson” areas, were originally named by R.T. Hill (1896, 1900) and W.T. Lee (1907). From a bio-geographic and regional-climate perspective, the entire study area is within the north-central Chihuahuan Desert (Schmidt 1986; Van Devender 1990). The distinctive geomorphic characteristic of this part of the Basin and Range province is the large extent of basin-floor areas relative to the flanking piedmont slopes and mountain uplifts (Figs. 1-2, 1-3, Plate 1). Most ranges are narrow and low-lying (less than 8,000 ft elev.) in comparison with highlands of the upper Rio Grande basin in northern New Mexico and Colorado.

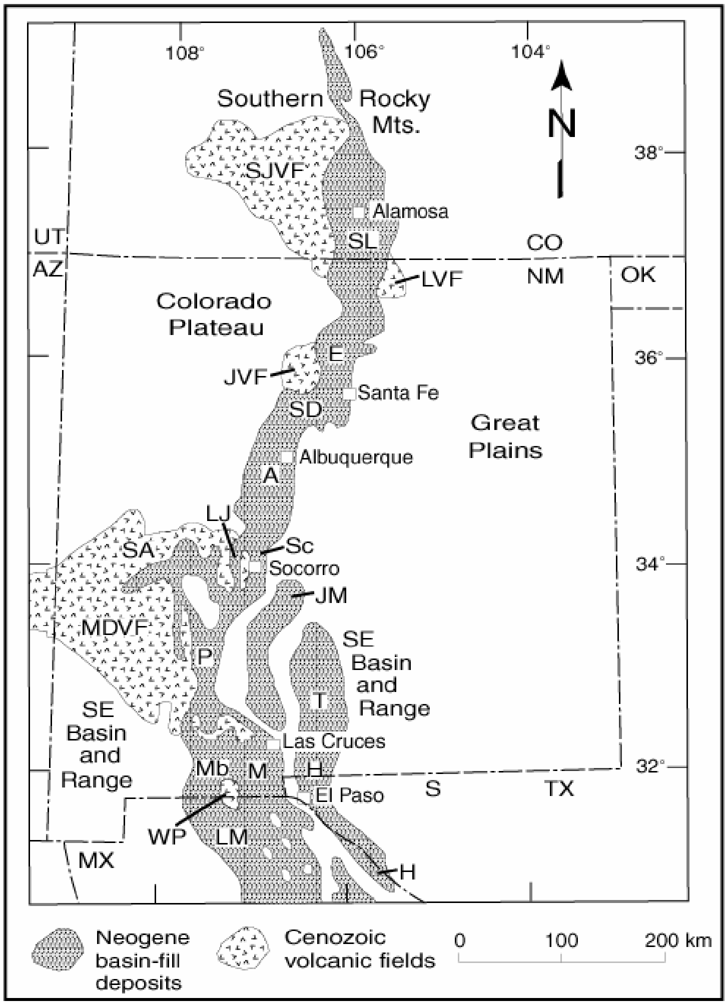

Figure 1-1. Index map showing location of the Mesilla Basin in the context of other basins and volcanic fields within the Rio Grande rift structural province. Basin abbreviations from north to south: San Luis (SL), Española (E), Santo Domingo (SD), Albuquerque (A), Socorro (Sc), La Jencia (LJ), San Agustin (SA), Jornada del Muerto (JM), Palomas-Rincon (PR), Tularosa (T), Mimbres (Mb), Mesilla (MB), Los Muertos (LM), Hueco (HB), and Salt (S). Cenozoic volcanic fields: San Juan (SJVF), Latir (LVF), Jemez (JVF), Mogollon-Datil (MDVF), and West Potrillo (WP). Modified from Keller and Cather (1994)

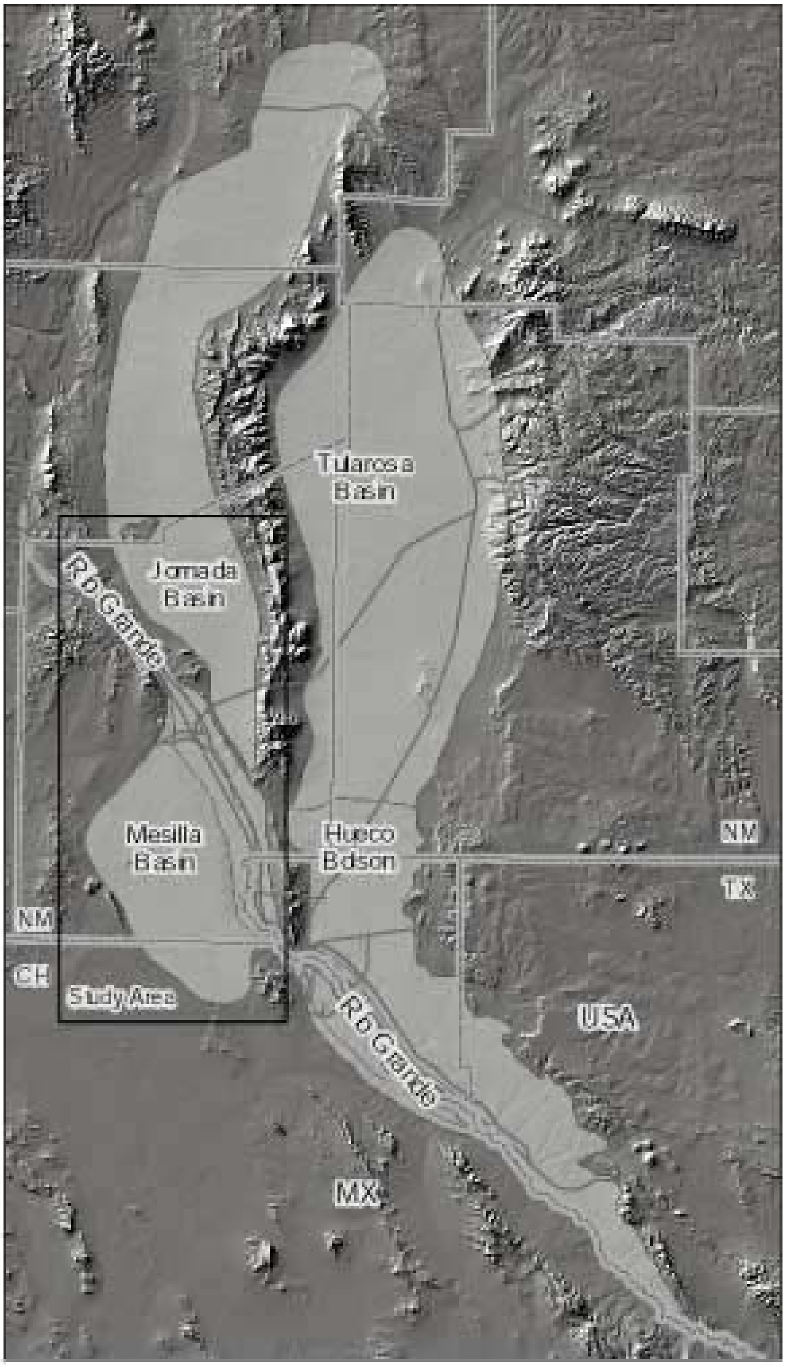

Figure 1-2. Shaded-relief index map of the south-central New Mexico border region, including adjacent parts of Trans-Pecos Texas and Chihuahua, Mexico. The major aquifer systems shown extend along the Rio Grande from Elephant Butte Reservoir to the southern part of Hueco Bolson, near Fort Quitman, Texas. They include 1) the shallow-alluvial systems in the Rincon, Mesilla and El Paso valleys of the Rio Grande, and 2) the intermediate and deep basin-fill (Santa Fe Gp) aquifers of the Palomas-Rincon, Jornada del Muerto, Mesilla, and Hueco basins. Shaded relief from latest available U.S. Geological Survey DEM database.

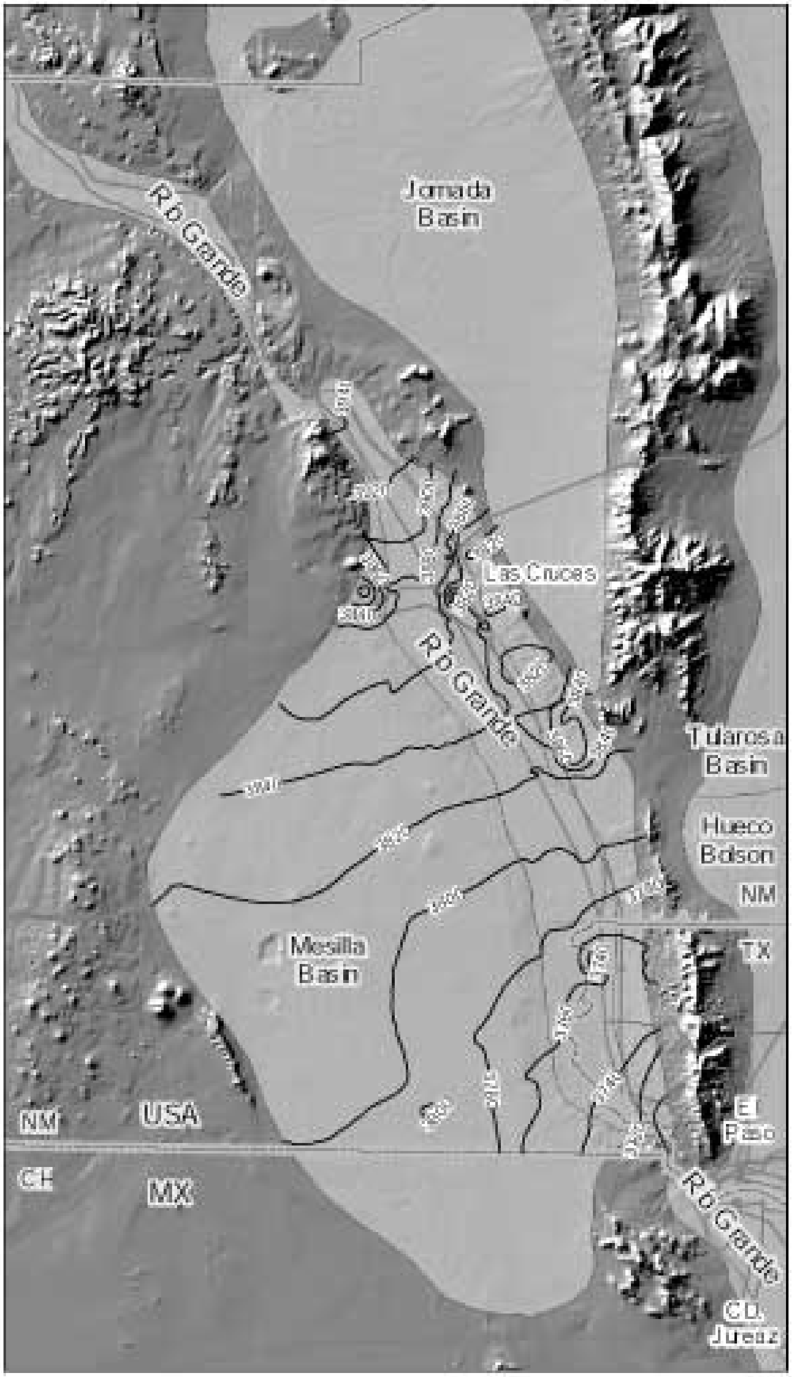

Figure 1-3. Shaded-relief index map of the Mesilla Basin area of southern New Mexico and adjacent parts of Texas and Chihuahua. The extent of major basin-fill (Santa Fe Group) and Mesilla Valley (Rio Grande alluvium) aquifer systems is shown; and the general water-table configuration and groundwater-flow direction in the basin's upper aquifer units are also illustrated. Adapted from Hibbs and others (1997), with shaded relief from latest available U.S. Geological Survey DEM database.

The Mesilla Basin, including the Mesilla Valley between Selden Canyon and El Paso del Norte (or El Paso Narrows), occupies most of the study area. To the north, the southern section of the Jornada del Muerto (or Jornada) topographic and structural basin is east of the lower Rincon Valley to upper Mesilla Valley reaches of the Rio Grande. Leasburg (irrigation-diversion) Dam, at the lower end of Selden Canyon (about 3,960 ft elev.), marks the northern boundary of both the Mesilla Valley and the "structural" Mesilla Basin. The very narrow El Paso del Norte segment of the Rio Grande Valley (floodplain elev. 3,715-25 ft) opens southeastward into the broad El Paso Valley section of the western Hueco Bolson. The river channel forms the International Boundary between El Paso del Norte and the Gulf of Mexico. Both the Selden Canyon and Paso del Norte constrictions are bedrock-floored features characterized by narrow valley floors (500-1,000 ft width range) and saturated-alluvial fills that are less than 75 ft thick.

1.3.2 Mesilla Basin and Valley

Excluding local mountain watersheds, the (topographic and structural) Mesilla Basin has an area of about 1,100 mi^2, including as much as 200 mi^2 in Chihuahua. It is bounded on the east by the Organ-Franklin-Sierra Juárez mountain chain and on the west by fault-block and volcanic uplands, which extend northward from the East Potrillo Mountains (near the International Boundary) to the Aden and Sleeping Lady Hills. El Paso del Norte occupies the narrow saddle between the Juárez–Cristo Rey and Franklin uplifts. Fillmore Pass (elev. ~4,200 ft) is a wide, alluvial-filled gap between the Franklin and Organ. Organ Needle (elev. 9,012 ft), in the central Organ Mountains, is the highest point on the basin perimeter. The Robledo and Doña Ana Mountains form the respective western and eastern boundaries in the upper Mesilla Valley section of the basin.

The Mesilla Basin extends southward about 65 mi from the mouth of Selden Canyon (Leasburg Dam site), to a poorly defined groundwater divide located about 20 mi south of the International Boundary southwest of the Santa Teresa Port of Entry and west of Sierra Juárez (Figs. 1-2, 1-3). The southern end of the topographic (and structural) basin merges southward with the floor of Bolson de Los Muertos in north-central Chihuahua (Córdoba et al. 1969; Hawley 1969; Morrison 1969; Reeves 1969; Hawley et al. 2000). Basin width varies from about 5 mi at its northern end to about 25 mi in its central part. The extensive, undissected basin floor west of the Mesilla Valley is locally designated the West Mesa or “La Mesa”. The former name is used in this report, following USGS-WRD practice (e.g., Wilson et al. 1981; Nickerson and Myers 1993), and “La Mesa” is used only in reference to the relict fluvial plain of the ancestral Rio Grande (Plio-Pleistocene) La Mesa geomorphic surface (Hawley 1975; Hawley and Kottlowski 1969; Gile et al. 1981; Gile, Hawley et al. 1995).

The entrenched Mesilla Valley segment of the Rio Grande Valley occupies much of the eastern part of the Mesilla Basin and includes the Las Cruces area. The northwestern El Paso-Ciudad Juárez “metroplex” extends through El Paso del Norte into the southern end of the valley. The valley-floor geohydrologic unit (Rio Grande floodplain and channel) is about 60 mi long and up to 5 mi wide, and its area is about 215 mi^2 (135,000 acres); and the river’s drainage basin above Leasburg Dam comprises about 28,000 mi^2 of New Mexico and southern Colorado (excluding the 2,940 mi^2 *closed basin* section of the San Luis Valley, Ortiz et al. 2001).

1.3.3 Jornada del Muerto Basin

The southern Jornada del Muerto Basin (area ~600 mi^2) is bounded on the east by the southern San Andres range and the north end of the Organ Mountains (between San Augustine Pass and Fillmore-Ice Canyon). The Doña Ana Mountains are the only major highland on the southwestern edge of the Jornada Basin. The dominant basin landforms comprise an extensive remnant of the ancestral Rio Grande fluvial plain (Plio-Pleistocene La Mesa geomorphic surface), and broad alluvial-fan-piedmont surfaces flanking the San Andres Range and Doña Ana Mountains (Gile et al. 1981, 1995; Gile 2002; Seager et al. 1987). The isolated Goat Mountain and Tortugas Mountain “hills” to the south of the Doña Ana’s (eastern Las Cruces metro-area) are the sole surface expression of the discontinuous bedrock high that separates the Mesilla and Jornada structural basins (Fig. 1-2, Plates 1, 3a-d, 5a). At the northern project border, near the Doña Ana-Sierra County Line (Fig. 1-2), the level of the Jornada Basin floor topography is “disrupted” by the Point of Rocks uplift and outlying hilly uplands in the Jornada Draw-Flat Lake area to the east. In the northwestern part of the study area, another buried-bedrock high connects the Doña Ana, Selden Hills, and Tonuco uplifts (Plate 3a). The Jornada Basin merges with the Rincon section of the Rio Grande Valley north of the Tonuco uplift (San Diego Mountain). This area is south of the Rincon Hills and Caballo Mountains and is transitional northwestward with the eastern Palomas Basin (site of Caballo Dam and Reservoir).

1.3.4 Rio Grande

The only significant surface-water resource is the Rio Grande. Moreover, many reaches of the present fluvial system include networks of canals, laterals and drainage ditches that receive, distribute, and contribute water to the surface and shallow subsurface flow. The river's drainage basin area above Caballo Dam (~25 mi upstream from Rincon) is about 27,700 mi^2 (Ortiz et al. 2001). Upstream from the Courchesne Bridge gaging station (upper El Paso Narrows), the river's watershed is about 29,200 mi^2. The river channel has remained in approximately the same position since the Civil War; however, it has been straightened and diked (canalized) since initiation of the Elephant Butte Irrigation Project in 1915. The gradient of the pre-1865 meandering channel was as low as 1.4 ft/mi, and maximum-channel sinuosity (length/meander-wave length) was about 2.5 (U.S. Reclamation Service 1914).

Observations of discharge variability since the late 16th Century document the extreme RG-flow range in the study region: from no flow to catastrophic floods (Ackerly 1999, 2000; Bailey 1963 [A.B. Gray 1854], Conover 1954; Emory 1987 [1857-1859]; Gregg 1954 [1844]; Hammond and Rey 1966; Mueller 1975; Scurlock 1998; Sonnichsen 1968; Wislizenus 1969 [1848]). Measured peak discharges during the great floods of 1904 and 1905 in the San Marcial to El Paso reach (Water Resources Division 1965) ranged from about 50,000 cfs (San Marcial on 10/11/04 [upper end of Elephant Butte Reservoir]) to 24,000 cfs (El Paso on 6/12/05). Peak Rio Grande discharge since closure of Caballo Dam (1/1938) is usually less than 8,000 cfs (Ortiz et al. 2001); and average discharges at Caballo Dam and El Paso are 850 cfs and 500 cfs, respectively (IBWC 1939-2000).

1.4 REGIONAL GEOLOGIC SETTING

The study region is located in the southern part of the Rio Grande rift tectonic province, which is characterized by north-south-trending series deep structural basins between tilted-fault-block ranges and volcanic highlands. This major continental rift zone extends through central New Mexico from southern Colorado to Trans-Pecos Texas and northern Chihuahua (Chapin and Seager 1975; Hawley 1978; Chapin and Cather 1994; Fig. 1-1). The primary aquifer systems of the Rio Grande rift region comprise 1) thin Upper Quaternary fluvial deposits of the inner Rio Grande Valley (valley-fill aquifer system), and 2) the thick sedimentary fill of intermontane basins (basin-fill aquifer system). The Upper Cenozoic Santa Fe Group forms the bulk of the latter unit. The hydrogeologic framework formed by 1) the lithofacies and stratigraphic subdivisions of these two aquifer systems and 2) associated rift – basin and range structures has a profound influence on groundwater and surface-water flow and quality in the entire region. Valley- and basin-fill aquifer systems are locally linked with respect to both surface and subsurface flow (Bryan 1938; King et al. 1971; Wilson et al. 1981; Nickerson and Myers 1993; Hawley and Kernodle 2000; Hawley et al. 2001). In the Las Cruces area and upstream, the entrenched Mesilla Valley of the Rio Grande provides an inter-basin connection for both surface-water and shallow-groundwater flow between the Jornada del Muerto and Mesilla Basins; while linkage for deeper groundwater flow is furnished by several "paleo-valleys" across a buried bedrock ridge east of the city.

1.5 HISTORY OF HYDROGEOLOGIC INVESTIGATIONS

1.5.1 Early Work

Major early sources of information on the geology and geohydrology of the Mesilla Basin area include reports by Hill (1900), Keyes (1905), Slichter (1905), Lee (1907), Richardson (1909), Dunham (1935), Bryan (1938) and Sayre and Livingston (1945). Slichter's investigation of the Mesilla Valley shallow-aquifer zone included a definitive study of underflow conditions through El Paso Narrows (Sections 4.3.1, 7.3). Lee (1907) developed the earliest model of ancestral Rio Grande evolution in the New Mexico region; and he emphasized the potential for locating a dam at the Elephant Butte site for irrigation-water storage and flood control.

One of the principal resource documents on the northern Rio Grande basin (Fig. 1-1) is the Rio Grande Joint Investigation Report of 1938. This “Regional Planning” document covers the entire upper-river basin from its southern Colorado headwaters area to Fort Quitman at the southeastern end of Hueco Bolson in Trans-Pecos Texas. Report sections by Kirk Bryan and C.V. Theis, respectively, on the "Geology and groundwater conditions of the Rio Grande depression in Colorado and New Mexico” and “Groundwater in the middle Rio Grande valley” are particularly relevant to the present study (Bryan 1938; Theis 1938). Bryan was the first person to recognize that the river-linked series of deep structural basins (his Rio Grande depression), which extend from southern Colorado to Trans-Pecos Texas, are a unified geologic and geohydrologic system. This regional tectonic feature is now designated the Rio Grande rift (Chapin and Seager 1975; Hawley 1978; Keller and Cather 1994). One of Bryan’s (1938) lasting contributions to the hydrogeology of the Rio Grande basin was his observation that: “The main body of sedimentary deposits of the Rio Grande depression, from the north end of the San Luis valley to and beyond El Paso, is considered to be the same general age and to belong to the Santa Fe formation (p. 205).”

Based on observations in Mexico and the American Southwest, C.F. Tolman (1909, 1937) also made a major contribution in better definition of the fundamental hydrogeologic distinction between depositional systems in aggrading intermontane basins with topographic closure (*bolsons*) and those that are open in terms of both surface and subsurface flow (*semibolsons*). The Bryan-Tolman conceptual model from a regional hydrogeologic perspective, which incorporates subsequent work in the Basin and Range—Great Basin section and in the Trans-Pecos Texas–Chihuahua bolson region is further discussed in the Section 3.

1.5.2 Studies from 1945 to 1980

The major advances in science and technology during and immediately after World War II introduced the present era of hydrogeologic-system characterization. Of special note are the developments of modern geophysical-survey, deep-drilling and geochemical-sampling methods that included innovations in borehole geophysics, sample recovery, aqueous geochemistry, and aquifer testing. The resultant breakthroughs in hydrologic, geologic, geophysical, geochemical and soil-geomorphic investigations involved the work of many federal, state, and local institutions, including the U.S. Bureau of Reclamation (USBR), U.S. Geological Survey – Water Resources Division (USGS-WRD), U.S. Department of Agriculture-Soil Conservation Service (USDA-SCS), Texas Water Commission, El Paso Water Utilities (EPWU), New Mexico Office of the State Engineer (NMOSE), New Mexico Bureau of Mines and Mineral Resources-New Mexico Tech (NMBMMR-NM) Tech, and Water Resources Research Institute-New Mexico State University (WRRI-NMSU). By 1980 much of the basic hydrogeologic information, that is the foundation for today's aquifer-system models was already available (e.g., Conover 1954; Knowles and Kennedy 1958; Kottlowski 1958, 1960; Leggat 1962; Leggat et al. 1962; Gile et al. 1966, 1981; Metcalf 1967, 1969; Cliett 1969; Hawley 1969; Hawley and Kottlowski 1969; Hawley et al. 1969; Morrison 1969; Reeves 1969; Zohdy 1969; King et al. 1971; Seager et al. 1971, 1975; Harbour 1972; Hawley 1975, 1978; King and Hawley 1975; Lovejoy 1976a; Zohdy et al. 1976; Uphoff 1978; Seager and Morgan 1979; Birch 1980; Wilson et al. 1981).

1.5.3 Developments in Hydrogeology Since 1980

Accelerated emphasis on geological and geophysical investigations in the Mesilla Basin area since 1980 has resulted in a very large body of published information, much of which is directly applicable to the development of the present generation of hydrogeologic models. The following reports and maps, many of which include cross-section views of basin deposit and structures, served as the primary baseline-information sources used in the present study: Gile and others (1981), Seager (1981, 1995), Wilson and others (1981), Gross and Icerman (1983), Wilson and White (1984), Hawley (1984), Seager and others (1982, 1984, 1987), Mack (1985), Myers and Orr (1986), Gross (1988) Hawley and Lozinsky (1992), Nickerson and Myers (1993), Mack and others (1993, 1997, 1998), Wade and Reiter (1994), Giles and Pearson (1998), Kennedy (1999), Keller and others (1998), Maciejewski and Miller (1998), Collins and Raney (2000), Jimenez and Keller (2000), and Hawley and others (2000, 2001). Our syntheses and interpretations of information from the above-cited sources are illustrated on Plates 1 to 6 and discussed in Sections 4.2, 5.1 and 5.3.

1.5.4 Groundwater-Flow Modeling Since 1980

Substantial progress has been made since 1981 in the development of basin-scale numerical models of groundwater-flow systems in the Mesilla Basin area (e.g., Peterson et al. 1984; Frenzel and Kaehler 1992; Nickerson and Myers 1993; Shomaker and Finch 1996; Balleau 1999; Heywood and Yager 2003). The Frenzel and Kaehler (1992) report also includes an excellent synthesis of then available information on groundwater chemistry by Scott Anderholm (see discussion in Witcher et al. 2004). Much current emphasis of numerical modeling has been on the well-integrated, surface-water and shallow groundwater systems of the irrigated-valley area of the Rio Grande Project (e.g., Hamilton and Maddock 1993); and it is important to note that recent studies also involve much needed assessments of the complex geochemical interrelationships between surface-water and shallow groundwater throughout the river basin (e.g., Anderholm et al. 1995; Anderholm and Heywood 2003; Healy 1996).

Detailed review of this topic is beyond the scope of this investigation; but the essential point made here is that all groundwater-flow models must meet the hydrogeologic constraints placed on flow regimes by lithofacies, stratigraphic, and structural-boundary conditions that are either well documented or reasonably inferred (Kernodle 1992a; Hawley and Kernodle 2000).

2.0 METHODS

2.1 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. 2-1a). 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. 2-1b). The first part is a two-letter prefix used to identify the county, with El Paso County 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. 2-1b), 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.

2.2 DATA COMPILATION, ANALYSIS, AND SYNTHESIS

Much of the comprehensive database compiled for this investigation had already been collected for the earlier geohydrologic and hydrogeologic research projects at New Mexico Tech (Hawley 1984; Peterson et al. 1984; Hawley and Lozinsky 1992). The major published sources of information used in those studies included Leggat and others (1962), Cliett (1969), King and others (1971), Wilson and others (1981), Wilson and White (1984), Myers and Orr (1986), Frenzel and Kaehler (1992), and Nickerson and Myers (1993). In addition, a large amount of unpublished data (primarily drilling, and borehole-sample and geophysical logs) was obtained from files of the USGS-WRD and the NMBMMR.

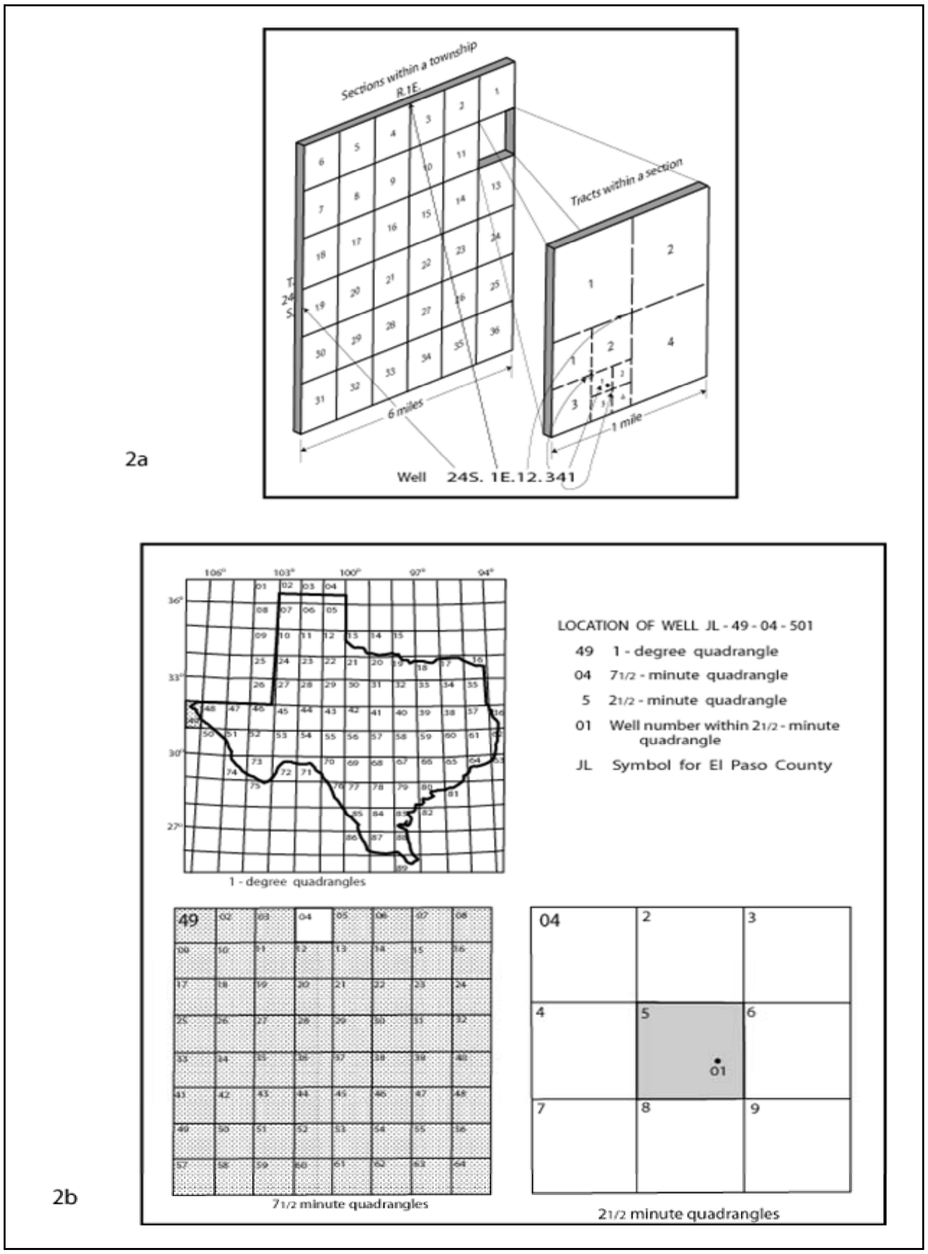

Figure 2-1. Well numbering systems: a. New Mexico; b. Texas.

Hydrogeologic investigations between 1986 and 1992 were a collaborative effort involving the NMBMMR-NM Tech (Hawley and Lozinsky), USGS-WRD (Ken Stevens), NMOSE (Francis West) and EPWU (Tom Cliett). Emphasis was on compilation and interpretation of subsurface geologic, geophysical and geochemical data. Key sources of borehole data were identified and located on available geologic maps of the Mesilla Basin (scales 1:24,000 and 1:100,000) for use as control points. These sources included borehole geophysical and sample logs, geothermal data, and geochemical analyses (Appendix—Tables A1 to A4, Plates A1 to A9). Six new test wells drilled by the USGS-WRD and EPWU provided supplemental information. The Afton, Lanark, La Union, and Noria test wells were drilled in the basin area west of Mesilla Valley (MT 1 to 4; 25.1.6.333, 27.1.4.121, 27.2.13.331, 28.1.34.414). The other two wells (CWF1D, CWF4D; JL-49-04-481, 469) are located in the Cañutillo Well Field area on the Rio Grande floodplain west of Vinton, Texas (Nickerson 1987, 1989; Nickerson and Myers 1993). 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). This database also includes water analyses from one or more sampling intervals in most of the key wells (Hawley and Lozinsky 1992, Table 4; Appendix—Tables A3, A4).

2.2.1 Drill-Cutting and Thin-Section Analyses

Tools needed to properly describe the sand-size fraction of basin-fill deposits include the binocular microscope for preliminary drill-cutting descriptions, the petrographic (light) microscope for 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 sand-size material from selected sets of drill cuttings and outcrop samples. 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) internals. Geophysical and driller logs facilitated drill-cutting interpretations.

Cuttings from the Afton (MT1, 25.1.6.333), Lanark (MT2, 27.1.4.121), La Union (MT3, 27.2.13.331), and Noria (MT4, 28.1.34.414) test wells were analyzed initially with a binocular microscope in order 1) to construct a stratigraphic column for each of these key wells (Plates 12-15 in Hawley and Lozinsky 1992) and 2) to determine intervals where sub-samples 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 Filed (CWF1D and CWF4D; Nickerson and Myers 1993) and from six outcrops of the *upper* and *middle* Santa Fe units. 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. 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 Hawley and Lozinsky (1992, Section III) and they are summarized in Section 4.3.3. 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-MT1, Lanark-MT2, La Union-MT-3, and Noria-MT4 test wells (Hawley and Lozinsky 1992, Plates 12-15).

2.2.2 Digitizing Geophysical Logs and Geologic Maps

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 mean sea level (asl). The vertical scale now used in borehole-log plotting is 1 in = 200 ft, 1 cm = 24 m. Digitizing of geophysical logs and plotting of cross-section worksheets was done in collaboration with Ken Stevens, formerly with the New Mexico USGS-WRD District Office. He developed the original computer-generated graphics system utilized in the Hawley and Lozinsky (1992) study for integrating geophysical, geophysical, geologic, and hydrologic data (Witcher et al. 2004; Appendix—Plates A1 to A9). During the past 4 years, the entire Mesilla area database, including all available geologic maps and cross-sections, has been upgraded and redigitized where necessary.

2.2.3 Digital Hydrogeologic Framework and GIS Syntheses

One of the major objectives of the current study has been the creation of a digital, GIS-based physical model of Mesilla Basin hydrogeology using ARCINFO®. Plate 1 is a map view of the Mesilla Basin's hydrostratigraphic framework, which shows the surface-distribution patterns of major bedrock and basin-fill mapping units. It has been compiled during the present (1999-2001) study phase, primarily from baseline geologic and soil-geomorphic mapping (Gile et al. 1981; Seager et al. 1987; Seager 1995).

Hawley and Lozinsky (1992, Plates 2-11, Table 4) prepared ten preliminary hydrogeologic cross-sections in their original synthesis of a Mesilla Basin model. Supported in part by additional contributions from Nickerson and Myers (1993), we updated and redigitized six of these sections for inclusion in the recent NMWRRI project report on “Sources of Salinity . . .” (Witcher et al. 2004, and Appendix—Plates A2 to A7). Much additional borehole geophysical and geochemical data, and hydrogeologic interpretations have been compiled for the present study in order to integrate all available surficial and subsurface information into a 3-D conceptual model of the basin hydrogeologic framework (Appendix—Tables A1 to A4). Of particular note is Plate 7, which is the first relatively detailed working model of basin-fill basal topography and structure.

3.0 BASIC HYDROGEOLOGIC CONCEPTS

3.1 BASIN AND RANGE GEOHYDROLOGIC SYSTEMS

The primary groundwater reservoirs in the Basin and Range province are in the poorly consolidated sediments that have accumulated in the intermontane structural basins (bolsons, semibolsons). While they are commonly referred to as "alluvial basins" (Wilkins 1986, 1998), their fills are not entirely of alluvial origin because they also include lesser amounts of lacustrine, eolian and colluvial deposits (Hawley et al. 1969, 2000, 2001; Seager 1995; Seager et al. 1987). Fractured volcanic rocks (basalts, andesites, and tuffs), which immediately underlie or are locally interlayered with the Santa Fe Group, form important aquifers in only a few places (Hawley et al. 2000). Groundwater production from most consolidated rocks of the region, however, is limited to low-yield fracture zones, which occur in a wide variety of bedrock types including sedimentary, volcanic, intrusive-igneous, and metamorphic.

Bedrock terranes of structural highlands are the ultimate source areas for the basin fill, and they usually form effective boundaries for basin-fill aquifer systems. Inter-basin and intrabasin boundary structures, such as faults and flexures, are also part of the group of tectonic and volcanic features that play a major role in groundwater-flow dynamics. Unlike some parts of the Basin and Range province (e.g., southern Nevada and Trans-Pecos Texas), there are no extensive bodies of carbonate rock that provide conduits for regional, inter-basin groundwater flow (Maxey 1968; Winograd and Thordarson 1975; Hibbs et al. 1998; Sharp 2001). As noted in Sections 4.2.1, 5.1 and 7.3, however, local bedrock terranes dominated by dissolution-prone carbonate and gypsiferous sedimentary units may play a significant role in intrabasin, geothermal-flow systems and as sources of saline groundwater. This important topic and ongoing need to evaluate bedrock aquifer systems, as at least locally important groundwater resources, is briefly discussed in Section 8.2.7.

Figure 3-1, adapted from Eakin and others (1976), illustrates the general model of hydrogeologic framework and groundwater flow that is applicable throughout the Basin and Range province. This block diagram also incorporates information from other studies in the B & R--Great Basin section (e.g., Mifflin 1968, 1988), and the West Texas--Chihuahua region (Hibbs et al. 1998; Sharp 2001). Note that the topographic terms *closed* and *open* are here used only in reference to the surface flow into, through, and from intermontane basins; whereas the terms *undrained*, *partly drained*, and *drained* designate basin types with groundwater-flow regimes involving intrabasin and/or inter-basin movement. *Phreatic* and *vadose*, respectively, indicate saturated and unsaturated subsurface conditions. *Phreatic playas* (with springs and seeps) are restricted to floors of *closed* basins (*bolsons, bolsones*) that are *undrained* or *partly drained;* while *vadose playas* occur in both *closed* and *open*, *drained* basins. *Cienegas* are a special wetland class located in places where the zone of saturation intersects an undissected valley-floor surface. Few intermontane basins (*bolsons* and *semibolsons*) of the southern Basin and Range province are truly *undrained* in terms of groundwater discharge, whether or not they are topographically *closed* or *open*. In the Mesilla Basin - Rio Grande rift region, the (intermediate) *partly drained* basin type, which is also "incompletely" *open*, represents the major geohydrologic system.

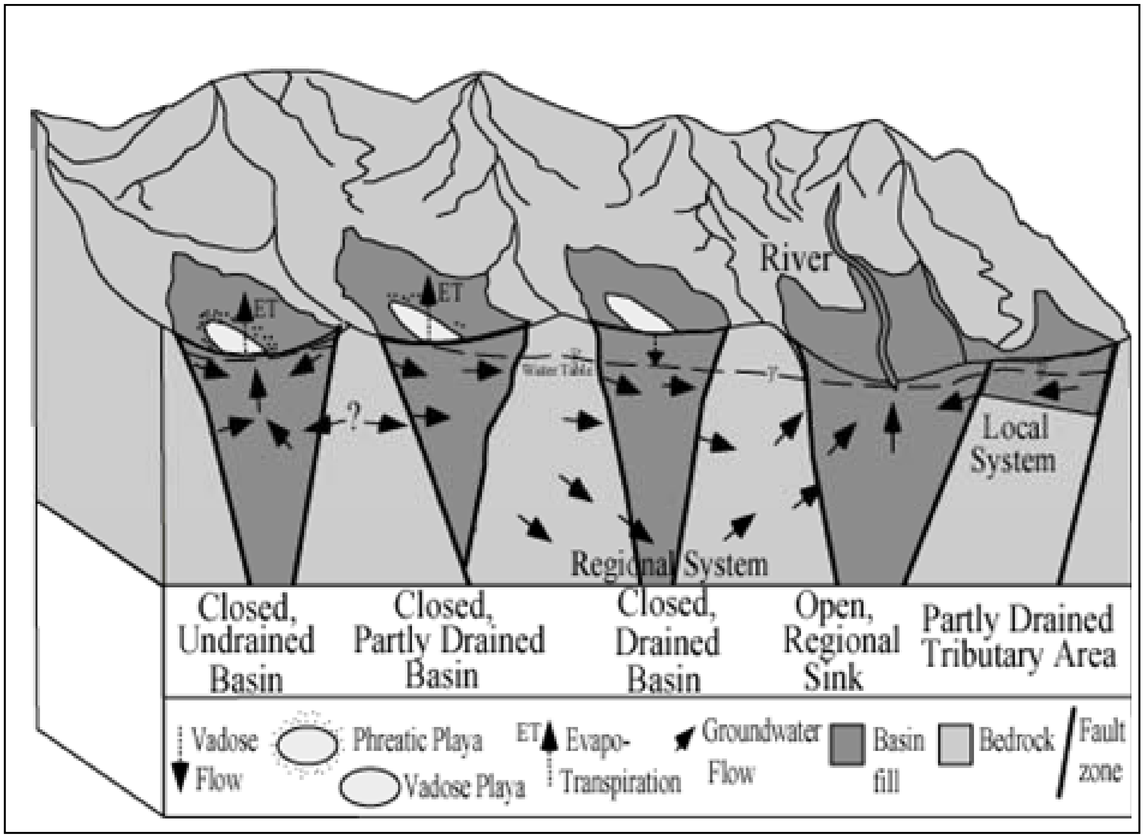

Figure 3-1. Schematic diagram showing hydrogeologic framework and groundwater-flow system in interconnected group of closed and open; undrained, partly drained, and drained intermontane basins. Modified from Eakin and others (1976), Mifflin (1986), and Hibbs and others (1998).

Under predevelopment conditions, groundwater discharge in the region occurred mainly through 1) interbasin subsurface leakage, 2) contributions to gaining reaches of perennial or intermittent streams, 3) flow from seeps and springs, 4) evapotranspiration from basin- and valley-floor wetlands (including *phreatic playas, bosques* and *cienegas*), and 5) evaporation from open-water bodies. Most recharge to basin-fill aquifers occurs by two mechanisms: “mountain front,” where some precipitation falling on bedrock highlands contributes to the groundwater reservoir along basin margins (Fig. 3-2); and “tributary,” where the reservoir is replenished and along losing reaches of larger intra-basin streams (Section 7.2; Hearne and Dewey 1988; Nickerson and Myers 1993; Anderholm 1994, 2001; Wasiolek 1995; Scanlon et al. 2001; Waltemeyer 2001; Naus 2002). Note that Figure 3-2 also illustrates the concept of “mountain-block” recharge whereby some fraction of upland precipitation percolates deeply into a bedrock block and emerges into the basin fill as a subsurface flow component (c.f. Feth 1964).

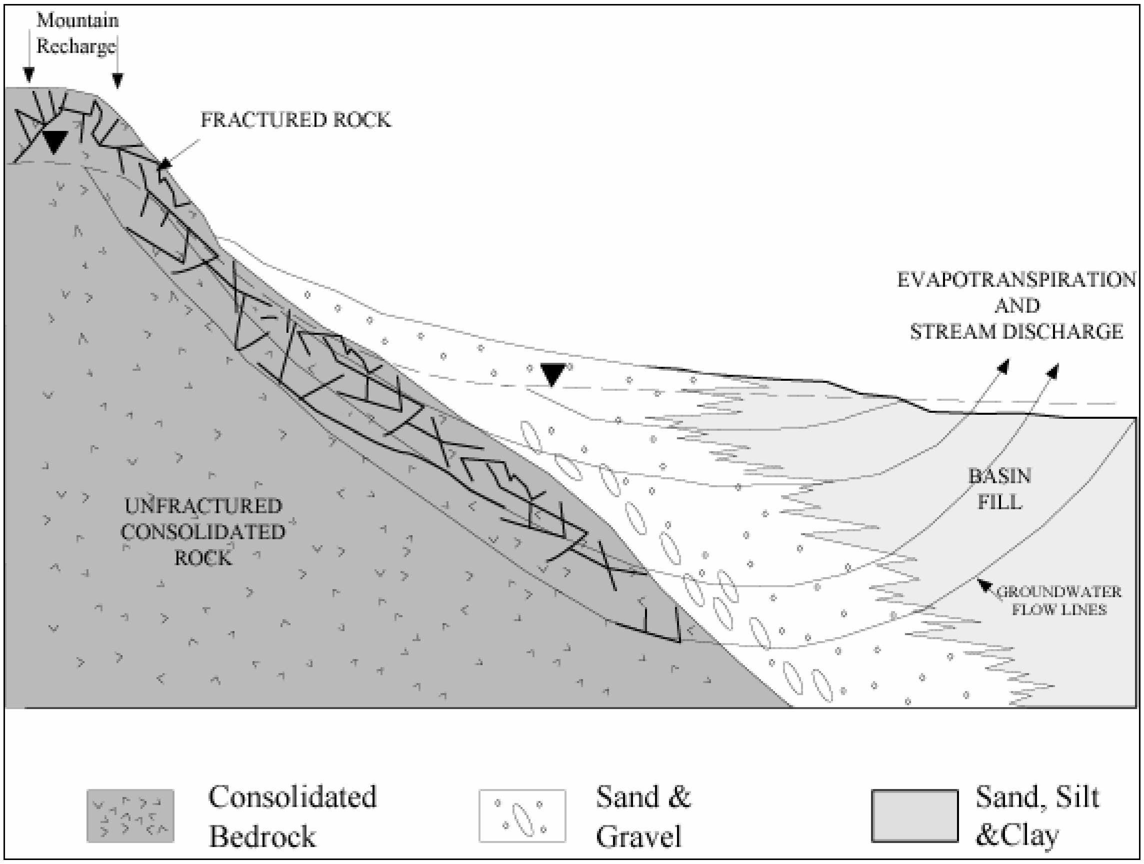

Figure 3-2. Two-dimensional conceptual model of a groundwater recharge system in a Basin and Range by hydrogeologic setting (from Wasiolek, 1995, modified from Feth 1964, and Mifflin 1986).

We also recognize that short- and long-term climatic changes have significant impacts on all water-resource concerns in this arid to semi-arid region (Sections 7.2, 7.3). Therefore, while very large quantities (millions of ac-ft) of fresh to slightly saline water are stored in the basin-fill aquifer system, much of it is not being effectively recharged under the warm-dry environmental conditions of the past 5 to 10 thousand years. Current research in the Rio Grande rift region indicates that most groundwater in storage is thousands to tens thousands of years old and was recharged during cooler and wetter parts of Quaternary glacial-pluvial cycles (Plummer et al. 2000; Scanlon et al. 2001).

3.2 CONCEPTUAL HYDROGEOLOGIC-FRAMEWORK MODEL

The hydrogeologic framework of basin-fill aquifers in the Rio Grande rift region, with special emphasis on features related to both groundwater flow and quality, is best characterized in terms of three basic building blocks: 1) lithofacies assemblages (LFAs), 2) hydrostratigraphic units (HSUs), and 3) bedrock and structural-boundary conditions (Hawley and Haase 1992; Hawley and Lozinsky 1992; Hawley et al. 1995). Our current conceptual model of interconnected shallow valley-fill—basin-fill and deep-basin aquifer systems was initially developed for use in groundwater-flow models of the Mesilla and Albuquerque basins (Peterson et al. 1984; Frenzel and Kaehler 1992; Thorn et al. 1993; Kernodle et al. 1995). However, basic design of the conceptual model is flexible enough to allow it to be modified for use in other basins of the Rio Grande rift and adjacent parts of the southeastern Basin and Range province (e.g., Hawley and Kernodle 2000; Hawley et al. 2000, 2001).

Hydrogeologic models of this type are simply qualitative to semi-quantitative descriptions (graphical, numerical, and verbal) of how a given geohydrologic system is influenced by 1) bedrock-boundary conditions, 2) internal-basin structure, and 3) lithofacies characteristics of various basin-fill stratigraphic units. They provide a mechanism for systematically organizing a large amount of relevant hydrogeologic information of widely varying quality and scale (from very general driller's observations to detailed bore-hole logs and water-quality data). Model elements can then be graphically displayed in combined map and cross-section (GIS) formats so that basic information and inferences on geohydrologic attributes (e.g., hydraulic conductivity, transmissivity, anisotropy, and general patterns of unit distribution) may be transferred to basin-scale, three-dimensional numerical models of groundwater-flow systems. As emphasized by Hawley and Kernodle (2000), however, this scheme of data presentation and interpretation is normally not designed for site-specific groundwater investigations.

3.2.1 Lithofacies Assemblages

Lithofacies assemblages (LFAs) are the basic building blocks of this hydrogeologic model (Fig. 3-3, Table 3-1), and they are the primary elements of the hydrostratigraphic units (HSUs) discussed below. These sedimentary-facies classes are defined primarily on the basis of grain-size distribution, mineralogy, sedimentary structures, and degree of post-depositional alteration. The secondary basis for definition is according to inferred environments of deposition. LFAs have distinctive geophysical, geochemical and hydrologic attributes; and they provide a mechanism for showing distribution patterns of major aquifers and confining units in hydrogeologic sections. Basin and valley fills are here subdivided into thirteen major LFAs that are ranked in decreasing order of aquifer potential (Tables 3-1 to 3-3; LFAs 1-10, a-c). Figure 3-3 is a schematic illustration of the distribution pattern of major facies assemblages observed in the basins of the Rio Grande rift region. Lithofacies properties that influence groundwater flow and production potential are summarized in Tables 3-2 and 3-3. Note that *Roman numeral* notations (I to X) used in earlier versions of this classification scheme (Hawley and Lozinsky 1992; Hawley et al. 1995) has been changed to *Arabic* style. This should facilitate development of alphanumeric attribute codes that are more appropriate for GIS applications and numerical modeling.

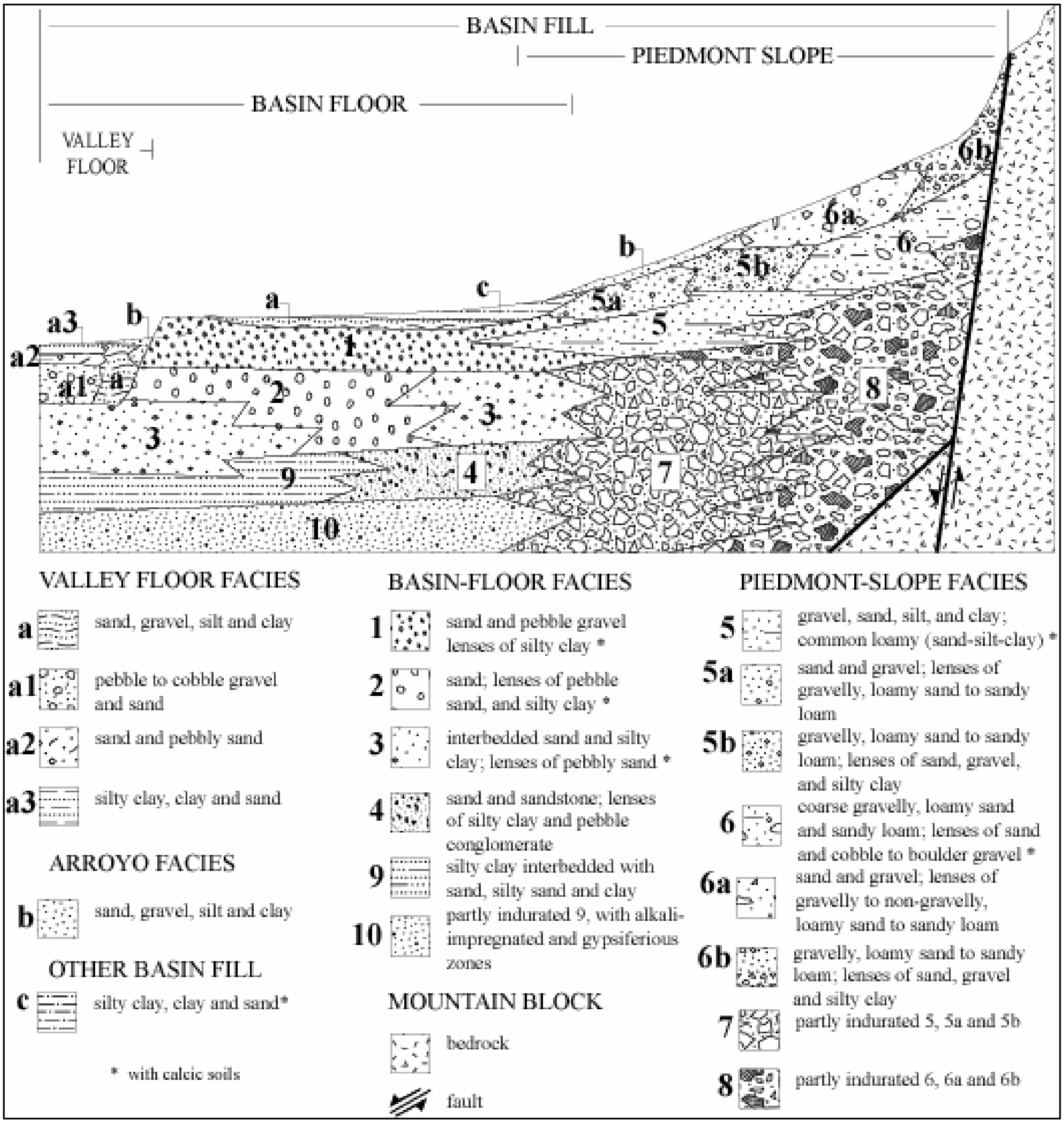

Figure 3-3. Schematic distribution pattern of major lithofacies assemblages (Tables 3-1 to 3-3) in basin and valley fills of the Rio Grande rift region (from Hawley et al., 2000).

Table 3-1. Summary of Gila and Santa Fe Group (1-10) and post-Gila and Santa Fe (a,b,c) lithofacies depositional settings and dominant texture in southwestern New Mexico (modified from Hawley and Haase 1992, Table III-2)

Lithofacies		Dominant depositional settings and process	Dominant textural classes
1		Basin-floor fluvial plain	Sand and pebble gravel, lenses of silty clay
2		Basin-floor fluvial, locally eolian	Sand; lenses of pebble sand, and silty clay
3		Basin-floor, fluvial-overbank, fluvial-deltaic and playa-lake; eolian	Interbedded sand and silty clay; lenses of pebbly sand
4		Eolian, basin-floor alluvial	Sand and sandstone; lenses of silty sand to clay
5		Distal to medial piedmont-slope; alluvial fan	Gravel, sand, silt, and clay; common loamy (sand-silt-clay)
	5a	Distal to medial piedmont-slope, alluvial fan; asociated with large watersheds;alluvial-fan distributary-channel primary; sheet-flood and debris-flow secondary	Sand and gravel; lenses of gravelly, loamy sand to sandy loam
	5b	Distal to medial piedmont-slope, alluvial fan; associated with small steep watersheds, debris-flow sheet-flood, and distributary-channel	Gravelly, loamy sand to sandy loam; lenses of sand, gravel, and silty clay
6		Proximal to medial piedmont-slope, alluvial-fan	Coarse gravelly, loamy sand and sandy loam; lenses of sand and cobble to boulder gravel
	6a	Like 5a	Sand and gravel; lenses of gravelly to non-gravelly, loamy sand to sandy loam
	6b	Like 5b	Gravelly, loamy sand to sandy loam; lenses of sand, gravel, and silty clay
7		Like 5	Partly indurated 5
8		Like 6	Partly indurated 6
9		Basin-floor-alluvial flat, playa, lake, and fluvial-lacustrine; distal-piedmont alluvial	Silty clay interbedded with sand, silty sand and clay
10		Like 9, with evaporite processes (paleophreatic)	Partly indurated 9, with gypsiferous and alkali-impregnated zones
a		River-valley, fluvial	Sand, gravel, silt and clay
	a1	Basal channel	Pebble to cobble gravel and sand (like 1)
	a2	Braided plain, channel	Sand and pebbly sand (like 2)
	a3	Overbank, meander- belt oxbow	Silty clay, clay, and sand (like 3)
b		Arroyo channel, and valley-border alluvial-fan	Sand, gravel, silt, and clay (like 5)
c		Basin floor, alluvial flat, cienega, playa, and fluvial-fan to lacustrine plain	Silty clay, clay and sand (like 3,5, and 9)

Table 3-2. Summary of properties that influence groundwater production potential of Gila and Santa Fe Group lithofacies (modified from Haase and Lozinsky 1992) [>, greater than; <, less than]

Lithofacies	Ratio of sand plus gravel to silt plus clay[1]	Bedding thickness (meters)	Bedding configuration[2]	Bedding continuity (feet)[3]	Bedding connectivity[4]	Hydraulic conductivity (K)[5]	Groundwater production potential
1	High	>1.5	Elongate to planar	>1000	High	High	High
2	High to moderate	>1.5	Elongate to planar	>1000	High to moderate	High to moderate	High to moderate
3	Moderate	>1.5	Planar	500 to 1000	Moderate to high	Moderate	Moderate
4	Moderate to low*	>1.5	Planar to elongate	100 to 500	Moderate to high	Moderate	Moderate
5	Moderate to high	0.3 to 1.5	Elongate to lobate	100 to 500	Moderate	Moderate to low	Moderate to low
5a	High to moderate	0.3 to 1.5	Elongate to lobate	100 to 500	Moderate	Moderate	Moderate
5b	Moderate	0.3 to 1.5	Lobate	100 to 500	Moderate to low	Moderate to low	Moderate to low
6	Moderate to low	0.3 to 1.5	Lobate to elongate	100 to 500	Moderate to low	Moderate to low	Low to moderate
6a	Moderate	0.3 to 1.5	Lobate to elongate	100 to 500	Moderate	Moderate to low	Moderate to low
6b	Moderate to low	0.3 to 1.5	Lobate	<100	Low to moderate	Low to moderate	Low
7	Moderate*	0.3 to 1.5	Elongate to lobate	100 to 500	Moderate	Low	Low
8	Moderate to low*	>1.5	Lobate	<100	Low to moderate	Low	Low
9	Low	>5	Planar	>500	Low	Very low	Very low
10	Low*	>5	Planar	>500	Low	Very low	Very low

[1] High >2; moderate 0.5-2; low <0.5

[2] Elongate (length to width ratios >5); planar (length to width ratios 1-5); lobate (asymmetrical or incomplete planar beds).

[3] Measure of the lateral extent of an individual bed of given thickness and configuration.

[4] Estimate of the ease with which groundwater can flow between individual beds within a particular lithofacies. Generally, high sand + gravel/silt + clay ratios, thick beds, and high bedding continuity favor high bedding connectivity. All other parameters being held equal, the greater the bedding connectivity, the greater the groundwater production potential of a sedimentary unit (Hawley and Haase 1992, VI).

[5] 10 to 30 m/day; moderate, 1 to 10 m/day; low, <1 m/day; very low, <0.1 m/day.

*Significant amounts of cementation of coarse-grained beds (as much as 30%)

Table 3-3. Summary of properties that influence groundwater production potential of post Santa Fe Group lithofacies assemblages [>, greater than; <, less than]

Lithofacies	Ratio of sand plus gravel to silt plus clay[1]	Bedding thickness (feet)[3]	Bedding configuration[2]	Bedding continuity (feet)[3]	Bedding connectivity[4]	Horizontal hydraulic conductivity (K)[5]	Groundwater production potential
a	High to moderate	>5	Elongate to planar	>1000	High to moderate	High to moderate	High to moderate
a1	High	>5	Elongate to planar	>1000	High	High	High
a2	High to moderate	>5	Planar to elongate	500 to 1000	Moderate to high	Moderate	Moderate
a3	Moderate to low	>5	Planar to elongate	100 to 500	Moderate to high	Moderate to low	Moderate to low
b	Moderate to low	1 to 5	Elongate to lobate	>300	Moderate	Moderate to low	Moderate to low
c	Low to moderate	1 to 5	Elongate to lobate	100 to 500	Low	Low	Low

[1] High>2;moderate 0.5-2; low <0.5

[2] Elongate (length to width ratios>5); planar (length to width ratios 1-5); Lobate (lenticular or discontinuous planar beds).

[3] Measure of the lateral extent of an individual bed of given thickness and configuration.

[4] Estimate of the ease with which groundwater can flow between individual beds within a particular ligholacies. Generally, high sand + gravel/silt + clay ratios, thick beds, and high bedding continuity favor high bedding connectivity. All other parameters

[5] General ranges: high 30 to 100ft/day; moderate, 3 to 30ft/day; low, <3ft/day; very low, <0.1ft/day.

3.2.2 Hydrostratigraphic Units

"A hydrostratigraphic unit (Seaber 1988) may represent an entire [litho] stratigraphic unit, a portion of a stratigraphic unit, or a combination of adjacent stratigraphic units with consistent hydraulic properties" (Giles and Pearson 1998, p.322). Most intermontane-basin fills in the southern New Mexico region are subdivisions of two broad lithostratigraphic categories, the Santa Fe Group in the Rio Grande rift (Hawley et al. 1969; Hawley 1978; Chapin and Cather 1994) and the Gila Group ("Conglomerate") in Basin and Range, and Datil-Mogollon areas to the west (Hawley et al. 2000). The bulk of these deposits are of Late Neogene age (Miocene and Pliocene; ~23 to 1.8 Ma). In many previous hydrogeologic studies, clear distinctions have not been made between "bolson or basin fill" and contiguous (formal or informal) subdivisions of the Santa Fe and Gila Groups. As a first step in organizing available information on basin-fill stratigraphy and sedimentology with emphasis on aquifer characteristics, a provisional hydrostratigraphic classification system has been developed that is applicable to most basins of the southeastern Basin and Range province. This is an ongoing process, with progressive system refinement occurring with each new study phase. To date this informal classification scheme has been used successfully in the Albuquerque and Mesilla Basins and in adjacent "Southwest Alluvial Basins" (Hawley 1984, 1996; Hawley and Haase 1992; Hawley and Lozinsky 1992; Hawley and Kernodle 2000; Hawley et al. 1995, 2000, 2001).

In Rio Grande rift basins south of Elephant Butte Dam (Palomas-Rincon, Jornada del Muerto, Mesilla, and Hueco-Tularosa basins, Fig. 1-1), the Santa Fe Group has been further subdivided into five major formation-rank units that record stages of basin filling and tectonic evolution prior to incision of the present river-valley system (Fig. 3-4). From youngest to oldest, these mapping units are formally named the Camp Rice, Palomas, Fort Hancock, Rincon Valley, and Hayner Ranch Formations (Section 4.3.2; Strain 1966; Seager et al. 1971; Gile et al. 1981; Lozinsky and Hawley 1986; Seager et al. 1982, 1984,1987; Seager 1995; Mack et al. 1998; Collins and Raney 2000).

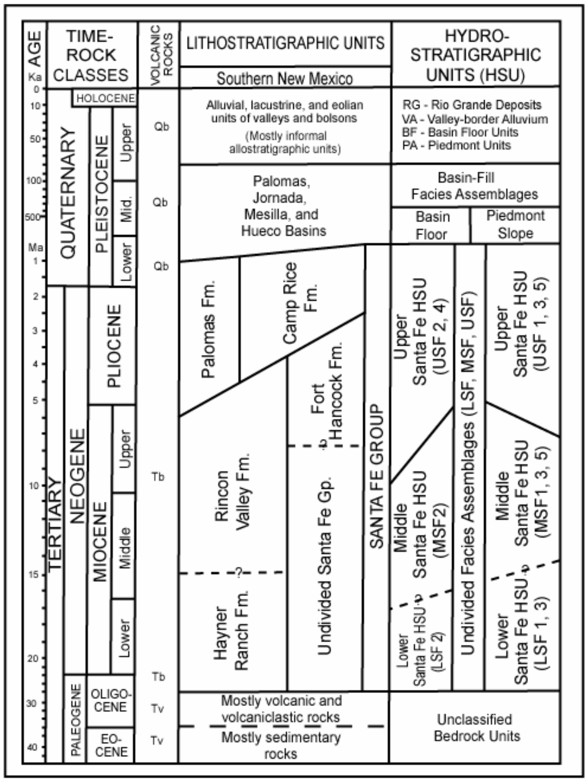

Figure 3-4. Regional summary and correlation of major chronologic, lithostratigraphic, and basin-fill hydrostratigraphic units in the Mesilla Basin region of southern New Mexico and Trans-Pecos Texas. Igneous rock symbols: Qb–Quaternary basalt, Tb–Tertiary mafic volcanics, and Tv–older Tertiary intermediate and silicic volcanics, and associated plutonic and sedimentary rocks. Modified from Hawley and Kernodle (2000).

Hydrostratigraphic units (HSUs) defined in the Rio Grande rift region are mappable bodies of basin and valley fill that are grouped according to genesis and position in both lithostratigraphic and chronostratigraphic sequences. Informal upper, middle, and lower Santa Fe hydrostratigraphic units (HSUs: USF, MSF, LSF) form the major basin-fill aquifer zones, and they correspond roughly to the upper (Camp Rice-Palomas), middle (Fort Hancock/Rincon valley, and lower (Hayner Ranch) lithostratigraphic subdivisions of the Santa Fe Group used in local and regional geologic mapping (Fig. 3-4). Dominant lithofacies assemblages in the upper Santa Fe HSU are LFAs 1-3, 5 and 6. The middle Santa Fe HSU is characterized by LFAs 3, 4, 7-9, and the lower Santa Fe commonly comprises LFAs 4, 7-10. Basin-floor facies assemblages 3 and 9 are normally present throughout the Santa Fe Group section in closed-basin (bolson) areas.

The other major hydrostratigraphic units comprise channel and floodplain deposits of the Rio Grande (HSU–RA) and its major arroyo tributaries (VA). These valley fills of Late Quaternary age (<130 ka) form the upper part of the region's most productive shallow-aquifer system. Surficial lake and playa deposits, fills of larger arroyo valleys, and piedmont-slope alluvium are primarily in the *vadose* zone. However, they locally form important groundwater discharge and recharge sites. Historical *phreatic* conditions exist, or have recently existed, in a few playa remnants of large pluvial lakes of Late Quaternary age (Hawley 1993). Notable examples are gypsum or alkali flats in the Tularosa, Jornada del Muerto and Los Muertos basins, which are contiguous to, but outside the area of discussion (Figs. 1-1 and 1-2; Hawley 1993; Lucas and Hawley 2002; Gile 2002).

3.2.3 Bedrock and Structural-Boundary Components

Bedrock and structural-boundary conditions that influence the behavior of basin-aquifer systems include bordering mountain uplifts, bedrock topography beneath the basin fill, fault zones and flexures within and at the edges of basins, and igneous (intrusive and extrusive) rocks that penetrate or are interbedded with basin fill (Plates 1 to 7). Tectonic evolution of the fault-block basins and ranges of the south-central New Mexico border region during the past 25 Ma has had a profound effect on the distribution of lithofacies assemblages and the timing and style of emplacement of all major hydrostratigraphic units (Figs. 3-3 and 3-4). Most of the significant bedrock- and structural-boundary features in the area now are well documented on geologic maps and cross sections by Collins and Raney (2000), Giles and Pearson (1998), Lovejoy (1976a), Maciejewski and Miller (1998), Seager (1981, 1995), Seager and Mack (1994), Seager and others (1982, 1987), and Woodward and Myers (1997). These topics are addressed in more detail in the following section (4.1, 4.2) and in Section 5.1).

4.0 GENERAL GEOLOGIC SETTING

4.1 OVERVIEW

Detailed discussion of the area's geologic history is beyond the scope of this paper; and the reader is referred to excellent reviews in Seager and others (1984), Chapin and Cather (1994), Keller and Cather (1994), Mack and others (1998), and Raatz (2001). Emphasis here is on those key elements of the geologic setting that directly apply to the Mesilla Basin's hydrogeologic framework and related aspects of groundwater flow and chemistry.

The Mesilla and Jornada structural basins are near the southern end of the north-trending series of basins and flanking mountain uplifts that constitute the Rio Grande rift tectonic province (Figs. 1-1, 1-2; Plates 1 to 6; Keller and Cather 1994). The ongoing rifting process began in Oligocene time, about 25 to 30 million years ago (Ma). 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. North-trending half-graben structures of the rift province, many with accommodation-zone terminations, are the dominant tectonic forms of the regional geologic terrane (Fig. 1-1); and they are commonly superimposed on mid-Tertiary volcano-tectonic features (e.g., Organ and Doña Ana uplifts), and still older Laramide structural highs and depressions (Seager and Mack 1986; Mack and Clemons 1988; Seager 2003; Seager and Mack 2003).

All Rio Grande rift basin fill that predate entrenchment of the present river-valley system is included in the Santa Fe Group (Spiegel and Baldwin 1963; Hawley et al. 1969; Hawley 1978, Charts 1 and 2; Chapin and Cather 1994). Geologic mapping and geochronologic studies throughout the region (Fig. 3-4) demonstrate the continuity of rift-basin fill that was originally recognized by Kirk Bryan (1938). The river itself flows southward through New Mexico in a series of canyons and valleys that follow the N-S trends of most rift basins from the San Luis basin to the southern end of the Mesilla Valley (Fig. 1.1). Beyond the Paso del Norte constriction (Fig. 1.2), the El Paso Valley reach of the Rio Grande follows the general southeast trend of the Hueco Bolson.

4.2 STRUCTURAL-GEOLOGIC FRAMEWORK

The general geologic setting of the Mesilla and southern Jornada Basins is illustrated by an index map (Fig. 4-1) that shows basin-scale structural features and locations of two schematic cross-sections, which extend across the northern (Las Cruces) and south-central (Anthony, NM-TX) parts of the basin (Figs. 4-2a, b). Section base elevation is 10,000 ft below sea level, and there is no vertical exaggeration. A much more detailed view of the basin’s hydrogeologic framework is provided by the hydrogeologic base map, cross-sections, and bedrock-topography map (Plates 1 to 7). These illustrations are the latest product of hydrogeologic/geophysical data synthesis using methods developed by Hawley and associates (1984-1995). However, many of our interpretations are based on earlier compilations of surface and subsurface geologic and hydrogeologic information by Hawley and others (1969) and King and others (1971). Other major contributors to the hydrogeologic interpretations presented in this report include Leggat and others (1962), Cliett (1969), Gile and others (1981), Wilson and others (1981), Wilson and White (1984), Myers and Orr (1986), Seager and others (1987), Seager (1995), Nickerson and Myers (1993), Mack and others (1998), and Ken Stevens (1985-1987, USGS-WRD unpublished).

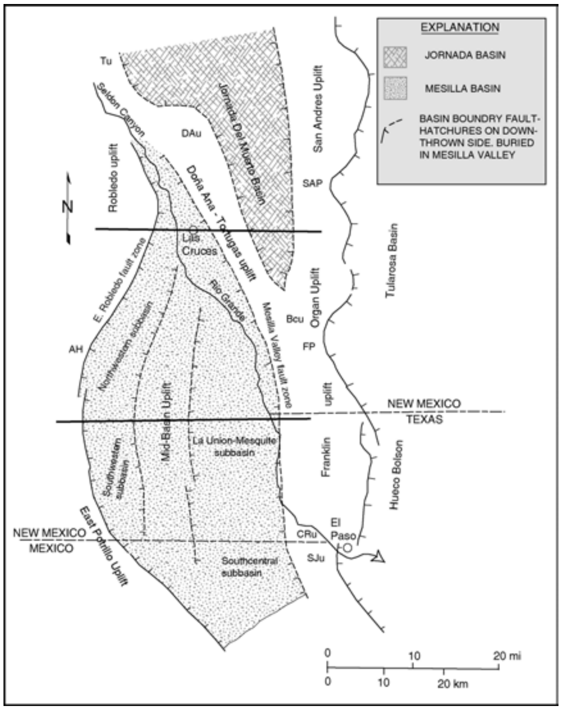

Figure 4-1. Index map of Mesilla Basin area showing major basin-boundary and intrabasin fault zones and uplifts. Locations of structural-geologic sections (Fig. 4-2 a, b) are also shown. Modified from Hawley and Lozinsky (1992).

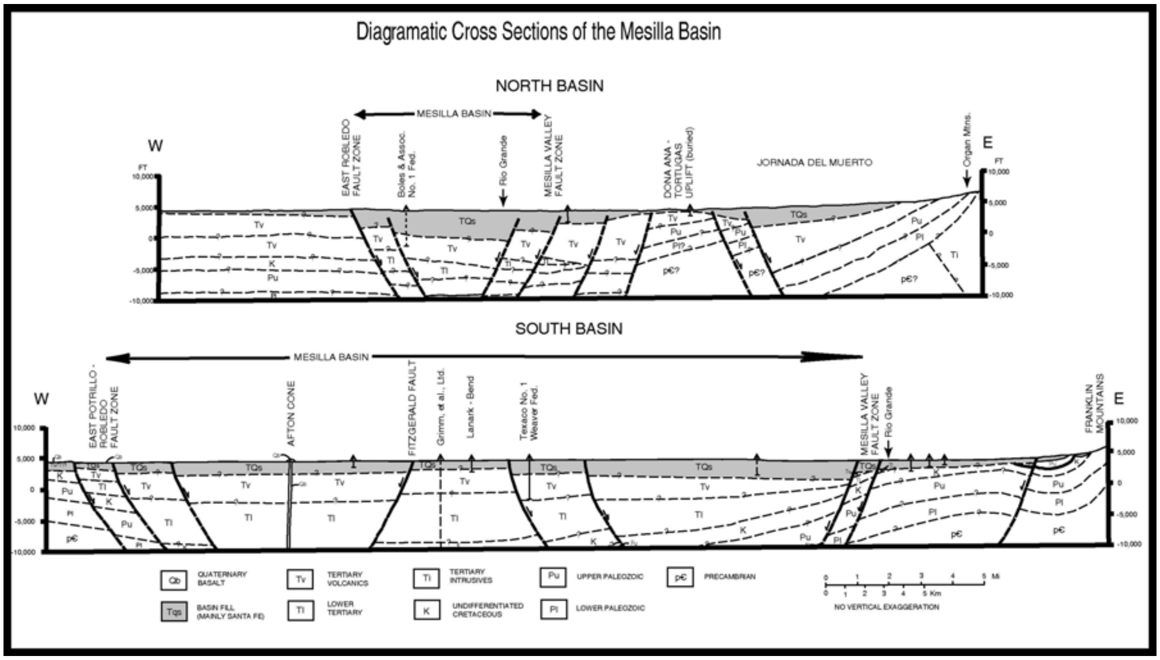

Figure 4-2. Schematic structural-geologic sections of the northern and central Mesilla Basin: **a**. West to east section from Robledo to Doña Ana-Tortugas uplifts across Las Cruces Metro-area. **b**. Section along 32nd Parallel from Aden-Afton volcanic field to Franklin uplift, NM-TX. Section locations shown on Figure 2.6. No vertical exaggeration. Modified from Hawley and Lozinsky (1992).

A distinctive feature of the Santa Fe Group in the Mesilla Basin and much of the southern Jornada Basin is that it is relatively thin (maximum saturated thickness of about 3,000 ft) when compared to fill thickness in adjacent parts of the Hueco-Tularosa and Mimbres basin systems (Seager et al. 1987; Seager 1995; Collins and Raney 2000). Geophysical and sample logs from deep wells drilled in the Mesilla Basin during the past two decades demonstrate that previous estimates of rift-basin-fill thickness are incorrect. For example, compare interpretations of Wilson and others (1981) and Hawley (1984) with those of Hawley and Lozinsky (1992) and Nickerson and Myers (1993). Basin-fill deposits (discussed in detail in following sections) are predominantly alluvial in origin, with eolian and lacustrine lithofacies occurring primarily in older parts of the depositional sequence. Interbedded basaltic volcanic rocks of Miocene age are also locally present, as are feeder conduits for the Quaternary basalts and ejecta from Maar (phreato-magmatic) eruptions, which cap the Santa Fe Group in some parts of the southwestern Mesilla Basin (Section 4.3.1).

4.2.1 Bedrock-Boundary Units

With the exception of the Franklin-Organ-San Andres chain of "basement-cored" uplifts, the Mesilla and southern Jornada Basins are not bounded by continuous ranges of high mountains (Seager 1989, 1995; Seager et al. 1987; Collins and Raney 2000). Onlap of basin fill has buried most of bedrock terrane that separates the Mesilla and Jornada structural basins (i.e., the Tonuco-Doña Ana-Tortugas-southern Organ-Bishop Cap uplifts); and the low East Potrillo-Aden-Robledo uplifts west of the Mesilla Basin are partly buried by Quaternary basalt flows as well as by basin fill (Figs. 4-1, 4-2; Plates 1 to 7).

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*-age) unit throughout middle Pliocene to early Pleistocene time (Mack et al. 1993, 1996, 1998). Widespread basin filling ceased about 700,000 years ago (0.7 ma, early Middle Pleistocene) due to regional entrenchment of the present Rio Grande Valley system. The thickest Santa Fe Group fills in the Mesilla and southern Jornada Basins are located in areas adjacent to the most active segments of four major boundary fault zones: Mesilla Valley, East Potrillo, East Robledo, and Jornada (Figs. 4-1, 4-2; Plates 3a-f, 4a-e, 5c, 6 and 7).

Almost all boundaries between the major subbasins and flanking uplifts appear to be formed by zones of high-angle normal faults. Most of the exposed mountain blocks are strongly tilted; and many of these blocks appear to have half-graben morphology and listric boundary faults that are typical of most continental rift basins (Seager and Morgan 1979; Seager et al. 1987; Mack and Seager 1990; Seager and Mack 1994; Seager 1995; Leeder et al. 1996). 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 that are bounded by high-angle normal faults that may or may not flatten significantly with depth (Fig. 4-2, Plates 3 and 4).

The northeastern Mesilla Basin structural border is formed by a partly buried bedrock ridge, here designated the Doña Ana-Tortugas uplift (Plates 1, 3d-f, 5a, 7). This narrow fault-block uplift marks the boundary between the northeastern Mesilla and southern Jornada structural basins. Recent surface geophysical surveys and test drilling by the U.S. Geological Survey (Woodward and Myers 1997) along the Doña Ana-Tortugas trend have confirmed previous inferences on its extent (Hawley et al. 1969; King et al. 1971; Hawley 1984, Plate H-H'). The eastern boundary fault of the uplift, is the Jornada Fault of Seager and others (1971, 1976, 1987), which is one of the most continuous and prominent basin-boundary faults of the study area. It continues northeastward between the Jornada Basin block and the Doña Ana and Tonuco (San Diego) uplifts. Still farther north it merges with the eastern boundary fault zone of the Rincon Hills (in the northwest part of Plate 1).

The Doña Ana-Tortugas uplift is flanked on the west by another major basin-boundary structure, the Mesilla Valley fault zone, which represents the northern continuation of a buried feature in the lower Mesilla Valley area that was originally named by Lovejoy (1975, 1976b). The two major western basin-boundary faults of the Mesilla Basin are the Robledo fault to the northwest and the East Potrillo fault to the southwest (Plates 1, 3, 4b-4e, 7). As already noted, the topographic basin merges northward with the Jornada Basin, northeast of Las Cruces, and southward with the Bolson de Los Muertos Plains, southwest of El Paso-Ciudad Ju<rez (Figs. 1-1, 1-2, 1-3, 4-1, 4-2). Topographic transition zones with the Mimbres and Hueco-Tularosa basin systems, westward and eastward respectively, are along the I-10 corridor and at Fillmore Pass (Plate 5b).

Tertiary igneous intrusives (granites to monzonites) and volcanics (rhyolites to andesites) are the dominant rocks exposed in the Doña Ana and southern Organ Mountains, with some Paleozoic and lower Tertiary sedimentary rocks being locally exposed (Seager et al. 1976; Seager 1981). Marine-carbonate and siliciclastic rocks of Paleozoic and early Cretaceous age are the dominant lithologic units exposed in the San Andres, Tortugas, Bishop Cap, Franklin, Ju<rez, East Potrillo, and Robledo uplifts

(Plates 1, 3, 4, 5, 6; Harbour 1972; Kelley and Matheny 1983; Seager et al. 1987; Seager and Mack 1994; Collins and Raney 2000). Also of note is the common occurrence of gypsite beds in upper Pennsylvanian rocks of the southern San Andres range, and the northern Franklin and Bishop Cap uplifts.

A variety of sedimentary and intermediate-intrusive rocks of Cretaceous and early Tertiary age crop out in the Paso del Norte area between the Franklin Mountains and Sierra de Juárez, which includes Cerro de Cristo Rey on the Chihuahua-New Mexico border (Plate 1; Córdoba et al. 1969; Lovejoy 1976a). Of special importance to ongoing evaluations of "sources of (groundwater) salinity" is the probability that Paleozoic and Cretaceous carbonate rocks can at least locally form conduits for significant volumes of deeply circulating groundwater. These units are widely exposed and/or shallowly buried along the Mesilla Basin's southern borders and on the western slopes of the San Andres Mountains. This inference is supported by the presence of extensive fracture systems associated with basin-boundary fault zones (Figs. 4-1, 4-2; Plates 1 to 7), and the local occurrence of dissolution features in carbonate and gypsiferous sedimentary rocks of this area, both in outcrop and subsurface.

Middle Tertiary volcanic and intrusive rocks of intermediate to silicic composition are exposed in isolated uplands on the western flank of the Mesilla Basin (e.g., the Sleeping Lady and Aden Hills at the southwestern end of the Robledo uplift, and Mount Riley northwest of the East Potrillo Mountains (Plate 1; Seager et al. 1987; Seager 1995; Seager and Mack 1994).

4.2.2 Internal Basin Structure and Buried Bedrock Terranes

The internal structure of both the Mesilla and southern Jornada Basins is complex (Figs. 4-1, 4-2, Plates 1 to 7). Subsurface structural interpretations in this report are based on oil and geothermal test-well, water-well, and surface and borehole geophysical data (also see Witcher et al. 2004, and Appendix—Tables A1 to A4, Plates A2 to A9). The major structural elements of the Mesilla Basin, all with general north-south trends, include three large subbasins (La Union-Mesquite, Southwestern, Northwestern) a buried mid-basin uplift, and an inferred south-central basin that extends into Chihuahua west of

Sierra Juárez. Hydrogeologic and geohydrologic implications of bedrock and structural controls are discussed in more detail in Sections 5.1 and 7.0.

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 (Plate 7). Oil and gas test holes, including wells 25.1.32.141 and 26.1.35.333 in the central part of the basin (Plates 4 and 5), encountered a thick sequence of lower to middle Tertiary volcanic and sedimentary rocks (Uphoff 1978; Seager et al. 1987). The lower Tertiary sedimentary units were deposited in deep, northwest-trending basins of Laramide age (Seager 2003), and are exposed only in a few places along the northern and eastern edges of the Mesilla Basin and the east flank of the Jornada Basin (Plate 3b, Kottlowski et al. 1956; 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 directly overlie lower Paleozoic and Precambrian rocks in a few areas (Plates 3b, 3c, 4b; Seager 1989; Seager et al. 1987).

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 sediments in the Mesilla Basin (Appendix—Tables A1 to A4, Plates A2 to A9). Besides the previously mentioned oil tests, water test wells that have definitely penetrated these units include wells 24.1.8.123, 25.16.333, 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 on the west edge of Doña Ana-Tortugas and Franklin uplifts (Plates 1, 3f, 4c, 5c). Several test wells have also penetrated Tertiary volcanics buried bedrock high that forms the structural boundary between the Mesilla Basin and the southern end of the Jornada Basin (Plates 1, 3d, 3e, 5a; Woodward and Myers 1997). Geothermal test borings near Tortugas Mountain at the east edge of the NMSU campus have encountered Lower Permian carbonate rocks as well as mid-Tertiary silicic volcanics (Plates 3f, 5a; Gross and Icerman 1983; Gross 1988).

Plates 3a-c are recent additions to the small group of hydrogeologic cross-sections of the southern Jornada del Muerto prepared during the past 40 years (e.g., Hawley and Kottlowski 1969; Hawley et al. 1969; King et al. 1971; King and Hawley 1975;

Kottlowski and Hawley 1975; Gile et al. 1881; Hawley 1984). These schematic sections (5-10x vertical exaggeration) also incorporate interpretations from much more "sophisticated" structural-geologic sections by W.R. Seager and associates (e.g., Seager 1981; Seager and Hawley 1973; Seager et al. 1971, 1976, 1982, 1987).

Early and recent hydrogeological and geophysical investigations (water-resource and environmental-geology related) at the NASA White Sands Test Facility on the west flank of the San Andres uplift have provided much of the high-quality information that is available for that part of the Jornada Basin (Doty 1963; Giles and Pearson 1998; Maciejewski and Miller 1998). Hydrogeologic interpretations for the eastern parts of Plates 3b, 3c **(**Sections BB' and CC') are derived to a great extent from these interpretive databases. Additional, shallow and deep borehole information was acquired (1963 to 1978) from mineral-exploration projects in the southern San Andres-San Augustine piedmont area between the NASA site and the Village of Organ on US-70 (AMAX and Bear Creek borehole-sample collections at the NMBG&MR-Socorro; see Plate 3d).

The other subsurface-database used in this investigation was derived from sample logging of a series of deep seismic-shot holes drilled by Globe Exploration Co. for Shell Oil Co. on the USDA-ARS Jornada Experimental in the central part of the southern Jornada Basin (1964-Hawley-USDA-SCS records). This information, combined with detailed mapping of the Tonuco-San Diego and San Andres uplifts (Kottlowski et al. 1956; Seager et al. 1971, 1987) served as the basis for the hydrogeologic-framework interpretations in Plate 3a. As further discussed in Report Sections 5 and 7**,** all subsurface investigations to date in the Jornada del Muerto sector of the study area indicate no significant fresh-water aquifer systems are present in the SFG basin-fill sequence (2,500 to 3,500-ft max. thickness) north of the area of irrigation, industrial, municipal production wells in T. 20-21 S., R. 2—3 E.

4.3 BASIN DEPOSITIONAL SYSTEMS

4.3.1 Upper Cenozoic Volcanics

Late Oligocene to Quaternary sedimentary deposits of the Rio Grande rift are locally interbedded with, and capped by basalt and andesite flows, and pyroclastic deposits (Crumpler 2001; Crumpler and Aubele 2001). Associated with these extrusive rocks are intrusive bodies that include feeder dikes, plugs, sills and breccia pipes (Plates 1, 4a-c; Figs. 3-4, 4-2). 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 parts of the southern Robledo and northeastern Potrillo uplifts (Hoffer 2001; Gile 1987; Seager et al. 1987; Seager 1987, 1989, 1995; Anthony and Poths 1992; Anthony et al. 1992; Williams et al. 1993; Williams 1999).

Basaltic andesites of late Oligocene age may also be present in the basal part of the Mesilla Basin fill (Fig 4-2). These rocks are locally interbedded with and intrude lower Santa Fe beds, and they are extensively exposed the Sierra de Las Uvas area southwest of the Rincon Valley (Plate 1). 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 they may be either flows of sills that are, respectively, interbedded with or intruded into the basin fill. A well drilled at the Las Cruces wastewater 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). A 563-ft ranch well at the eastern of the Aden-Afton volcanic field in the west-central part of the basin (26.1W.25.414) encountered 33º C water at about 375 ft bls (Wilson et al. 1981, p. 294-295). The reported very high specific capacity of the well (789 gpm/ft of drawdown), if accurate, suggests that it is producing from a highly permeable basaltic intrusive or flow unit (see Sections 5.3.1, 6.4).

4.3.2 Santa Fe Group Lithostratigraphy

The Santa Fe Group (Spiegel and Baldwin 1963; Hawley et al. 1969; Chapin and Cather 1994) comprises almost all the basin fill. In southern New Mexico and western Trans-Pecos Texas, the Santa Fe 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 (Fig. 3-6). Fill thickness in most of the central Mesilla Basin (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 the following section.

The *lower* Santa Fe Group is dominated by fine-grained, basin-floor sediments that intertongue with alluvial fan deposits beneath the distal parts of bordering piedmont slopes. Records from deep test borings (Plates 3 to 7) indicate that both *middle* and *lower* Santa Fe basin-floor facies include extensive and thick playa-lacustrine deposits in the southern Jornada del Muerto Basin and in many parts of the south-central Mesilla Basin. In addition, subsurface records from adjacent basins document the presence of calcium sulfate (gypsum-selenite) and sodium sulfate (mirabilite-thenardite) in the form of both primary evaporites, and secondary cements and segregations in basin-floor facies throughout the Santa Fe Group (e.g., Hawley et al. 1969; Reeves 1969; King et al. 1971; Seager et al. 1987; Lucas and Hawley 2002; Gile 2002). Note that sulfate minerals in the basin-fill deposits of the study region (including the Tularosa and Los Muertos basins) are also present in post-Santa Fe units.

Lower Santa Fe eolian sediments also form thick sheets and lenticular bodies that are interbedded with both basin-floor and piedmont-slope deposits in the southern part of the Mesilla Basin. Buried dune complexes as much as 600 ft thick have been identified beneath the Mesilla Valley in the Anthony-Cañutillo area (Cliett 1969; Hawley 1984) and are probably preserved in other parts of the La Union-Mesquite subbasin (Plates 3f, 4a-j). 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 range in age from about 25 to 10 Ma. They 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., San Andres, Organ, Franklin, East Potrillo, Robledo, and Doña Ana uplifts). 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 filling of subbasins adjacent to the major boundary fault zones (Jornada, Mesilla Valley, East Robledo) was accelerated. In many areas, rates of erosion of uplifted basin borders and deposition on adjacent piedmont slopes increased relative to those of the preceding interval. Alluvial flats that terminated in extensive playa-lake plains dominated broad, rapidly aggrading basin floors; and most mid-basin uplifts were deeply buried by *middle* Santa Fe deposits. Alternating beds of clean sand, silty sand, and silt-clay mixtures are the dominant lithofacies (discussed in more detail in the following section) 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 *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 and Hawley 1973; 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 major *upper* Santa Fe subdivision in the Hueco-Mesilla-Jornada Basin region is the Camp Rice Formation of Strain (1966). Its Hueco Bolson type area is near Fort Hancock in Hudspeth County, Texas (Figs. 1-1, 1-2). This Plio-Pleistocene unit has been mapped in detail from the southern Palomas and Jornada Basins, across the Mesilla and southern Tularosa Basins, and throughout the Hueco Bolson (Strain 1966; Seager et al. 1971, 1976, 1982, 1987; Gile et al. 1981; Gustavson 1991; Collins and Raney 2000). Camp Rice deposits are very well preserved throughout most of the Mesilla-Jornada Basin system, with significant dissection only occurring in the Rincon-Mesilla-El Paso Valley section, including the valleys of a few major arroyo tributaries. Formation thickness is as much as 700 ft in the north-central part of the Mesilla Basin (HSU-USF2, Plates 3d-f, 5c), but in most places the Camp Rice is more than 350 ft thick.

The Camp Rice Formation contrasts markedly with older Santa Fe units in terms of lithologic character (and hydraulic properties); because its primary depositional environment was dominated by broad aggrading plains of a large braided fluvial system, the ancestral "upper" Rio Grande. The geomorphic transformation from a *closed* to an *open* system in the Mesilla Basin area probably occurred between 3 and 4 million years ago. It is also important to note that the ancestral-river basin at that time already extended as far north as the San Juan and Sangre de Cristo Mountains of southern Colorado and northern New Mexico (Southern Rocky Mountain province).

Braided distributary channels of "Camp Rice" fluvial system spread southward and eastward (via Fillmore Pass) and ultimately terminated in the extensive playa-lake plains of the Bolson de Los Muertos (northern Chihuahua) and the Tularosa-Hueco basin floor (Figs. 1.1, 1.2; Hawley 1969, 1975; Strain 1971; Gile et al. 1981; Seager 1981; Seager et al. 1987; Gustavson 1991; Mack et al. 1997). Medium to coarse-grained deposits of this fluvial-deltaic complex continued to accumulate on the Mesilla Basin floor through early Pleistocene time. Recent research on basin-fill magnetostratigraphy and biostratigraphy, and dating of tephra (volcanic-ash and pumice) lenses in the upper part of the Camp Rice Formation demonstrate that widespread basin-floor aggradation (and Santa Fe Group deposition) ended about 700 thousand years ago (Vanderhill 1986; Mack et al. 1993: Gile, Hawley et al. 1995; Mack et al. 1996; Mack, Salyards et al. 1998; Lucas et al. 1999; Gile 2002). Presence of Yellowstone-derived Lava Creek Ash in oldest inset-river deposits in Selden Canyon and El Paso Narrows (300 to 250 ft about the present RG floodplain), demonstrates that initial Mesilla Valley cutting occurred no later than about 0.65 Ma (Seager et al. 1975; Izett and Wilcox 1982; Gile et al. 1981, 1995; Dethier 2001).

The dominant Camp Rice lithofacies is a thick sequence of fluvial sand and pebbly sand deposited by the ancestral Rio Grande during an interval of 2 to 3 million years. However, because of complex river-channel shifts (influenced by both tectonism and climatic factors) during basin-floor aggradation, fine-grained (slack-water) facies are also locally present. The other important Camp Rice lithofacies is a piedmont-slope assemblage that is primarily composed of fan alluvium and associated debris-flow deposits. In the south-central Mesilla Basin area, basal Camp Rice strata appear to intertongue with and overlap fine-grained alluvial and playa-lake deposits of the upper Fort Hancock Formation. In their type area near Fort Hancock in Hudspeth County, Texas, the Camp Rice/Fort Hancock Formation contact has been dated at about 2.5 Ma (Strain 1966; Vanderhill 1986; Gustavson 1991).

An extensive lacustrine facies of the Camp Rice Formation also occurs in the southern Jornada Basin (Paleo-"Lake Jornada" of Gile 2002). Gypsum (var. selenite) is an important cementing constituent in deposits of this long-lived lacustrine system of Late Pliocene and Early Pleistocene (?) age. It was primarily fed by distributaries of the ancestral Rio Grande and Jornada Draw fluvial systems. Differential basin-range displacement along the Jornada fault zone (Early Pleistocene?) ultimately produced uplift of the Tortugas-Doña Ana and Tonuco blocks and topographic closure of the southern Jornada Basin; and the ancestral Rio Grande was diverted to the area of the present Rincon and upper Mesilla Valleys ((Plates 1, 3a-d) and following section).

4.3.3 Santa Fe Group Sedimentary Petrology

R.P. Lozinsky's petrographic analyses of medium- to coarse-grained sediments of the Santa Fe Group and underlying Oligocene rocks (primarily drill cuttings, Methods Section 2.2.1) in the Mesilla Basin and Rincon Valley areas are described in Hawley and Lozinsky (1992, Section III). Petrographic interpretations of rock fragments and mineral grains that are major framework components of sandy Santa Fe Group lithofacies assemblages are summarized here. Anderholm (1985) has also made preliminary x-ray analyses of clay-size materials from several Rio Grande rift basins (including the Mesilla Basin); and Mack (1985) has described the petrography of drill cuttings from two test wells in the Las Cruces West Mesa (including 23.1.30.422**,** Plates 3e, 5d).

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 of Hawley and Lozinsky 1992), 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 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.

Most information on the mineralogy of clay-size material (<4 microns) in the Mesilla Basin area relates to soils and soil-parent sediments of the upper Camp Rice Formation that were sampled at NRCS-NMSU Desert Project sites (e.g., Gile et al. 1981; Gile, Hawley et al. 1995; Monger and Lynn 1996). A few analyses of clay-size material from older parts of the Santa Fe Group have reported by Anderholm (1985). There are, however, places in other Rio Grande rift basins (including Albuquerque, Socorro, and Jornada del Muerto-Rincon) where clay-mineral analyses from representative Santa Fe sections are available (e.g., Anderholm 1985; Bowie and McLemore 1987; McGrath and Hawley 1987; Hawley and Haase 1992 [Sec. IV]); Machette et al. 1997). As with the sand fraction, the dominant clay-size component in these rift basins is detrital material that reflects the lithologic character of the various source terranes; however, some mineral varieties of authigenic and/or polygenetic origin have been identified.

Clay-mineral assemblages that are almost always present (but in varying proportions) in Santa Fe Group deposits include: illite (clay-size mica), smectite, mixed-layer illite/smectite (I/S clay), kaolinite, and montmorillonite (a dioctahedral sodium smectite). Authigenic clay minerals are commonly associated with alkaline-playa environments or partly indurated calcic-soil horizons, and include montmorillonite, I/S clay, and chain-lattice clays of the magnesium-rich sepiolite—palygorskite group. Zeolites are another secondary mineral group associated with feldspar alteration under alkaline-diagenetic conditions; and their occurrence as cementing agent has been reported primarily in piedmont facies derived from silicic-volcanic source terranes (e.g., Seager et al. 1975; Anderholm 1985; Hawley and Haase 1992 [sec. IV]). As noted in the preceding description of the *lower* to *upper* Santa Fe Group sequence, gypsum and selenite (of both primary and secondary origin) are common constituents of fine-grained playa-lacustrine facies; and if alkali-lake environments ever existed, sodium-sulfate-enriched zones may also be present. Of special interest are extensive gypsiferous lacustrine sediments associated with late Pliocene to mid-Pleistocene flooding of the Jornada Basin floor northeast of the Doña Ana Mountains ("Lake Jornada" of Gile 2002; Plates 3a-c).

Almost all of the above-mentioned rock and mineral types, from sand to clay size, play a significant role in the chemical evolution of groundwater moving through, or stored for long intervals in basin-fill aquifers. Water-sediment interactions, including solution-precipitation and cation exchange, are a major topic covered in an unpublished project-completion report by Witcher and others (2004) and in a recent paper on the southern Jornada Basin by Schultz-Makuch and others (2003). The latter research addresses the very important subject of "microbial" processes in the evolution of groundwater-geochemical and diagenetic-authigenic systems in basin-fill deposits. Of particular interest is the presence of significant metallic sulfide and oxide mineralization in the bedrock source terrane of the northern Organ Mountains (Seager 1981).

4.3.4 Post Santa Fe Deposits

Post-Santa Fe Group sediments were deposited in two contracting geomorphic settings: 1) valleys of the Rio Grande and tributary arroyo systems, and 2) extensive intermontane-basin areas still topographically *closed* (Fig. 3-1; Hawley and Kottlowski 1969; Reeves 1969; Hawley 1969, 1975; Gile et al. 1981).

Valley-fill units of middle and late Quaternary age were deposited during repeated episodes of the 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) bordering the river floodplain was produced by multiple episodes of valley entrenchment during glacial (pluvial) stages, and subsequent intervals of valley aggradation during interglacial (interpluvial) stages (Section 6.5). 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 1992) is a product of 1) valley cutting by a high-energy fluvial system during the last glacial stage of the Pleistocene, which ended 10 to 15 thousand years ago (ka), and 2) subsequent inner-valley filling that has continued during the Holocene interglacial stage (Fig. 3-4). Tributary alluvial systems have delivered more sediment to the valley floor than the river could transport out of the drainage basin during this 10-15 ka interval of net fluvial aggradation (Hawley 1975; Gile et al. 1981).

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," Hawley and Kottlowski 1969) are generally above the water table; and they are not described in this report. Thin (<30 ft, 10 m) alluvial, eolian, and playa-lake sediments deposited in parts of the Mesilla and Jornada Basins that are still not integrated with the Rio Grande are also not covered herein. Much the "veneer" of Middle and Late Pleistocene surficial alluvial, colluvial, and eolian sediments is included with *upper* Santa Fe hydrostratigraphic units in the hydrogeologic cross sections (Plates 3 to 6; see following section). Younger valley and basin fills, and soil-geomorphic relations are the subject of numerous reports by L. H. Gile and associates (e.g., Gile and Grossman 1979; Gile et al. 1966, 1981; Gile, Hawley et al. 1995).

5.0 HYDROGEOLOGIC FRAMEWORK OF THE AQUIFER SYSTEM

From a geohydrologic perspective, the Mesilla and southern Jornada Basins occupy broad topographic depressions that are separated as well as linked by the entrenched Mesilla and Rincon Valleys of the Rio Grande. Both topographic basins, in turn, overlie a geohydrologically linked group of deep structural subbasins and intervening buried-bedrock highs (Plate 1, Figs. 4-1, 4-2a,b). Both intrabasin and basin-boundary structures play a major role in terms of groundwater flow and geochemistry. Figure 5-1 is a schematic hydrogeologic cross-section of the south-central Mesilla Basin, and it is aligned approximately along the 32nd Parallel and close to the position of Figure 4-2b and Plate 4c. Basic concepts of hydrogeologic framework and groundwater flow in incompletely *closed* and *partly drained* intermontane-basin systems like the Mesilla Basin have been introduced in Sections 3.1 and 2.5 (Figs. 3-1 to 3-3; Tables 3-1 to 3-3).

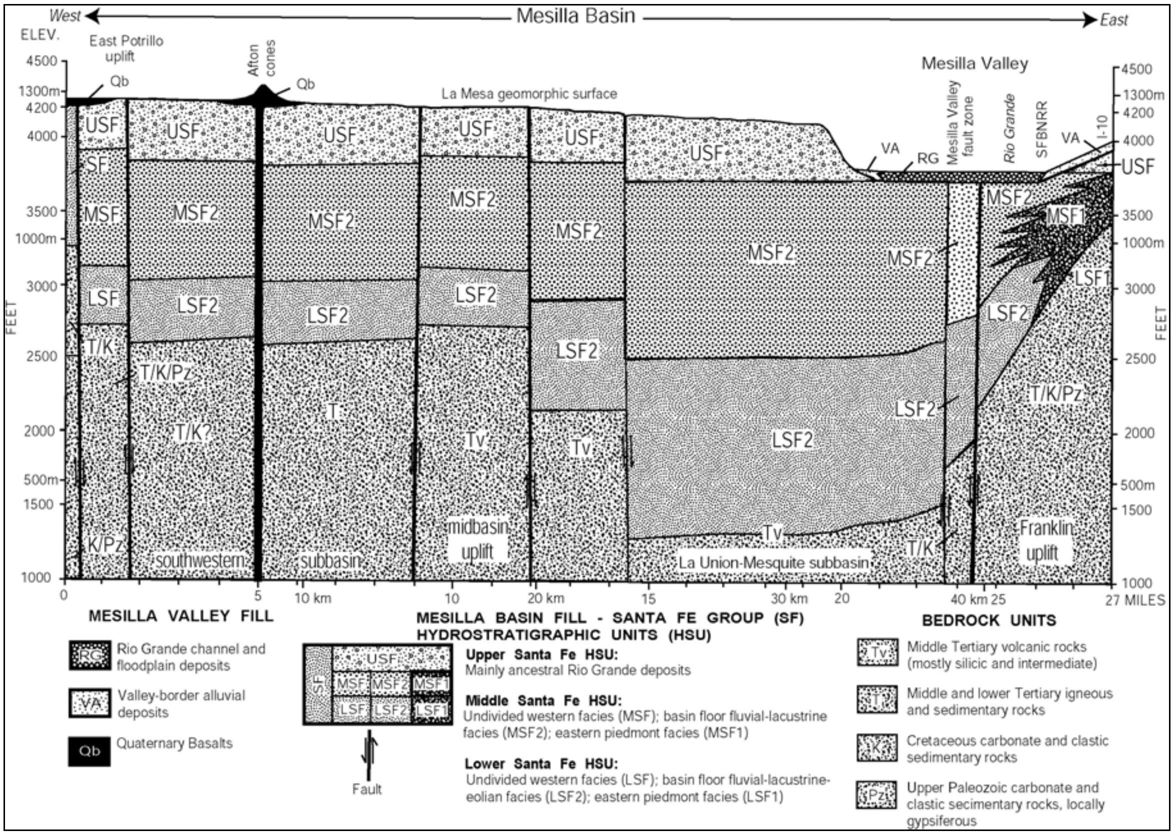

Figure 5-1. Schematic hydrogeologic cross section of the south-central Mesilla Basin near the 32nd Parallel in Doña Ana County, N M and El Paso County, TX, Vertical exaggeration about 10x. Modified from Plate 4c.

5.1 STRUCTURAL AND BEDROCK ELEMENTS

In terms of overall basin and range architecture, the major hydrogeologic-framework component includes the bedrock units and tectonic features that form important boundary zones with respect to the basin-fill aquifer system and related aspects of groundwater flow and chemistry. Distribution patterns of large-scale framework components, including major fault zones and volcanic-feeder conduits, are shown on Plate 1 (map view) and Plates 3 to 6 (cross-section view). Relatively impermeable Igneous and sedimentary bedrock units of Oligocene and older age, crop out along the basin margins, and underlie the Mesilla and Jornada Basins land surface at depths of as much as 3,000 ft. One of the significant contributions of the present study is that there is now much better definition of the contacts between bedrock boundary units and the basin fill. Compare Plates 3 to 6 with earlier cross-section interpretations (e.g., Wilson et al. 1981; and Hawley 1984).

We need to emphasize here, however, that there is still much to be learned about the basin's internal structure. Based on recent experience in other parts of the Rio Grande rift, notably the Albuquerque Basin, additional drilling and geophysical studies (including aeromagnetic, gravity and seismic-reflection surveys) should lead to much greater precision in the identification of structural-boundary conditions throughout the binational Mesilla-Jornada-Hueco-Tularosa basin system (Fig. 1-2; Keller and Cather 1994; Hawley et al. 1995; Allen et al. 1998; Connell et al. 1998; Keller et al. 1998; Grauch 1999; Grauch et al. 2000; Plummer et al. 2000; Sanford et al. 2000; Kucks et al. 2001).

5.1.1 Mesilla Basin

Locations of the major basin-boundary faults are shown on Plate 1 and Figures 4-1 and 4-2. The Robledo and East Potrillo faults, respectively, form the northwestern and southwestern boundaries of the "deeper" basin used in recent groundwater-flow models (Peterson et al. 1984; and Frenzel and Kaehler 1992). The broad Mesilla Valley fault zone is entirely buried by Late Quaternary valley fill, but it still forms the major eastern-boundary feature of the Mesilla "structural basin." In the Las Cruces metro-area, the fault zone marks the western edge of the bedrock high that 1) includes the partly buried Tortugas-Doña Ana Mountain uplift, and 2) the area of topographic and structural transition between the Mesilla and Jornada (del Muerto) Basins (Woodward and Myers 1997). This fault zone, however, has not been used as a numerical-model boundary (Frenzel and Kaehler 1992).

Slichter (1905) clearly demonstrated that the Rio Grande valley constriction at the International Dam site in El Paso del Norte (Fig. 5-2, Plates 1, 4c, 6) is an effective barrier to underflow discharge into the upper El Paso Valley (7.3.1). The bedrock-boundary units at the "El Paso Narrows" are Cretaceous sedimentary and Lower Tertiary igneous-intrusive rocks that have very low hydraulic conductivities (primarily mudstone, sandstone, limestone, and andesite porphyry). No zones of enhanced permeability due to limestone dissolution or open-fracture systems have ever been identified. The saturated valley fill (HSU RA) is no more than 75 ft thick; and it is restricted to an inner-valley area that has a width of about 500 ft in the narrowest bedrock constrictions. Figure 5-2 is a geologic sub-crop map with structural contours showing the general topography of the Pre-Santa Fe Group bedrock surface and location of major segments of the buried Mesilla Valley fault zone. This map and accompanying (down-valley) hydrogeologic cross section (Fig. 5-3) cover the entire lower Mesilla Valley area. *Note that Figure 5-3 is a reduced-scale copy of Plate 6.*

Structural segmentation of the Mesilla Basin into three major subbasins (Northwestern, Southwestern, and La Union-Mesquite) and a N-S trending structural high (the Mid-Basin uplift) is illustrated on Figures 4-1 to 4-3, and Plates 1, 4 and 5. A maximum basin-fill thickness of about 3,000 ft is inferred from borehole data in the La Union-Mesquite subbasin, but rarely exceeds 2,000 ft in the Northwestern and Southwestern subbasins (Plates 1, 3f, 4a-e). The La Union-Mesquite subbasin is bordered on the east by the Mesilla Valley fault zone, and on the west by the Mid-basin uplift (informally named by Hawley and Lozinsky 1992)(Figs. 4-1, 4-3; Plates 1, 4a-d). The poorly defined fault zone marking the eastern border of this structural high is locally expressed by alignment of volcanic centers and some low scarps on the West Mesa surface (Plate 1); but it is most prominently displayed in the subsurface as offsets of distinct stratigraphic-marker units on borehole electric logs (Witcher et al. 2004, Plate 4, Appendix I.3, I.4). The Santa Fe Group is only about 1,500 ft thick above the central part of the Mid-Basin uplift near the Lanark MT2 well site (Plates 1, 4c, 5d; 27.1.4.121). The best-documented surface expression of the uplift's western boundary is the (down-to-west) Fitzgerald fault zone (Plates 1, 3f, 4a-d; Figs. 4-1, 4-2).

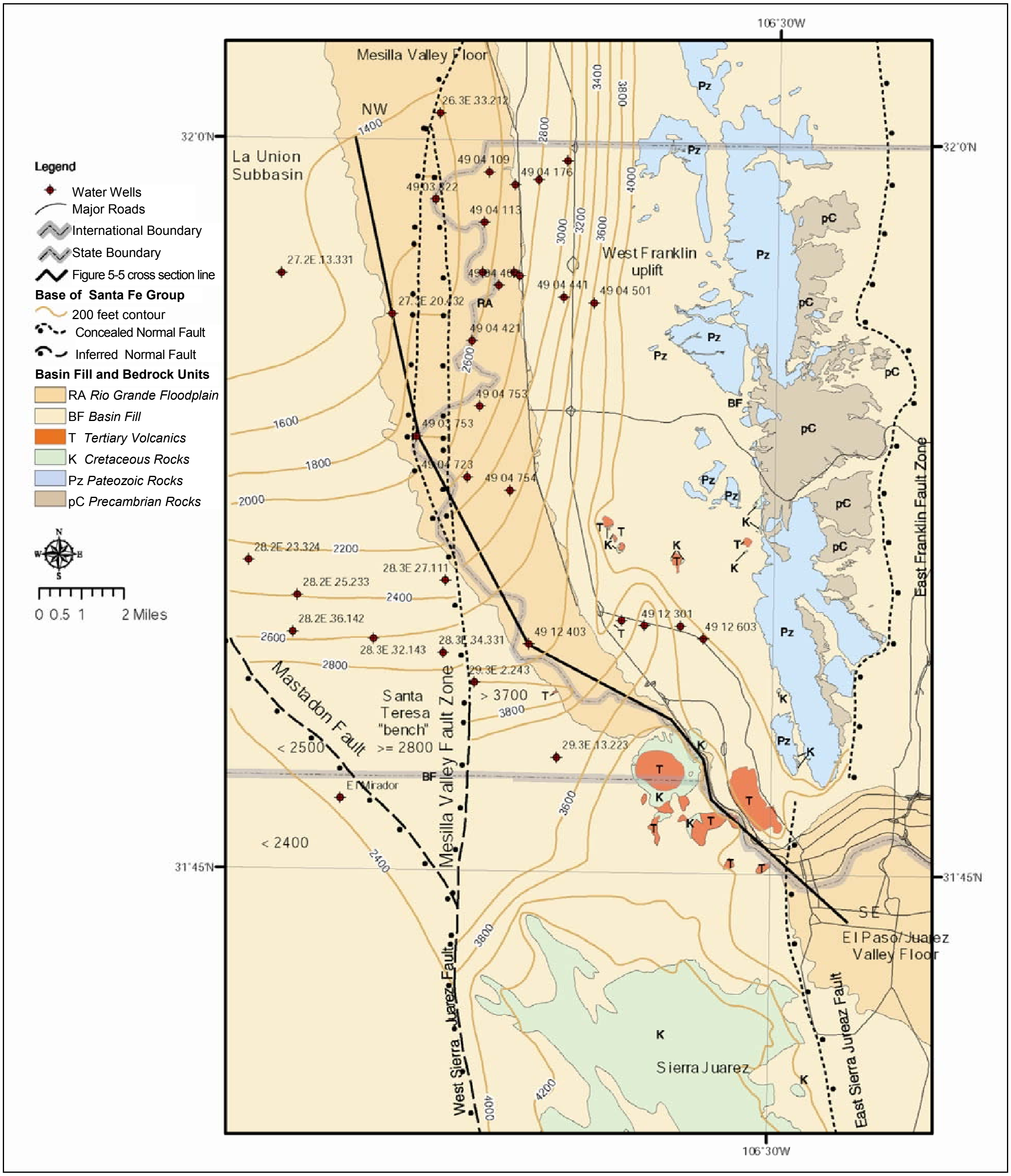

Figure 5-2. Structure contour map of the southern Mesilla Valley. Contour lines (200 foot interval) illustrate the base of the Santa Fe Group deposits. Cross-section line corresponds to Figure 5-3. Scale is 1:200,000.

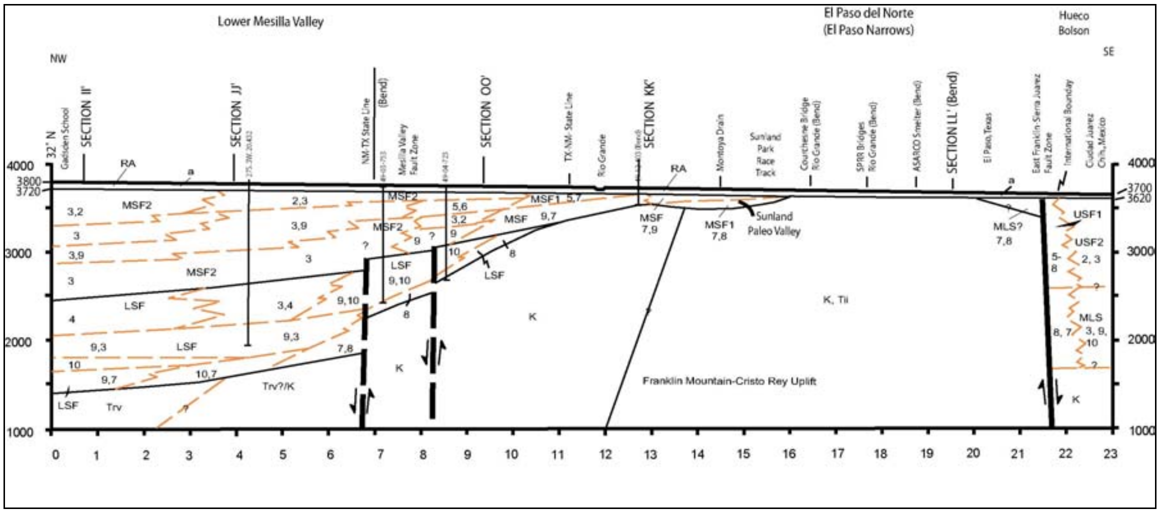

Figure 5-3. Hydrogeologic section of Lower Mesilla Valley and Paso del Norte reach of the Rio Grande Valley Floor, from Anthony-Gadsden area, NM to central El Paso, Texas and Ciudad Juarez, Chihuauha. Scale is 1:200,000.

5.1.2 Jornada Basin

The available database on structural and bedrock boundary conditions in the southern Jornada del Muerto Basin has already been reviewed in Section 4.2.2. Locations of the major basin-boundary faults and inferred intra-basin faults are shown on Plates 1, 3a-d and 5a; and Figure 4-2b and Plate 3e cover the broad zone of structural and topographic transition that characterizes boundary between the Jornada and Mesilla Basins (Section 4.2.1 and 5.1.1 discussions). The Jornada and West San Andres (West SA or West-side faults), respectively, form the (approximate) western and eastern boundaries of the "deeper" southern subbasin used in a recent groundwater-flow models (Shomaker and Finch 1996). The curvilinear Jornada fault has been mapped in detail where it is exposed in the Rincon Hills and San Diego Mountain-Selden Canyon area (Seager 1975; Seager et al. 1971, 1976); and east of the Doña Ana-Tortugas uplift its general location is known from water-well driller and sample logs (King et al. 1971; Wilson et al. 1981). The eastern basin-boundary fault "zone" is entirely buried by upper Quaternary basin fill; but its location is well established in the NASA-WSTF Organ-Moongate areas by the geologic mapping, test-drilling, and geophysical surveys reviewed in Section 4.2.2 (Doty 1963; King et al. 1971; Seager 1981; Seager et al. 1987; Giles and Pearson 1998; Maciejewski and Miller 1998).

Geophysical Surveys indicate that the Santa Fe Group is as much as 2,500 ft thick in the section of the Jornada Basin between the NASA site and the northern Doña Ana Mountains (Plates 3b, 3c; Maciejewski and Miller 1998); and detailed study of a nearly complete (lower, middle and upper) Santa Fe section exposed in the Tonuco (San Diego) uplift suggests that basin-fill thickness may locally exceed 3,500 ft in that area (Hawley et al. 1969; Seager et al. 1971; Seager 1975). Lower to Middle Tertiary volcanic and volcaniclastic rocks of intermediate composition probably are the major component of the deep-bed rock substrate in the basin-floor area between the San Andres Mountains and the Doña Ana-Selden Hills-Tonuco uplift (Plates 3a, 3b). The latter feature constitutes a partly buried bedrock high, which appears to form a continuous barrier for inter-basin discharge from the Jornada basin-fill aquifer system to the Selden Canyon-upper Mesilla Valley segment of the Rio Grande Valley (Plate 3a; King et al. 1971). See brief discussion of possible geothermal flow in bedrock aquifer systems of the Jornada del Muerto area in Section 7.3.

5.2 HYDROSTRATIGRAPHIC UNITS AND LITHOFACIES ASSEMBLAGES

5.2.1 Santa Fe Group Units

Three hydrostratigraphic subdivisions of the Santa Fe Group form the basin-fill aquifer system. These HSUs are ordered in upper to lower (younger to older) stratigraphic sequence (Plate 1, Figs. 3-4, 5-1). The *upper* Santa Fe HSU (USF1, 2) is generally correlative with the Camp Rice Formation, and the most productive aquifer zone (LFAs 1*&2*, Table 3-3) consists of ancestral Rio Grande channel sand and gravel (HSU-USF2). However, only the lower part of this unit is saturated. It has also already been noted (Section 4.3.2) that *upper* Santa Fe (USF2) lithofacies assemblages in parts of the southern Jornada Basin floor are at least locally gypsiferous as the result of restricted drainage associated with the formation of "Lake Jornada" (Gile 2002).

The *middle* Santa Fe HSU (MSF1, 2) correlates with much of the Fort Hancock Formation in the Hueco Bolson and the Rincon Valley Fm in the Jornada and Palomas Basins. Fine-grained, fluvial-overbank, alluvial-flat and playa-lake sediments dominate these lithostratigraphic units (Fig. 3-4). In the study area, however, the dominant basin-floor facies assemblage (HSU-MSF2; LFA 3) includes extensive layers of clean fluvial and eolian (?) sand that are interbedded with silty clay; and it probably forms the major aquifer zone in the basin, because its saturated thickness is locally as much as 2,000 ft). Leggat and others (1962) originally identified HSU-MSF2 and LFA3 in deep wells of the EPWU-Cañutillo well field (old Figs. 4-2b, 5-1, Plates 4c, 4d, 5c).

The *lower* Santa Fe HSU (LSF) is primarily fine grained and party consolidated throughout much of the basin (LFAs 3, 9, 10); and it only forms a significant part of the aquifer system in the lower Mesilla Valley area that extends from near Mesquite (NM) to Cañutillo and La Union (NM). Leggat and others (1962) first identified this part of the LSF unit in deepest wells of the Cañutillo well field; and they informally named it the "deep aquifer" zone (HSU-LSF 2, Fig. 5-1). The major lower Santa Fe (LSF) component in the lower Mesilla Valley area is a distinctive eolian-sand facies (LFA 4) that intertongues mountainward with piedmont fanglomerates (LFAs 7, 8*)*, and basinward with basin-floor facies assemblages (LFAs 3, 9, 10). The latter facies are here interpreted as fluvial-deltaic and playa-lake deposits (Fig. 3-4, Table 2-1).

5.2.2 Valley-Fill Units

The Rio Grande valley-fill aquifer system (primarily HSU RA, LFAs a and b) underlies the river-valley floor across the entire study area, including the lower Rincon Valley, Selden Canyon, Mesilla Valley, and El Paso del Norte (Plates 1, 5c, 6). HSU RA comprises river-channel and overbank facies ranging in texture from sand and gravel to silt and clay (Tables 3-1, 3-3). The base of these fluvial deposits is about 60 to 80 ft below the inner-valley floor, which ranges up to five miles in width. The basal-channel gravel and sand layer is as much as to 40 feet thick; and it extends laterally for hundreds of feet beyond the present floodplain in some areas. Most of this unit was deposited during the last interval of maximum valley incision and widening in Late Pleistocene (Wisconsinan) time (Section 4.3.4). Valley-fill HSUs RA and VA are continuous from Elephant Butte and Caballo reservoirs, through the Rincon, Mesilla and El Paso valleys, to the Fort Quitman area of the lower Hueco Bolson (Fig. 1.2). The shallow aquifer system of the river valley is formed by 1) the saturated parts of the inner-valley fill (HSUs RA and VA), and 2) fluvial sand and gravelly sand in underlying Santa Fe HSUs.

The latter were deposited by the ancestral-river system during the Pliocene interval of basin filling (primarily HSUs USF2/MSF2 and LFAs 1 to 3).

5.3 LATE CENOZOIC EVOLUTION OF THE HYDROGEOLOGIC SYSTEM

5.3.1 Introduction

Because the Mesilla and southern Jornada Basins are part of an active rift tectonic zone that has been evolving for more than 25 million years, the distribution of lithostratigraphic and hydrostratigraphic units and associated lithofacies assemblages (Plates 1 to 6, Figs 3-3, 3-4, 4-1, 4-2,5-1) must be interpreted in terms of ongoing, but episodic crustal extension and basin subsidence. Regional and local extension and differential displacement, including rotation, of basin and range blocks clearly act as effective controls on basin sedimentation. On the other hand, obvious climate controls on geomorphic processes in the Quaternary stratigraphic record, which locally relate to Quaternary glacial-interglacial cycles, demonstrate that forces other than rift tectonism will also materially influence depositional processes (Gile et al. 1981; Leeder et al. 1996).

On the 25 Ma-time and space scale represented by Santa Fe Group deposits, however, structural deformation and associated igneous activity must be recognized as major controlling factors in terms of the basin-filling process. The *lower* Santa Fe hydrostratigraphic unit (early to middle Miocene) and associated lithofacies (primarily LFAs 3, 4, 7, 9, 10) were deposited in a broad, shallow basin that predated major uplift of the flanking mountain blocks (uplifts) bounded by the Jornada, West San Andres, Mesilla Valley, East Potrillo and East Robledo fault zones (Plates 1 to 6). The deepest and most actively subsiding part of the early-stage Mesilla Basin appears to have been in the "Southwestern subbasin" east of the East Potrillo uplift (Plate 4e).

With respect to the evolution of groundwater-flow and hydrogeochemical systems throughout the study area, the onset of river-valley entrenchment has had profound implications (Section 7). Prior to 700 thousand years ago, in the early Pleistocene, almost all of the Santa Fe Group beneath the floor of the Mesilla Basin was saturated. Subsequent (Middle and Late Pleistocene) Rio Grande Valley incision has caused a water-table drop of 300 to 350 ft beneath much of the West Mesa area. It is also important to note that an analog of the early Pleistocene groundwater-flow regime and hydrogeochemical environment still exists in the southern Mimbres basin system and the Bolson de Los Muertos west and south of the Mesilla Basin (Hawley et al. 2000, Chapters 3 and 4). Recent studies in that area provide excellent models of early stages of flow-system evolution throughout the Mesilla Basin (e.g., Hanson et al. 1994; Love and Seager 1996; Mack et al. 1997; Hibbs et al. 1999). It must be emphasized, however, that because the lower Mimbres—Los Muertos basin complex has continued to aggrade during the Middle and Late Quaternary, it is the only basin-boundary zone with significant groundwater- inflow potential (Sections 7.1 to 7.3). The lacustrine deposits of "pluvial" Lake Palomas in the Bolson de los Muertos demonstrate that paleo-water-table elevations during Late Pleistocene and Early Holocene deep-lake intervals were as much as 200 ft higher than the potentiometric surface at the lower end of the Mesilla Valley (3,960 vs. 3,760 ft).

5.3.2 Early-Stage Basin Aggradation

Petrographic studies of drill cuttings as well as interpretations based on other analyses of samples and driller's logs (Plates 2 to 7) indicate that depositional environments in the *lower* Santa Fe HSU (LSF) contrast markedly with those in younger basin fill (Sections 4.3.2, 4.3.3). During early stages of basin filling, the Mesilla Basin received a major influx of fine- to medium-grained sediments (silt-clay to sand) 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- Ju<rez chain) had not yet formed, wedges of coarse-gained piedmont deposits were limited to the extreme basin margins. The most striking lithofacies assemblage (LSF4) in the *lower* Santa Fe HSU comprises thick deposits of clean, fine to medium sand, which are now well documented in the Eastern (La Union-Mesquite) and Southwestern subbasins, including the EPWU—Cañutillo well field and several other parts of the Mesilla Valley (Cliett 1969; Wilson et al. 1981; Hawley 1984). These partly indurated beds are as much as 600 ft thick in the La Union-Mesquite subbasin. In the Southwestern subbasin, immediately east of the east Potrillo fault zone, correlative deposits may be 900-1,000 ft thick (Plates 2 to 4, 6, 7, 8b-e, 9a). In the latter area, however, borehole electric and

temperature logs that the lower Santa Fe section may be finer grained and/or saturated with slightly saline-to-saline groundwater (Witcher et al. 2004, Section 2.9).

5.3.3 Middle and Late Stages of Basin Aggradation

Distribution patterns of both piedmont-slope and basin-floor LFAs (1-3, 5-10) in *middle* and *upper* Santa Fe HSUs (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, 3c-f, 4a-f, 5, 6). As has been previously noted (Sections 4.2, 5.2), late Miocene tectonic subsidence was particularly active in the La Union-Mesquite subbasin.

Middle Santa Fe Events. The Middle Santa Fe HSU 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, Ju<rez, East Potrillo, Robledo and Mid-Basin uplifts. East of the Rio Grande Valley, both the *middle* and *upper* Santa Fe HSUs (MSF and USF) are dominated by coarse clastic material (fan-piedmont alluvium) derived from the rapidly rising southern Organ and Franklin uplifts (LFAs 5-8). The developing Robledo and East Potrillo Mountains contributed fan sediments to the Western subbasins during the same interval. LFA 3 is the major component of the *middle* Santa Fe HSU (MSF2) 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 3f, 4a-d, 5c). 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, Appendix A1, Tables A1, A2).

East of the Mesilla Valley fault zone, fan deposits (LFAs 5 and 7) prograded westward almost to present location of I-25 during much of the *middle* Santa Fe depositional 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 9a; MSF; LFAs 2, 3, 5, 7, and 9). Analyses of drillers and sample logs show 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.

Upper Santa Fe Events. The *upper* Santa Fe HSU 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, which 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 of the Tularosa Basin and Hueco Bolson (via Fillmore Pass, Fig. 1-2; Plates 4b, 5b) as well as to the Bolson de Los Muertos (Hawley 1969; Strain 1971; Hawley 1975; Gile et al. 1981; Seager 1981; Seager et al. 1987; Gustavson 1991).

The final stage of widespread basin aggradation throughout the central and southern New Mexico region (LFAs 1 and 2) occurred during eruptions of the Jemez volcanic center that produced the Bandelier Tuff and the Valles caldera 1 to 1.6 million years ago (Goff et al. 1996). 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. 1.3, Plate 1). Complex intertonguing of ancestral Rio Grande and piedmont-slope LFAs (1-3, 5) characterize the *upper* Santa Fe HSU (USF) east of the Mesilla Valley fault zone (Plates 5 and 6). At times progradation of alluvial fans from the Organ and Franklin uplifts was very active (LFA 5), and the piedmont alluvial apron expanded across the Mesilla Valley fault zone as far west as the present central Mesilla Valley.

5.3.4 Pliocene-Quaternary Deformation and Volcanism

In many places, patterns of *upper* Santa Fe Group sedimentation have been influenced not only by major climate cycles but also by volcanic and tectonic processes, (Gile et al. 1981; Mack and Seager 1990; Leeder, Mack, and Salyards 1996; Leeder et al. 1996; Mack et al. 1997). Structural deformation has produced more than 2,000 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, East Robledo and Jornada faults in Plio-Pleistocene time (past 4-5 million years); and this tectonic process clearly influenced the final position of the ancestral Rio Grande and the distribution patterns of LFAs 1-3 and *5* in the *upper* Santa Fe HSU-USF1, 2 (Figs. 4-1, 4-2, 5-1; Plates 1 to 6). Diversion of ancestral-river distributaries related to differential uplift of the Tortugas, Doña Ana and Tonuco blocks along the Jornada fault zone, and formation of the "Lake Jornada" depression was briefly discussed in Sections 4.3.2 and 5.2.1.

Movement along the major basin-bounding fault zones shown on Plate 1 also continued in post-Santa Fe (Quaternary) time and has controlled the general trend of Mesilla Valley and bordering river terraces from the Selden Canyon to Paso del Norte narrows (Figs. 1-2, 3-4, 4-1). Older valley fill units are definitely offset by faults east of the Robledo Mountains; and the major centers of basaltic volcanism are located on many prominent fault trends, in both basin-boundary and intrabasin positions (Plates 1 to 5).

5.3.5 Quaternary Valley Incision and Basin Filling

Cyclic incision of the regional RG Valley system since the Early Pleistocene (past 700,000 yrs) has led to episodic, but progressive drainage of aquifers in contiguous "alluvial-basin" (bolson) areas (see Gile et al. 1981, p. 56, Fig. 6). The last interval of major valley entrenchment and widening occurred sometime during the last full-glacial (pluvial) cycle, but at least 10,000 to 15,000 yrs ago (Hawley 1975). With respect to the evolution of groundwater-flow and hydrogeochemical systems in the southern Mesilla Basin, the Middle and Late Quaternary depositional history of the Bolson de los Muertos and lower Mimbres Basin are also extremely important. The lacustrine deposits (both lake-floor and strand-line) of "pluvial" Lake Palomas demonstrate that paleo-water tables during many Pleistocene and Holocene deep-lake intervals were substantially higher than the potentiometric surface at the lower end of the Mesilla Valley (Sections 7.2, 7.3).

6.0 MAJOR BASIN AND VALLEY AQUIFER SYSTEMS

6.1 HYRAULIC PROPERTIES OF HYDROGEOLOGIC UNITS

6.1.1 Introduction

The following overview of hydraulic properties of "alluvial-basin" fill is primarily based on investigations by the U.S. Geological Survey, starting with information presented by Wilson and others (1981). Emphasis here is on the Mesilla Basin portions of the study area. Irrigation-well specific-capacity data and a few aquifer-performance tests provide the basis for many of the published interpretations of hydraulic properties and sustained production potential of Mesilla Basin aquifer systems (Wilson et al. 1981; Frenzel and Kaehler 1992; Wilkins 1998). Almost all of the large irrigation wells and centers of municipal pumping (Las Cruces and El Paso Metro-areas) are located in the inner Mesilla Valley. Well yields range from a few to more than 3,000 gpm, and average discharge rates of deep irrigation wells in the central part of the Mesilla Valley are about 2,300 gpm (Wilson and White 1984).

Specific yield estimates vary from 0.1 to 0.2, assuming unconfined aquifer conditions. This assumption is inappropriate in many parts of the aquifer system, however, because of semiconfined (leaky-confined) to confined conditions. Therefore estimates of groundwater availability, as well as assessment of aquifer-deformation and land-subsidence potential, will require much smaller storage-coefficient values (Land and Armstrong 1985; Kernodle 1992a, b; Heywood 1995). Estimates of specific storage used in modeling groundwater flow in confined parts of the Santa Fe Group aquifer system range from $1x10^{-5}$ to $1x10^{-6}$/ft (Kernodle 1992a; Frenzel and Kaehler 1992). The storage-coefficient range noted by Wilson and others (1982) is $2x10^{-3}$ to $3x10^{-5}$ (Nickerson and Myers 1993).

Well specific-capacity data, and transmissivity (T) and hydraulic-conductivity (K) estimates from aquifer testing collectively suggest that the broad ranges in horizontal hydraulic conductivity listed in Tables 3-2 and 3-3 are reasonable values for basinwide modeling (see Kernodle 1992). This inference is based on the observation (supported by hydrogeologic syntheses in Plates 1 to 6) that the dominant valley-fill and Santa Fe Group lithofacies assemblages (LFAs) in the upper (0-600 ft) and lower (600-1,800 ft) intervals tested are LFAs a, 1, 2, & 5 and LFAs 3, 4, & 7, respectively.

6.1.2 Mesilla Valley Area

Specific capacities of 10 to 217 gpm/ft are reported for wells completed mainly in the coarse-grained fluvial facies (LFAs 1 and 2) of the upper Santa Fe Group HSU-USF2 and overlying river-channel deposits of the inner Mesilla Valley (HSU-RA; LFAs a1**,** a2). The average specific capacity reported by Wilson and others (1981) is 69 gpm/ft, and the saturated-fill thickness ranges from 150 and 200 ft. Limited specific-capacity data from 68 wells located in the Mesilla Valley area, which are completed from 200 to 1,600 ft below the water table, show values ranging from 5 to 75 gpm/ft of drawdown, with an average of about 25 gpm/ft (Wilson et al. 1981, Table 2). Wells completed in the 200 to 600-ft depth zone produce primarily from the basal upper Santa Fe and middle Santa Fe HSUs (LFAs 2 to 5); and their specific capacities are usually less than 40 gpm/ft. Wells completed at depths below 600 ft commonly penetrate fine-grained and partly indurated basin fill of the middle to lower Santa Fe HSUs (LFAs 3-9); and specific capacities of wells that produce primarily from these units are in the 1 to 10 gpm/ft range.

Estimated aquifer transmissivities of the upper 1,200 ft of saturated fill are as high as 50,000 ft^2/d at a few localities; but most values for Santa Fe Group and Mesilla Valley fill vary from 10,000 to 40,000 ft^2/d in the central part of the Mesilla Basin (Wilson et al. 1981). Estimated aquifer transmissivities of the shallow aquifer system (upper 150 ft of valley and basin fill) of the inner Mesilla Valley area locally exceed 30,000 ft^2/d; but most values range from 10,000 to 20,000 ft^2/d (Wilson et al. 1981, Plate 11). According to Frenzel and Kaehler (1992, Fig. 13), a calculated "lower to upper quartile" range in horizontal hydraulic conductivity for the upper 200 ft of the shallow (Mesilla Valley) aquifer system is from 43 to 110 ft/d, with a median value of 70 ft/d. These deposits are composed primarily of LFAs a1, a2, 1 to 3 and HSUs RA, VA, USF2/MSF2 (Plate 5c).

6.1.3 Mesilla Basin—West Mesa Area

The well with the highest reported specific capacity (789 gpm/ft) is located at the east edge of the Aden-Afton volcanic field at the Jay Gardner Ranch (26.1W.25.414) and less than 3 mi east of the Afton basalt cones (Plates 1, 4c; Figs. 4-2b). A driller's report cited by Wilson and others (1981, p. 294-295) states that this 563-ft well can produce about 30 gpm from a 188-ft zone of saturation (375-ft WT depth) with essentially no drawdown. As mentioned in Section 4.3.1, this particular well, with a measured water temperature of 33º C, is probably producing from a very permeable, intrusive-basalt unit or buried basalt-flow sequence, which according to the interpretation illustrated in Plate 4c, is near the USF2 / MSF2 contact.

Average aquifer transmissivity for the West Mesa area may be only about 10,000 ft^2/d (Wilson et al. 1981). Based on an aquifer test in the central West Mesa area, an estimated transmissivity of 5,900 ft^2/d was calculated for a well screened at selected depth intervals between 710 to 1,210 feet. In the northern part of the West Mesa area, aquifer transmissivity was estimated to be 10,000 ft^2/d, with a (confined) storage coefficient of $2x10^{-5}$. Average horizontal hydraulic conductivities may be as high as 70 ft/d in the uppermost part of the groundwater-flow system; but aquifer tests also show that they decrease markedly with depth. Frenzel and Kaehler (1992, Fig. 13) report a "lower to upper quartile" hydraulic-conductivity range of 9 to 43 ft/d in the upper 600 ft of saturated basin fill, with a median value of 22 ft/d. However, this depth zone is probably only representative of the *upper* to uppermost *middle* Santa Fe units (HSUs USF2/MSF2). Horizontal hydraulic conductivities of tested *middle* and *lower* Santa Fe HSUs (MSF2/LSF) in the 600 to 1,600 ft depth interval had a "lower to upper quartile" range of 2 to 14 ft/d, with a median value of 5 ft/d according to Frenzel and Kaehler (1992). Horizontal hydraulic conductivities in conglomeratic piedmont facies of the lower Santa Fe HSU (LFAs 7,8) rarely exceed 1 ft/d; and fine-grained basin-floor units (LFAs) not only are much less permeable but also contain saline water.

Vertical hydraulic conductivity values were found to range from about 0.2 ft/d to 3.0 ft/d for the entire thickness of the confining layers at West Mesa aquifer-test sites (Frenzel and Kaehler 1992). They also estimated that the ratio of horizontal to vertical hydraulic conductivity (anisotropy ratio) for the entire modeled stratigraphic sequence range was about 200; however, they indicate (p. 103) that this estimate is "not considered to be very accurate;" and Kernodle (1992a) suggests that a range in ratios of 200:1 to 1,000:1 may be more appropriate for basin-fill aquifer systems of the Rio Grande rift region (Hawley and Kernodle 2000).

6.2 THE MESILLA BASIN AQUIFER SYSTEMS

The most-productive aquifer zones are in the eastern half of the Mesilla Basin and vary in thickness from about 300 to 2,000 feet (Wilson et al. 1981; Wilson and White 1984; Nickerson 1986, 1989; Frenzel and Kaehler 1992; Nickerson and Myers 1993). The thickest section underlies the east-central West Mesa and adjacent parts of the Mesilla Valley floor in an area extending from Las Cruces to near Cañutillo (TX) and La Union (Plates 1, 3d-f, 4a-d, 5c). Basic aquifer properties of Santa Fe HSUs in the Mesilla Basin are very similar to those in adjacent parts of the Hueco-Tularosa and Jornada del Muerto basins (Cliett 1969; Wilson et al. 1981; Hawley 1984; Orr and White 1985; Orr and Myers 1986; Bedinger et al. 1989; Ashworth 1990; Orr and Risser 1992; Shomaker and Finch 1996; Hibbs 1999). The extent of these partly connected aquifer systems, and the amount of interbasin groundwater flow is controlled in great part by the hydraulic properties of basin-boundary features, lithofacies distribution patterns, and the Rio Grande Valley base level (all depending, of course, on "post-development" flow gradients). While fault zones and fine-grained facies commonly form effective barriers to interbasin flow, a small amount of underflow may enter or leave the basin at low barrier points associated with zones of relatively high permeability.

The major reservoirs of fresh to slightly saline groundwater in the Mesilla Basin are from basin-floor facies assemblages (LFAs 1 to 4) in the *middle* to *upper* parts of the Santa Fe Group (HSUs USF2 and MSF2). The dominant central-basin facies group comprises 1) thick sequences of fine-grained alluvial and lacustrine sediments that 2) interfinger with (LFA 3) and are overlapped by coarser-grained, ancestral-river deposits (LFAs 1 and 2). Along basin margins both of these *upper* and *middle* Santa Fe facies units are transitional with piedmont-slope alluvium (USF1, 3 and MSF1, 3; LFAs 5 to 8).

Inferred subsurface distribution patterns of lithofacies assemblages with aquifer potential in the Mesilla Basin area are shown on Plates 3c-f, 4a-f, 5 and 6. They are components of five HSUs (LSF, MSF, USF, RA and VA) and include LFAs 1 to 5. Documentation of these patterns varies from good (where petrographic analysis of drill cutting, borehole geophysical logs, and detailed drilling records are available) to strictly inferential (where few or no field data exist). This variation in data quality is clearly illustrated in the lithofacies interpretations presented on Plates 3 to 6. In the large areas and/or depth zones without adequate subsurface control only the most general attributes of the hydrostratigraphic units can be shown. However, all information collected to date does indicate that the entire basin-fill sequence is increasingly thinner and finer grained to the south. Fine- to medium-grained basin-floor facies are dominant units near the International Boundary west of Cerro de Cristo Rey, an area that includes the Santa Teresa and Noria (MT4) well sites (Plates 4e, 4f, 5c, 5d; LFAs 3, 9 and 10). How far this basin-fill fining and thinning trend continues towards the Bolson del Muertos area of northern Chihuahua has not yet been determined; limited test drilling, geophysical data, and photogeologic interpretations suggest that the Mesilla "structural" basin extends no more than 20 mi (33 km) into Mexico (Figs. 1-1, 1-2; Section 4.2).

As in the Albuquerque Basin to the north and the Hueco Bolson to the southeast, the most productive and thickest aquifers are ancestral Rio Grande fluvial deposits (LFAs 1 and 2) of the upper Santa Fe HSU (USF2). However, coarse-grained fluvial facies only extend well below the water table in the northeastern part of the Mesilla Basin near Las Cruces (Hawley and Lozinsky 1992). Throughout the southern and western part of the Mesilla Basin (and in most of the southern Jornada Basin), the *upper* Santa Fe HSU is entirely in the vadose zone; and the most productive aquifers occur in middle and lower Santa Fe HSUs (MSF2/LSF2: LFAs 3 and 4). A particularly productive aquifer zone is the "deep aquifer" of Leggat and others (1962), which underlies much of the lower Mesilla Valley in the Anthony-Cañutillo area (HSU-LSF 2, Fig. 5-1, Plates 4b-d, 5c, 6). This unit includes a distinctive eolian sand facies (LFA 4) that intertongues mountainward with piedmont fanglomerates (LFAs 7-8), and basinward with basin-floor facies assemblages (LFAs 3, 9 and 10?). The latter facies are here interpreted as playa-lake and fluvial-deltaic-deposits (Table 3-1, Fig. 3-4).

6.3 JORNADA BASIN AQUIFER SYSTEMS

As noted in Section 4.2.2, all subsurface geologic, geophysical and hydrogeologic investigations to date in the Jornada del Muerto sector of the study area indicate that T. 20 S., R. 2-3 E. marks the approximate northern limit of a basinfill aquifer system that is capable of producing significant quantities of fresh water for irrigation, industrial, and urban-suburban uses. Consideration and comparison of hydrogeologic interpretations illustrated in Plates 3c and 3d also suggest that most, if not all major producing wells in this area are tapping groundwater resources in the *middle* Santa Fe unit MSF1, which primarily comprises distal to medial piedmont-slope lithofacies assemblages (LFAs 5 to 8). Much of this upper Miocene basin-fill alluvium has low to moderate horizontal hydraulic conductivity (K); and very few wells penetrate more than 50 ft of saturated *upper* Santa Fe deposits with relatively high K (e.g., HSU-USF2, LFAs 2, 3). The primary (mountain-front) recharge area for this aquifer system extends southward from Bear Canyon in the southern San Andres Range (NASA site) to the Fillmore Canyon area of the central Organ Mountains. North of the center line of T. 20 S. (Plates 3a, 3b), the dominant *middle* and *upper* Santa Fe Group lithofacies assemblages are fine-grained basin-floor sediments with silty clay beds that are impregnated with gypsiferous cements or are inter layered with evaporites (LFAs 9, 10; see Sections 4.3.2, 5.2.1)

7.0 THE GROUNDWATER-FLOW SYSTEM

7.1 OVERVIEW

The hydrogeologic interpretations presented in preceding discussions support the basic conceptual model for groundwater-flow in the Mesilla Basin area that was recently developed by the U.S. Geological Survey (Frenzel and Kaehler 1992, Figs. 11, 15; p. C64-C74). The following discussion emphasizes aspects of geohydology that have not had much attention in prior descriptions of the basinwide flow system, and its inter-relationships with groundwater-flow regimes in the adjacent Jornada Basin and Bolson del Muertos areas (Figs. 1-1, 1-2).

With respect to surface flow, the Mesilla Basin is a geomorphic feature with both *open and closed* (topographic) components (Section 2.4); but it is externally *drained* in terms of groundwater flow (Fig. 2-3). The general potentiometric-surface map (Fig. 2-1) shows the major, near-surface elements of a flow system that discharges at the lower end of the Mesilla Valley above El Paso Narrows. Groundwater in the New Mexico and Texas parts of the basin generally moves from its flanking highlands and the upstream river valley (Rincon Valley-Selden Canyon) toward and sub-parallel to the Mesilla Valley. While a small amount of predevelopment groundwater inflow (probably less than 850 ac-ft/yr) was received from the southern end of the Jornada Basin across saddles in the buried section of the Doña Ana-Tortugas uplift (Plate 5a), the bulk of subsurface flow in the Jornada del Muerto is northwestward toward an underflow discharge area to the Rincon Valley between the Tonuco uplift and Rincon Hills (Plates 1, 3a-e; King et al. 1971; Wilson et al. 1981). Thus the *closed* southern Jornada (groundwater) Basin is also part of an extensive *drained- bolson* complex; and all of its ephemeral-lake depressions (*playas*) overlie a thick (>250-ft) vadose zone.

The hydraulic gradient in the shallow Mesilla Basin aquifer system in and near the Mesilla Valley (primarily HSUs RA and USF2) is essentially the slope of the river floodplain (~0.001; ~5 ft/mi). In the West Mesa area the hydraulic gradient in the upper basin-fill aquifer zone (primarily HSU MSF2) ranges from about 0.002 in the northwestern Mesilla Basin to 0.0004 near the International Boundary. The amount of groundwater underflow that enters the southern part of the basin from the Bolson de los Muertos area of north-central Chihuahua may be quite large (Section 2.8.4).

As in other intermontane-basin flow systems, basin-wide flow gradients in the Mesilla (groundwater) Basin have a downward component in upslope recharge areas and an upward one in discharge zones (Fig. 2.3). The ultimate Mesilla Basin discharge zone is near the lower end of the Mesilla Valley between La Union-Cañutillo and the river-gaging station at Courchesne (Fig. 5.2, Plates 1, 4e, 5c, 6). There has been very little groundwater outflow through El Paso del Norte since the last major cycles of deep-valley incision occurred in the Middle to Late Pleistocene (see Sections 4.3.2, 6.3, 6.5, 7.3). Most pre-development discharge from the combined basin and valley aquifer systems was by evapotranspiration from the extensive valley-floor wetlands that still existed when W.T. Lee (1907) initially mapped the water table and shallow aquifer system in the lower Mesilla Valley.

In and adjacent to heavily developed areas, such as the Mesilla and Rincon Valley, local-flow direction is influenced by a new set of hydrologic conditions, such as the river, canals, drains, well pumpage, and heavily irrigated fields (Richardson et al. 1972; Frenzel and Kaehler 1992). At the present time, the water table is approximately 10 to 25 ft below the floodplain surface in most of the inner Mesilla Valley; and detailed hydraulic-gradient measurements at hydrologic sections near the Las Cruces, Mesquite, and Cañutillo well fields demonstrate that the river is a losing stream in those areas (Nickerson and Myers 1993; Nickerson 1999). Present discharge occurs primarily through evapotranspiration from irrigated croplands and riparian vegetation, flow to drains, and an increasing amount of pumping from all available aquifer zones (including both municipal-industrial and irrigation-agriculture consumption).

Much of the groundwater pumped for irrigation is derived from the unconfined to semi-confined parts of the shallow aquifer zone, which are no more than 250 to 600 ft thick. The *middle* Santa Fe HSU is the most heavily developed aquifer zone, in terms of both drinking-water production and industrial consumption; and this unit is increasingly being pumped for irrigation (Wilson and White 1984). Most discharge from the *lower* Santa Fe unit occurs as municipal and industrial pumping in the Anthony (NM-TX) to Cañutillo (TX) area.

7.2 RECHARGE PRESENT AND PAST

Most recharge to the basin-fill aquifer system occurs 1) through vertical and lateral underflow from the "shallow" alluvial-aquifer zone of the inner Rio Grande Valley, and 2) by mountain-front mechanisms with some "mountain-block" contributions (Fig. 3.2, Section 3.2; Richardson et al. 1972; Peterson et al. 1984; Nickerson and Myers 1993; Anderholm 1994, 2001; Wasiolek 1995; Waltemeyer 2001; Naus 2002). Recharge estimates for the arid to semiarid Chihuahuan Desert region are based on the conservative assumptions that 1) only 1 to 3% of mean-annual precipitation contributes to recharge, 2) this contribution is distributed very unevenly, and 3) it is most effective in mountain-front zones adjacent to larger and higher watersheds, and in the valleys of perennial streams and major arroyos (Hawley et al. 2000; Scanlon et al. 2001). Recharge to the shallow aquifer zone of the Mesilla-Rincon Valley area, comprising integrated parts of the valley- and basin-fill aquifer systems, occurs primarily as vertical flow from the surface-water system (river, canals, laterals, irrigated cropland, and drains) except in times of extreme drought. This inner-valley-aquifer unit is, in turn, the major source of recharge to underlying and laterally adjacent basin fill of the Santa Fe Group (mainly HSUs USF2 and MSF2). Except for a few perennial springs and seeps, and short reaches of intermittent mountain streams, there are no permanent surface-water bodies in the small highland watersheds on the flanks of the Mesilla and Jornada Basins. Mountain-front recharge is, therefore, very low; and losing reaches of the Rio Grande channel and associated irrigation-canal systems are the major present sources of groundwater replenishment.

7.2.1 Mesilla Basin Recharge

Mountain-front recharge contribution to Mesilla Basin aquifers, exclusive of the 215 mi^2 Mesilla Valley area, is probably less than 10,000 ac-ft/yr. *Note that present and projected, basinwide groundwater use greatly exceeds this amount.* In other words, only about 2% of a mean annual precipitation of 8 to 9 inches actually contributes to recharge outside the inner river valley. Frenzel and Kaehler (1992, Fig. 18) estimate that average-annual mountain-front recharge is about 9,700 ac-ft, with about two thirds being derived from higher and larger watersheds of the Organ and Franklin Mountains. They also estimate that another 2,200 ac-ft/yr is derived from the western group of uplands that includes the East Potrillo Mountains and the West Potrillo volcanic field. Small highland areas with relatively low relief, such as the Doña Ana and Robledo Mountains, and Aden-Sleeping Lady Hills are very small recharge sources.

Much of the West Mesa (La Mesa) area west and southwest of the Mesilla Valley is a very gently sloping plain (<5ft/mi) with numerous shallow depressions and a discontinuous veneer of eolian sand (Plate 1). An indurated calcic-soil zone is normally present 3 to 10 ft below the surface. Due to common presence of fractures and pipe-like discontinuities, indurated soil-carbonate horizons is not necessarily the major factor limiting deep percolation of soil moisture in the uppermost vadose zone. This 300 to 400-ft thick zone, which is primarily composed of interbedded layers of clean sand to gravelly sand and silty to sandy clay, forms an effective barrier to downward movement of soil water, particularly in the context of an arid climatic regime during the past 5 to 10 thousand years. The other major limiting factor affecting basin-floor recharge simply relates to the very high efficiency of desert vegetation in soil-moisture extraction (e.g., Gile et al. 1995, 1998).

7.2.2 Speculations on Predevelopment and Late Quaternary Recharge

The significance of present and past climatic conditions on "predevelopment" groundwater-flow regimes is very well documented by both modern meteorological data, and the historic and pre-historic tree-ring record (U.S. Dept. of Commerce 1999; Thomas 1962, 1963; Schmidt 1986; D'Arrigo and Jacoby 1992). For example, the region experienced prolonged droughts from the late 1940s until the late 1970s; and the following two decades were abnormally wet. Whether or not we are entering another drought period remains to be seen. Major climate cycles of the past two millennia are also well documented. The information compiled by Scurlock (1998) and review papers by Ackerly (1999, 2000) on the Rio Grande basin above Fort Quitman are particularly useful resource documents.

Much larger-scale, glacial-interglacial and pluvial-interpluvial cycles of the Quaternary Period have also had a major impact on both groundwater and surface-water flow regimes, and are of particular relevance to geohydrologic concerns in the Mesilla

Basin as well as in other parts of the northern Chihuahua Desert region (Sections 6.5, 7.1; Hawley et al. 2000, Table 3-1). The pluvial-lake record in nearby *closed* and *undrained* basins, and other geomorphic and paleoecologic indicators of major environmental shifts associated with glacial-interglacial cycles of the Quaternary Period, is especially important (Hawley 1993; Hawley et al. 2000). Emphasis here is on the fact that groundwater-flow regimes observed during the past century have major recharge and storage components inherited from thousands to tens of thousands of years ago. This observation is confirmed by recent research on groundwater geochemistry and ^{14}C age in other basins of the Rio Grande rift (e.g., Plummer et. al. 2000; Sanford et al. 2000; Anderholm 2001; Scanlon et al. 2001).

Relict shorelines and other lacustrine features, ancient river-channel deposits, and plant and animal fossil assemblages, most dating from Late Pleistocene through mid-Holocene time (~130 to 2 Ka), demonstrate that environmental conditions of the relatively recent past differed markedly from those of historic and late pre-historic time. Detailed discussion of this topic is beyond the scope of this report; but it is very well documented that long intervals of the last glacial (Wisconsinan) stage, and even parts of the Holocene, were significantly wetter and cooler than the present (Metcalf 1967, 1969; Gile et al. 1981; Betancourt et al. 1990; Hawley 1993; Harris 1997; Wilkins and Currey 1997; Krider 1998; Connin et al. 1998; Castiglia and Fawcett 2001; Metcalfe et al. 2002). While glacial-pluvial paleoclimatic and associated hydrologic regimes obviously varied depending on basin and range physiographic setting, it is now clear that cool-season precipitation/runoff increased, evapotranspiration was suppressed, and groundwater recharge was enhanced during much of the recent geologic past. The great importance of the Late Quaternary history of "pluvial" Lake Palomas in the Bolson de los Muertos to the evolution of the Mesilla Basin groundwater-flow system is discussed in the following section (7.3.1).

7.3 MOVEMENT

Buried bedrock highs between southern Jornada and adjacent parts of lower Rincon Valley, Selden Canyon and upper Mesilla Valley definitely restrict interbasin groundwater movement in all but the shallowest parts of the regional flow system. Work to date on the geohydrology of the Mesilla Basin and contributing parts of the southern Jornada Basin leads to one conclusion: Essentially all groundwater in the basinwide-flow system that is not intercepted by evapotranspiration and pumping must ultimately move toward a discharge area in the southernmost part of the inner Mesilla Valley. In terms of large quantity and relatively short residence time, the dynamic part of the groundwater-flow system is in the shallow aquifer zone beneath and adjacent to the river-valley floor (King et al. 1971; Wilson et al. 1981; Frenzel and Kaehler 1992).

7.3.1 Mesilla Basin

Beneath a large part of the Mesilla Valley floor extending from Doña Ana (Plate 3d) to the NM-TX border near Anthony (Plates 4c, 4d, 5c, 6), major aquifer units of the *upper* and *middle* Santa Fe Group (HSUs-USF2/MSF2) are well integrated with both river-valley fill (HSU RA) and surface-water-flow systems. The saturated thickness of this sequence of ancestral and modern river deposits ranges from about 600 ft near Las Cruces to 250 ft at Cañutillo (Plates 3d-f, 4a-d, 5c; Hawley and Lozinsky 1992; Nickerson and Myers 1993). Compared with *middle* and *lower* Santa Fe HSUs (LFAs 3, 4, 7, 8), upper-zone hydraulic conductivities are high to moderate (Tables 3-2, 3-3). Moreover, hydrogeologic controls on underlying components of the basinwide flow system are also significant. Of special importance are those parts of the deeper flow regime, characterized by long flow paths and travel times, that ultimately discharge to the shallow aquifer zone and surface-flow system in the lower part of the Mesilla Valley (Figs. 5-2, 5-3; Plate 6).

Paleozoic and Cretaceous carbonate rocks, such as those exposed in most of the basin-boundary uplifts (Plate 1), probably provide conduits for inter-basin groundwater flow in some areas (Sections 3.1, 4.2.1, 5.1.2). A temperature log in carbonate rocks at the south end of the East Potrillo uplift (Plate 4, borehole 29.1W.6.410; Snyder 1986) has a distinct isothermic profile segment that indicates significant groundwater circulation at that locality. Similar geothermal and groundwater-flow conditions occur along much of eastern border zone of the Mesilla Valley (Section 4.2, 5.1; Swanberg 1975; Gross and Icerman 1983; Gross 1988; Ross and Witcher 1998; Frenzel and Kaehler 1992, Fig. 47).

The buried bedrock high extending from the Doña Ana to the Tortugas uplifts northeast of Las Cruces (Figs. 4-1, 4-2b, Plates 3d-f, 5a; Woodward and Myers 1997) forms a discontinuous hydrogeologic barrier between the Mesilla and southern Jornada structural basins. This feature restricts, but doesn't completely block underflow contributions from the central Organ Mountains (Las Cruces and Tortugas Arroyo watersheds). The same observation can be made concerning the small groundwater inflow through river-valley fill at the mouth of Selden Canyon near Leasburg Dam. Moreover, while there is 400 to 500 ft of saturated basin fill (mainly HSUs USF2/MSF) at Fillmore Pass between the Organ Cap and Franklin uplifts, there is no evidence of any significant interflow between Mesilla Basin and Hueco Basin aquifer systems because of negligible hydraulic gradient (Plates 4b, 5b; Orr and White 1985). Orr and Risser (1992) assign an underflow contribution of about 260 ac-ft/yr in northern Hueco Bolson groundwater-flow model.

Flow at the southern end of the Mesilla Basin near the International Boundary is eastward toward the ultimate discharge zone of the groundwater-flow system at the upper end of El Paso del Norte (Plates 4c, 6; Wilson et al. 1981). Slichter (1905) clearly demonstrated that the valley constriction at the International Dam site in El Paso Narrows (Figs. 5.2, 5.3; Plates 1, 4c, 6) is an effective barrier to underflow discharge into the upper El Paso Valley. The bedrock-boundary units at the Narrows are Cretaceous and Lower Tertiary are rock types that have very low hydraulic conductivities (primarily mudstone, sandstone, limestone and andesite). No zones of enhanced permeability due to limestone dissolution or open-fracture systems have ever been identified. The saturated valley fill (HSU RA) is no more than 75 ft thick; and it is restricted to an inner-valley area that has a maximum width of about 500 ft. Hydraulic conductivity also appears to be relatively low (probably in the low to moderate range, Table 3-3); and the hydraulic gradient of both surface and subsurface flow components is about 0.001. Therefore, Slichter's (1905) estimate of about 81 ac-ft/yr (50 gpm, 0.1 cfs) of groundwater outflow through the Narrows is probably at the upper limit of potential subsurface discharge to aquifer systems of the western Hueco Bolson.

Excellent documentation demonstrates that at several sites in the Texas section of the lower Mesilla Valley that an upward groundwater-flow gradient existed in that area prior to development of municipal and industrial wells in intermediate and deep aquifer zones (HSUs MSF2 and LSF). Leggat and others (1962, p. 16, well Q172) reported that the artesian head in the deep aquifer zone in Well JL 49-04-402 (Plate 4d, Table A2) was 8 ft above the shallow water table and 1.25 ft above the land surface in 1957. This well site is near Vinton at the east edge of the floodplain (Plate 8d). Another flowing well, the 1,074-ft Lippincott oil test (JL 49-04-723) drilled in 1922 produced warm saline water from Cretaceous bedrock that was penetrated below 822-940 ft (Figs. 5-2, 5-3; Plates 5c, 6, Table A2; Leggat et al. 1962, page 16, well Q138). Precision temperature logs of USGS-WRD monitoring wells near Cañutillo also record upward-flow gradients in the intermediate and deep aquifer zones of depths greater than about 600 ft below the shallow water table (CWF 1D-4D: JL-49-04-481, 477, 473, 468—Nickerson and Myers 1993; Wade and Reiter 1994; Reiter 2001).

More work still must be done with respect to transboundary underflow conditions in the broad Mesilla Basin area between the bedrock uplifts formed by Sierra Juárez and Cerro de Muleros (del Cristo Rey), and the East Potrillo Mountains (Figs. 2-1, 2-3; Plates 1, 4e, 4f, 5c, 5d, 6). Unpublished water-level data from several 1,000-ft test wells in the Mexican part of the basin indicate that, at least the shallow part of the groundwater-flow system in HSU MSF2 (mostly *LFA 3*) is northeastward toward the Santa Teresa area (e.g., La Joya and El Mirador tests; Figs. 5-2, 5-3; Plates 1, 4f, 5c, 5d, 6).

Current research on the Late Quaternary history of “pluvial Lake Palomas (Reeves 1969)” by Castiglia and Fawcett (2001), and Castiglia (2002) demonstrates that the floor of Bolson de los Muertos, and adjacent parts of the Mimbres, Casas Grandes Santa Maria, and Freznal basins were periodically inundated by very large and deep lakes as late as early to middle Holocene time (8,400 to 6,500 ^{14}C yrs BP). The watershed contributing to these basin systems is about 12,650 mi^2. Elevations of the deep-lake stages are in the 3,940 to 3,965-ft range, or 160 to 185 ft above the “predevelopment” potentiometric surface (3,780 to 3,770 ft) in the Noria to Santa Teresa area about 30 mi to the northeast (Fig. 2-1, Plates 1, 4e, 4f, 5c, 5d; Wilson et al. 1981). Furthermore, the floor of the Wisconsinan “Ice Age” bedrock channel of the ancestral Rio Grande at El Paso Narrows was scoured out to a depth of about 85 ft below present floodplain level (channel-base elev. of ~ 3,635 ft.). Therefore, during these Lake Palomas high stands, the northeastward gradient of (at least) the shallow part of the groundwater-flow system would have been at least 5 ft/mi, with underflow discharge to the Mesilla Valley shallow aquifer system in the Anapra, Sunland Park, (lower) Santa Teresa area. Since the present potentiometric surface in the north-central part of the Bolson de los Muertos is about 3,775 ft (Córdoba et al. 1969, p. 7), there may still be a slight northeast-trending pressure gradient toward the International Boundary area northwest of Cerro del Cristo Rey (Fig. 2-1).

7.3.2 Jornada Basin

The major component of predevelopment-groundwater flow in the southern Jornada Basin was northwestward from its highest-mountain-source watershed, which extends from Fillmore Canyon in the Organ Mountains to Bear Canyon in the San Andres Range (Plates 1, 3c, 3d, 3e; King et al. 1971; King and Hawley 1975). The flow axis was along the structurally and topographically lowest point of the basin, which nearly coincides with the western margin of the downthrown (hanging-wall) block of the Jornada fault (Section 5.1.2, Plates 3b, 3c). Part of this flow system along the curved base of the Doña Ana uplift still discharges as underflow to the Rincon Valley through the broad and deep structural gap between the Tonuco uplift (San Diego Mountain) and the Rincon Hills. Near the northern border of the study area, from Rincon Arroyo to east of Point of Rocks, the northwestward flow regime is joined by a major groundwater contribution from the flanks of the San Andres and Caballo ranges that form the respective flanks of the "central" Jornada Basin to the north. This part of the Mesilla and Jornada basins has a single major axial drainageway, the south-flowing Jornada Draw, which discharges to Flat Lake "playa" SE of Point of Rocks.

Only a minor component of predevelopment flow (probably less than 850 ac-ft/yr) spilled as underflow discharge to the Mesilla Valley area though shallow gaps in the buried Doña Ana-Goat Mountain-Tortugas uplift near the U.S. 70 corridor (Plates 3d, 5a). Therefore, most of the direct underflow-discharge to the Mesilla Valley inferred by Schulz-Makuch and others (2003, Figs. 1 and 2) for the southernmost Jornada Basin is here considered to have been directed "up-basin" as suggested by King and others (1971, p. 58). Major geothermal groundwater resources at Tortugas Mountain, Radium Hot

Springs (adjacent to Leasburg Dam), San Diego Mountain, and Rincon do suggest, however, that deeper (regional) groundwater flow regimes are present in fractured bedrock aquifer systems of the southern Jornada Basin study area (Ross and Witcher 1998; Witcher 1988, 1991, 1998). This important topic definitely needs further study, but is beyond the scope of the current project.

7.4 STORAGE AND PRODUCTION POTENTIAL

The maximum saturated thickness of the Santa Fe Group in the deepest structural subbasins of the Mesilla and southern Jornada Basins is about 3,000 ft (Plates 3 to 6). As emphasized throughout this report, however, productive aquifer zones are usually restricted to the upper 1,000 ft of saturated basin fill (HSUs RA/USF2/MSF2; LFAs a, 1-3). The eastern and western structural subbasins may also restrict or “partition” deeper parts of the groundwater-flow system beneath the West Mesa area of the Mesilla Basin; but head distribution and water quality/temperature changes with depth in that area can (at best) only be inferred, because data from deep-piezometer nests are still unavailable.

The most productive aquifers in the 1,100-mi^2 Mesilla “groundwater” basin are formed by 1) unconsolidated to weakly indurated basin fill of the upper and middle Santa Fe HSUs, and 2) overlying Mesilla Valley fill deposited by the Rio Grande (HSU RA). The total saturated thickness of the latter unit rarely exceeds 60 ft; while the *upper* and *middle* Santa Fe units extend from about 600 to 1,600 ft below the water table in the structurally deepest parts of the basin (Plates 3d-f, 4a-f, 5c, 5d). Limiting assumptions used in this study for preliminary estimates of available water stored in the basin-fill aquifers of the Mesilla Basin: 1) the estimated average thickness of the unconfined to semi-confined part of the system is about 200 ft in an inner-basin area of about 1,000 mi^2, 2) specific yield is 0.1, and 3) quality is potable (or fresh, <1,000 mg/L TDS). If these assumptions prove to be valid, then our estimate of available water in storage is about 13 million ac-ft. Based on review of data in the Frenzel and Kaehler (1992) flow model, Balleau (1999, p. 46) estimated that about 14 million ac-ft of available fresh water is stored in the upper 100 ft of saturated fill in the West Mesa area (about 360,000 acres in NM).

Estimated average thickness of fill that is saturated with fresh to slightly saline water (< 3,000 mg/L TDS) is about 1,000 ft in the deepest parts of the Mesilla Basin. Since the areal extent of the deeper subbasins is about 750 mi^2, there could be as much as 480 million ac-ft of saturated, poorly consolidated basin fill in the central and eastern parts of the Mesilla Basin. As noted above, essentially all of the aquifer zones more than 200 ft below the potentiometric surface are confined or semiconfined. So even if an assumed “available porosity” value of 10% proves to be reasonable, there will always be large variation in our estimates of the amount of recoverable groundwater (as much as 50 million ac-ft), given the constraints imposed by technology, economics, environmental concerns, and socio-political forces.

8.0 CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

This project's primary purpose was to create a digital hydrogeologic-framework model for the Mesilla Basin and contiguous parts of the southern Jornada Basin in the south-central New Mexico border region (Plates 1 to 6). The scope of work was dictated by requirements of the LRGWUO and the NMISC for the best-available hydrogeologic information that will provide a sound basis for ongoing updates to the existing groundwater-flow model of the Lower Rio Grande-Mesilla Basin study area. Of particular importance are concurrent efforts by Maddock and others to refine flow-model components, and related work supported by the NMOSE and the USGS-WRD. The long-term objective of this study, however, is to develop a state-of-the-art hydrogeologic model that will lead to significant improvements in present and future geohydrologic models in the south-central New Mexico region. Emphasis was on 1) the hydrogeologic framework of intermontane-basin and river-valley fills that collectively form the region's major aquifer systems; and 2) how basin-fill composition and structural-boundary conditions influence groundwater flow and chemistry. GIS methodology (ARCINFO® platform) has been used to portray and integrate major framework components that include aquifer-system lithology and stratigraphy, basin boundaries, and internal basin structure.

This project completion report represents the first synoptic, basin-scale integration of hydrogeologic information in a study region that includes the Rincon-Selden Canyon-Mesilla-Paso del Norte sections of the Rio Grande Valley, and the Las Cruces-El Paso-Ciudad Juárez metropolitan district of southern New Mexico, western Texas and northern Chihuahua. From a flow-model perspective, hydrogeologic databases and interpretations have, heretofore, only been available in a variety of formats with a wide range of scale and interpretive quality. While all geology-based models tend to be "works in progress," we believe that our digital-framework template represents a significant scientific and technological advance over previously published work.

The "template" for our hydrogeologic-framework model is three-dimensional and has a combined surface-map—fence-diagram format (Plates 1 to 6) with a map-scale of 1:100,000; 10x vertical exaggeration of cross sections, and a base elevation of 1,000 ft asl (above MSL). Baseline information for about 160 “key wells” is used in design of 17 (schematic) hydrogeologic sections (Plates 3 to 6). It includes: 60 digitized borehole geophysical logs, driller and drill-cutting logs, groundwater head and chemical data, and interpretations of the major lithofacies, hydrostratigraphic and structural elements of basin hydrogeology (Appendix, Tables A1, A2, A3). GIS-framework components include area features (polygons), such as planimetric units that express the spatial extent of geologic-mapping units, line features representing the surface expression of fault-zones, and point features showing the location of important wells that provide detailed information on subsurface geology.

The primary aquifer systems of study region comprise thick sedimentary fills of a series of Rio Grande rift basins that are linked by the valley of the Rio Grande (Figs. 1-1 to 1-3). The Santa Fe Group of Late Cenozoic age (0.7 to 25 Ma) forms the bulk of unconsolidated to partly consolidated intermontane-basin fill. Thin Upper Quaternary fluvial deposits of the inner Rio Grande Valley form the other important aquifer unit. The hydrogeologic framework of basin-aquifer systems, with special emphasis on features related to both groundwater flow and quality, has three basic components: 1) lithofacies assemblages (LFAs), 2) hydrostratigraphic units (HSUs), and 3) bedrock and structural-boundary conditions. Basin- and valley-fill aquifers are only partly linked with respect to surface and subsurface flow. In the northern Mesilla Valley to Rincon Valley area, the deeply entrenched river valley provides an inter-basin connection for both surface and shallow-subsurface flow between the Mesilla Basin and the southern Jornada Basin. Linkage for limited inter-basin underflow is also furnished by several “paleo-valleys” across the buried-bedrock “high” the separates the basins northeast of Las Cruces (Doña Ana-Tortugas uplift). Bedrock narrows at Selden Canyon and El Paso del Norte form very effective barriers to substantial inter-basin groundwater flow between aquifer systems of the Rincon Valley and northern Mesilla Basin, and the lower Mesilla Valley and western Hueco Bolson, respectively.

While the Mesilla and Jornada basins share most characteristics of Rio Grande rift hydrogeologic systems (e.g., basic structural and hydrostratigraphic elements), they also have distinct differences with respect to lithofacies distribution patterns and their position in the regional groundwater-flow system. In most places, the upper and middle parts of the Mesilla Basin and Valley aquifer systems are well integrated with the surface and shallow-subsurface flow regime of the inner Rio Grande Valley. Moreover, in terms of groundwater quantity and quality, thickness and extent of lithofacies assemblages (LFAs 1 - 4) with "favorable aquifer potential" are very large. Finally, there is a substantial (but still unquantified) "paleo-recharge" contribution to groundwater flow in the southernmost Mesilla Basin from the large drainage basin of "pluvial-Lake Palomas (~12,650 mi^2). The Jornada Basin aquifer system, on the other hand, is characterized by a "tributary" groundwater-flow regime that is essentially isolated from the Mesilla Basin-river valley system except for one or two sites of small predevelopment discharge to the upper Mesilla Valley across narrow gaps in the buried Doña Ana-Tortugas uplift (est. < 1,000 ac-ft/yr). In addition, aquifers with potential for long-term, high-yield production and localized mountain-front recharge sources are limited to Jornada Basin areas south of the central parts of T. 20 S., R. 1-4 E. Fine-grained, gypsiferous basin-floor lithofacies (LFAs 9, 10) and brackish-water conditions characterize basin-fill aquifers in the Jornada del Muerto study area north of the Doña Ana Mountains and east of the Rincon Valley.

A major contribution of this and related New Mexico Water Resources Research Institute cooperative studies of border-region aquifer systems is the development of a mechanism for systematically classifying and organizing large amounts of relevant hydrogeologic information of widely varying quality and scale (from very general driller's observations to detailed bore-hole logs and water-quality data). Conceptual models of this type are simply qualitative to semi-quantitative descriptions (graphical, numerical, and verbal) of the basic architecture of a "typical" geohydrologic system in a Basin and Range hydrogeologic setting (Figs. 3-1 to 3-3, 5-1 to 5-3). Framework components can then be graphically displayed in combined map and cross-section (GIS) formats so that basic information and inferences on geohydrologic attributes (e.g., hydraulic conductivity, transmissivity, anisotropy, and general patterns of unit distribution) may be transferred to basin-scale, three-dimensional numerical models of groundwater-flow systems. There is also increasing recognition of the relevance of this type of hydrogeologic model to characterization and interpretation of groundwater geochemical/geothermal conditions, including "sources of salinity" in surface and shallow-subsurface systems of certain river-valley areas (e.g., Hawley and Kernodle 2000; Hawley et al. 2000; Hibbs et al. 2003; Witcher et al. 2004).

8.2 RECOMMENDATIONS

The first recommended action item (8.2.1) implements the primary project objective: Creation of a digital hydrogeologic-framework model that will lead to significant improvements in existing groundwater-flow models of the Mesilla Basin and contiguous parts of the southern Jornada Basin. The other six recommendations (8.2.2 to 8.2.7) emphasize the basic framework components (e.g., aquifer-system lithostratigraphy, bedrock boundaries, and internal basin structure) and how they influence geochemical and geothermal aspects of the flow system and related geotechnical concerns.

8.2.1 Groundwater-Flow Model Improvement and Integration

Our three-dimensional GIS "template" integrates the basic hydrogeologic-framework elements of the partly linked, aquifer systems of the Mesilla and southern Jornada basin area. Moreover, these elements (lithofacies assemblages, hydro-stratigraphic units, bedrock-boundary, and internal-basin structure) are defined in the context of general ranges of hydraulic properties and geohydrologic conditions. This synoptic portrayal of basin-scale hydrogeology, therefore, should be used immediately as an important tool in modifying and updating the existing groundwater-flow model of the Lower Rio Grande Basin area. It is also designed to be used in development of a unified-flow model for the entire Mesilla-southern Jornada Basin area, if and when that action becomes necessary. From a flow-modeler's perspective, hydrogeologic databases and interpretations (like most other geology-based models) tend to be "works in progress." Database gaps and interpretive flaws, however, will only be resolved by model testing in the context of a "feed-back loop" systems process (see below).

8.2.2 Test Drilling, and Installation of Piezometers/Extensometers

Documentation of hydrogeologic, geohydrologic, geophysical and hydro-geochemical conditions ranges from good to poor depending on the availability and quality of borehole-sample and geophysical logs, and other detailed records. The large variation in data quality is clearly illustrated by the hydrostratigraphic and lithofacies interpretations presented on Plates 3 to 6. In the large areas and/or depth zones without adequate subsurface control, only the most general attributes of the hydrogeologic units can be shown. Major target sites for test drilling and piezometer/extensometer installation are in areas of active or planned urban-suburban expansion (including municipal/industrial well fields). These localities include the tri-state, binational boundary area of the southeastern Mesilla Basin and lower Mesilla Valley, the Las Cruces-Mesilla area, and the southernmost Jornada Basin near the U.S. 70 corridor. As in other intermontane-basin flow systems, basin-scale flow gradients in the Mesilla Basin have a downward component in upslope and up-valley recharge areas and an upward-flow gradient in the lower Mesilla Valley discharge area. Moreover, essentially all of the intermediate and deep parts of the basin-fill aquifer system are confined. Accurate interpretations of groundwater flow and land-subsidence potential in the Mesilla-Jornada basin complex clearly require the best possible information on head distribution and aquitard/aquiclude properties.

8.2.3 Transboundary-Flow Characterization

Much more work is needed on transboundary underflow conditions in the broad southern Mesilla Basin area between the Sierra Juárez - Cristo Rey uplift and the East Potrillo Mountains (Figs. 2-1, 2-3; Plates 1, 4e, 4f, 5c, 5d, 6). This effort will require close binational cooperation at local, state and federal levels. Unpublished water-level data from several 1,000-ft test wells in the Chihuahua part of the basin indicate that, at least the shallow part of the groundwater-flow system in HSU MSF2 (mostly LFA 3) is northeastward toward the Santa Teresa area (e.g., La Joya and El Mirador tests; Figs. 5-2, 5-3; Plates 1, 4f, 5c, 5d, 6). Current research on history of “pluvial Lake Palomas” demonstrates that the floors of Bolson de los Muertos and adjacent basins were periodically inundated by deep lakes as late as early to middle Holocene time (8,400 to 6,500 ^{14}C yrs BP). The watershed contributing to this basin system is about 12,650 mi^2 and includes the Mimbres, Casas Grandes, Santa Maria, and Carmen river basins.

Elevations of Lake Palomas high stands are in the 3,940 to 3,965-ft range, or 160 to 185 ft above the “predevelopment” potentiometric surface (3,780 to 3,770 ft) in the

Noria to Santa Teresa area about 30 mi to the northeast (Figs. 1-2, 1-3; Plates 1, 4e, 4f, 5c, 5d). Furthermore, ancestral-river base-level elevation at the El Paso Narrows ranged from 3,635 to 3,715 ft. Therefore, during these deep "pluvial-lake" stages, the northeastward gradient of (at least) the shallow part of this transboundary-flow system would have been about 5 ft/mi, with underflow discharge to the Mesilla Valley shallow aquifer in the Anapra-Sunland Park area. Since the present potentiometric surface in the northern Bolson de los Muertos is about 3,775 ft, there may still be a slight northeastward flow gradient toward the International Boundary area between Cerro del Cristo Rey and Santa Teresa (Fig. 1-3).

8.2.4 Geochemical Sampling

In addition to continuing standard documentation of groundwater chemistry throughout the study area, we recommend the use of geochemical and isotopic tracers to better define 1) flow dynamics between recharge and discharge areas, and 2) sources of groundwater salinity. Oxygen, carbon and hydrogen isotopes can be used to identify and trace water sources, and constrain groundwater-residence time (e.g., ^{3}H to identify regions of recent recharge, and ^{14}C to provide age control). Noble gas studies as a means to further refine conceptual models of recharge and groundwater residence times may also be appropriate. With respect to salinity sources, boron isotopes should be used to help discriminate between mixing end-member waters, such as "natural" groundwater, and water from anthropogenic sources (e.g., treated municipal wastewater and irrigation-return flow). Oxygen and hydrogen isotopic composition will help distinguish between other saline end-members, including evaporated water, in Rio Grande valley-fill and deeper basin-fill aquifer systems; and sulfur and oxygen isotopes in dissolved sulfate could serve as indicators of sources of dissolved solids. Comparison of ionic ratios of chloride, bromide, and iodide may also be very helpful in providing insights on mixing mechanisms and sources of salinity.

8.2.5 Surface Geophysical Surveys

Subsurface geophysical methods (borehole-logging) are routinely used in the study area; but only a few of the many available surface-survey methods have been applied as tools to better define hydrogeologic components of local aquifer systems. While considerable progress has been made in using gravity (density-based) techniques to define buried-basin margins and to estimate general thickness ranges of basin fill, very few seismic (refraction/reflection) surveys have been designed for definition on subbasin-scale features. Therefore, a high priority should be placed on the application of other "state-of-the-art" survey methods (both ground-based and airborne/satellite) for subsurface investigations at a broad range of scales. For example, many structural-framework components of a very similar hydrogeologic system in the Albuquerque Basin are now well documented by airborne-aeromagnetic surveys (USGS-contracts); and ground-electromagnetic techniques are proving to be useful in detecting fine-grained sediments in shallow river valley fill (Bartolino and Cole 2002). Ground displacements caused by hydrostatic-pressure variations in aquifer systems of the Albuquerque metro-area have also been "observed using interferometric synthetic aperture radar" (InSAR—satellite-platform; Heywood et al. 2002).

8.2.6 Evaluation of Brackish Groundwater Resources

There is a pressing need for quantification of the production potential of brackish (slightly to moderately saline) groundwater resources throughout the study area. Our provisional estimate of average thickness of basin fill that is saturated with fresh to slightly saline water (< 3,000 mg/L TDS) is about 1,000 ft in the central and eastern parts of the Mesilla Basin (~750 mi^2). If this estimate is valid, there could be as much as 480 million ac-ft of poorly consolidated, saturated fill in that area. Assuming an "available porosity" value of 10%, as much as 50 million ac-ft fresh to slightly saline water might be recoverable. Nearly all of the aquifer system more than 200 ft below the water table, however, is confined to semiconfined, and flow-regime specifics (e.g., storage and recharge potential) are only broadly defined. Current "guesstimates" of production potential, therefore, should be viewed with great caution, particularly, given the constraints imposed by technology, economics, environmental concerns, and socio-political forces.

8.2.7 Evaluation of Bedrock Aquifer Conditions and Geothermal Resources

Assessment of subbasin-scale bedrock aquifer systems and geothermal resources are beyond the scope of our investigation, but these topics definitely deserve detailed evaluation. As noted in Section 3.1, groundwater production from most bedrock units of the study area is limited to low-yield fracture zones, which occur in a wide variety of rock types of Proterozoic to Mid-Cenozoic age. However, there are a number of places were fracture zones in a variety of rock types, and dissolution-prone carbonate and gypsiferous sedimentary rocks form groundwater reservoirs and play a significant role in local to subbasin-scale flow dynamics. Marine-carbonate and siliciclastic rocks of Paleozoic and early Cretaceous age are the dominant lithologic types exposed in the San Andres, Tortugas, Bishop Cap, Franklin, Juárez, East Potrillo, and Robledo uplifts; and these units commonly extend for large distances beneath the fills of adjacent basins (Plates 1, 3, 4, 5, 6). For Example, the 1,074-ft Lippincott oil test (JL 49-04-723) drilled in 1922 and located near the southern end of the Mesilla Valley was a flowing well that produced warm brackish water from Cretaceous bedrock encountered below 822-940 ft (Figs. 5-2, 5-3, Plates 5c, 6, Table A2).

Important geothermal-groundwater resources at Tortugas Mountain, Radium Springs (adjacent to Leasburg Dam), San Diego Mountain, and Rincon indicate that deeper (inter-basin and intrabasin) flow regimes are present in fractured bedrock aquifers in some parts of the study area. Paleozoic and Cretaceous carbonate rocks, such as those exposed in most of the basin-boundary uplifts (Plate 1); probably provide the primary conduits for inter-basin flow (Sections 2.4, 2.6.3). For example, a temperature log in carbonate rocks at the south end of the East Potrillo uplift (Plate 4, borehole 29.1W.6.410) has a distinct isothermic profile segment that indicates significant deep-groundwater circulation at that locality. Similar geothermal and groundwater-flow conditions have been observed along much of eastern border zone of the Mesilla Valley (Section 4.2, 5.1).

9.0 REFERENCES

Ackerly, N.W. 1999. The evolution of the Rio Grande. In *Proceedings of the 43rd Annual New Mexico Water Conference: Water Challenges on the Lower Rio Grande*. Edited by C.T. Ortega Klett. New Mexico Water Resources Research Institute Report No. 310. 26-32.

Ackerly, N.W. 2000. Paleohydrology of the Rio Grande: A first approximation. In *Proceedings of the 44th Annual New Mexico Water Conference: The Rio Grande Compact: It's the Law*. Edited by C.T. Ortega Klett. New Mexico Water Resources Research Institute Report No. 312. 113-123.

Akermann, H. 1982. Unpublished interpretations of Geophysical Service Inc. (Western Division-Midland, TX), Refractions with Vibroseis. U.S. Geological Survey.

Allen, B.D., S.D. Connell, J.W. Hawley, and B.D. Stone. 1998. Core drilling provides information about Santa Fe Group aquifer beneath Albuquerque's West Mesa. *New Mexico Geology*. 20:8-13.

Anderholm, S. K. 1985. *Clay-size fraction and powdered whole-rock X-ray analyses of alluvial basin deposits in central and southern New Mexico.* U.S. Geological Survey Open-File Report 85-163. 18 p.

Anderholm, S.K. 1994. *Ground-water recharge near Santa Fe, north-central New Mexico.* U.S. Geological Survey Water Resources Investigations Report 94-4078. 68 p.

Anderholm, S.K. 2001. *Mountain-front recharge along the eastern side of the Middle Rio Grande basin, central New Mexico*. U.S. Geological Survey Water-Resources Investigations Report 00-4010. 36 p.

Anderholm, S.K. and C.E. Heywood. 2003. *Chemistry and age of ground water in the southwestern Hueco Bolson, New Mexico and Texas*. U.S. Geological Survey Water-Resources Investigations Report 02-4237. 16 p.

Anderholm, S. K., M.J. Radell, and S.F. Richey. 1995. *Water-quality assessment of the Rio Grande Valley study unit, Colorado, New Mexico, and Texas—Analyses of selected nutrient, suspended-sediment, and pesticide data.* U.S. Geological Survey Water-Resources Investigations Report 94-4061. 203 p.

Anthony, E.Y. and J. Poths. 1992. The surface exposure dating and magma dynamics, the Potrillo Volcanic Field, Rio Grande Rift, New Mexico. *Geochimica et Cosmochimica Acta*. 56:4105-4108.

Anthony, E.Y., J.M. Hoffer, W.K. Waggoner, and W. Chen. 1992. Compositional diversity in Late Cenozoic mafic lavas in the Rio Grande Rift and Basin and Range Province, southern New Mexico. *Geologic Society of America Bulletin*.104: 973-979.

Ashworth, J. B. 1990. *Evaluation of ground-water resources in El Paso County, Texas.* Texas Water Development Board Report 324. 25p.

Bailey, L.R. 1963 (editor). *The A.B. Gray Report; Survey of a Route on the 32nd Parallel for the Texas Western Railroad, 1854.* Los Angeles. Westernlore Press. 240 p. *See comments on EPN reach on p. 35, 42-43, 50-60, 137,153-155, 184-185*

Balleau, W.P. 1999. Groundwater modeling in the lower Rio Grande. In *Proceedings of the 43rd Annual New Mexico Water Conference: Water Challenges on the Lower Rio Grande*. Edited by C.T. Ortega Klett. New Mexico Water Resources Research Institute Report No. 310. 46-38.

Bartolino, J.R. and J.C. Cole. 2002. *Ground-water resources of the Middle Rio Grande Basin.* U.S. Geological Survey Circular 1222, 132 p.

Bedinger, M.S., K.A. Sargent, and W.H. Langer. 1989. *Studies of Geology and Hydrology in the Basin and Range Province, Southwestern United States, for Isolation of High-level Radioactive Waste: Characterization of the Rio Grande Region, New Mexico and Texas*. U.S. Geological Survey Professional Paper 1370-C. 42 p.

Betancourt, J.L., T.R. Van Devender, and P.S. Martin. 1990. *Packrat Middens: The last 400,000 Years of Biologic Change*. The University of Arizona Press, 1230 N. Park Avenue, Tucson, Arizona 85719. 467 p.

Birch, F. S. 1980. *Three-dimensional gravity model of basin hydrologic parameters in New Mexico*. Unpublished report prepared for the U.S. Geological Survey by the University of New Mexico under contract 14-08-001-17899. 27 p.

Bowie, M.W. and V.T. McLemore. 1987. Clay mineralogy of selected sedimentary and volcanic rocks, Socorro County, New Mexico. In *Guidebook to the Socorro area, New Mexico*. Compiled by V.T. McLemore and M.W. Bowie. New Mexico Bureau of Mines & Mineral Resources Guidebook: 46-54.

Bryan, K. 1938. Geology and ground-water conditions of the Rio Grande depression in Colorado and New Mexico. In *Rio Grande Joint Investigation in the Upper Rio Grande Basin in Colorado, New Mexico, and Texas*. National Resources Committee, Regional Planning, Part VI. Washington, D.C., U.S. Government Printing Office. 1, part 2: 196-225.

Castiglia, P.J. 2002. *Late Quaternary climate history of the pluvial Lake Palomas system, Chihuahua, Mexico.* The University of New Mexico, unpublished M.S. Thesis. 161 p.

Castiglia, P.J. and P.J. Fawcett. 2001. Shoreline and lacustrine records of late Quaternary climate change in the Chihuahuan Desert, Mexico. *Eos, Transactions of the American Geophysical Union.* 82: 47 [AGU Fall Meeting Supplement, Abstract PP22A-0507. F757].

Chapin, C.E. and S.M. Cather. 1994. Tectonic setting of the axial basins of the northern and central Rio Grande Basin, New Mexico. In *Basins of the Rio Grande Rift—Structure, stratigraphy, and tectonic setting*. Edited by G.R. Keller and S.M. Cather. Geological Society of America Special Paper 291. 5-25.

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

Cliett, T. 1969. Groundwater occurrence of the El Paso area and its related geology. *New Mexico Geological Society, 20th Annual Field Conference Guidebook*. 209-214.

Collins, E.W. and J.A. Raney. 2000. *Geologic map of west Hueco Bolson, El Paso region, Texas*. The University of Texas at Austin, Bureau of Economic Geology, Miscellaneous Map No. 40, scale 1:100,000.

Connell, S.D., B.D. Allen, and J.W. Hawley. 1998. Subsurface stratigraphy of the Santa Fe Group from borehole geophysical logs, Albuquerque area, New Mexico. *New Mexico Geology*. 20:2-7.

Connin, S.L., J. Betancourt, and J. Quade. 1998. Late Pleistocene C4 plant dominance and summer rainfall in the southwestern United States from isotopic study of herbivore teeth. *Quaternary Research*. 50:179-193.

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

Córdoba, D.A., S.A. Wengerd, and J.W. Shomaker (editors). 1969. The Border Region (Chihuahua, Mexico, and the United States). *New Mexico Geological Society, 20th Annual Field Conference Guidebook*. 228 p.

Crumpler, L.S. 2001. Volcanism in New Mexico: An overview. In *Volcanology in New Mexico*. Edited by L.S. Crumpler and S.G. Lucas, New Mexico Museum of Natural History and Science Bulletin. 18: 17-29.

Crumpler, L.S. and J.C. Aubele. 2001. Volcanoes of New Mexico: An abbreviated guide for non-specialists. In *Volcanology in New Mexico*. Edited by L.S. Crumpler and S.G. Lucas, New Mexico Museum of Natural History and Science Bulletin. 18:5-15.

Cuniff, R.A. 1986. *New Mexico State University Geothermal Exploratory Well, DT-3; Final completion report*. New Mexico State University Physical Science Laboratory, Las Cruces, NM-88003-3458. 151 p.

D'Arrigo, R.D. and G.C. Jacoby. 1992. A tree-ring reconstruction of New Mexico winter precipitation and its relation to El Niño/southern oscillation events. In *El Niño: Historical and paleoclimatic aspects of the Southern Oscillation*. Edited by H.F. Diaz and V. Markgraf. New York: Cambridge University Press. 476 p.

Darton, N.H. 1916. *Geology and Underground Water of Luna County, New Mexico*. U.S. Geological Survey Bulletin 618. 188 p.

DeAngelo, M.V. and G.R. Keller. 1988. Geophysical anomalies in southwestern New Mexico. *New Mexico Geological Society, 49th Annual Field Conference Guidebook*. 71-75.

Dethier, D. P. 2001. Pleistocene incision rates in the western United States calibrated using Lava Creek B tephra. *Geology*. 29: 9: 783-786.

DGGTN. 1990. CD Juárez H13-1, *Cartas Geologica*, Escala 1:250,000: Direccion General de Geografia del Territorio Nacional.

Dickinson, W. R. 1970. Interpreting detrital modes of graywacke and arkose. *Journal of Sedimentary Petrology*. 40: 695-707.

Doty, G.C. 1953.*Water-supply development at the National Aeronautics and Space Agency—Apollo Propulsion System Development System, Doña Ana County, New Mexico.* U.S. Geological Survey, Open-File Report, 40 p.

Dunham, K. C. 1935. *The geology of the Organ Mountains*. New Mexico Bureau of Mines and Mineral Resources Bulletin. 11, 272 p.

Eakin, T.E., D. Price, and J.R. Harill. 1976. *Summary appraisals of the nation's groundwater resources-Great Basin region*. U.S. Geological Survey Professional Paper 813-G. 37 p.

Ellis, S.R., G.W. Levings, L.F. Carter, S.F. Richey, and M.J. Radell. 1993. Rio Grande Valley, Colorado, New Mexico, and Texas. *Water Resources Bulletin*. 29: 4: 617-646.

Emory, W.H. 1857-1859. *Report on the United States Mexican Boundary Survey*. 34th Congress, 1st Session, House of Representatives, Executive Document No. 135, 2 vol., Washington, D.C., Cornelius Wendell [reprinted by Texas Historical Association, 1987].

Faulds, J.E. and R.J. Varga. 1998. The role of accommodation zones and transfer zones in the regional segmentation of extended terranes. In *Accommodation Zones and Transfer Zones: The Regional Segmentation of the Basin and Range Province*. Edited by J.E. Faulds and J.H. Stewart. Boulder, Colorado: Geological Society of America Special Paper 323:1-45.

Fenneman, N.M. 1931. *Physiography of the Western United States*. New York: McGraw-Hill Book Co. 534 p.

Feth, J.H. 1964. Hidden recharge. *Groundwater*. 2:4:14-17.

Frenzell, P.F. and C.A. Kaehler. 1992. *Geohydrology and simulation of ground-water flow in the Mesilla Basin, Doña Ana County, New Mexico and El Paso County, Texas; with a section on water quality and geochemistry by S. K. Anderholm*. U.S. Geological Survey Professional Paper 1407-C. 105 p.

Gile, L.H. 1987. A pedologic chronology of Kilbourne Hole, southern New Mexico: I. Soils in tuff; II. Time of the explosions. *Soil Science Society of America Journal*. 51. 746-760.

Gile, L.H. 2002. Lake Jornada, an early-middle Pleistocene lake in the Jornada del Muerto Basin, southern New Mexico. *New Mexico Geology* 24: 1: 3-14.

Gile, L.H. and R.B. Grossman. 1979. *The Desert Project Soil Monograph*. U.S. Department of Agriculture, National Technical Information Service, Document No. PB80-13534, Springfield, VA 22161. 984 p.

Gile, L.H., R.P. Gibbens and J.M. Lenz. 1995. Soils and sediments associated with remarkable, deeply penetrating roots of crucifixion thorn (Koeberlinia spinosa Zucc.). *Journal of Arid Environments*. 35:137-151.

Gile, L.H., R.P. Gibbens,and J.M. Lenz. 1998. Soil-induced variability in root systems of creosotebush (Larrea tridentata) and tarbush (Flourensia cernua). *Journal of Arid Environments*. 39:57-78.

Gile, L.H., J.W. Hawley, and R.B. Grossman. 1981. *Soils and geomorphology in a Basin and Range area of southern New Mexico–Guidebook to the Desert Project*. New Mexico Bureau of Mines and Mineral Resources Memoir 39. 222 p.

Gile, L.H., F.F. Peterson, and R.B. Grossman. 1966. Morphological and genetic sequences of carbonate accumulation in desert soils. *Soil Science*. 101:5:347-360.

Gile, L.H., J.W. Hawley, R.B. Grossman, H.C. Monger, C.E. Montoya and G.H. Mack. 1995. *Supplement to the Desert Project Guidebook, with emphasis on soil micromorphology*. New Mexico Bureau of Mines and Mineral Resources Bulletin. 142. 96 p.

Giles, G.C. and J.W. Pearson. 1998. Characterization of hydrostratigraphy and ground-water flow on the southwestern San Andres Mountains pediment, NASA-JSC White Sands Test Facility. *New Mexico Geological Society, 49th Annual Field Conference Guidebook*. 317-325.

Goff, F., B.F. Kues, M.A. Rogers, L.D. McFadden, and J.N. Gardner (editors). 1996. The Jemez Mountain region. *New Mexico Geological Society, 47th Annual Field Conference Guidebook*. 484 p.

Grauch, V.J.S., 1999, Principal features of high-resolution aeromagnetic data collected near Albuquerque, New Mexico. *New Mexico Geological Society 50th Annual Field Conference Guidebook,* 115-118.

Grauch, V.J.S., C.L. Gillespie, and G.R. Keller. 1999. Discussion of new gravity maps for the Albuquerque basin area. *New Mexico Geological Society, 50th Annual Field Conference Guidebook.* 119-124.

Grauch, V.J.S., D.A. Sawyer, G.R. Keller, and C.L. Gillespie. 2000. Geologic and hydrologic framework: A. Contributions of gravity and aeromagnetic studies to improving the understanding of subsurface hydrogeology, Middle Rio Grande Basin, New Mexico. In *U.S. Geological Survey Middle Rio Grande Basin Study—Proceedings of the Fourth Annual Workshop, Albuquerque, New Mexico*. February 15-16, 2000. Edited by J.C. Cole. U.S. Geological Survey Open File Report 00-488. 3-4.

Gregg, Josiah. 1954. *Commerce of the Prairies [1844],* edited by Max L. Moorhead: University of Oklahoma Press, Norman, 469 p. *See comments on EPN reach on p. 98-101,272-275.*

Gross, J. 1988. *A hydrogeological investigation of the Las Cruces geothermal field*. New Mexico State University, unpublished Master's Thesis. 212 p.

Gross, J. and L. Icerman. 1983. *Subsurface investigations for the area surrounding Tortugas Mountain, Doña Ana County, New Mexico*. New Mexico Energy Research and Development Institute, Interim Report NMERDI 2-67-2238 (2). 70 p.

Gustavson, T.C. 1991. *Arid basin depositional systems and paleosols: Fort Hancock and Camp Rice Formations (Pliocene-Pleistocene) Hueco Bolson, West Texas and adjacent Mexico*. The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 198. 49 p.

Haase, C.S. and R.P. Lozinsky. 1992. Estimation of hydrologic parameters. In *Hydrogeologic Framework of the Northern Albuquerque Basin*. Compiled by J.W. Hawley and C.S. Haase. New Mexico Bureau of Mines and Mineral Resources Open File Report 387. p. VI-1-VI-3.

Hamilton, S.L. and T. Maddock III. 1993. *Application of a groundwater flow model to the Mesilla Basin, New Mexico and Texas*. University of Arizona Department of Hydrology and Water Resources Document Number 93-020.

Hammond, G.P. and A. Rey. 1966. *The rediscovery of New Mexico, 1580-1594: The explorations of Chamuscado, Espejo, Canstano de Sosa, Morlete, and Leyva de Bonilla and Humaña.* Albuquerque, University of New Mexico Press.

Hanson, R.T., J.S. McLean, and R.S. Miller. 1994. *Hydrogeologic framework and preliminary simulation of ground-water flow in the Mimbres Basin, southwestern New Mexico*. U.S. Geological Survey Water Resources Investigations Report 94-4011.118 p.

Harbour, R.L. 1972. *Geology of the northern Franklin Mountains, Texas and New Mexico*. U.S. Geological Survey Bulletin 1298, 129 p.

Harris, A.H. 1997. Geographic and chronologic patterns in Late Pleistocene vertebrate faunas, southern New Mexico. In *New Mexico's Fossil Record 1*. Edited by S.G. Lucas, J.W. Estep, T.E. Williamson, and G.S. Morgan. New Mexico Museum of Natural History and Science Bulletin No. 11: 129-134.

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

Hawley, J.W. 1975. Quaternary history of Dona Ana county regions south-central New Mexico. *New Mexico Geological Society, 26th Annual Field Conference Guidebook.* 138-150.

Hawley, J.W. (compiler). 1978. *Guidebook to the Rio Grande Rift in New Mexico and Colorado*. New Mexico Bureau of Mines and Mineral Resources Circular 163. 241 p.

Hawley, J.W. 1984. *Hydrogeologic cross sections of the Mesilla Bolson, New Mexico and Texas.* New Mexico Bureau of Mines and Minerals Resources Open-File Report 190. 10 p. [Appendix B in Hawley and Lozinsky, 1992]

Hawley, J.W. 1986. Physiographic provinces (and) landforms of New Mexico. In *New Mexico in Maps.* Edited by J.L. Williams. Albuquerque, NM: University of New Mexico Press. 28-31.

Hawley, J.W. 1993. *Geomorphologic Setting and Late Quaternary History of Pluvial-lake Basins in the Southwestern New Mexico Region*. New Mexico Bureau of Mines and Mineral Resources Open File Report 391. 28 p.

Hawley, J.W. 1996. Hydrogeologic framework of potential recharge areas in the Albuquerque Basin, central New Mexico. In *Hydrogeology of Potential Recharge Areas and Hydrogeochemical Modeling of Proposed Artificial Recharge Methods in Basin- and Valley-fill Aquifer Systems, Albuquerque Basin, New Mexico.* Edited by J.W. Hawley and T.M. Whitworth. New Mexico Bureau of Mines and Mineral Resources Open File Report 402-D. 1-70.

Hawley, J.W. and C.S. Haase. 1992. *Hydrogeologic framework of the northern Albuquerque Basin.* New Mexico Bureau of Mines and Mineral Resources Open File Report 387. variously paged.

Hawley, J.W. and J.M. Kernodle. 2000. Overview of the hydrogeology and geohydrology of the northern Rio Grande basin – Colorado, New Mexico, and Texas. In *Proceedings of the 44th Annual New Mexico Water Conference: The Rio Grande Compact: It's the Law*. Edited by C.T. Ortega Klett. New Mexico Water Resources Research Institute Report No.310. 46-38.

Hawley, J.W. and F.E. Kottlowski. 1969. Quaternary geology of the south-central New Mexico border region. In *Border Stratigraphy Symposium*. New Mexico Bureau of Mines and Mineral Resources Circular 104. 89-115.

Hawley, J.W. and R.P. Lozinsky. 1992. *Hydrogeologic Framework of the Mesilla Basin in New Mexico and Western Texas*. New Mexico Bureau of Mines and Mineral Resources Open File Report 323. 55 p.

Hawley, J.W., C.S. Haase, and R.P. Lozinsky. 1995. Hydrogeologic framework of the northern Albuquerque Basin. In *Proceedings of the 39th Annual New Mexico Water Conference, The water future of Albuquerque and Middle Rio Grande Basin.* Edited by C. Ortega Klett. New Mexico Water Resources Research Institute, Technical Report No. 290. 37-55.

Hawley, J.W., J.F. Kennedy, and B.J. Creel. 2001. The Mesilla Basin aquifer system of New Mexico, West Texas and Chihuahua—an overview of its hydrogeologic framework and related aspects of groundwater flow and chemistry. In *Aquifers of West Texas*. Edited by R.E. Mace, W.F. Mullican III and E.S. Angle. Austin, Texas Water Development Board Report 356: 76-99.

Hawley, J.W., J.F. Kennedy, B.J. Hibbs, and M. Cleary. 2002. Basin-fill aquifers of the southern New Mexico border region, USA and Mexico: Their hydrogeologic framework, and related aspects of groundwater flow and chemistry. In *Integrated Trans-boundary Water Management*. Proceedings of a special joint conference of Universities Council on Water Resources (UCOWR), Environmental & Water Resources Institute of ASCE (EWRI), U.S. Army Corps of Engineers Institute for Water Resources (CEIWR), and National Ground Water Association (NGWA). 164-172 [electronic version available at hgeomatters@qwest.net].

Hawley, J.W., F.E. Kottlowski, W.S. Strain, W.R. Seager, W.E. King, and D.V. LeMone. 1969. The Santa Fe Group in the south-central New Mexico border region. In *Border Stratigraphy Symposium*. New Mexico Bureau of Mines and Mineral Resources Circular 104. 52-76.

Hawley, J.W., B.J. Hibbs, J.F. Kennedy, B.J. Creel, M.D. Remmenga, M. Johnson, M. Lee, and P. Dinterman. 2000. *Trans-International Boundary Aquifers in Southwestern New Mexico*. New Mexico Water Resources Research Institute, New Mexico State University, prepared for U.S. Environmental Protection Agency-Region 6 and International Boundary and Water Commission; Technical Completion Report-Interagency Contract X-996350-01-3.126 p.

Healy, D.F. 1996. *Water-quality assessment of the Rio Grande Valley study unit, Colorado, New Mexico, and Texas—Occurrence and distribution of selected pesticides and nutrients at selected surface-water sites in the Mesilla Valley, 1994-1995.* U.S. Geological Survey Water-Resources Investigations Report 96-4069. 85 p.

Hearne, G.A. and J.D. Dewey. 1988. *Hydrologic Analysis of the Rio Grande Basin North of Embudo, New Mexico, Colorado and New Mexico.* U.S. Geological Survey Water Resources Investigations Report 86-4113. 244 p.

Heywood, C.E. 1995. Investigation of aquifer-system compaction in the Hueco basin, Texas, USA. In *5th International symposium on land subsidence.* Delft, Netherlands. International Association of Hydrological Sciences Publication 234: 35-45.

Heywood, C. E. and R.M. Yager. 2003. *Simulated ground-water flow in the Hueco Bolson, an alluvial-basin aquifer system near El Paso, Texas.* U.S. Geological Survey, Water Resources Investigations Report 02-4108. 27 p.

Heywood, C.E., D.E. Galloway, and S.V. Stork. 2002. *Ground displacements caused by aquifer-system water-level variations using Interferometric Synthetic Aperture Radar [InSAR] near Albuquerque, New Mexico.* U.S. Geological Survey, Water Resources Investigations Report 02-4235. 17 p.

Hibbs, B. 1999. Hydrogeologic and water quality issues along the El Paso/ Ju<rez corridor: An international case study. *Environmental & Engineering Geoscience*. V:1:27-39.

Hibbs, B., B.K. Darling, and I.C. Jones. 1998. Hydrogeologic regimes of arid-zone aquifers beneath low-level radioactive waste and other waste repositories in Trans-Pecos, Texas and northern Chihuahua, Mexico. In *Gambling with Groundwater–Physical, Chemical, and Biological Aspects of Aquifer-stream Relationships*. Edited by J. Van Brahana and others. St. Paul, Minnesota: American Institute of Hydrology. 311-322.

Hibbs, B.J., M.M. Lee and J.W. Hawley. 1999. Evolution of hydrochemical facies in the Mimbres Basin aquifer system: A transboundary resource. In *Hydrological issues of the 21st Century: Ecology, Environment, and Human Health*. American Institute of Hydrology, Hydrological Science and Technology. 15. 1-4:52-65.

Hibbs, B.J., R.N. Boghici, M.E. Hayes, J.B. Ashworth, A.T. Hanson, Z.A. Samani, J.F. Kennedy, and B.J. Creel. 1997. *Transboundary Aquifers of the El Paso/Ciudad Ju<rez/Las Cruces Region*. Texas Water Development Board and New Mexico Water Resources Research Institute. Special Report for U.S. Environmental Protection Agency, Region 6, Dallas, Texas. 155 p.

Hibbs, B., F. Phillips, J. Hogan, C. Eastoe, J. Hawley, J. Kennedy, F. Nuñez, A. Granados, and T. Kretzschmar. 2003. Binational Study of the Surface and Ground Water Resources of the El Paso/Juárez International Corridor. In *Trans-Boundary Water Issues*. Edited by K. Rubin. The Universities Council on Water Resources. Water Resources Update. Issue No. 125. 25-30. [electronic version available at hgeomatters@qwest.net]

Hibbs, B., R. Boghici, J. Ashworth, M. Hayes, D. Peckham, R. Guillen, O. Fuentes, N. Laloth, M. Morales, A. Maldonado, B. Creel, J. Kennedy, A. Hanson, Z. Samani, F. Nuñez, R. Lemus, G. Moreno, E. Rascon, R. Kuo, S. Waggoner, C. Ito, J. Robinson, J. Valdez, D. Little, A. Rascon, A. Reyes, K. Williams, M. Vaughan, O. Cabra, T. Kelly, and C. King. 1998. *Transboundary aquifers and binational ground-water data base, City of El Paso/Ciudad Ju<rez area; Base de datos binacional del acuifero transfronterizo, de Ciudad Ju<rez, Chih./El Paso, Texas*. First binational aquifer report and data base sanctioned by the governments of the United States and Mexico, 47 p. + appendices and CD-ROM. Participating agencies; International Boundary and Water Commission, U.S. Environmental Protection Agency, Texas Water Development Board, New Mexico Water Resources Research Institute, Comision Internacional de Limites y Aguas, Comision Nacional del Agua, Junta Municipal de Agua y Saneamiento de Ciudad Ju<rez.

Hill, R.T. 1896. Descriptive topographic terms of Spanish America. *National Geographic*. 7: 291-302.

Hill, R.T. 1900. *Physical geography of the Texas region*. U.S. Geological Survey Topographical Atlas, Folio 3. 12 p.

Hoffer, J.M. 2001. Geology of the West Potrillo Mountains. In *Volcanology in New Mexico*. Edited by L.S. Crumpler and S.G. Lucas, New Mexico Museum of Natural History and Science Bulletin 18: 141-145.

IBWC. 1939—2000. *Flow of the Rio Grande and related data from Elephant Butte Dam, New Mexico, to the Gulf of Mexico.* International Boundary and Water Commission Water Bulletin Nos. 9 to 70.

Izett, G.A. and R.E. Wilcox. 1982. *Map Showing Localities and Inferred Distributions of the Huckleberry Ridge, Mesa Falls, and Lava Creek Ash Beds (Pearlette Family Ash Beds) of Pliocene and Pleistocene Age in the Western United States and Southern Canada*. U.S. Geological Survey Miscellaneous Investigations Map I-1325, scale 1:4,000,000.

Jimenez, A.J. and G.R. Keller. 2000. Rift Basin Structure in the Border Region of Northern Chihuahua. *New Mexico Geological Society, 51st Annual Field Conference Guidebook.* 79-83.

Keller, G.R. and S.M. Cather (eds.). 1994. *Basins of the Rio Grande rift: Structure, stratigraphy and tectonic setting*. Geological Society of America Special Paper 291. 304 p.

Keller, G.R., B.S. Penn, and S.H. Harder. 1998. Las Cruces country: A geophysical and remote sensing perspective. *New Mexico Geological Society, 49th Annual Field Conference Guidebook. 87-91.*

Kelley, S.A. and J.P. Matheny. 1983. *Geology of Anthony quadrangle, Doña Ana County, New Mexico*. New Mexico Bureau of Mines and Mineral Resources, Geologic Map 54, scale 1:24,000.

Kennedy, J.F. 1999. Aquifer sensitivity assessment for the Mesilla Valley. In *Proceedings of the 43rd Annual New Mexico Water Conference: Water Challenges on the Lower Rio Grande*. Edited by C.T. Ortega Klett. New Mexico Water Resources Research Institute Report No. 310. 84-104.

Kennedy, J.F., J.W. Hawley, and M. Johnson. 2000. The hydrogeologic framework of basin-fill aquifers and associated ground-water-flow systems in southwestern New Mexico—an overview. *New Mexico Geological Society, 51st Annual Field Conference Guidebook*. 235-244.

Kernodle, J.M. 1992a. *Summary of U.S. Geological Survey ground-water-flow models of basin-fill aquifers in the Southwestern Alluvial Basins region, Colorado, New Mexico, and Texas*. U.S. Geological Survey Open File Report 90-361. 81 p.

Kernodle, J.M. 1992b. *Results of simulations by a preliminary numerical model of land subsidence in the El Paso, Texas area*. U.S. Geological Survey Water Resources Investigations Report 92-4037. 35 p.

Kernodle, J.M., D.P. McAda, and C.R. Thorn. 1995. *Simulation of Ground-water Flow in the Albuquerque Basin, Central New Mexico*. U.S. Geological Survey Water Resources Investigations Report 94-4251. 114 p.

Keyes, C.R. 1905. Geology *and underground water conditions of the Jornada del Muerto, New Mexico.* U.S. Geological Survey Water-Supply and Irrigation Paper no. 123. 42 p.

King, W.E. and J.W. Hawley. 1975. Geology and ground-water resources of the Las Cruces area. *New Mexico Geological Society, 26th Annual Field Conference Guidebook*. 195-201.

King, W.E., J.W. Hawley, A.M. Taylor, and R.P. Wilson. 1971. *Geology and Ground-water Resources of Central and Western Doña Ana County, New Mexico*. New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 1. 64 p.

Knowles, D.B. and R.A. Kennedy. 1958. *Ground-water resources of the Hueco Bolson northeast of El Paso, Texas.* U.S. Geological Survey Water-Supply Paper 1426. 186 p.

Kottlowski, F.E. 1958. Geologic history of the Rio Grande near El Paso. *West Texas Geological Society, Guidebook 1958 Field Trip*. 46-54.

Kottlowski, F.E. 1960. *Reconnaissance geologic map of Las Cruces 30-minute quadrangle*. New Mexico Bureau of Mines and Mineral Resources, Geologic Map 14.

Kottlowski, F.E. and J.W. Hawley. 1975. First day road log from Las Cruces to southern San Andres Mountains, and return. *New Mexico Geological Society, 26th Annual Field Conference Guidebook.* 1-16, 69-70.

Kottlowski, F.E., R.H. Flower, M.L. Thompson, and R.W. Foster. 1956. *Stratigraphic studies of the San Andres Mountains, New Mexico.* New Mexico Bureau of Mines and Mineral Resources Memoir 1, 132 p.

Krider, P.R. 1998. Paleoclimatic significance of late Quaternary lacustrine and alluvial stratigraphy, Animas Valley, New Mexico. *Quaternary Research*. 50:283-289.

Kucks, R.P., P.L. Hill and C. E. Heywood. 2001. *New Mexico aeromagnetic and gravity maps and data: A web site for distribution of data*. U.S. Geological Survey Open-File Report 01-0061.

Land, L.F. and C.A. Armstrong. 1985. *A preliminary assessment of land-surface subsidence in the El Paso area, Texas*. U.S. Geological Survey Water Resources Investigations Report 85-4155. 96 p.

Lee, W.T. 1907. *Water Resources of the Rio Grande Valley in New Mexico*. U.S. Geological Survey Water-Supply Paper 188. 59 p.

Leeder, M.R., G.H. Mack, and S.L. Salyards. 1996. Axial—transverse fluvial interactions in half-graben: Plio-Pleistocene Palomas Basin, southern Rio Grande Rift, New Mexico, USA. *Basin Research*. 12:225-241.

Leeder, M.R., G.H. Mack, J. Peakall, and S.L. Salyards. 1996. First quantitative test of alluvial stratigraphic models: Southern Rio Grande rift, New Mexico. *Geology*. 24. 1: 87-90.

Leggat, E.R. 1962. *Development of ground-water of the El Paso district, Texas*. Texas Water Commission, Bulletin 6204. 56 p.

Leggat, E.R., M.E. Lowry, and J.W. Hood. 1962. *Ground-water resources of the lower Mesilla Valley, Texas and New Mexico.* Texas Water Commission Bulletin 6203. 191p.

Love, D.W. and W.R. Seager. 1996. Fluvial fans and related basin deposits of the Mimbres drainage. *New Mexico Geology*. 18:4:81-92.

Lovejoy, E.M.P. 1975. An interpretation of the structural geology of the Franklin Mountains, Texas. *New Mexico Geological Society, 26th Annual Field Conference Guidebook*. 261-268.

Lovejoy, E.M.P. 1976a. *Geology of Cerro de Cristo Rey uplift, Chihuahua and New Mexico*. New Mexico Bureau of Mines and Mineral Resources Memoir 31. 84 p.

Lovejoy, E.M.P. 1976b. Neotectonics of the southeast end of the Rio Grande rift along the Mesilla Valley fault zone and the course of the Rio Grande, El Paso, Texas. In *Symposium on the stratigraphy of the Franklin Mountains.* El Paso Geological Society, Quinn Memorial Volume: 123-138.

Lovejoy, E.M.P. (editor). 1979. *Sierra de Ju<rez, Chihuahua, Mexico: Structure and history.* El Paso Geological Society Special Publication. 59 p.

Lovejoy, E.M.P. and J.W. Hawley. 1978. Southern rift guide 1, El Paso to New Mexico--Texas state line. In *Guidebook to Rio Grande rift in New Mexico and Colorado*. New Mexico Bureau of Mines and Mineral Resources Circular 163: 57-71.

Lovejoy, E.M.P. and W.R. Seager. 1978. Discussion of structural geology of Franklin Mountains. In *Guidebook to Rio Grande rift in New Mexico and Colorado*. New Mexico Bureau of Mines and Mineral Resources Circular 163 p. 68-69.

Lozinsky, R.P. and J.W. Hawley. 1986. The Palomas Formation of south-central New Mexico -- a formal definition. *New Mexico Geology*. 8. 4, p: 73-82.

Lucas, S. G., and J.W. Hawley. 2002. The Otero Formation, Pleistocene lacustrine strata in the Tularosa Basin, southern New Mexico. *New Mexico Geological Society, 53rd Annual Field Conference Guidebook*.

Lucas, S.G., G.S. Morgan, J.W. Estep, G.H. Mack and J.W. Hawley. 1999. Co-occurrence of the Proboscideans Cuvieronius, Stegomastodon, and Mammuthus in the Lower Pleistocene of Southern New Mexico. *Journal of Vertebrate Paleontology*. 19:3:595-597.

Machette, M.N., T. Long, G.O. Bachman, and N.R. Trimbel. 1997. *Laboratory data for Calcic soils in central New Mexico: Background information for mapping Quaternary deposits in the Albuquerque Basin*. New Mexico Bureau of Mines and Mineral Resources Circular 205. 63 p.

Maciejewski, T.J. and K.C. Miller. 1998. Geophysical interpretations of subsurface geology, pediment of the San Andres Mountains to the Jornada del Muerto Basin, New Mexico. *New Mexico Geological Society, 49th Annual Field Conference Guidebook*. 101-116.

Mack, G.R. and R.E. Clemons. 1988. Structural evidence for Laramide (early Tertiary) Burro uplift in southwestern New Mexico. *New Mexico Geological Society, 39th Annual Field Conference Guidebook*. 59-66.

Mack, G.H. and W.R. Seager. 1990. *Tectonic controls on facies distribution of the Camp Rice and Palomas Formations (Pliocene-Pleistocene) in the southern Rio Grande rift*. Geological Society of America Bulletin, 102: 45-53.

Mack, G.H., D.W. Love, and W.R. Seager. 1997. Spillover models for axial rivers in regions of continental extension: The Rio Mimbres and Rio Grande in the southern Rio Grande rift, USA. *Sedimentology*. 44:637-652.

Mack, G.H., F.E. Kottlowski, and W.R. Seager. 1998. The stratigraphy of south-central New Mexico. *New Mexico Geological Society, 49th Annual Field Conference Guidebook*. 135-153.

Mack, G.H., W.C. McIntosh, M.R. Leeder, and H.C. Monger. 1996. Plio-Pleistocene pumice floods in the ancestral Rio Grande, southern Rio Grande rift, USA. *Sedimentary Geology*. 103:1-8.

Mack, G., H., S.L. Salyards, and W.C. James. 1993. Magnetostratigraphy of the Plio-Pleistocene Camp Rice and Palomas formations in the Rio Grande rift of southern New Mexico. *American Journal of Science*. 293: 49-77.

Mack, G.H., S.L. Salyards, W.C. McIntosh, and M.R. Leeder. 1998. Reversal magnetostratigraphy and radioisotopic geochronology of the Plio-Pleistocene Camp Rice and Palomas Formations, southern Rio Grande rift. *New Mexico Geological Society, 49th Annual Field Conference Guidebook*. 229-236.

Mack, P.D.C. 1985. *Correlation and provenance of facies within the upper Santa Fe Group in the subsurface of the Mesilla Valley, southern New Mexico*. Las Cruces, New Mexico State University, unpublished Master's Thesis. 137 p.

Maxey, G.B. 1968. Hydrogeology of desert basins. *Ground Water*. 6:1-22.

McGrath, D.B. and J.W. Hawley. 1987. Geomorphic evolution and soil-geomorphic relationships in the Socorro area, central New Mexico. In *Guidebook to the Socorro area, New Mexico*. Compiled by V.T. McLemore and M.W. Bowie. New Mexico Bureau of Mines & Mineral Resources Guidebook: 55-67.

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

Metcalf, A.L. 1967. *Late Quaternary mollusks of the Rio Grande Valley, Caballo Dam to El Paso, Texas*. Texas Western Press, University of Texas at El Paso, Science Series No. 1. 62 p.

Metcalf, A.L. 1969. Quaternary surface sediments and mollusks--southern Mesilla Valley, New Mexico and Texas. *New Mexico Geological Society, 20th Annual Field Conference Guidebook*. 158-164.

Metcalfe, S., A. Say, S. Black, R. McCullock, and S. O'Hara. 2002. Wet conditions during the last glaciation in the Chihuahuan Desert, Alta Babicora basin, Mexico. *Quaternary Research*. 57: 91-101.

Mifflin, M.D. 1988. *Delineation of Groundwater Flow Systems in Nevada*. University of Nevada/Reno, Desert Research Institute, Technical Report Series H-W, Hydrology and Water Resources Publication 4. 109 p.

Mifflin, M.D. 1988. Region 5, Great Basin. In *Hydrogeology–The Geology of North America*. Edited by W. Back, J.S. Rosenshein, and P.R. Seaber. Geological Society of America DNAG. O-2. 69-78.

Monger, H.C. and W.C. Lynn. 1996. Clay mineralogy of the Desert Project and Rincon Surface study area. In *Studies of soil and landscape evolution in southern New Mexico.* Supplement to the Desert Project Soil Monograph, v. II. Edited by L.H. Gile and R.J. Ahrens. Lincoln, NB. Soil Survey Investigations (NRCS) Report 44: 111-155.

Morrison, R.B. 1969. Photointerpretive mapping from space photographs of Quaternary geomorphic features and soil associates in northern Chihuahua and adjoining New Mexico and Texas. *New Mexico Geological Society, 20th Field Conference, Guidebook*. 116-129.

Mueller, J.E. 1975. *Restless river: International law and the behavior of the Rio Grande*. The University of Texas at El Paso, Texas Western Press. 155 p.

Myers, R.G. and B.R. Orr. 1986. *Geohydrology of the aquifer in the Santa Fe Group, northern West Mesa of the Mesilla Basin near Las Cruces, New Mexico.* U.S. Geological Survey, Water-Resources Investigations Report 84-4190. 37 p.

Nickerson, E.L. 1987. *Selected geohydrologic data for the Mesilla Basin, Doña Ana County, New Mexico and El Paso County, Texas*. U.S. Geological Survey, Open-File Report 87-75. 59 p.

Naus, C.A. 2002. Conceptual model of the bolson-fill aquifer, Soledad Canyon area, Doña Ana County, New Mexico. *New Mexico Geological Society, 53rd Field Conference Guidebook*. 309-318.

Nickerson, E.L. 1989. *Aquifer tests in the flood-plain alluvium and Santa Fe Group at the Rio Grande near Canutillo, El Paso County, Texas*. U.S. Geological Survey Water-Resources Investigations Report 89-4011. 29 p.

Nickerson, E.L. 1995. *Selected geohydrologic data for the Mesilla ground-water basin, 1987 through 1992 water years, Doña Ana County, New Mexico and El Paso County, Texas*. U.S. Geological Survey, Open-File Report 95-111. 123 p.

Nickerson, E.L. 1999. U.S. Geological Survey seepage investigations of the Lower Rio Grande in the Mesilla Valley. In *Water Challenges on the Lower Rio Grande*. Edited by C.T. Ortega Klett. Proceedings of the 43rd Annual New Mexico Water Conference, New Mexico Water Resources Research Institute Report No. 310: 59-68.

Nickerson, E.L. and R.G. Myers. 1993. *Geohydrology of the Mesilla ground-water basin, Doña Ana county, New Mexico, and El Paso County, Texas*. U.S. Geological Survey Water-Resources Investigations Report 92-4156. 89 p.

Orr, B.R. and R.G. Myers. 1986. *Water resources in basin-fill deposits in the Tularosa Basin, New Mexico*. U.S. Geological Survey Water Resources Investigations Report 85-4219. 94 p.

Orr, B.R. and D.W. Risser. 1992. *Geohydrology and potential effects of development of freshwater resources in the northern part of the Hueco Bolson, Doña and Otero Counties, New Mexico, and El Paso County, Texas*. U.S. Geological Survey Water-Resources Investigations Report 91-4082. 92 p.

Orr, B.R. and R.R. White. 1985. *Selected hydrologic data from the northern part of the Hueco Bolson, New Mexico and Texas*. U.S. Geological Survey Open-File Report 85-696. 88 p.

Ortiz, D., K.M. Lange, and L.V. Beal. 2001. *Water resources data, New Mexico, Water Year 2000, volume 1. The Rio Grande Basin, the Mimbres River Basin, and the Tularosa Valley Basin*. U.S. Geological Survey Water-Data Report NM-00-1. 411 p.

Peterson, D.M., R. Khaleel, and J.W. Hawley. 1984. *Quasi Three-dimensional Modeling of Groundwater Flow in the Mesilla Bolson, New Mexico*. New Mexico Water Resources Research Institute Technical Completion Report No. 178, New Mexico State University, Las Cruces, NM. 185 p.

Plummer, L.N., Bexfield, L.M., S.K. Anderholm, Sanford, W.E., and E. Busenberg. 2000. Geologic and hydrologic framework: C. Geochemical characterization of ground water flow paths in parts of the Santa Fe Group aquifer system, Middle Rio Grande Basin, New Mexico. In *U.S. Geological Survey Middle Rio Grande Basin Study—Proceedings of the Fourth Annual Workshop, Albuquerque, New Mexico*, February 15-16, 2000. Edited by J.C. Cole. U.S. Geological Survey Open File Report 00-488. 7-12.

Raatz, W.D. 2002. A stratigraphic history of the Tularosa Basin area, south-central New Mexico. *New Mexico Geological Society, 53rd Annual Field Conference Guidebook.* 141-147.

Reeves, C.C. Jr. 1969. Pluvial Lake Palomas, northwestern Chihuahua, Mexico. *New Mexico Geological Society, 20th Annual Field Conference Guidebook*. 143-154.

Reiter, M. 2001. Using precision temperature logs to estimate horizontal and vertical groundwater flow components. *Water Resources Research*. 37: 3:663-674.

Reynolds, C.B. & Associates. 1986. *Shallow seismic reflection survey, Canutillo area, Texas and New Mexico*. Unpublished consultant's report for U.S. Geological Society by Charles B. Reynolds & Associates, 4409 San Andres Ave., NE, Albuquerque, NM 87110. 8 p., 2 figs., 12 enclosed seismic profiles.

Reynolds, C.B. & Associates. 1987. *Shallow seismic reflection line CA-1, Doña Ana County, New Mexico and El Paso County, Texas*. Unpublished consultant's report for U.S. Geological Society by Charles B. Reynolds & Associates, 4409 San Andres Ave., NE, Albuquerque, NM 87110. 4 p., 1 fig., 2 enclosed seismic profiles.

Richardson, G.B. 1909. *Description of the El Paso quadrangle, Texas*. U.S. Geological Survey Geological Atlas, El Paso folio, series 116. 11 p.

Richardson, G.L, T.G. Gebbard, Jr., and W.F. Brutsaert. 1972. *Water-table investigation in the Mesilla Valley*. Las Cruces, New Mexico State University, Engineering Experiment Station Technical Report 76. 206 p.

Ross, H.P. and J.C. Witcher. 1998. Self-potential surveys of three geothermal areas in the southern Rio Grande rift, New Mexico. *New Mexico Geological Society, 49th Annual Field Conference Guidebook*. 93-100.

Sanford, W.E., L.N. Plummer, D.P. McAda, L.M. Bexfield, and S.K. Anderholm. 2000. Geologic and hydrologic framework: B. Estimation of hydrologic parameters for the ground-water model of the Middle Rio Grande Basin using Carbon 14 and water-level data. In *U.S. Geological Survey Middle Rio Grande Basin Study—Proceedings of the Fourth Annual Workshop, Albuquerque, New Mexico*, February 15-16, 2000. Edited by J.C. Cole. U.S. Geological Survey Open File Report 00-488. 4-6.

Sawyer, D.A. and J.S. Pallister. 1989. Geologic Framework of the southern Basin and Range. In *Field Excursions to Volcanic Terranes in the Western United States, Vol. I: Southern Rocky Mountain Region*. Edited by C.E. Chapin and J. Zidek. New Mexico Bureau of Mines and Mineral Resources Memoir 46. 121-126.

Sayre, A. N. and P. Livingston. 1945. *Ground-water resources of the El Paso area, Texas*. U.S. Geological Survey Water-Supply Paper 919. 190 p.

Scanlon, B.R., B.K. Darling, and W.F. Mullican III. 2001. Evaluation of groundwater recharge in basins of Trans-Pecos Texas. In *Aquifers of West Texas*. Edited by R.E. Mace, W.F. Mullican III, and E.S. Angle. Austin, Texas Water Development Board Report 356:26-40.

Schmidt, R.H., Jr. 1986. Chihuahuan climate. In *Invited Papers from the Second Symposium on Resources of the Chihuahuan Desert Region—United States and Mexico, II*, Alpine, Texas, October, 1983. Chihuahuan Desert Research Institute. 40-63.

Schmidt, R.H. Jr. and R.A. Marston. 1981. Los Medanos de Samalayuca, Chihuahua, Mexico. *New Mexico Journal of Science*. 21:2:21-27.

Schultz-Makuch, D., P. Goodell, T. Kretzschmar, and J.F. Kennedy. 2003. Microbial and chemical characterization of a groundwater flow system in an intermontane basin of southern New Mexico, USA. *Hydrogeology Journal*. 11. 3:401-412.

Scurlock, Dan. 1998. *From the Rio to the Sierra: An environmental history of the Middle Rio Grande basin*. U. S. Department of Agriculture, Rocky Mountain Research Station, Forest Service General Technical Report, RMRS-GTR-5. 440 p.

Seaber, P.R. 1988. Hydrostratigraphic units. In *Geology of North America–Hydrogeology*. Edited by W. Back, J.S. Rosenshein, and P.R. Seaber. Geological Society of America. 0-2:69-78.

Seager, W.R. 1975. *Geologic map of the southern half of the San Diego Mountain fifteen-minute quadrangle, New Mexico.* New Mexico Bureau of Mines and Mineral Resources Geologic Map 60, scale 1:125,000.

Seager, W.R. 1981. *Geology of the Organ Mountains and southern San Andres Mountains, New Mexico*. New Mexico Bureau of Mines and Mineral Resources, Memoir 36. 97 p.

Seager, W.R. 1983. Laramide wrench faults, basement-cored uplifts and complementary basins in southern New Mexico. *New Mexico Geology*. 5:69-76.

Seager. W.R. 1987. Caldera-like collapse at Kilbourne Hole Maar, New Mexico. *New Mexico Geology*. 9:4:69-73.

Seager, W.R. 1989. Geology beneath and around the West Potrillo Basalts, Doña Ana and Luna Counties, New Mexico. *New Mexico Geology*. 11:3:53-58.

Seager, W.R. 1995. *Geologic map of the southwest part of Las Cruces and northwest part of El Paso.* 1x2 degree sheets, New Mexico, New Mexico Bureau of Mines and Mineral Resources Geologic Map GM-60, scale 1:125,000.

Seager, W.R. 2003. Laramide (Late cretaceous-Eocene) tectonics of southwestern New Mexico. In *The Geology of New Mexico*. New Mexico Geological Society Special Publication (in press).

Seager, W.R. and J.W. Hawley. 1973. *Geology of Rincon quadrangle, New Mexico.* New Mexico Bureau of Mines and Mineral Resources Bulletin 102. 56 p.

Seager, W.R. and G.H. Mack. 1986. *Laramide paleotectonics of southern New Mexico*. American Association of Petroleum Geologists. Memoir 41. 660-685.

Seager, W.R. and Mack, G.H. 1994. *Geology of the East Potrillo Mountains and vicinity, Doña Ana County, New Mexico*. New Mexico Bureau of Mines and Mineral Resources Bulletin 113. 27 p.

Seager, W.R. and Mack, G.H. 2003. *Geology of the Caballo Mountains, New Mexico*. New Mexico Bureau of Mines and Mineral Resources, Memoir 49. 136 p.

Seager, W.R. and P. Morgan. 1979. Rio Grande rift in southern New Mexico, west Texas, and northern Chihuahua. In *Rio Grande Rift: Tectonics and Magnetism*. Edited by R.E. Riecker. American Geophysical Union, Washington, D.C. 87-106.

Seager, W.R., R.E. Clemons, and J.W. Hawley. 1975. *Geology of Sierra Alta Quadrangle, Doña Ana County, New Mexico*. New Mexico Bureau of Mines and Mineral Resources Bulletin 102. 56 p.

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

Seager, W.R., F.E. Kottlowski, and J.W. Hawley. 1976. *Geology of Doña Ana Mountains, New Mexico.* New Mexico Bureau of Mines and Mineral Resources Circular 147. 36 p., 2 tables, 13 figs., 3 sheets.

Seager, W.R., R.E. Clemons, J.W. Hawley, and R.E. Kelley. 1982. *Geology of northwest part of Las Cruces* 1^o *x* 2^o *sheet, New Mexico*. New Mexico Bureau of Mines and Mineral Resources Bulletin 97. 38 p.

Seager, W.R., J.W. Hawley, F.E. Kottlowski, and S.A. Kelley. 1987. *Geology of the east half of Las Cruces and northeast El Paso, 1x2 degree sheets, New Mexico.* New Mexico Bureau of Mines and Mineral Resources Geologic Map GM-57, scale 1:125,000.

Seager, W.R., G.H. Mack, M.S. Raimonde, and R.G. Ryan. 1986. Laramide basement-cored uplift and basins in south-central New Mexico. *New Mexico Geological Society, 37th Annual Field Conference Guidebook*. 123-130.

Seager, W.R., M. Shafiqullah, J.W. Hawley, and R.F. Marvin. 1984. *New K-Ar dates from basalts and evolution of the southern Rio Grande Rift*. Geological Society of America Bulletin. 95:87-99.

Sharp, J.M., Jr. 2001. *Regional groundwater flow systems in basins in Trans-Pecos Texas. In Aquifers of West Texas*. Edited by R.E. Mace, W.F. Mullican III and E.S. Angle. Austin, Texas Water Development Board Report 356:41-55.

Shomaker, J.W. and S.R. Finch Jr. 1996. *Multilayer ground-water flow model of southern Jornada del Muerto Basin, Doña Ana County, New Mexico, and predicted effects of pumping wells LRG-430-S-29 and -S-30*. Albuquerque, New Mexico. John Shomaker & Associates, Inc. 26 p.

Slichter, C.S. 1905. *Observations on ground waters of the Rio Grande valley*. U.S. Geological Survey Water-Supply Paper 141. 83 p.

Smith, G.A. 1994. *Climatic influences on continental deposition during late-stage filling of an extensional basin, southeastern Arizona*. Geological Society of America Bulletin. 106: 1212-1228.

Snyder, J.T. 1986. *Heat flow in the southern Mesilla Basin, with an analysis of East Potrillo geothermal system, Doña Ana County, New Mexico.* New Mexico State University, unpublished Master's Thesis. 252 p.

Sonnichsen, C.L. 1968. *Pass of the North, four centuries on the Rio Grande.* The University of Texas at El Paso, Texas Western Press. 469 p. *See comments on EPN reach on p.14-17, 29, 79, 89-91,106-107,132,135-136,147,262, 282-284.*

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

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

Strain, W.S. 1971. *Late Cenozoic bolson integration in the Chihuahua tectonic belt. In The geologic framework of the Chihuahua tectonic belt.* West Texas Geological Society Publication No. 71-59. 167-173.

Swanberg, C.A. 1975. Detection of geothermal components in ground waters of Doña Ana County, southern Rio Grande rift, New Mexico. *New Mexico Geological Society, 26th Annual Field Conference Guidebook.* 175-180.

Theis, C.V. 1938. Ground water in the middle Rio Grande valley. In *Rio Grande Joint Investigation in the Upper Rio Grande Basin in Colorado, New Mexico, and Texas*. National Resources Committee, Regional Planning, Part VI. Washington, D.C., U.S. Government Printing Office. 1, part 2: 268-291.

Thomas, H.E. 1962. *The meteorologic phenomenon of drought in the Southwest--Drought in the Southwest, 1942-56.* U.S. Geological Survey Professional Paper 372-A. A1-A43.

Thomas, H.E. 1963. *General summary of the effects of the drought in the southwest, 1942-56.* U.S. Geological Survey Professional Paper 372-H. H1-H22.

Thorn, C.R., D.P. McAda, and J.M. Kernodle. 1993. *Geohydrologic Framework and Hydrologic Conditions of the Albuquerque Basin, Central New Mexico.* U.S. Geological Survey Water Resources Investigations Report 93-4149. 106 p.

Tolman, C.F. 1909. Erosion and deposition in southern Arizona bolson region. *Journal of Geology*. XVII:II:136-163.

Tolman, C.F. 1937. *Ground Water*. New York, McGraw-Hill Book Co. 593 p.

Uphoff, T.L. 1978. *Subsurface stratigraphy and structure of the Mesilla and Hueco bolsons, El Paso region, Texas and New Mexico.* The University of Texas at El Paso, unpublished Master's Thesis. 66 p.

U.S. Department of Commerce. 1999. *Cooperative Weather Station Data Files*. National Oceanic and Atmospheric Administration, National Climate Data Center.

U.S. Reclamation Service. 1914. *Maps of the Mesilla Valley showing various known river channels*. U.S. Department of the Interior, Bureau of Reclamation, Rio Grande Project.

Vanderhill, J.B. 1986. *Lithostratigraphy, vertebrate paleontology, and magnetostratigraphy of Plio-Pleistocene sediments in the Mesilla Basin, New Mexico*. Austin, The University of Texas, unpublished Ph.D. dissertation. 311 p.

Van Devender, T.R. 1990. Late Quaternary vegetation and climate of the Chihuahuan Desert, United States and Mexico. In *Packrat middens*. Edited by J.L. Betancourt, T.R. Van Devender, and P.S. Martin. University of Arizona Press, Tucson. 104-133.

Wade, S.C. and M. Reiter. 1994. Hydrothermal estimation of vertical ground-water flow, Cañutillo, Texas. *Ground Water*. 32:5: 735-742.

Waltemeyer, S.D. 2001. *Estimates of mountain-front streamflow available for potential recharge to the Tularosa Basin, New Mexico*. U.S. Geological Survey Water-Resources Investigations Report 01-4013. 8 p.

Wasiolek, M. 1995. *Subsurface Recharge to the Tesuque Aquifer System from Selected Drainage Basins along the Western Side of the Sangre de Cristo Mountains near Santa Fe, New Mexico*. U.S. Geological Survey Water Resources Investigations Report 94-4072. 43 p.

Water Resources Division. 1965. *Magnitude and frequency of floods in the United States—Part 8, Western Gulf of Mexico basins*. U.S. Geological Survey Water-Supply Paper 1682:418-419.

Wen, C-L. 1983. *A study of bolson-fill thickness in the southern Rio Grande rift, southern New Mexico, west Texas and northern Chihuahua*. The University of Texas at El Paso, unpublished Master's Thesis. 74 p.

West, F. 1996. The Mesilla Valley: A century of water resources investigations. In *Proceedings of the 40th Annual New Mexico Water Conference. Reaching the limits: Stretching the resources of the Lower Rio Grande*. Edited by C.T. Ortega Klett. New Mexico Water Resources Research Institute Report No. 297. 21-28.

Wilkins, D.E. and D.R. Currey. 1997. Timing and extent of Late Quaternary paleolakes in the Trans-Pecos closed basin, west Texas and south-central New Mexico. *Quaternary Research*. 47:306-315.

Wilkins, D.W. 1986. *Geohydrology of the Southwest Alluvial Basins, Regional Aquifer-systems analysis in parts of Colorado, New Mexico, and Texas*. U.S. Geological Survey Water Resources Investigations Reports 84-4224. 61 p., plates.

Wilkins, D.W. 1998. *Summary of the Southwest Alluvial Basins, Regional Aquifer-systems Analysis in Parts of Colorado, New Mexico, and Texas*. U.S. Geological Survey Professional Paper 1407-A. 49 p.

Williams, W.J.W. 1999. *Evolution of Quaternary intraplate mafic lavas using ^{3}He surface exposure and ^{40}Ar/^{39}Ar dating, and detailed elemental He, Sr, Nd, and Pb isotopic signatures: Potrillo Volcanic Field, New Mexico, U.S.A., and San Quintín Volcanic Field, Baja California Norte, México*. The University of Texas at El Paso, unpublished Ph.D. dissertation. 195 p.

Williams, W.J.W., E.Y. A.M. Whitelaw, J. Poths, H. Healey, and J. Geissman. 1993. ^{3}He surface exposure dates and chemistry of the Potrillo volcanic field, Rio Grande rift, and magmatic ^{3}He/^{4}He signatures of Quaternary lavas of the southwestern United States. *International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI)*, 1993 General Assembly in Canberra, Australia, Abstract Volume: 123.

Wilson, C.A., R.R. White, R.B. Orr, and R.G. Roybal. 1981. *Water Resources of the Rincon and Mesilla Valleys and Adjacent Areas*. New Mexico State Engineer Technical Report 43. 514 p.

Wilson, C.A. and R.R. White. 1984. *Geohydrology of the Central Mesilla Valley, Doña Ana County, New Mexico*. U.S. Geological Survey, Water Resources Investigations Report 82-555. 144 p.

Winograd, I.J. and W. Thordarson. 1975. *Hydrogeologic and Hydrogeochemical Framework, South-central Great Basin, Nevada-California, with Special Reference to the Nevada Test Site*. U.S. Geological Survey Professional Paper 712-C. 126 p.

Wislizenus, A. [Frederick Adolph(us)]. 1969. *Memoir of a tour to northern Mexico, connected with Col. Doniphan's expedition in 1846 and 1847 [1848]. With foreword by Jack D. Rittenhouse*. Albuquerque, Calvin Horn Publisher, Inc. 141p. *See comments on El Paso Narrows reach on pp. 39-43.*

Witcher, J.C. 1988. Geothermal resources of southwestern New Mexico. *New Mexico Geological Society, 39th Annual Field Conference Guidebook.* 191-197.

Witcher, J.C. 1991. The Rincon geothermal system, southern Rio Grande rift, New Mexico; a preliminary report on a recent discovery. *Transactions, Geothermal Resources Council.* 15:205-212.

Witcher, J.C. 1998. The Rincon SLH 1 discovery well. *New Mexico Geological Society 49th Annual Field Conference Guidebook*. 93-100.

Witcher, J.C., J.P. King, J.W. Hawley, J.F. Kennedy, J. Williams, M. Cleary, and L. Bothern. 2004. *Sources of Salinity in the Rio Grande and Mesilla Basin Groundwater*. New Mexico Water Resources Research Institute Technical Completion Report No. 330, New Mexico State University, Las Cruces, NM. 183 p.

Woodward, D.G. and R.G. Myers. 1997. *Seismic Investigation of the Buried Horst between the Jornada del Muerto and Mesilla Ground-Water Basins near Las Cruces/Dona Ana County, New Mexico*. U.S. Geological Survey Water Resources Investigations Report 97-4147. 45 p.

Zohdy, A. A. R. 1969. The use of Schlumberger and equatorial soundings in groundwater investigations near El Paso, Texas. *Geophysics*. 4:713-728.

Zohdy, A. A. R., R.J. Bisdorf and J.S. Gates. 1976. *Schlumberger soundings in the lower Mesilla Valley in the Rio Grande, Texas and New Mexico*. U.S. Geological Survey Open-File Report 76-324. 77 p.